Redefining Recovery: The Role of Sleep, Nutrition, and Technology in Athlete Rehabilitation

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ABSTRACT

This review examines the crucial roles of sleep, nutrition, and emerging technologies in promoting athlete recovery and rehabilitation. Quality sleep is crucial for physical recovery, cognitive function, and injury prevention, as insufficient sleep increases the risk of musculoskeletal injuries. Nutritional strategies, particularly macronutrient timing and supplementation, play a crucial role in tissue repair, controlling inflammation, and accelerating recovery timelines. Wearable technologies, including sensors and biomechanical assessments, provide real-time data, enabling the development of personalized recovery strategies tailored to individual needs. Despite these advances, further research is needed to refine recovery modalities and integrate sport-specific, individualized recovery plans. Future directions should optimize sleep, nutrition, and technology to achieve a comprehensive and multidimensional recovery approach, thereby helping athletes reduce injury risks and enhance their long-term performance.

Keywords: Athlete rehabilitation, Sleep quality, Macronutrient timing, Wearable technologies, Personalized recovery

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Additional material is published online only. To view please visit the journal online.

Cite this as: Ahmed R. Redefining Recovery: The Role of Sleep, Nutrition, and Technology in Athlete Rehabilitation. Premier Journal of Sports Science 2025;2:100006

DOI: https://doi.org/10.70389/PJSPS.100006

Received: 11 May 2025
Revised: 12 July 2025
Accepted: 12 July 2025
Published: 26 July 2025

Ethical approval: N/a
Consent: N/a
Funding: No industry funding
Conflicts of interest: N/a
Author contribution: Riaz Ahmed – Conceptualization, Writing – original draft, review and editing
Guarantor: Riaz Ahmed
Provenance and peer-review: Unsolicited and externally peer-reviewed
Data availability statement: N/a

Background and Introduction

Sleep, nutrition, and technology are vital in athlete recovery and rehabilitation. A recent study shows that sleep deprivation ≤7 hours significantly raises the risk of musculoskeletal injuries, and athletes who sleep below 7 hours will be 1.7 times more likely to suffer from injuries after 14 days of sleep deprivation.[1] Sleep is crucial for athletic recovery, mental resilience, and injury prevention, as it is associated with poor sleep performance and an increased risk of injury.[2] Macronutrient timing and supplementation, including omega-3s and collagen, play a key role in accelerating recovery and reducing inflammation and tissue damage (see Figure 1).[3]

Wearable tools that track sleep and recovery variables (HRV, readiness scores) have been proven to help increase recovery processes with up-to-date information.[4] Post-exercise recovery can be enhanced by incorporating cryotherapy and compression therapy, as they have been shown to reduce muscle soreness and inflammation.[5] Periodized recovery protocols related to cooling and heating interventions, tailored to the state of an athlete, are suggested to control fatigue and enhance recovery effectiveness.[5] Although significant progress has been achieved, further research is essential to refine recovery techniques and develop sport-specific models that integrate sleep, nutrition, and technology harmoniously.

Research Objectives

- To examine the physiological and psychological impact of sleep on athletic recovery and injury rehabilitation
- To analyze the role of nutritional strategies in enhancing tissue repair, inflammation control, and recovery timelines.
- To explore integrating emerging technologies (wearables, cryotherapy, neurostimulation) in monitoring and accelerating athlete rehabilitation.
- To synthesize current evidence to propose a multidimensional recovery model that synergizes sleep, nutrition, and technology.
- To identify research gaps and future directions for optimizing athlete recovery through integrative approaches.

Scope of the Review

This review examines the role of sleep, nutrition, and novel technologies in the recovery and rehabilitation of athletes. It examines the impact of sleep quality on physical and mental abilities, as well as how nutritional interventions can promote tissue healing and combat inflammation. Moreover, it examines how wearable technology helps monitor recovery results. This review discusses existing methods in rehabilitation and highlights the importance of personalized, comprehensive recovery plans tailored to individual athletes. It also identifies key areas of existing knowledge that require attention and suggests improvements that may lead to more effective recovery practices in various sports. Furthermore, this review emphasizes the importance of integrating interdisciplinary approaches in recovery, combining expertise from sports medicine, psychology, and nutrition to develop holistic rehabilitation strategies.

Methodology

This review synthesizes studies from 2020 to 2025 that explore the roles of sleep, nutrition, and technology in athlete recovery and rehabilitation (Figure 2). Articles were selected based on their relevance to the topic, publication in peer-reviewed journals, and focus on human subjects (Table 1). Studies examining sleep deprivation, nutritional strategies, and wearable technologies were included, while those focused on non-athletic populations or animal studies were excluded. This review aimed to identify key research gaps and propose an integrated approach to recovery that incorporates sleep, nutrition, and technological advancements.

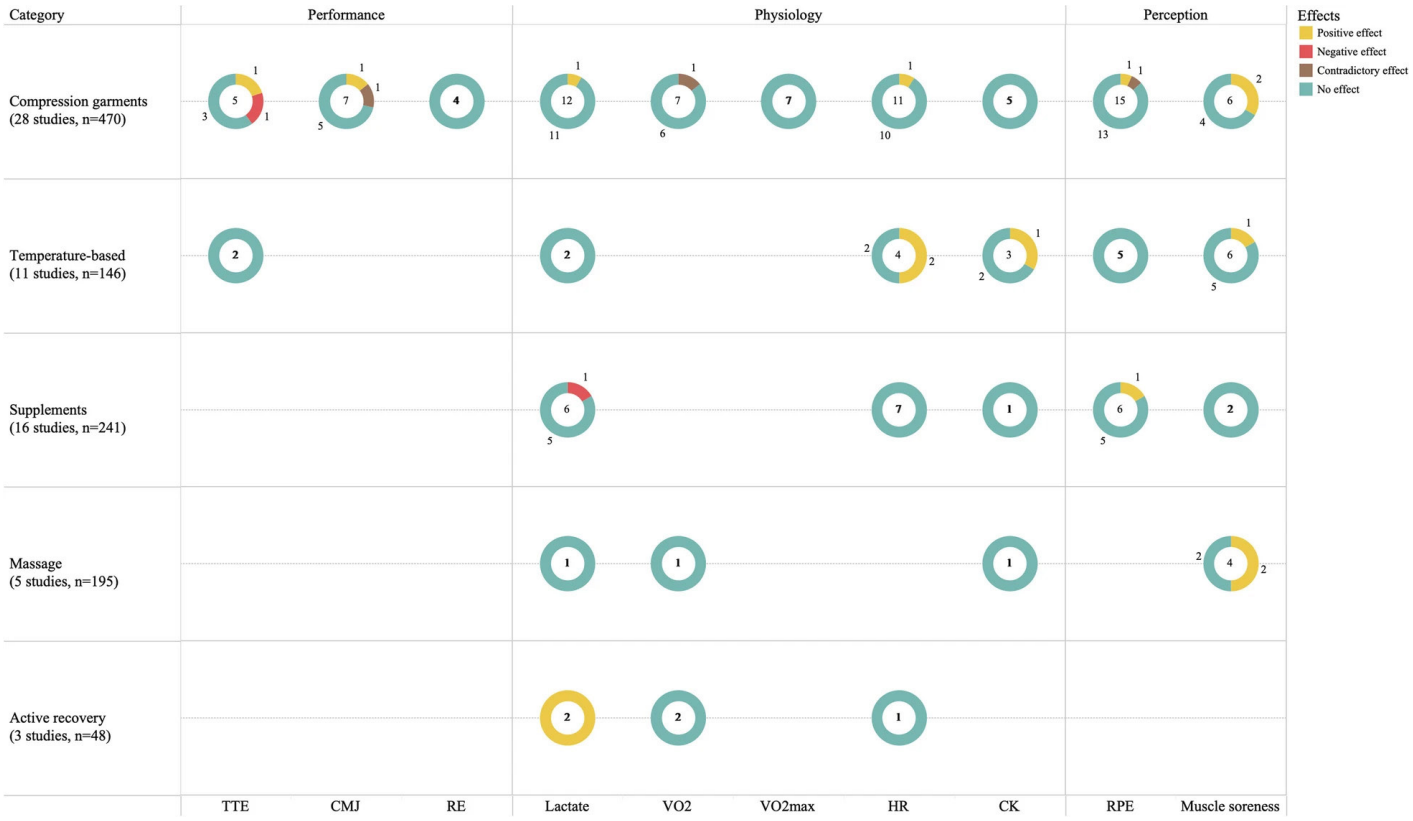


Fig 1 | Effect in endurance-athlete[3]

Table 1 | Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
Studies on sleep, nutrition, or wearable devices in athletes	Studies focusing on non-athletic populations
Peer-reviewed journal articles published between 2020 and 2025	Animal studies
Research on injury prevention, rehabilitation, and recovery	Articles not related to rehabilitation or recovery processes
Articles with human subjects	Studies published in non-peer-reviewed sources
Studies discussing macronutrient timing and supplementation	Studies with an insufficient sample size or poor methodological rigor

The Science of Sleep in Recovery

Sleep Quality and Athletic Performance

Sleep is a crucial component of athletic performance and recovery, with studies highlighting its significant impact on various aspects of physical and cognitive function. When athletes sleep for less than 7–8 hours a day, it can result in poor muscular strength, slower speeds, impaired cognitive function, and reduced athletic performance. Constantly insufficient sleep increases the risk of injuries, particularly musculoskeletal ones. Athletes also have insomnia and sleep apnea regularly, meaning that this can contribute to poorer performance and delayed recovery.[6]

A lack of sufficient sleep can lead to functional decline in athletes, impacting their attention, memory, and judgment on the field. Moreover, sleep deprivation can lead to elevated levels of stress hormones like cortisol, which can hinder muscle repair and recovery. For example, fatigued athletes may suffer slower reaction times and less effective decision-making, increasing their susceptibility to concussions and other harm.[7] Evidence correlates sleep quality to injury risk and underscores the need to favor sleep to prevent injuries and aid recovery. Research indicates that cognitive behavioral therapy for insomnia (CBT-I) is likely to improve the quality of sleep and potentially reduce the risk of injury by addressing sleep issues and cognitive discomfort.[7]

The Role of Napping and Sleep Interventions

Napping has been identified as an effective strategy to mitigate the effects of sleep deprivation, enhance performance, and improve nighttime sleep. Science shows that napping typically lasts between 20 and 90 minutes and is most effective between 1:00 and 4:00 PM.[8] It can significantly enhance physical abilities, brain performance, and psychological states. In addition to promoting nocturnal sleep, napping alleviates sleep inertia, allowing athletes to recuperate more quickly and exhibit higher performance in post-nap training or competition activities. By taking regular naps, athletes frequently report feeling better in terms of mood, experiencing reduced muscle soreness, and

DOI: https://doi.org/10.70389/PJSPS.100006 | Premier Journal of Sports Science 2025;2:100006

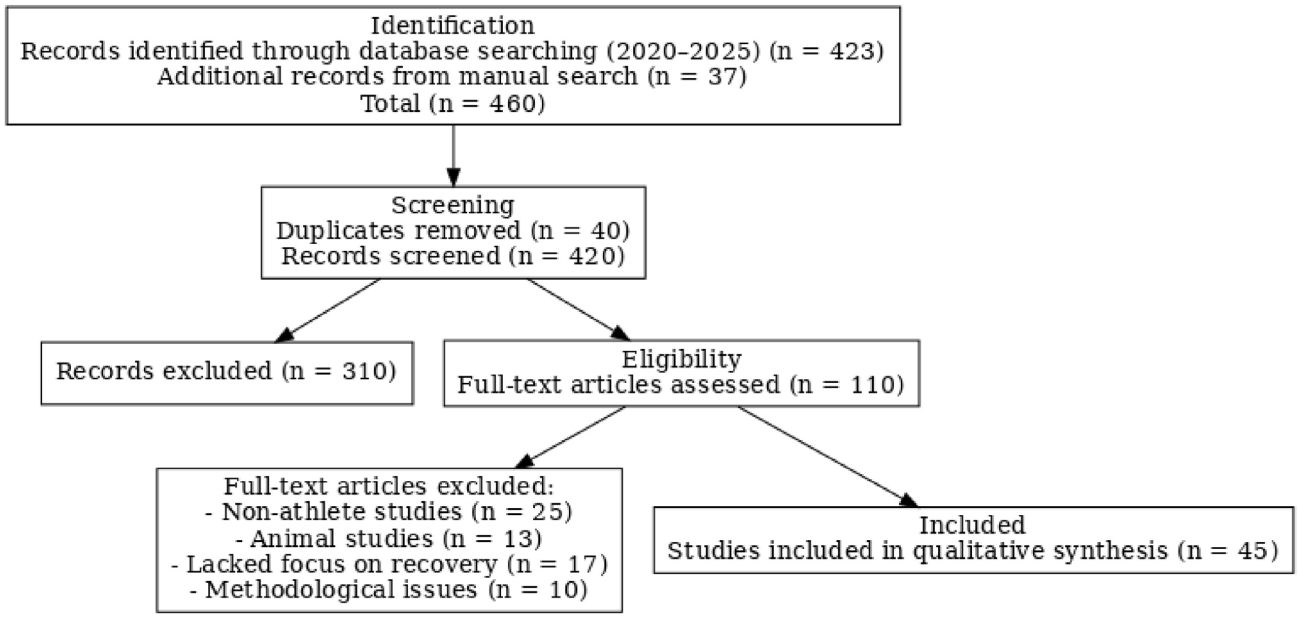


Fig 2 | PRISMA flow of the paper

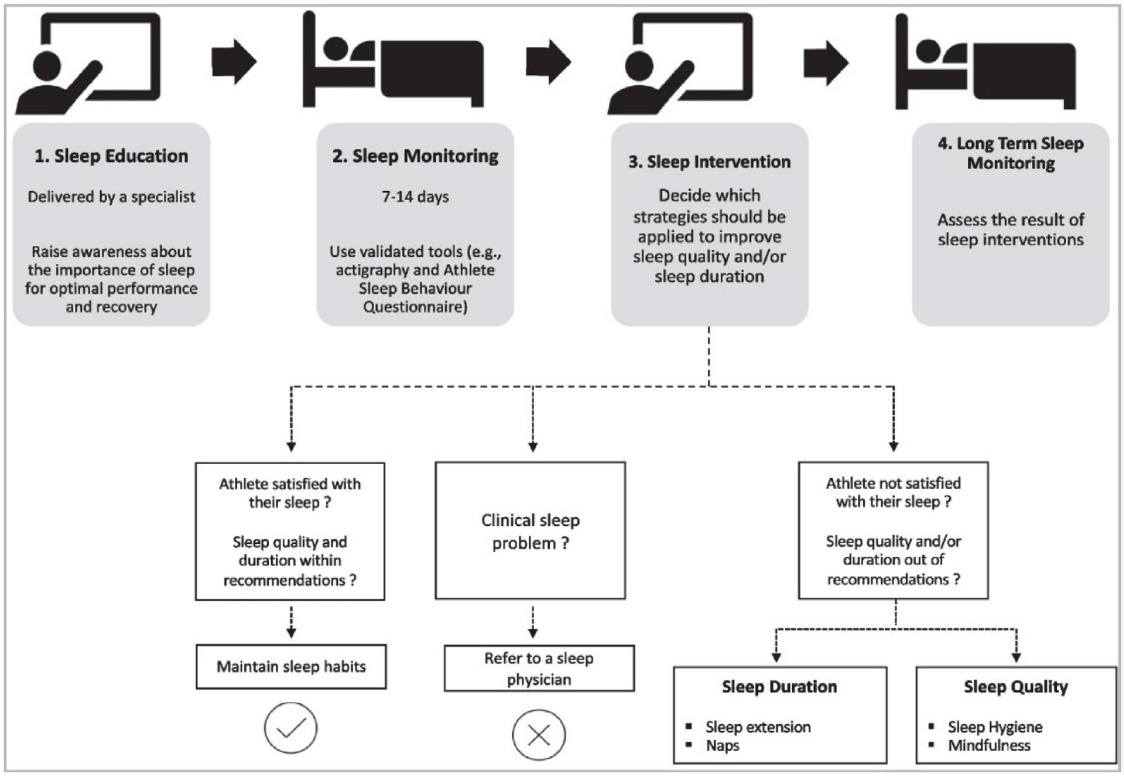


Fig 3 | Sleep intervention aimed at improving sleep and recovery[10]

an enhanced level of alertness, all of which facilitate effective training sessions and prevent injuries.[8,9] A controlled increase in sleep time is associated with improvements in critical areas of sports performance, including shorter reaction times, enhanced sprinting results, and improved skill execution during activities such as swimming and basketball. Sleeping profusely before crucial moments, which is sometimes referred to as "banking sleep," that athletes ensure for themselves, may help them avoid the predicament brought about by a lack of rest.[9]

Furthermore, practices such as mindfulness and light therapy have demonstrated promising results regarding sleep and athletic performance; however, further exploration is needed to determine their effectiveness (see Figure 3).[10] A night of adequate sleep

has a positive impact not only on athletic performance benefits and injury prevention but also on athlete performance improvement and injury prevention. Sleep of good quality and sufficient sleep is necessary to enhance optimal recovery and prevent injuries among athletes. Training plans that incorporate strategies such as napping and adjusting sleep time, as well as CBT-I, can significantly enhance athletic performance and recovery. When athletes proactively address sleep challenges in a timely manner, they can enhance their physical and cognitive capabilities, ultimately leading to improved sports performance.

Nutrition as a Recovery Modulator

Nutritional Strategies for Post-Exercise Recovery

Nutritional strategies are essential in optimizing post-exercise recovery by replenishing energy stores, repairing muscle damage, and enhancing subsequent performance. The intake of carbohydrates after exercising is a vital component in replenishing glycogen levels. Nutritionists emphasize that selecting suitable carbohydrates and consuming them at the right time is beneficial, as it can lead to increased glycogen storage and enhanced muscle recovery after exercise.[11] Protein is essential for muscle recovery, as it facilitates a positive nitrogen balance, which is crucial for muscle development and tissue repair. When carbohydrate intake is low, combining protein with carbohydrates or fats increases muscle recovery.[12] The importance of hydration in recovery cannot be overstated, as milk-based drinks and electrolytes can help balance the body and maximize recovery. Furthermore, incorporating healthy fats and micronutrients, such as vitamins and minerals, can further support tissue repair and reduce inflammation.

Micronutrients, such as omega-3 fatty acids, antioxidants, and sodium bicarbonate, have been shown to benefit muscle damage, particularly when combined with optimal acid-base balance and muscle repair.[11] Personalized recovery strategies are essential for optimal recovery, particularly for athletes with short recovery periods. Figure 4 illustrates the integral function of food supplements in stimulating post-exercise recovery, which describes their specific role in supporting recovery systems and enhancing athletic performance.[13]

Macronutrient and Micronutrient Role in Injury Recovery

Injury recovery requires a balanced diet to minimize muscle loss, promote tissue repair, and expedite the return-to-play process. In line with recommendations,[12] daily intake of 25–30 kcal/kg body weight ensures excess energy, which helps oppose sarcopenia and accelerate recovery. Host studies suggest a perioperative daily protein intake of 1.5–2.0 g/kg during recovery, with extra focus on exceeding 2.0 g/kg in cases of extreme tissue damage or post-surgical intervention.[14] Inadequate levels of protein intake help repair muscles, create collagen, and reduce inflammation, thus becoming essential for overall recovery. Carbohydrates are essential in restoring glycogen stores and maintaining muscle, although omega-3 polyunsaturated Fatty acids, omega-3 PUFAs, may reduce muscle loss with immobilization, while the latter's effects on wound healing during the initial stage of recovery have been the subject of debate.[14] Sources of antioxidants, anti-inflammatory supplements, and probiotics are essential in countering the latter, minimizing oxidative damage, and increasing immune activity; all collectively help in muscle recovery and reduce the ravages of reinjury.[14] By optimizing the intake of these macronutrients and micronutrients, athletes can recover faster, build stronger muscles, and avoid additional injuries when recuperating from injuries.

Emerging Trends in Post-Exercise Recovery Nutrition

Functional foods, such as tart cherry juice, omega-3-rich foods (e.g., fish, flaxseeds), and turmeric, are gaining attention for their bioactive compounds that mitigate oxidative stress and inflammation, both of which are important for recovery.[13] Supplements benefit gut health due to the presence of pre- and probiotics, which help strengthen the immune system and are critical factors in successful recovery. This personalized nutrition strategy, based on genetic and metabolic testing, has great potential.

Supplement Name	Supplement Key Features	Benefits and Potential Drawbacks	Contraindications/Side Effects
Protein Supplements (Whey, Casein, Plant-Based)	Rapid digestion (whey), sustained release (casein), plant-based options for complete amino profiles	Enhances muscle repair and hypertrophy; convenience; potential bloating or allergies with whey [63,64,65]	Allergic reactions (soy, whey); gastrointestinal issues [98]
Branched-Chain Amino Acids (BCAAs)	Includes leucine, isoleucine, and valine; readily used as energy in muscle	Reduces muscle soreness and fatigue; supports endurance; risks with excess intake [77,78]	Potential contribution to atherosclerosis if overconsumed [81]
Creatine Monohydrate	Enhances ATP production; aids high-intensity recovery	Minimizes muscle damage and inflammation; supports muscle growth and cognitive clarity [82,83]	May cause water retention kidney stress with long-term misuse [86]
Electrolyte Supplements	Supports fluid and electrolyte balance (sodium, potassium, magnesium)	Prevents dehydration; supports nerve function and recovery in hot conditions [87,88]	Excessive sodium intake could affect blood pressure [91]

Fig 4 | Role of food supplements in post-exercise recovery[13]

DOI: https://doi.org/10.70389/PJSPS.100006 | Premier Journal of Sports Science 2025;2:100006

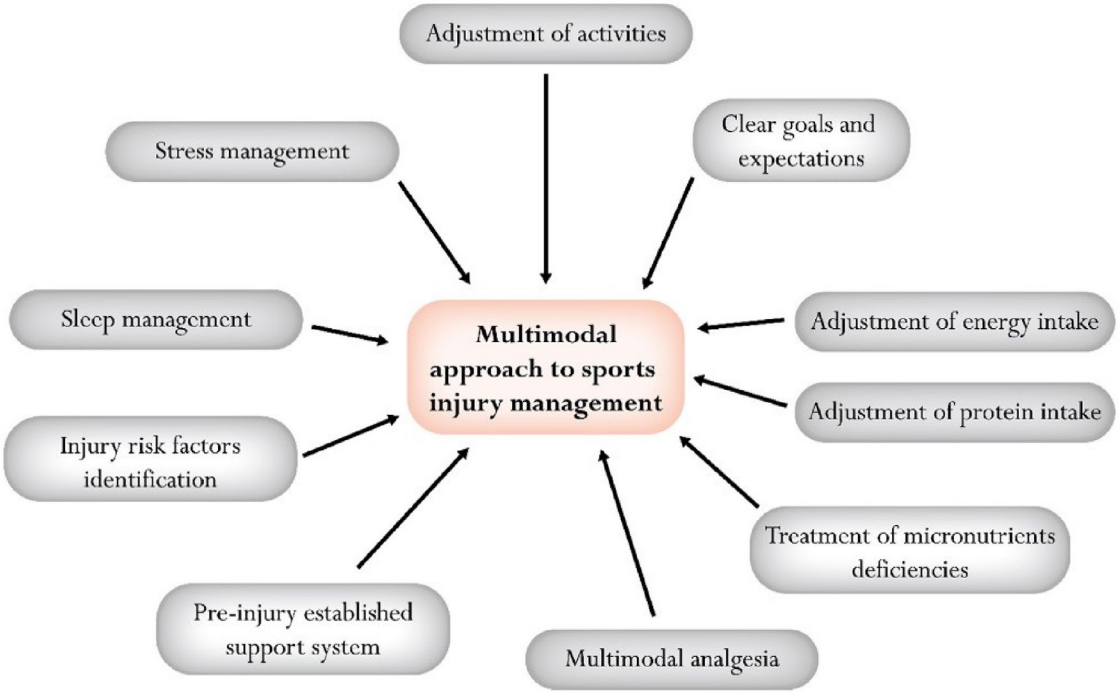


Fig 5 | Multimodal approach to sports injury management[10]

Personalized nutrition, which caters to each athlete's unique metabolic needs, contributes to improved recovery and performance.[13] Moreover, strong immune function with support from proper nutrition is critical to effective injury recovery and reducing the chances of getting injuries. A nutritious diet rich in protein, carbohydrates, fats, and essential micronutrients is crucial for tissue repair and overall health during rehabilitation. The clinical perspective is of great importance from the standpoint of this approach and can serve as a helpful basis for integrating several strategies to manage physical activity stress.[10] (see Figure 5). A well-rounded recovery strategy focuses on balancing nutrition rather than relying solely on supplementation.

Technology-Driven Recovery Tools

Wearable Sports Rehabilitation Systems

Wearable sports rehabilitation systems are transformative in optimizing recovery and rehabilitation processes. According to Xu et al., the use of big data technology in wearable rehabilitation systems increases the accuracy of rehabilitation data by 11.9% and, on average, by 20.8% in treatment cases.[15] Figure 5 illustrates that the systems are centered on sensor data and cloud infrastructure, providing instantaneous and personalized assistance.[15] Including such systems provides valuable information to help researchers and healthcare professionals make informed adjustments to rehabilitation procedures over time.

However, as Rodgers et al. indicated, despite the suggestive nature of its use in integrating wearable technology into rehabilitation, most of the available evidence involves short-term use, primarily in physical therapy and for managing extremity injuries.[16] The authors urged further research to determine the reliability of these technologies for long-term home use, especially regarding energy consumption, standard practices, and personal information security. Making wearable rehabilitation tools usable in a real-world scenario outside of hospitals entails facing and overcoming such challenges, which should increase their long-term usability and promote user engagement.

Furthermore, advancements in wearable technology, such as incorporating AI and machine learning algorithms, can provide real-time feedback and adapt recovery plans based on an athlete's progress. Other findings suggest that wearable devices are essential in the athlete's injury management process, as they can help athletes better manage inflammation and ensure proper hydration and recovery during exercise. The contribution of wearable devices to improving athletic performance and recovery is, without a doubt, significant, as the sports technology industry is projected to exceed $30 billion in 2 years.[17] Providing athletes with a way of monitoring their physical response during exercise and recovery, these technologies give them an edge over other athletes.

Injury Prevention and Optimization Through Sensors

Sensor-enhanced wearables have revolutionized injury prevention and performance optimization in sports by providing real-time data on an athlete's physiological and biomechanical metrics. Sensors embedded within wearables enable monitoring of critical parameters such as heartbeat, muscle function, and movement analysis.[18] Machine learning techniques analyze data to produce significant analytics and forecasts, enabling informed strategies that prevent injuries such

as soft-tissue damage and heat illness. This approach will enable athletes and coaches to rely on resources to make informed decisions, thereby creating safe training conditions. Wearable sensor devices (WSDs) play a critical role in the success of rehabilitation and injury prevention efforts.[19] Using these devices, athletes can control important parameters, such as joint displacement, velocity of body segments, and heart rate, which can indicate possible safety issues and inefficiencies in movement.

Real-time biomechanical information from WSDs enables clinicians and athletes to detect and correct performance problems that might cause severe injuries. WSDs, combined with motion capture and force plate technologies, enable a thorough analysis of athletic motion, which supports better injury prevention strategies. Force-plate technologies in plans to reduce injuries have borne positive results. When using these technologies, the injury rates recorded a 23% decline compared with a 14% increase in those not using them ($P = 0.049$), demonstrating significant declines in healthcare costs and the incidence of injuries.[19] Such data highlights the need to apply sensor technologies not only at rehabilitation sites but also during training, underscoring their contribution to reducing incidents of athlete injuries and enhancing their effectiveness. Furthermore, integrating sensor-based wearables into daily training routines enables athletes to monitor their physical limits, track progress, and make timely adjustments.

Integrative and Personalized Recovery Models

Personalized Injury Management and Recovery

Personalized injury management is crucial for optimizing recovery in athletes, particularly those involved in youth sports. Aldanyowi and AlOraini investigated the relationship between musculoskeletal injuries and quality of life in 130 youth athletes across various sports disciplines (see Figure 6). Notably, 55.4% of the respondents indicated that they experienced an acute injury during the previous 6 months with an average recovery period of 4 weeks.[20] There also existed significant relationships between overuse injuries and deteriorations in physical functioning ($r = -0.42$), bodily pain ($r = -0.38$), and mental health ($r = -0.31$).[20] This highlights the importance of personalized approaches to managing injuries in the physical and mental health support of youth athletes. The contribution of wearable technologies to injury prevention and the ability to adapt to injury training was measured by Rebelo et al., who identified player load and workload ratios as a significant predictor of injuries.[21]

As specified in the study, using force plates helps analyze fatigue and can be crucial in rehabilitating knee and ankle injuries.[21] Moreover, personalized recovery models that take into account an athlete's specific injury history, body type, and sport demands are essential for ensuring efficient rehabilitation. Adaptation of the level of training intensity based on these metrics can help load up injury prevention protocols. Jow emphasized the key role that individual recovery strategies play in addressing the unconventional needs of individual athletes.[22] The findings showed that individualized recovery, including physical rehabilitation, nutritional support, and mental well-being, is more effective in allowing swifter recoveries and reducing the likelihood of future injuries.

Holistic and Biopsychosocial Approaches to Recovery

A holistic recovery approach considers both physical and psychological factors to optimize athletic recovery. Edholm et al. concluded that factors such as nutrition

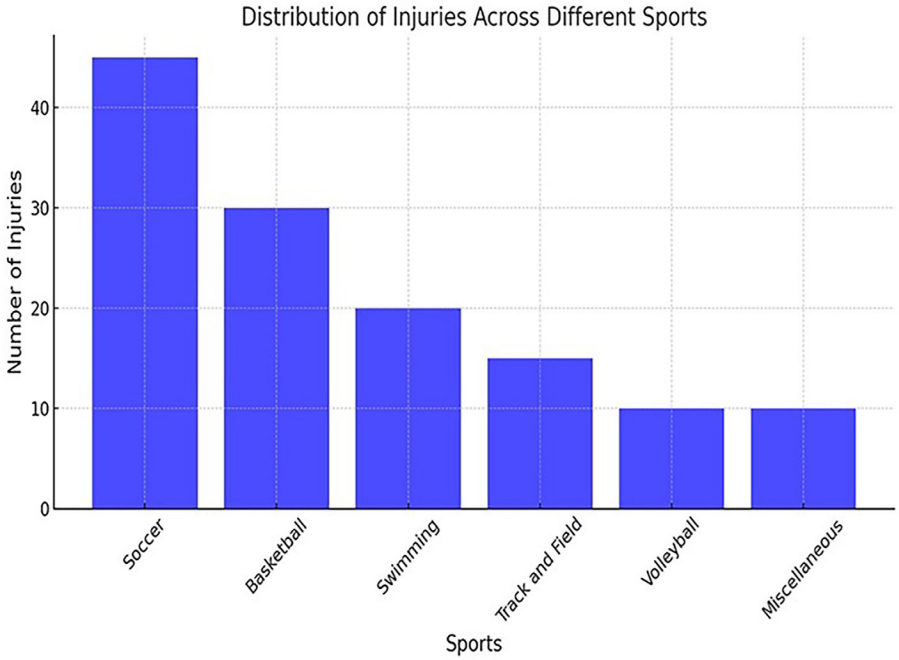


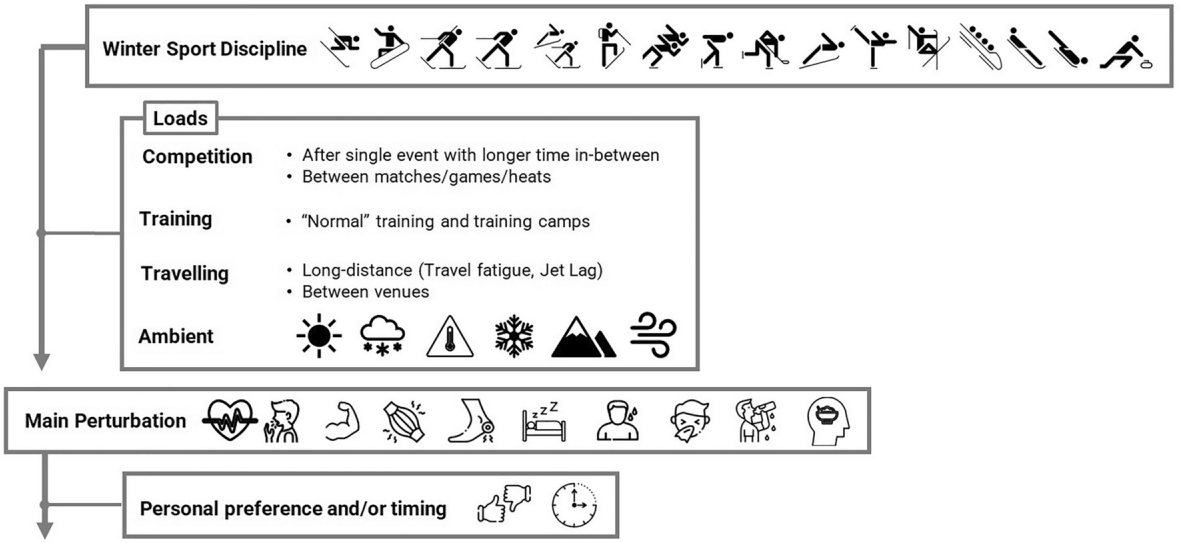
Fig 6 | Frequency of sports injuries[20]

DOI: https://doi.org/10.70389/PJSPS.100006 | Premier Journal of Sports Science 2025;2:100006

and sleep have a significant influence on recovery effectiveness.[23] The findings of the studies also identified cold-water immersion and massage as effective in reducing muscle soreness, whereas stretching had a limited effect. The study proposes a multi-component recovery plan tailored to each athlete, while further emphasizing the need for elite winter athletes competing in rigorous competition at the Milano-Cortina 2026 Olympic Games (Figure 7 outlines this approach). The research suggests that athletes, particularly those engaging in high-intensity activities, should receive personalized recovery strategies to optimize their performance response. The study examines the use of data science for surveillance of resilience warning markers, enabling individual feedback to athletes and their coaching staff. Paying attention to both body and mind enhances athletes' durability and overall endurance.

Data-Driven Personalization in Recovery

Personalized recovery programs are increasingly informed by data analytics and wearables, enabling real-time monitoring of an athlete's recovery progress. Wearable devices are a prerequisite for individualizing the recovery process. As reported, based on Rebelo et al.'s research, insights from wearables, such as player load and workload metrics, enabled the optimization of training loads and the prevention of injuries.[21] The integration of these technologies enables timely adjustments to recovery models based on the athlete's state. Moreover, Jow mentioned that personalized recovery programs combine physical therapy and psychological care.[22] Diagnostic imaging and biomechanical studies, supported by the data science discipline, enable the development of highly personalized recovery programs that not only maximize the chances of recovery but also sustain their effects over the long term. Harnessing data from wearables and high-tech diagnostic tools, individualized recovery programs for athletes help enhance recovery by addressing issues at both physical and psychological levels. Furthermore, the continuous collection and analysis of recovery data from wearables allows for predictive modeling, which can forecast potential setbacks or injuries before they occur.



Method	Main proposed effect	Infrastructure/ Cost	How often?	How long?	When?	Scientific support
Sleep/Naps	Improved memory consolidation, cellular repair, immune function and well-being	Low	1-2x/d	8h+	Nap 1-3 PM	High
Nutrition/Hydration	Restoring energy, water & electrocyte levels	Low	3x/d +	n.a.	Pre & Post	High
Massage Therapies	Reduce muscle swelling and tension, analgesic effects, Increased well-being	Moderate	1x/d	20-60 min	>2h post	Moderate
Cold-based Therapies	Reduce muscle temperature and blood flow, analgesic effects	Moderate/ High	1x/d	10-15 min	post	Moderate
Compression Garments	Reduced post-traumatic edema	Low	n.a.	Hours	post	Moderate
Heat-based Therapies	Increased muscle temperature/blood flow	Moderate/ High	1x/d	10-60 min	post	Low
Active Recovery by Exercise or by NMES	Increased muscular blood flow	Low/ Moderate	1x/d	5-10 (60) min	post	Low
Stretching-based Therapies	Increased ROM and analgesic effects	Low	n.a.	5-30 min	post	Low
Acupuncture/Dry Needling	Analgesic benefits	Moderate	1x/d	5-30 min	post	Low
Hyperoxia	Increased oxygen saturation	High	1x/d	10-20 min	post	Low

Fig 7 | Recovery optimization for Milano-Cortina 2026[23]

Current Debates and Limitations

Sports injury prevention and rehabilitation face several challenges, particularly due to the complex nature of injuries and the varying responses of athletes to treatment. While emphasizing these limitations, Edouard and Ford responded to the barriers by noting that no single prevention strategy has been shown to work for all athletes, resulting in uncertain benefits in many injury prevention interventions, especially in high-contact sports.[19] Furthermore, Paraskevopoulos et al. analyzed the barriers and motivators for successfully adhering to rehabilitation in injured volleyball athletes, and they found that a lack of motivation and fear of reinjury are usual impediments. Conversely, a good environment and communication with a healthcare provider are supportive factors.[24] King et al. emphasized that coaches play a crucial role in athletes' recovery, and effective communication and emotional support are essential for achieving positive rehabilitation outcomes.[25] Furthermore, customizing the recovery approach, especially in terms of periodization, is essential for athletes to achieve optimal performance and reduce recovery time individually.[26] Oya-Casero et al. reported that supervised eccentric exercise participants experienced far greater improvement in lateral elbow tendinopathy than participants who did self-exercise, highlighting the usefulness of skilled direction in rehabilitation attempts.[27] These studies highlighted the need to integrate extensive and individual strategies to prevent and overcome injuries. The limitations of current injury prevention and rehabilitation strategies underscore the necessity for a more personalized approach that considers an athlete's unique needs, motivations, and responses to treatment.

Future Directions

The future of sports rehabilitation holds exciting possibilities, with new technologies and approaches driving progress. Malhotra et al. examine the effects of Kinesio taping on muscle soreness and calf muscle flexibility in endurance athletes, using varying time intervals.[28] The results support the assumption that Kinesio taping may be of critical value for muscle recovery, indicating the effectiveness of the new method in combating soreness and enhancing athletes' flexibility. Richardson examines how private-sector sports rehabilitation transforms legacy models that may not meet the needs of contemporary athletes. The trend may be to develop individualized rehabilitation methods based on data and accessible technologies to meet the unique needs of athletes, rather than the currently prevailing but ineffective procedures.

Moreover, the addendum to the IOC consensus aims to guide Para sport researchers in accurately recording and interpreting health data specific to athletes with impairments. It offers tailored definitions and recommendations to address unique factors such as adaptive equipment and impairment classification.[29] The study of Dhahbi is dedicated to maximizing performance and avoiding injuries by improving biomechanics.[30] The integration of advanced technologies, such as AI-driven analytics, personalized data from wearables, and biomechanical assessments, will likely revolutionize how rehabilitation programs are tailored to each athlete. Biomechanics research can transform how athletes prepare and recover by providing information on a more fine-tuned level of movement mechanics and risk of injury mitigation. Utilizing biomechanics in conjunction with state-of-the-art technologies, such as wearables and AI, can enhance rehabilitation techniques to achieve optimal recovery for athletes and sustain peak performance in the long run. These findings indicate the path that sports rehabilitation takes, where custom therapies, integrative technologies, and biomechanical advances are critical considerations.

Conclusion

This review highlights the critical roles of sleep, nutrition, and emerging technologies in optimizing athlete recovery and rehabilitation. Recent studies highlighted the importance of proper sleep in enhancing performance, protecting cognition, and preventing injuries. These studies emphasized the importance of maintaining proper sleeping habits and how they can reduce the risk of injury. A nutrition strategy focused on targeting is crucial when it comes to (a) timely intake of macronutrients and supplementation, (b) supporting tissue repair, (c) reducing inflammation, and (d) accelerating recovery. Furthermore, integrating cutting-edge technologies (wearable devices and biomechanical assessments) into rehabilitation programs provides the latest information to personalize science-based recovery schemes.

There are recommendations for clinicians, coaches, and researchers to consider recovery and rehabilitation holistically and personally, thereby enhancing athlete outcomes. Systematic and comprehensive rehabilitation strategies should be given priority, especially for athletes returning to competitive training. Paster et al. promoted a holistic recovery strategy involving physical therapy, mental skills training, and preparation for special sports to allow a full return to competition.[31] Similarly, Trease et al. emphasized the important role of managing psychological and social aspects, such as stress, motivation, and support systems, in promoting recovery.[32] With this holistic approach, experts expedite effective recovery, minimize the chances of reinjury, and increase performance levels in elite athletes.

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