



MULTIMODAL FATIGUE MONITORING AND THRESHOLD IDENTIFICATION IN SOCCER: A SYSTEMATIC REVIEW

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Abstract: Fatigue monitoring is crucial in soccer to optimize performance, reduce injury risk, and enhance recovery strategies. This systematic review explores multimodal approaches to fatigue assessment, integrating physiological, biomechanical, and subjective measures to identify thresholds that indicate performance decline. A comprehensive search of relevant databases was conducted to evaluate studies utilizing diverse monitoring tools such as heart rate variability, neuromuscular markers, biochemical indicators, and player-reported metrics. Findings suggest that multimodal fatigue assessment provides a more holistic understanding of player readiness and load management compared to single-method approaches. However, variability in measurement protocols and threshold determination presents challenges in standardization and practical application. Future research should focus on refining multimodal integration techniques and establishing sport-specific fatigue thresholds to enhance decision-making in soccer training and competition.

Index Terms: Fatigue Monitoring, Soccer, Multimodal Assessment, Physiological Markers, Neuromuscular Fatigue, Biochemical Indicators, Heart Rate Variability, Load Management, Performance Thresholds, Injury Prevention

1. INTRODUCTION

Fatigue is an intrinsic and multifaceted phenomenon in soccer, primarily due to the sport's high-intensity, intermittent demands that necessitate sustained physical, neuromuscular, and cognitive engagement (Mohr et al., 2005). Elite players are regularly exposed to various forms of fatigue—ranging from physical and neuromuscular to central, peripheral, and cognitive—which can adversely impact technical execution, tactical decision-making, and overall match performance (Rampinini et al., 2011). A nuanced understanding of fatigue typologies, their underlying physiological and psychological mechanisms, modulatory factors, and assessment modalities is critical for performance optimization, injury prevention, and recovery management in soccer (Halsen, 2014).

Over the last two decades, the scientific research of fatigue in soccer has expanded considerably, driven by the need to improve player load management and performance sustainability (Thorpe et al., 2015). Both subjective (athlete-reported outcome measures) and objective (neuromuscular tests, salivary biomarkers, reaction time assessments) tools have been employed to assess fatigue (Saw et al., 2016). Despite these advancements, significant gaps persist in elucidating the dynamic interplay between fatigue and variables such as match congestion, cumulative training load, environmental stressors, and psychological stress (Silva et al., 2018).

Moreover, the dynamic interplay between central (originating in the central nervous system) and peripheral (muscle-based) fatigue, the context-specific efficacy of various recovery modalities, and the real-world feasibility of fatigue monitoring in elite settings continue to be active areas of exploration (Enoka & Duchateau, 2016). Variability in study methodologies, ecological validity concerns, and a lack of standardized protocols further complicate the translation of findings into practical applications (Thorpe et al., 2015).

This systematic literature review aims to consolidate and critically evaluate existing research on fatigue in soccer, with an emphasis on elite youth and professional players. Specifically, it will:

- To categorize and describe the principal types of fatigue examined in soccer over the past 25 years, including but not limited to physical, neuromuscular, central, peripheral, and mental fatigue.
- To identify and appraise the standard assessment tools utilized for fatigue monitoring, encompassing both subjective (wellness questionnaires, perceived exertion scales) and objective (biochemical assays, countermovement jump tests, reaction time tasks) methodologies.
- To explore the multifactorial influences on fatigue development and recovery, including match-play demands, training intensity and volume, sleep quality, nutritional status, environmental factors (heat, pollution), and psychosocial stressors.
- To delineate current knowledge gaps and methodological limitations within the literature, and to propose directions for future research aimed at advancing fatigue science in applied soccer contexts.

By synthesizing interdisciplinary evidence, this review seeks to inform best practices for fatigue evaluation and mitigation.

2. TYPES OF FATIGUE IN SOCCER PLAYERS

2.1 Physical Fatigue (Physiological)

Physical fatigue in soccer is a multifactorial phenomenon rooted in the sport's intense and intermittent demands, which require continuous engagement of both aerobic and anaerobic energy systems. It manifests as a progressive decline in the ability to produce force or sustain high-intensity effort, particularly evident after repeated sprints, accelerations, and decelerations common in match play (Carling, 2010; Hill-Haas et al., 2009). This type of fatigue is underpinned by physiological mechanisms such as the depletion of muscle glycogen, accumulation of metabolic byproducts, neuromuscular disruption, and, under extreme conditions, dehydration and thermal strain (Mohr et al., 2005; Nédélec et al., 2014). These stressors collectively impair physical output and technical execution, particularly in the latter stages of games or under congested match schedules. Understanding the temporal and physiological dynamics of physical fatigue is critical for tailoring training loads, optimizing recovery, and maintaining peak performance in competitive soccer.

2.2 Neuromuscular Fatigue

Neuromuscular fatigue in soccer refers to the transient reduction in the muscle's ability to generate force or power, resulting from high-intensity, repeated match demands that place sustained stress on the neuromuscular system. This type of fatigue arises from both central factors—pertaining to reduced motor drive from the central nervous system—and peripheral mechanisms, including disruptions in excitation-contraction coupling and metabolic accumulation at the muscular level. *Peripheral fatigue* refers to changes at or distal to the neuromuscular junction and within muscle fibers (impaired excitation-contraction coupling, ion imbalance, metabolite buildup) that reduce muscle force. Repeated high-intensity efforts can disturb muscle ion homeostasis (such as K^+ and Ca^{2+} handling) and contribute to fatigue independently of lactate or pH effects. *Central fatigue* refers to a reduction in the central nervous system's ability to activate muscles, often quantified as a drop in voluntary activation of muscle fibers. In practice, soccer match-play causes substantial central and peripheral fatigue: studies using electrical stimulation report ~8% declines in central drive and ~14% drops in muscle twitch force after matches. These central and peripheral impairments can take 1–2 days to recover. In elite soccer players, neuromuscular fatigue is particularly relevant due to the frequent execution of accelerations, decelerations, and eccentric movements like jumping and tackling, which elicit muscle damage and impair force production (Mohr et al., 2005; Brownstein et al., 2017).

2.3 Mental Fatigue

Mental (cognitive, psychological) fatigue in soccer is recognized as a psychobiological state arising from prolonged periods of demanding cognitive activity, which can impair both psychological functioning and physical performance. It is particularly relevant in elite environments where players are exposed to high levels of decision-making, emotional stress, and tactical concentration during training and matches (Kunrath

et al., 2020). Characterized by a sense of tiredness, reduced motivation, and compromised executive function, mental fatigue has been shown to deteriorate attention, reaction time, and technical execution—even when physical capacity remains intact. It is induced by extended periods of concentrated effort (video analysis, strategic planning, or even academic work before training) and can negatively impact performance (Nédélec et al., 2012). Studies show that induced mental fatigue (via 30–60 minutes of computer-based cognitive tasks) leads to worse outcomes in soccer-specific skills and decisions such as slower and less accurate decision-making, more errors in passing, and reduced running output. Nutritional strategies, such as carbohydrate or caffeine supplementation, have been explored as potential countermeasures, given their role in maintaining central nervous system activity. Moreover, mental fatigue is sensitive to sleep quality, circadian rhythms, and accumulated psychological stress, factors that fluctuate throughout a competitive season and can influence player readiness (Paul et al., 2015).

3. TOOLS AND TESTS TO ASSESS FATIGUE IN SOCCER

Researchers and practitioners use a combination of subjective self-reports and objective measurements to assess fatigue in soccer players. Each approach captures different aspects of fatigue, and together they provide a more holistic evaluation.

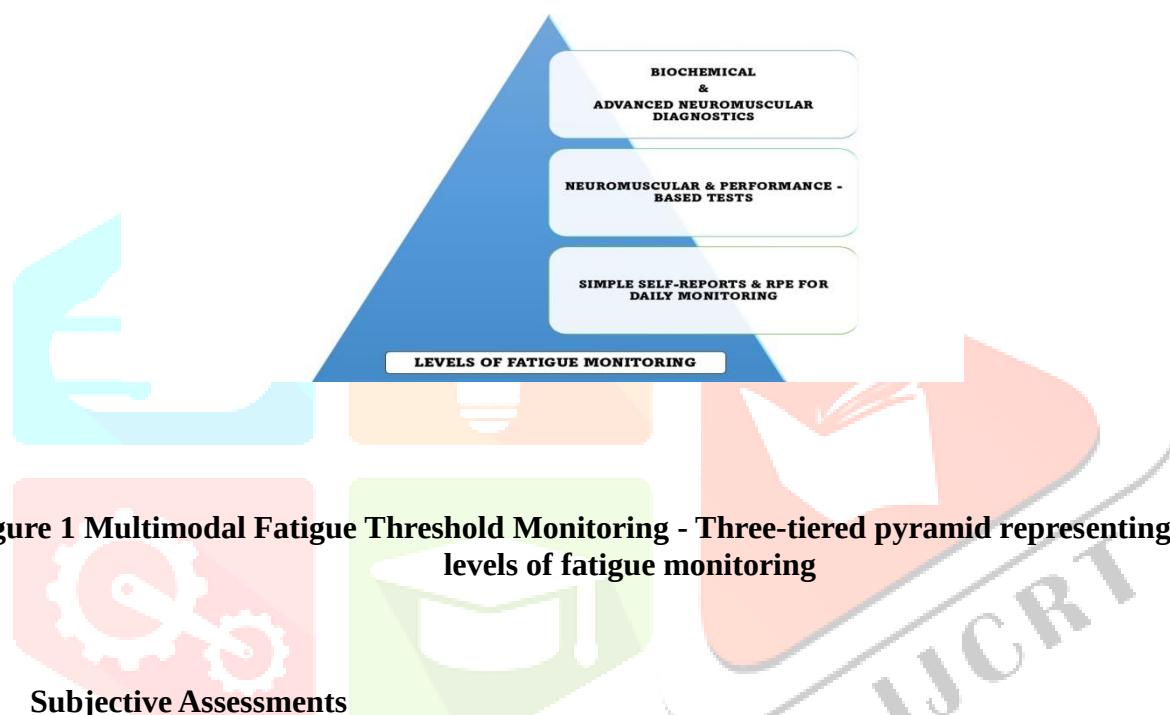


Figure 1 Multimodal Fatigue Threshold Monitoring - Three-tiered pyramid representing different levels of fatigue monitoring

3.1. Subjective Assessments

In soccer, accurately identifying and quantifying fatigue is crucial for optimizing player performance and minimizing injury risk. Subjective assessments serve as practical tools in this endeavor, capturing players' self-reported perceptions of their physical and psychological states. Among these, the Rate of Perceived Exertion (RPE) scale is widely utilized, enabling players to evaluate the intensity of training sessions and matches on a standardized scale, thereby offering insights into internal load and exertion levels. The Hooper Index is another prevalent tool, assessing key wellness parameters such as sleep quality, stress levels, fatigue, and muscle soreness; collectively, these indicators provide a comprehensive overview of an athlete's recovery status and readiness to perform. Additionally, the Profile of Mood States (POMS) questionnaire measures various mood dimensions—including tension, depression, anger, vigor, fatigue, and confusion—facilitating the detection of psychological fatigue and its potential impact on physical performance (Lourenço et al., 2023). Furthermore, the Total Quality of Recovery (TQR) scale allows athletes to self-assess their perceived recovery status, aiding in the evaluation of recovery strategies and their effectiveness. General wellness questionnaires, tailored to specific team contexts, often encompass items related to sleep, stress, fatigue, muscle soreness, and mood, offering a holistic perspective on player well-being.

3.2. Objective Assessments

Objective assessments provide quantifiable data on an athlete's physiological state, offering valuable insights into fatigue levels. Among these, the Countermovement Jump (CMJ) test is widely utilized to evaluate neuromuscular function by measuring jump height and power output; decrements in CMJ performance can indicate fatigue-induced impairments in the stretch-shortening cycle of lower limb muscles. Similarly, the Squat Jump (SJ) test assesses explosive strength and has been employed to monitor fatigue-related changes in muscle function. Biochemical markers, such as creatine kinase (CK) levels, serve

as indicators of muscle damage and metabolic fatigue; elevated CK concentrations post-match reflect the extent of muscle Fiber disruption. Metabolic analysers assess metabolic fatigue by measuring physiological parameters such as oxygen consumption (VO_2 max), carbon dioxide production, and lactate thresholds during exercise, providing information on metabolic efficiency and endurance capacity (Brownstein et al., 2017). Additionally, submaximal running tests, incorporating accelerometer-derived metrics like Player Load, offer insights into movement efficiency and can detect alterations in mechanical workload associated with fatigue (Lourenço et al., 2023). Electromyography (EMG) is another objective tool employed to assess muscle activation patterns and detect neuromuscular fatigue by analysing changes in electrical activity of muscles during contraction. Additionally, tensiomyography (TMG) is a non-invasive technique that assesses muscle contractile properties, offering valuable data on muscle stiffness, fatigue, and recovery status. Cognitive tasks, including reaction time tests and Stroop tests, are utilized to detect mental fatigue by evaluating declines in cognitive performance and decision-making abilities following prolonged cognitive or physical exertion. Table 1 summarizes common methods:

Table 1. Key subjective and objective tools used in studies to assess fatigue in soccer players.

Assessment Method	Examples	Type of Fatigue Assessed	Purpose in Fatigue Monitoring	References
Subjective Self-Reports	Wellness questionnaires (fatigue, sleep, soreness ratings), Session-RPE, POMS (Fatigue subscale)	General, Mental, Physical	Captures perceived exertion, wellness, and readiness; allows for non-invasive, daily monitoring of recovery trends.	Hooper & Mackinnon, 1995; McNair et al., 1971
Performance Tests	Countermovement Jump (CMJ), Sprint tests (10 m, 30 m), Isometric strength test (MVC)	Neuromuscular	Identifies declines in explosive power, sprint speed, or maximal strength indicating neuromuscular fatigue.	Fitzpatrick et al., 2021; Brownstein et al., 2017
Physiological Measures	Heart Rate Variability (HRV), Heart rate recovery, Blood lactate concentration post-exercise	Metabolic, Cardiovascular	Tracks autonomic nervous system recovery and internal load; reflects training adaptation or fatigue states.	Thorpe et al., 2017
Biochemical Markers	Salivary/blood cortisol, testosterone, Creatine Kinase (CK), Blood urea nitrogen (BUN)	Metabolic, Muscular	Monitors muscle damage and endocrine response to stress; assists in determining recovery needs.	Thorpe et al., 2015; Nédélec et al., 2012
Cognitive Tests	Reaction time tasks, Stroop test, Decision-making accuracy in video simulations, Psychomotor vigilance test (PVT)	Mental, Cognitive	Assesses effects of fatigue on attention, decision speed, and mental acuity; useful in evaluating readiness for tactical tasks.	Gantois et al., 2020; Angius et al., 2022

4. FACTORS AFFECTING FATIGUE IN SOCCER

Fatigue in soccer is influenced by a myriad of factors that can be broadly grouped into physical demands, recovery-related factors, environmental conditions, and individual player characteristics (including psychological state). Over the past 25 years, research has identified the following key factors modulating fatigue

4.1. Match Demands and Scheduling

The intensity and duration of match play are primary drivers of fatigue. Match demands and scheduling play a pivotal role in the development of fatigue among soccer players, particularly in elite settings where the frequency and intensity of competition are high. When matches are scheduled in close succession—often referred to as fixture congestion—players are exposed to repeated high-intensity efforts with insufficient time for physiological and psychological recovery. This accumulation of load can impair neuromuscular function, reduce high-intensity running capacity, and increase subjective fatigue levels, ultimately compromising performance and elevating the risk of injury (Carling et al., 2015). Moreover, congested periods often coincide with travel, tactical preparation, and limited training time, further disrupting recovery processes such as sleep and nutrition. Studies have consistently shown that performance indicators, particularly those linked to high-speed actions and repeated sprints, decline during successive matches, highlighting the detrimental impact of inadequate recovery windows.

4.2. Training Load

Training load is a critical determinant of fatigue in soccer, as it represents the cumulative physiological and psychological stress imposed on players through structured exercise. Both external load (such as distance covered, accelerations, high-speed efforts) and internal load (like heart rate, perceived exertion) influence how the body responds and recovers from training stimuli (Coutts et al., 2007). When mismanagement of training load occurs—either due to excessive volume or abrupt increases in intensity—it can lead to acute fatigue, impair neuromuscular function, and disrupt hormonal and metabolic balance. Prolonged exposure to high or poorly regulated training loads without sufficient recovery can escalate into non-functional overreaching or even overtraining syndrome, conditions linked to chronic fatigue, reduced performance, and increased injury susceptibility (Halson, 2014). Conversely, well-calibrated training loads can stimulate performance adaptations and enhance resilience, underscoring the importance of individualized load monitoring systems (Sahlin, 1992; Halson, 2014).

4.3. Recovery Strategies and Interventions

Recovery strategies serve as a cornerstone in the management of fatigue in soccer, given their critical role in restoring both physiological and psychological function after training and competitive play. The sport's demanding structure—characterized by high-intensity movements, limited recovery windows, and dense match calendars—places players at significant risk of accumulating fatigue that, if not addressed, can impair performance and increase injury vulnerability (Rampinini et al., 2011). Different studies emphasize that interventions such as sleep optimization, cold-water immersion, nutritional support, and active recovery enhance the regeneration of neuromuscular, metabolic, and cognitive systems (Dupuy et al., 2018). These strategies support muscle repair, reduce inflammation, and modulate hormonal activity, thereby maintaining systemic balance (Kellmann et al., 2018). Furthermore, structured recovery positively influences psychological states—improving mood, reducing stress, and enhancing motivation—which are essential for sustained performance in high-pressure environments. The inter-individual variability in recovery needs reinforces the importance of personalized and periodized recovery plans that align with specific workloads, positions, and physiological profiles. As such, recovery is not a supplementary aspect of training but a scientifically grounded, indispensable element of performance management in elite soccer.

4.4. Environmental Conditions

Environmental conditions play a pivotal role in shaping fatigue responses in soccer, primarily by influencing the body's thermoregulatory, cardiovascular, and neuromuscular systems during match play. Competing in hot and humid environments imposes a significant thermal load, accelerating dehydration, increasing core body temperature, and ultimately impairing physical and cognitive performance (Nassis et al., 2015). These effects are particularly pronounced during high-stakes competitions in tropical climates, where recovery between matches is already constrained. In contrast, exposure to cold temperatures can limit neuromuscular efficiency by increasing muscle stiffness and reducing nerve conduction velocity, which negatively affects coordination, agility, and power output. High-altitude conditions pose additional physiological challenges by reducing oxygen availability, compromising aerobic energy production, and accelerating the onset of fatigue, especially among athletes who are not fully acclimatized (Bartlett et al., 2012).

4.5. Nutrition and Hydration

Nutrition and hydration profoundly influence the onset and progression of fatigue in soccer by regulating key physiological systems that support energy metabolism, thermoregulation, and neuromuscular function. Muscle glycogen availability—largely determined by carbohydrate intake before and during activity—is a primary factor in sustaining high-intensity performance, particularly during the latter stages of a match. When glycogen stores are insufficient due to suboptimal pre-match fueling or congested match schedules, players are more prone to early fatigue and reduced sprint capacity (Burke et al., 2013). Carbohydrate ingestion during gameplay, especially at halftime or in the form of sports drinks during extended or intense matches, can help maintain blood glucose, supporting both central and peripheral energy demands (Hulton et al., 2022). In contrast, low carbohydrate availability has been associated with increased perceived exertion (central fatigue) and reduced muscular force production (peripheral fatigue) (Mohr et al., 2005). Hydration status further modulates fatigue; even mild dehydration, defined as a 2% loss in body mass, has been shown to impair cognitive performance, increase core temperature, and elevate cardiovascular strain, thereby intensifying the subjective experience of fatigue (Sawka et al., 2007). Electrolyte loss, particularly sodium depletion through excessive sweating, may contribute to cramping and premature muscular fatigue. Post-match nutrition also plays a key role in recovery; protein aids in muscle repair and attenuates soreness, while antioxidant-rich foods may counteract inflammation. While substances like caffeine can acutely reduce perceived fatigue and enhance focus, overreliance may disrupt sleep and hinder long-term recovery. Ultimately, evidence supports that players who follow individualized, periodized nutrition and hydration plans are better equipped to delay fatigue, recover efficiently, and maintain peak performance throughout the season.

4.6. Psychological Factors

Psychological factors are deeply intertwined with the experience and progression of fatigue in soccer, influencing both how fatigue is perceived and how it manifests physically. A player's mental state—shaped by stress, motivation, emotional well-being, and cognitive workload—can accelerate or buffer fatigue depending on the context. Elevated anxiety, pressure, or emotional distress can drain cognitive resources and raise perceived exertion, causing athletes to report greater fatigue even when physiological markers remain stable (Smith et al., 2016). This is closely linked to the concept of central fatigue, where the brain, acting as a regulatory control center, downregulates motor output as a protective response when effort is perceived as excessive (Pageaux, 2014). Psychological strain can also impair sleep quality and disrupt hormonal balance, thereby extending recovery times and increasing susceptibility to overtraining. Experimental studies have shown that pre-exercise mental tasks—such as solving complex problems or coping with emotional stress—can diminish subsequent physical performance, highlighting the tangible impact of mental fatigue on the neuromuscular system (Broadbent et al., 2019). Conversely, positive psychological states like intrinsic motivation, confidence, or a supportive team environment can delay fatigue by enhancing resilience and focus, especially during high-stakes matches. Even external elements, such as the presence of a home crowd, have been shown to modulate psychological energy and reduce perceived fatigue. Therefore, addressing psychological readiness and implementing mental recovery strategies—such as stress management, cognitive rest, and emotional support—are essential components of fatigue management in elite soccer (Coutts, 2016; Kellmann, 2018).

4.7. Individual Differences

Apart from the above, individual factors such as fitness level, training status, age, and even genetics affect fatigue. Fitter players (aerobically and anaerobically) can sustain high intensities longer and recover quicker during pauses, showing less fatigue in match second halves. Stronger players may resist neuromuscular fatigue better (maintaining sprint performance). Younger players generally recover faster between bouts, whereas older players might accumulate fatigue more. There's also evidence that training age (years of high-level training) can make athletes more robust against fatigue, up to a point. Muscle fiber composition is a factor – players with more Type I fibers have great endurance (less peripheral fatigue in long efforts) but may lack late-game sprint capacity, whereas Type II-dominant players can perform explosive actions but might fatigue faster if pushed beyond their aerobic capacity. Injuries or muscle damage history can cause certain muscles to fatigue quicker due to altered mechanics. Even chronotype (morning vs evening person) can influence performance time-of-day effects related to fatigue perception (Ciorciari et al., 2023). While these individual factors are numerous, the key takeaway is that fatigue is highly individual: the same match can leave one player exhausted and another relatively fine,

depending on these variables (Nédélec et al., 2015). This is why personalized fatigue monitoring is emphasized – large inter-player variability exists in fatigue responses (Robertson et al., 2017).

In essence, fatigue in soccer is multifactorial (Sahlin, 1992). High physical loads (from matches or training) create the basis for fatigue, but factors like effective recovery, sleep, nutrition, environment, and psychology critically mediate how that load translates into a fatigue outcome. Understanding these factors helps coaches design better schedules (to avoid excessive fatigue) and implement interventions (like recovery protocols, mental recovery sessions, or diet plans) to mitigate fatigue's impact.

5. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite extensive study of fatigue in soccer over the last two decades, several important gaps and open questions remain.

Historically, fatigue research in football focused on physical and physiological aspects (muscles, cardiovascular), with much less attention to cognitive or tactical fatigue. Only in recent years has mental fatigue in soccer been systematically studied, and thus far the research is limited. All these studies used controlled experiments to induce mental fatigue (prolonged cognitive tasks) and observed performance in either drills or small-sided games. While they consistently suggest mental fatigue impairs various performance facets (technique, decision-making, running output), the real-world incidence and management of mental fatigue in competitive settings are not fully understood. One gap is *ecological validity*: current experimental protocols (having players watch a screen for 30 minutes to induce mental fatigue) may not perfectly mimic how mental fatigue develops during a competitive season. Researchers have called for more ecologically valid methods – inducing mental fatigue via realistic soccer-specific tasks or studying naturally occurring mental fatigue (from tactical meetings, travel, stress) and its impact on match play. Also, the interaction between mental and physical fatigue is not well-explored. Do mentally fatigued players pace themselves differently and thus reduce physical fatigue, or does mental fatigue simply add on top of physical fatigue? Initial evidence is mixed and further field studies are needed. Future directions include examining long-term mental fatigue (accumulated over a season or tournament), testing interventions like psychological skill training or “brain endurance” training to reduce cognitive fatigue, and integrating cognitive fatigue metrics into routine monitoring.

While it's established that both central and peripheral fatigue occur in soccer, the precise mechanisms and their relative contributions need more clarity. Studies using advanced neurophysiological techniques (TMS, nerve stimulation) have been limited to small sample sizes. These indicate that after 90 minutes, both central drive and muscle contractility are impaired, but we don't fully know *why* central fatigue occurs in soccer (beyond general factors like neurotransmitter changes or mental strain). There are still uncertainties about the underlying causes of central fatigue – is it primarily due to metabolite feedback from muscles, brain thermoregulation, or motivational factors?

And how much does central fatigue versus peripheral fatigue each contribute to performance decrements in various contexts (short-term intense fatigue vs. end of game fatigue)? Another gap is how training or interventions might selectively affect central or peripheral fatigue. Could certain mental training reduce central fatigue, or could nutritional supplements (like branched-chain amino acids or tyrosine) attenuate central fatigue by affecting brain neurotransmitters? These questions remain partly unanswered. Future research could explore central fatigue in more depth, potentially identifying ways to measure it practically (since lab methods are invasive) and strategies to reduce central inhibition (mental resilience training, stimulants in safe amounts, etc.). On the peripheral side, more work is needed on muscle-level adaptations: do some players have more resistance to peripheral fatigue (perhaps via muscle buffer capacity or oxidative capacity), and can that be trained further?

Despite many tools to measure fatigue, there is no single gold-standard marker of fatigue in soccer. Research highlights that objective and subjective indicators often diverge, and each metric has limitations. For example, jump performance might not drop if a player is mentally hyped up, even though they are fatigued, whereas a player might report high fatigue but still be physiologically ready. This leads to a gap in how to best *quantify* fatigue and readiness. There is “no single, definitive marker” identified that reliably covers all aspects of fatigue. The current approach is to use a combination of measures but interpreting them requires expert insight and is often subjective. Moreover, many of the biochemical or neuromuscular tests used in studies are not practical for daily use by teams (blood draws or specialized lab equipment). Thus, a gap exists between research and practice: field-applicable fatigue diagnostics. Coaches and sports scientists need simple, quick, and non-invasive tools that correlate well with true fatigue. Some promising developments include wearable technology to assess neuromuscular function on the fly, or algorithms that analyze training load and wellness data to flag abnormal fatigue levels. However, more validation is needed.

Additionally, the literature has mostly focused on acute fatigue (within days). Chronic fatigue and overtraining in soccer are less studied – how repeated weeks of heavy load might lead to a state of constant fatigue and performance decrement is not fully clear in team-sport context. Future work might examine markers of chronic fatigue (immune changes, hormonal disturbances over time) in soccer players.

Another gap is that most fatigue studies in soccer have been done on male players (often senior or youth male squads), with relatively fewer on female players. The physiology of fatigue could differ by sex (some evidence suggests females may resist fatigue differently in certain tasks), and the competitive demands in women's soccer are also high. Recent years show more research emerging in the female game, but further study is needed to confirm if fatigue patterns (and optimal recovery strategies) differ between men and women. Youth players and scheduling of youth tournaments (often games on consecutive days) is another area with limited data – young athletes might recover faster, but we need to ensure we're not overloading them. Furthermore, elite professional players versus sub-elite: many controlled studies recruit sub-elite players for convenience, which may limit generalization. The “real-world relevance” of some findings has been questioned, because elite players have access to superior training, recovery and are accustomed to high loads. For example, an experimental protocol might show a certain fatigue effect in amateurs, but pros might cope differently. Likewise, fatigue monitoring that works in a research setting (with full compliance) may face challenges in pro clubs (where players might under-report fatigue to avoid being rested). Bridging this gap requires studies conducted in professional environments. Some recent “in-season” studies and surveys of practitioners suggest that coaches sometimes see little change in performance metrics even in congested schedules (likely due to squad rotation and top fitness). This highlights a need to contextualize fatigue findings to actual match performance outcomes – do measured fatigue markers correlate with a drop in match physical performance or increased injury risk? That link is not fully established, representing a gap in evidence. Future directions should include longitudinal studies within clubs, tracking fatigue markers alongside match performance and injury data, to truly verify the utility of monitoring and to identify threshold values that matter.

From a methodological standpoint, fatigue research can be challenging, and some gaps persist in experimental design. For mental fatigue, as mentioned, better methods to induce and measure it in soccer-specific ways are needed. For physical fatigue, replicating the demands of match-play in a standardized way is difficult – thus, results can vary depending on whether a treadmill run, intermittent shuttle test, or actual match was used to induce fatigue. The field would benefit from more standardized fatigue protocols that are ecologically valid. Another conceptual gap lies in the interaction of *tactical* performance and fatigue. Tactical decision-making and team coordination might suffer under fatigue, but it's complex to measure in research. Only one or two studies have tried to quantify tactical changes (like team spacing or synchronization) under fatigue. This remains a relatively uncharted territory. Moreover, the psychological aspect of *perceiving fatigue vs actual fatigue* is intriguing – some researchers propose that fatigue is partly an emotion or perception governed by the brain. The central governor or psychobiological models imply that if we can alter the perception (e.g. through motivation or brain stimulation), we might extend performance even when physically fatigued. Studying such interventions (mental strategies, feedback) in soccer is a future avenue.

Finally, a gap often noted is the uncertainty in interpreting fatigue data and acting on it in real time. Coaches ask: “If a player's jump is down 5% and he says he feels tired, what next? Do we rest him, and does that actually improve performance next game?” The literature doesn't yet provide clear-cut answers on how much fatigue is too much. The thresholds at which fatigue significantly raises injury risk or drops performance are not universally defined. There is still debate about how meaningful many of the measured changes are and how to use them. Some studies have even found that elite players can sometimes maintain performance in successive games despite fatigue markers, thanks to rotations and other factors. This suggests we need more research on the functional significance of fatigue metrics: linking physiological changes to actual game performance decrements. It also indicates a need for cost-benefit analysis of monitoring – some argue constant monitoring might not be needed if players show no drop in outputs. This is a gap where more evidence could guide best practices. Future work might focus on intervention trials: implementing a fatigue-monitoring and recovery program vs. not doing so, and seeing if it yields fewer injuries or better sustained performance over a season.

While our understanding of soccer fatigue has advanced (we now recognize multiple types of fatigue – physical and mental – and use various tools to monitor them), researchers highlight that fatigue is complex and individual. There remain open questions about the precise mechanisms, the best ways to measure fatigue reliably, and how to optimally mitigate it without blunting fitness adaptations. Addressing these gaps will likely involve interdisciplinary research – combining physiology, neuroscience, psychology, and data

analytics – to further unravel how fatigue works in the context of the world's most popular sport and how players and coaches can best manage it for peak performance.

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