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## The Association Between Sleep Quality, Training Load and Injury Risk in Athletes

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### Abstract

Sleep is an essential component of athletic recovery, yet inadequate sleep is common among athletes and may influence both performance and injury risk. Training load also plays an important role, particularly when high workloads are combined with insufficient recovery. This article examines the relationship between sleep quality, training load, and injury risk in athletes. Current evidence suggests that poor sleep is associated with impaired recovery, reduced physical and cognitive performance, and a higher likelihood of musculoskeletal injury. Excessive or rapidly increasing training loads may further increase this risk when recovery is inadequate. However, the relationship is complex and influenced by individual, psychological,

and environmental factors. Monitoring sleep and training load may therefore help coaches, athletes, and medical staff identify periods of increased risk and improve recovery strategies. Further prospective research is needed to establish clearer causal relationships.

**Keywords:** athlete sleep; sleep quality; training load; workload management; sports injury; recovery; injury prevention; sports medicine; fatigue; monitoring.

## 1. Introduction

In high-performance sport, injury prevention is often framed as a question of physical preparation: Is the athlete strong enough, fast enough, conditioned enough and technically proficient enough to tolerate the demands of competition? That framing is necessary, but incomplete. The same external training stimulus can be well tolerated by one athlete and poorly tolerated by another depending on accumulated fatigue, recent workload history, musculoskeletal capacity, illness, psychological stress, travel, nutrition and sleep. Modern sports medicine therefore increasingly views injury risk as a dynamic state that changes from day to day rather than as a fixed characteristic of the athlete [1-4].

Sleep is central to this dynamic model. Athletes require sleep not only to feel rested, but to support neuromuscular function, learning, memory, endocrine regulation, immune processes, pain modulation and psychological recovery. The 2021 expert consensus on athlete sleep concluded that athletes are particularly susceptible to inadequate sleep and that a one-size-fits-all prescription is unlikely to be appropriate; sleep needs should be individualized around perceived requirements, training, travel and competition [5]. A broader review similarly described sleep as a fundamental component of performance optimization and as a factor relevant to injury risk and recovery [6].

At the same time, training is the stimulus that produces adaptation. Avoiding load is not a realistic injury-prevention strategy. International Olympic Committee (IOC) guidance emphasizes that poorly managed load, including rapid changes in training and competition exposure, competition congestion, psychological load and travel, can contribute to injury and illness [1,2]. The practical challenge is therefore to distinguish a productive load from a poorly tolerated load and to identify when the athlete's current recovery resources are insufficient for the demands being placed upon them.

Sleep and training load may influence injury risk through several shared pathways. A demanding training week can shorten sleep opportunity, delay sleep onset, fragment sleep or increase physiological arousal. Conversely, insufficient sleep may increase perceived exertion,

worsen vigilance and reaction time, reduce mood and impair the athlete's ability to respond to technical or tactical demands. These changes may reduce the margin between what the athlete is exposed to and what the athlete can safely absorb [5-8].

The purpose of this article is to synthesize the current evidence on the association between sleep quality, training load and injury risk in athletes; explain plausible mechanisms; examine the strengths and limitations of different monitoring approaches; and translate the evidence into practical recommendations suitable for applied sports medicine. The focus is on association and risk management, not on claiming that sleep or training-load metrics can predict injury with certainty.

## **2. Conceptual Framework: From Exposure to Injury**

Sports injury is best understood as the result of multiple interacting factors rather than a single cause. Training load is an exposure; injury is an outcome; and the athlete's capacity to tolerate that exposure is shaped by physical, biological, psychological and contextual variables. In this framework, sleep is neither simply a passive recovery behavior nor a standalone "protective factor." It is one component of recovery capacity that may modify the response to a given workload [1,3,5].

A useful distinction is between external and internal load. External load refers to what the athlete does: running distance, high-speed running, accelerations and decelerations, repetitions, throws, jumps, sessions, minutes played or total volume. Internal load refers to the athlete's physiological and perceptual response: heart rate, blood lactate in selected contexts, session rating of perceived exertion (sRPE), heart-rate-derived measures, perceived fatigue or other individualized response markers [3,9]. Two athletes can therefore receive an identical external workload yet experience different internal strain.

Capacity is equally important. Training increases capacity when repeated stressors are followed by sufficient recovery and adaptation. When the same athlete is exposed to excessive intensity, insufficient variation, abrupt increases, repeated competition or inadequate recovery, the balance can shift toward fatigue and reduced tolerance. The IOC consensus identifies rapid load changes and competition congestion as important considerations, but also stresses that load should be interpreted alongside athlete well-being and contextual information [1].

This framework helps explain why "high load" is not synonymous with "high injury risk." High-performing athletes often train at high workloads, and some forms of load are protective because they develop the physical qualities required for sport. The relevant question

is whether the current load is appropriate for the athlete's current capacity and whether recovery is keeping pace with demand [4,10].

### **3. Sleep in Athletes: Quantity, Quality and Timing**

#### **3.1 Sleep quantity**

Sleep quantity is usually expressed as total sleep time or time in bed, but quantity alone does not fully capture sleep health. The athlete may have enough opportunity for sleep yet spend substantial time awake, experience repeated awakenings, or have a schedule that is misaligned with competition and circadian biology. Consensus guidance therefore recommends individualized sleep targets based on the athlete's perceived sleep requirement and circumstances rather than applying a rigid universal number [5].

Habitual short sleep is common in elite sport. Training schedules can begin early in the morning, competition can finish late in the evening, and travel can create rapid shifts in sleep opportunity. The result may be a recurrent mismatch between biological sleep need and practical opportunity. This is particularly important in sports where athletes train twice daily or compete across time zones [5,11].

Sleep extension studies provide useful evidence that sleep is not merely a background behavior. In collegiate basketball players, extending time in bed to approximately 10 hours was associated with longer objective sleep and improvements in sprint performance, shooting accuracy, reaction time, daytime sleepiness and mood [12]. In endurance cyclists and triathletes, a short period of sleep extension helped maintain endurance performance compared with restricted sleep and improved psychomotor vigilance [13]. Although these studies were small and not designed to test injury prevention directly, they demonstrate that sleep opportunity can modify performance-relevant processes.

#### **3.2 Sleep quality**

Sleep quality encompasses subjective and objective dimensions, including sleep continuity, ease of falling asleep, night awakenings, perceived restfulness and sleep efficiency. In sports settings, quality can be affected by late competition, post-match excitement, muscle soreness, room environment, travel, anxiety and anticipation. The athlete who spends eight hours in bed may not obtain eight hours of consolidated restorative sleep.

Recent evidence strengthens the importance of quality as distinct from duration. In a 2025 prospective cohort study of 339 adult runners followed for 26 weeks, poorer sleep quality

was associated with a higher risk of running-related injury (hazard ratio 1.36, 95% CI 1.04-1.78), while elevated fatigue and muscle soreness appeared in the weeks immediately preceding injury [14]. This study is particularly relevant because sleep, recovery indicators and training load were followed longitudinally rather than measured only once at baseline.

Earlier research in collegiate sport also supports a possible relationship. Among 19 male collegiate basketball players followed across two seasons, greater sleep duration was independently associated with a lower risk of in-season injury even after adjustment for training load and subjective well-being [15]. By contrast, a systematic review of 12 prospective cohort studies concluded that, across adult athletic populations, the evidence was limited and too heterogeneous to establish poor sleep as an independent injury risk factor [16]. Taken together, these findings support cautious interpretation: sleep may matter, but its contribution varies by population, measurement method and context.

### **3.3 Sleep timing and circadian disruption**

Sleep opportunity is strongly influenced by when training and competition occur. Early-morning sessions can force athletes to wake before their preferred biological sleep period, while evening competition can delay the onset of sleep after exercise, travel and emotional arousal. Circadian disruption may therefore create a “hidden” load that is not captured by session distance or sRPE [5,11].

This is relevant to congested schedules. When an athlete competes every two or three days, the recovery window narrows. A late finish followed by early travel and morning training can reduce sleep opportunity even when the physical workload of the following day appears modest. In this situation, the injury risk may reflect the combined effect of residual fatigue, insufficient sleep, repeated exposure and limited time for tissue recovery rather than any single session.

## **4. Training Load and Injury Risk**

### **4.1 What is training load?**

Training load is a multidimensional concept. Volume, intensity, density, mechanical strain, metabolic demand and psychological stress all contribute. Monitoring guidance recommends a multidisciplinary approach rather than reliance on a single metric [3]. Common measures include total duration, distance, high-speed running, accelerations, repetitions, resistance-training volume, heart-rate load and sRPE. The best measure depends on the sport and the decision that the monitoring system is intended to support.

Load monitoring is most useful when it informs action. A data stream that does not change a training decision is unlikely to justify excessive complexity. The practitioner should be able to answer practical questions: Is the athlete coping with the planned week? Is fatigue accumulating? Has the athlete recently returned from injury? Has competition density increased? Has a key workload dimension changed abruptly? Is the athlete reporting poor sleep or soreness at the same time?

#### **4.2 Rapid changes and load spikes**

The IOC consensus identifies rapid changes in training and competition load as a major consideration in injury prevention [1]. The underlying idea is biologically intuitive: tissues adapt to repeated load, but the rate of adaptation is not unlimited. A sudden increase in running, sprinting, jumping or contact exposure can outpace local tissue capacity. However, the literature does not support a simplistic rule that any percentage increase in weekly volume automatically produces injury.

A systematic review of running-related injury research found very limited evidence that sudden changes in training load alone were consistently associated with injury, illustrating how difficult it is to isolate load from confounding factors [17]. In particular, the field contains substantial differences in how load is defined, how much an athlete has previously trained, what type of injury is studied and whether load is measured externally or internally.

This distinction is clinically important. A 20% increase for a highly trained athlete may be tolerable if it occurs in a planned progression with adequate recovery, whereas a smaller increase may be problematic for an athlete returning from injury or illness. The same numerical change can therefore represent a very different physiological event.

#### **4.3 Acute:chronic workload ratio: useful concept, imperfect tool**

The acute:chronic workload ratio (ACWR) became popular as a way of comparing recent workload with the athlete's recent training history. Systematic reviews have reported associations between higher ACWR values and non-contact or time-loss injury, which helped drive widespread adoption in elite sport [18,19].

However, the metric has also attracted substantial methodological criticism. Andrade and colleagues found considerable heterogeneity in the way ACWR is calculated, including differences in the workload metric, averaging method, time windows and injury definitions [20]. Other analyses argue that ratio-based metrics can introduce statistical artefacts, obscure causal interpretation and encourage overconfident thresholds [21,22].

For current practice, the most defensible position is therefore that ACWR can be one descriptive signal within a broader monitoring system, but should not be treated as a diagnostic test or injury predictor in isolation. The athlete's history, current readiness, sleep, soreness, injury status, competition schedule and actual sport-specific exposures remain essential to interpretation.

## **5. How Sleep and Training Load Interact**

Sleep and training load are often monitored on separate dashboards, but the athlete experiences them as one system. A demanding training block can worsen sleep; poor sleep can reduce tolerance to the next training stimulus; the resulting fatigue can alter training quality, movement strategy and perceived effort; and the cycle can reinforce itself. This bidirectional relationship is why longitudinal monitoring is more informative than a single "sleep score."

In professional soccer, daily training load has been linked to perceived sleep, fatigue, stress and delayed-onset muscle soreness, demonstrating that the athlete's wellness state changes alongside training exposure [23]. A 12-team prospective study of NCAA Division I men's and women's soccer found that lower chronic loading, greater training monotony, acute workload spikes and lulls, and having only one rest day in the previous week were associated with higher non-contact injury rates. Alterations in previous-week sleep quality were also associated with injury, while chronic sleep behavior and short-term sleep changes did not show consistent independent associations [24].

The most important implication is that sleep should be interpreted as a component of the recovery context surrounding load. When poor sleep appears together with high workload, rising soreness and fatigue, the athlete may warrant a different training decision than when poor sleep occurs in isolation with otherwise stable readiness. This is risk management, not a claim that a single poor night causes injury.

## **6. Mechanisms That May Link Poor Sleep to Injury Risk**

### **6.1 Neuromuscular and psychomotor function**

One plausible pathway from sleep loss to injury is impaired vigilance. A 2024 systematic review and meta-analysis of 44 studies found that a single night of sleep restriction significantly increased subjective sleepiness and impaired sustained attention, including slower reaction times and more attentional lapses [25]. In sport, where safe movement can depend on rapid perception and response to changing opponents, surfaces, trajectories and teammates, small decrements in attention may matter most when the athlete is already fatigued.

Sleep extension has produced improvements in reaction time and sport-specific performance in small athlete samples [12,13]. A recent randomized crossover trial in elite youth ice hockey players found that a 10-hour time-in-bed sleep-extension condition improved performance on a demanding cognitive interference task and reduced fatigue, although short physical tests did not change [26]. These results suggest that sleep effects can be task-specific and may be most visible in situations that require sustained cognitive control.

## **6.2 Fatigue, perceived exertion and pacing**

Sleep restriction changes how difficult exercise feels. In endurance athletes, restricted sleep has been associated with poorer vigilance and increased mood disturbance, while sleep extension improved endurance performance and vigilance [13]. If a prescribed session feels harder than expected because of inadequate sleep, the athlete may alter pacing, concentration or movement strategy even when objective workload is unchanged.

For team sports, this matters because the highest-risk actions are often not performed in a calm, laboratory environment. Sprinting, cutting, landing, tackling and rapid deceleration occur under cognitive pressure. A fatigued athlete may still generate the required force, but may have less reserve for technical control, decision-making or unexpected perturbations.

## **6.3 Musculoskeletal recovery and tissue tolerance**

Sleep is also relevant to physical recovery. Reviews of athlete sleep describe links with pain perception, endocrine and metabolic regulation, immune function and inflammation [5,11]. These pathways are biologically plausible contributors to load tolerance, but direct evidence that sleep deprivation measurably weakens specific tissues enough to cause sports injury remains incomplete.

The 2025 runner study is informative because poorer sleep quality was followed by higher injury risk, while fatigue and soreness increased in the weeks immediately before injury [14]. This pattern is compatible with a model in which sleep deterioration acts as an early warning signal of declining recovery reserve rather than as a single direct cause of tissue failure.

## **6.4 Immune and illness pathways**

Training, travel and insufficient sleep can interact with immune function. The athlete who develops an upper respiratory illness may reduce training, alter movement patterns, lose conditioning and then resume at a load that is poorly matched to current capacity. The IOC consensus on load and illness specifically highlights high loads, rapid changes, competition

congestion and psychological stress as contributors to illness risk [2]. Thus, sleep may participate in injury pathways indirectly through illness and interrupted training.

### **6.5 Pain, mood and psychological recovery**

Poor sleep can also modify pain sensitivity and psychological state [5,11]. In practice, an athlete with poor sleep may report greater soreness or feel less recovered from a session that would normally be well tolerated. That subjective change should not be dismissed as “just psychological.” In a dynamic monitoring model, athlete-reported sleep, stress, soreness and fatigue are part of the information needed to judge readiness.

## **7. What Does the Current Evidence Actually Show?**

A high-quality sports medicine article must distinguish between association, prediction and causation. The evidence is strongest for a relationship between sleep disruption and performance, and increasingly suggestive for a relationship between poor sleep and injury in some populations. The evidence is weaker for a universal causal claim that poor sleep independently causes sports injuries across all athletic contexts.

The discrepancy between studies is partly methodological. Sleep can be assessed by self-report, diaries, questionnaires, actigraphy or polysomnography. Injury definitions vary from all complaints to time-loss injuries. Training load may be measured by distance, accelerations, sRPE, heart-rate-derived measures or composite scores. Samples may include adolescents, collegiate athletes, professionals, endurance athletes or mixed populations. These choices affect effect estimates and make direct comparison difficult [16,24,27].

A 2026 scoping review focused specifically on actigraphy found 17 studies across 10 sports; among seven studies evaluating sleep metrics and injury occurrence, four reported that decreased sleep was associated with increased injury occurrence. The authors emphasized that the literature remains heterogeneous, but the actigraphy-focused findings add weight to the hypothesis that objectively measured sleep loss can precede injury in some sports [27].

The most reasonable synthesis is therefore probabilistic. Sleep quality is a potentially modifiable risk marker and may be part of a causal pathway, while training load is a necessary exposure that becomes hazardous when progression, density or recovery are poorly matched to athlete capacity. Injury risk is more likely to rise when multiple adverse signals cluster: high or changing load, poor sleep, increased soreness, fatigue, psychological stress, previous injury and restricted recovery opportunities.

## **8. Measurement in Practice**

### **8.1 Measuring sleep**

Sleep monitoring should be feasible, repeated and interpretable. A pragmatic system can combine a short daily sleep diary with a validated questionnaire when more detail is required. The main variables are sleep duration, perceived quality, sleep latency, awakenings, timing and daytime sleepiness. Actigraphy can provide objective estimates of sleep-wake patterns over longer periods, while polysomnography remains the diagnostic standard for specific sleep disorders but is rarely practical for routine team monitoring [5,27].

The goal is not maximal measurement. Too many metrics create burden and can reduce compliance. For most athletes, a simple daily scale for sleep quality and sleep duration, reviewed against training load and wellness data, may be more actionable than a complex dashboard that no one consistently uses.

### **8.2 Measuring internal and external training load**

External load is sport-specific. In football, total distance, high-speed distance, accelerations, decelerations and minutes played can be relevant. In running, mileage, vertical gain, pace and session duration may be more important. In strength training, sets, repetitions, external load and proximity to failure may matter. For combat or collision sports, contact exposure may need separate attention. Internal load can complement these measures with sRPE, heart rate and athlete-reported responses [3,9].

The monitoring system should prioritize variables that can be interpreted in context. For example, a moderate external load that produces unusually high sRPE and poor sleep may represent a different physiological situation from the same external load completed with normal sleep and low perceived effort.

### **8.3 Monitoring readiness and wellness**

Short daily wellness measures can include sleep quality, fatigue, muscle soreness, stress and mood. The Hooper framework is one established example used in applied sport settings [23]. Wellness data should not be treated as a diagnostic test; rather, they are longitudinal signals. Trends and deviations from the individual athlete's normal state are generally more meaningful than comparisons between athletes.

## 9. Practical Risk-Management Model for Coaches and Clinicians

The literature supports a layered approach. No single sleep duration, workload ratio or wellness threshold can reliably identify who will be injured tomorrow. The purpose of monitoring is to improve the quality of decisions under uncertainty.

| Domain         | What to monitor                                                                             | Interpretation                                                     | Actionable response                                                                                       |
|----------------|---------------------------------------------------------------------------------------------|--------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Sleep quantity | Total sleep time;<br>time in bed;<br>schedule<br>consistency                                | Look for persistent short<br>sleep or abrupt decline               | Protect sleep<br>opportunity; review<br>session timing; consider<br>reducing nonessential<br>late demands |
| Sleep quality  | Subjective quality;<br>awakenings;<br>restfulness;<br>actigraphy when<br>appropriate        | Persistent deterioration<br>may signal reduced<br>recovery reserve | Assess travel, stress,<br>environment, illness,<br>caffeine timing and late<br>competition                |
| External load  | Distance, high-<br>speed running,<br>accelerations,<br>minutes, volume,<br>contact exposure | Identify changes in<br>sport-specific exposure                     | Progress key load<br>dimensions deliberately;<br>avoid unnecessary<br>spikes                              |
| Internal load  | sRPE, heart rate,<br>perceived effort                                                       | Shows how hard a given<br>external load feels                      | Investigate mismatch<br>between external and<br>internal load                                             |
| Wellness       | Fatigue, soreness,<br>stress, mood                                                          | Clustered deterioration<br>is more informative than<br>one value   | Adjust load or recovery<br>inputs; consider clinical<br>review when persistent                            |
| Injury history | Recent injury,<br>tissue-specific<br>exposure, return-to-<br>sport stage                    | Previous injury can<br>modify tolerance to new<br>load             | Individualize<br>progression and target<br>the previously injured<br>capacity                             |

| Domain   | What to monitor                                             | Interpretation                       | Actionable response                        |
|----------|-------------------------------------------------------------|--------------------------------------|--------------------------------------------|
| Schedule | Rest days, travel, early sessions, late matches, congestion | Context changes recovery opportunity | Build recovery windows into the microcycle |

## 10. Interventions: Improving Sleep Without Undermining Training

### 10.1 Sleep opportunity first

The most defensible first intervention is to increase the opportunity for sleep. Sleep extension is not a shortcut that replaces appropriate load management; it is a recovery input that may help the athlete tolerate training more effectively. Small trials suggest improvements in performance, vigilance, mood and perceived well-being when sleep opportunity is increased [12,13].

Scheduling is therefore a sports-medicine issue. If an athlete must wake at 05:30 for training, the relevant question is not whether the athlete “should sleep more,” but whether the schedule makes sufficient sleep physically possible. Where feasible, moving early sessions later or reducing unnecessary pre-training obligations can be more effective than repeating generic sleep-hygiene advice. A recent randomized crossover study in national-level swimmers found that delaying the start of an early morning session from 07:00 to 09:00 increased the practical opportunity to sleep and was designed specifically around recovery and performance consequences of early training [28].

### 10.2 Sleep hygiene and behavioral strategies

Evidence-based sleep support commonly includes regular routines, a suitable bedroom environment, management of caffeine and alcohol, appropriate exposure to light, winding-down routines and strategies for pre-competition anxiety [5]. These measures are most effective when embedded in an athlete-centered plan rather than presented as a checklist.

Technology should support rather than undermine sleep. Wearables can be useful for observing patterns, but sleep-stage estimates from consumer devices should not be interpreted as diagnostic. The athlete’s own report remains clinically important, particularly when device data and perceived sleep quality disagree.

### 10.3 Sleep extension and “banking” sleep

Short periods of sleep extension may be considered before known periods of sleep restriction, travel or competition. Evidence from athlete trials suggests benefits for some performance domains, although systematic reviews describe the evidence base as small and at risk of bias

[12,29]. In other words, sleep extension is promising, but it should not be presented as a proven injury-prevention intervention.

#### **10.4 Nutrition and sleep**

Nutrition and sleep are connected through energy availability, meal timing and specific nutrients. Athlete reviews describe possible roles for carbohydrate availability, tryptophan-related pathways, tart cherry products and other interventions, but the evidence is not sufficiently uniform to justify broad supplement prescriptions [11,30]. A 2025 scoping review of nutrition strategies in elite athletes found promising signals for kiwi fruit, tart cherry juice and adequate dairy intake in selected studies, while also emphasizing small sample sizes and mixed results [30].

From a medical perspective, the priority remains meeting overall energy and nutrient requirements. Sleep-targeted supplements should be considered only after basic sleep opportunity, schedule and environment have been addressed, with attention to sport-specific anti-doping rules and medical contraindications.

### **11. Special Contexts**

#### **11.1 Adolescent athletes**

Adolescents may be particularly vulnerable because biological sleep need is high while school, social obligations and sports schedules restrict sleep opportunity. A widely cited prospective study of adolescent athletes reported an association between chronic lack of sleep and increased sports injury risk [31]. A separate collegiate cross-country study found poor sleep quality, large mileage increases and pre-season injury were associated with higher in-season injury risk [32].

The practical implication is not to remove adolescent athletes from hard training, but to recognize sleep as part of safeguarding development. Training plans should be compatible with school schedules and age-appropriate recovery requirements.

#### **11.2 Endurance athletes and runners**

Running provides a useful model for studying load because exposure can be quantified relatively well, but the literature still demonstrates complexity. Training parameters such as weekly volume, intensity, surface and change in loading can interact with biomechanics, previous injury and individual tissue capacity [17,33]. The 2025 prospective runner study adds sleep quality to this model, suggesting that poorer sleep may precede running-related injury [14].

For endurance athletes, sleep should therefore be reviewed alongside monotony, intensity distribution, recent volume changes, long-run progression, strength training and signs of under-recovery. A low sleep score in an otherwise stable week may not require a training change; a low sleep score combined with increasing soreness and a sudden increase in running load deserves more attention.

### **11.3 Team sport athletes and congested competition**

Team sports expose athletes to variable external loads and dense competition schedules. The 12-team collegiate soccer study illustrates this well: injury incidence varied according to competition phase, rest availability, training timing relative to matches, chronic loading, training monotony, workload spikes and sleep-quality changes [24]. This supports the idea that injury prevention depends on the interaction of training, match scheduling and recovery opportunity.

In congested periods, the most useful intervention may be schedule optimization rather than simply cutting load. Coaches can preserve critical high-intensity or tactical stimuli while removing low-value volume, increasing recovery windows and protecting sleep opportunity. This is an example of “precision loading”: maintaining the stimulus that matters most while reducing unnecessary stress.

### **11.4 Return from injury**

Return-to-sport is a period of elevated uncertainty. An athlete is rebuilding capacity while simultaneously attempting to re-enter the sport’s normal workload. Consensus guidance describes load progression as a central part of return-to-sport decisions and emphasizes that readiness is multifactorial [34]. Sleep becomes especially relevant because pain, worry, disrupted routines and reduced activity may alter sleep during rehabilitation.

The correct approach is individualized progression. Sleep data can be used as one component of the daily recovery picture, but should not override clinical assessment of the injured structure, functional testing or sport-specific capacity.

## **12. Methodological Limitations of the Evidence**

The evidence base has several recurring limitations. First, many studies rely on self-reported sleep, which is practical but vulnerable to recall bias and changes in perception. Second, studies often use small samples from a single team or sport, limiting generalizability. Third, injury definitions differ substantially. Fourth, training load measures are heterogeneous, and some studies analyze ratios or thresholds that may not reflect causal physiology [16,20-22].

Confounding is another major issue. An athlete may sleep poorly because they are already sore, anxious or developing an illness. The same factors may also increase injury risk. In that situation, poor sleep may be a marker of deteriorating health rather than an independent cause. Longitudinal studies that repeatedly measure sleep, load and wellness help address this problem, but even they cannot fully resolve time-varying confounding without strong causal designs.

There is also an important publication and implementation gap. Studies that identify clean thresholds are easier to communicate than studies showing complex, nonlinear relationships. In practice, however, injury risk rarely follows a single cut-off. The athlete's baseline, accumulated load and current recovery state matter.

### **12.1 Sleep disorders and when screening should move beyond routine monitoring**

Routine athlete monitoring should not be used to normalize persistent sleep problems. Repeated difficulty initiating sleep, frequent awakenings, excessive daytime sleepiness, loud snoring, witnessed apnoeas, morning headaches or persistent non-restorative sleep may indicate a sleep disorder rather than ordinary training fatigue. A 2025 systematic review of sleep-related breathing disorders in athletes and para-athletes highlighted that these conditions can occur in athletic populations and may be overlooked because high-performance environments often interpret fatigue as a normal consequence of training [35].

The clinical response should be proportionate. A single poor night after travel does not require a medical work-up. Persistent abnormalities, unexplained daytime impairment or a major mismatch between training demands and sleep recovery should prompt a structured sleep history and, where clinically indicated, referral to a clinician with expertise in sleep medicine. Athlete monitoring systems should therefore include a pathway for escalation rather than treating every sleep disturbance as a coaching problem.

This distinction also protects the athlete from an unintended consequence of data-driven sport: excessive surveillance. Sleep is not a performance score that the athlete must “win” every night. The objective is to identify modifiable barriers and clinically significant problems while preserving autonomy, privacy and a healthy relationship with sleep.

### **12.2 An applied example: interpreting the same workload in two athletes**

Consider two athletes completing the same high-intensity field session. Athlete A reports normal sleep quality, normal soreness and typical sRPE, has stable recent workload exposure and has no recent injury. Athlete B completed the same session after several nights of poor

sleep, reports increasing soreness and fatigue, has recently increased high-speed running exposure and is entering a congested competition period. The external workload is identical, but the context is not. It would be inappropriate to interpret the two responses as equivalent.

For Athlete A, the session may represent an expected training stimulus. For Athlete B, the combination of poor sleep, rising wellness symptoms, recent exposure change and schedule congestion suggests a smaller recovery reserve. The reasonable response may be to preserve the key tactical or physiological stimulus while reducing low-value volume, increasing recovery time, or modifying the next day rather than the current session. This illustrates the central principle of integrated monitoring: risk is expressed through patterns and interactions, not a single threshold.

### **12.3 Communication, athlete autonomy and organizational culture**

Sleep recommendations succeed only when the sport environment makes them realistic. Athletes may be reluctant to report poor sleep if they believe it will be interpreted as low commitment or a reason to remove them from selection. Likewise, coaches may view sleep data as an additional constraint on an already difficult schedule. A high-quality monitoring system therefore depends on culture as much as measurement technology.

Practitioners should communicate that sleep data are used to improve decisions, not to judge professionalism. The athlete should understand which variables are being collected, who can see them and how they will be used. Individual trends should be prioritized over league tables or public rankings of sleep. This approach can reduce stigma and encourage earlier reporting of problems that might otherwise remain hidden until performance or health deteriorates.

### **12.4 A practical decision sequence after a poor-sleep report**

When an athlete reports a sudden deterioration in sleep, the first step is not automatically to reduce training. The practitioner should establish whether the change is acute or persistent, whether it is associated with travel, stress, late competition, illness, pain or environmental disruption, and whether workload or injury risk has simultaneously changed. The next step is to determine whether the athlete is functioning normally in warm-up, skill execution, concentration and perceived effort.

If sleep is poor but all other signals are stable, the appropriate response may be to protect the following night and continue with a modified or normal session depending on the sport. If poor sleep is accompanied by marked fatigue, high sRPE for a routine workload, escalating

soreness, illness symptoms or a recent exposure spike, greater caution is justified. This is consistent with the broader principle of multidimensional monitoring recommended in athlete-load consensus guidance [3].

### **12.5 Research priorities for the next generation of studies**

The next phase of research should move beyond simple correlations between “hours of sleep” and “number of injuries.” First, studies should use repeated measures so that investigators can establish the temporal order between sleep changes, workload changes and injury. Second, objective sleep measures such as actigraphy should be combined with athlete-reported sleep quality, because objective and subjective measures capture different dimensions of sleep health [27].

Third, studies should treat workload as sport-specific exposure rather than a single universal number. A sprinting load, collision load, resistance-training load and endurance-volume load stress tissues differently. Fourth, future studies should model interaction effects: for example, whether poor sleep has a larger association with injury when high-speed running, match congestion or return-to-sport exposure is also elevated. Fifth, intervention trials should examine whether changes in sleep opportunity actually alter injury incidence, not just performance or sleep scores.

Finally, research should be more representative. Many existing datasets are dominated by young adult men in professional team sports. Women, adolescents, masters athletes, para-athletes, individual-sport athletes and lower-resource sporting environments should be studied more deliberately. Standardized sleep definitions, injury surveillance and workload reporting would make future evidence easier to combine and translate into practice.

## **13. Recommendations for Applied Practice**

The evidence can be translated into several practical principles for sports medicine teams. These recommendations are intentionally framed as risk-management principles rather than rigid prescriptions.

- Use sleep as a routine recovery variable, not an occasional wellness question. Track both sleep quantity and perceived quality, and interpret changes relative to the individual athlete’s normal pattern [5,14].

- Pair sleep monitoring with internal and external workload. A poor sleep score is more informative when it coincides with rising sRPE, soreness, fatigue, competition congestion or abrupt changes in a key load variable [3,24].
- Protect sleep opportunity through scheduling. Review early-morning sessions, late finishes, travel, rooming arrangements and recovery periods before adding more interventions [5,28].
- Progress training loads according to sport-specific capacity and recent exposure. Avoid using a single percentage rule or ACWR threshold as a universal injury-prevention prescription [1,17,20-22].
- Pay particular attention to clusters of adverse signals. Persistent poor sleep, rising soreness, fatigue, psychological stress and high or changing workload should trigger review of the microcycle rather than automatic continuation of the plan.
- Use objective monitoring selectively. Actigraphy can add information where sleep disturbance is suspected, but consumer wearable outputs should be treated as estimates and not as diagnostic measurements [27].
- Involve the athlete in interpretation. Perceived sleep quality and readiness can identify meaningful changes that are not obvious in workload data alone. Shared decision-making improves the clinical usefulness of monitoring [5].
- Do not promise injury prevention from sleep alone. The current evidence supports sleep as an important component of recovery and a potentially modifiable risk marker, not as a standalone guarantee against injury [16].

#### **14. Toward an Integrated Sleep-Load-Injury Model**

A useful future direction is an integrated model in which the athlete's state is described as the balance between exposure and recoverable capacity. Training load increases the stimulus for adaptation. Sleep, nutrition, rest, psychological recovery and medical support influence the ability to absorb that stimulus. The risk signal emerges when the exposure-capacity balance becomes unfavorable.

Such a model can be represented conceptually as: current sport exposure + contextual stressors versus available recovery and tissue capacity. Sleep is one of the most accessible recovery variables because it is relatively inexpensive to measure, modifiable through scheduling and behavior, and closely linked to performance. But it should be interpreted as one part of the system.

Future research should prioritize multicenter prospective studies with repeated objective and subjective sleep measures, standardized injury definitions, detailed sport-specific workload data and modern causal-inference approaches. Studies should include women, adolescent athletes, para-athletes and athletes from individual sports rather than concentrating heavily on male professional team-sport samples. The field would also benefit from intervention trials that test whether improving sleep actually reduces injury incidence, rather than merely improving performance or sleep metrics.

## **15. Conclusion**

Sleep quality, training load and injury risk are connected components of athlete health. The current evidence indicates that poor sleep is common in athletes, that inadequate or disrupted sleep can impair performance-relevant functions, and that poorly managed or rapidly changing training loads can increase injury risk. The relationship between sleep and injury is more nuanced: some prospective studies demonstrate meaningful associations, whereas systematic reviews have found the overall adult evidence inconsistent and insufficient to establish sleep as a universal independent causal risk factor [14-16,27].

The practical conclusion is therefore not “train less and sleep more.” It is to manage the athlete as an integrated system. A well-designed training plan develops capacity, sleep protects recovery opportunity, and monitoring helps detect when the current demands are no longer being tolerated as expected. When poor sleep, rising fatigue or soreness and challenging workloads occur together, the cluster should be treated as a potential reduction in recovery reserve. Decisions should then focus on preserving essential training while reducing unnecessary stress and restoring sleep opportunity.

For coaches and clinicians, the most useful mindset is probabilistic and longitudinal. No single sleep score or workload ratio can reliably predict injury. The goal is to recognize patterns early, understand the athlete’s context and make timely adjustments. In this model, sleep is not a luxury added after training is complete; it is one of the conditions that determines whether training becomes adaptation or accumulated strain.

## **Practical Take-Home Message for Sport Staff**

The most defensible evidence-based approach is simple: protect sleep opportunity, monitor sleep quality and quantity, quantify relevant training exposures, track individual changes in fatigue and soreness, and interpret all of these variables together. When recovery signals deteriorate at the same time as workload rises or competition becomes congested, the athlete

may need a temporary adjustment in training density or volume. The objective is not to avoid load, but to keep the load appropriate to current capacity.

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