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Neurobiomechanical Effects of Fatigue on Climbing Performance and Injury Risk

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ABSTRACT

Introduction and Purpose:

Sport climbing poses significant physical and neuromuscular demands, with muscular fatigue representing a critical factor affecting performance, technique, and injury susceptibility. As climbing participation increases, understanding the medical implications of fatigue becomes essential. This review explores how central and peripheral muscle fatigue influence motor coordination, climbing biomechanics, and injury risk, from a neurophysiological and biomechanical perspective.

Current Knowledge:

Central fatigue disrupts motor unit recruitment by impairing central nervous system output, while peripheral fatigue compromises muscle fiber contractility. Both forms of fatigue degrade proprioception, coordination, and postural control, leading to inefficient movement and increased mechanical load on joints and tendons. Fatigue-related motor impairments contribute to a higher incidence of overuse injuries—particularly affecting the fingers, shoulders, and knees—and increase the likelihood of falls due to delayed reaction time and impaired decision-making. Although experienced climbers exhibit compensatory strategies, these adaptations are not sufficient to mitigate all health risks.

Conclusion:

Muscle fatigue is a significant medical concern in sport climbing, with direct implications for musculoskeletal injury and neuromotor control. Preventive strategies should involve targeted conditioning, fatigue monitoring (e.g., HRV, RPE), and early identification of biomechanical compensations. Further interdisciplinary research is needed to inform evidence-based guidelines for injury prevention, especially in novice and youth climbers.

Key words: Sport climbing, muscle fatigue, motor coordination, climbing technique, injury risk, central fatigue, peripheral fatigue, neurophysiology, biomechanics, training load

Introduction

Sport climbing has been gaining popularity significantly in recent years, especially since its inclusion in the Olympic Games in Tokyo 2020.(1) Alongside many professional athletes who train regularly according to strict schedules, climbing gyms are also frequented by a growing number of amateurs who climb occasionally or treat climbing as a complement to other forms of physical activity.(2) The main climbing disciplines include bouldering, speed climbing, and lead climbing. The latter, in particular, demands not only a high level of physical fitness but also technical proficiency and safety awareness. During lead climbing, the athlete must clip the rope into protection points while ascending, which minimizes the risk of injury in case of a fall.(3) Climbing is a highly demanding sport that engages the entire body. It requires muscular strength, endurance, mobility, coordination, and movement precision. Technical skills play a crucial role — not only do they allow athletes to perform complex movement sequences, but they also help prevent overuse injuries and dangerous situations.(4) Muscle fatigue is one of the main physiological limitations in strength-endurance sports.(5) In climbing, it may affect movement quality, decision-making ability, and overall safety. Despite increasing scientific interest in climbing-related physiology and biomechanics, the effects of muscle fatigue on technique and injury risk remain under-researched. The aim of this review is to explore how muscle fatigue influences climbing technique and the associated risk of injury, with a particular focus on biomechanical and neurophysiological aspects.

Muscle Fatigue – Definitions and Mechanisms

Muscle fatigue is defined as a temporary reduction in the muscle's ability to generate force or power, resulting from activity-induced changes within the muscle itself or in the nervous system. Based on this, fatigue can be divided into two primary types: peripheral fatigue, which originates in the muscle, and central fatigue, which involves the central nervous system (CNS).(6)

Central fatigue refers to a decrease in the CNS's ability—particularly within the motor cortex, subcortical regions, and spinal cord—to activate muscles, even when the muscles themselves remain physiologically capable of contracting. Several physiological mechanisms underlie this form of fatigue. One of the key mechanisms is impaired signal transmission from the primary motor cortex.(7) During prolonged or intense physical activity, the activity of cortical motor neurons diminishes. This occurs as a result of afferent feedback from exercising muscles, where metabolites such as hydrogen ions (H^+), lactate, inorganic phosphate (Pi), and ADP accumulate. These metabolites stimulate group III (mechanoreceptors) and group IV (chemoreceptors) afferent fibers, which transmit signals to the brain indicating muscular overload.(8) The brain interprets this input as a signal of potential danger and activates protective responses aimed at preventing muscle damage, overheating, dehydration, or energy substrate depletion. One such response is the inhibition of motor cortex activity, which reduces voluntary force generation.(9) Additionally, activation of group III and IV afferents increases inhibitory input via spinal interneurons—mainly through enhanced GABAergic activity—thereby reducing the responsiveness of anterior horn motor neurons to descending signals from the brain. These processes also increase perceived exertion (Rate of Perceived Exertion, RPE), contributing to an overall decline in neuromuscular performance.(10) Neurotransmitters play a significant role in central fatigue.(11) During exercise, the activity of the raphe nuclei increases, leading to elevated synthesis and release of serotonin. High serotonin levels are associated with decreased motivation and increased drowsiness, a phenomenon known as the *central fatigue hypothesis*.(12) In contrast, dopamine—critical for motivation, psychomotor arousal, and attentional processes—tends to increase during short or moderate exercise, but its levels decline as the duration or intensity of effort increases, which can heighten fatigue perception and reduce the willingness to continue activity.(13) Similarly, norepinephrine levels rise during exercise, enhancing alertness, energy mobilization, and sympathetic nervous system activity. However, with prolonged or highly intense exertion, these levels may decrease or receptor desensitization may occur, resulting in impaired focus, coordination, and physical performance.(14) All of these mechanisms ultimately lead to a reduction in central motor drive, defined as the CNS's ability to voluntarily activate skeletal muscle. One commonly used method to assess this is the Interpolated Twitch Technique (ITT). This involves delivering an electrical stimulus to the muscle during a maximal voluntary contraction. If the stimulus induces additional force, it indicates incomplete voluntary activation and thus confirms the presence of central fatigue.(15) Peripheral muscle fatigue is defined as a decline in the ability to generate muscular force due to alterations occurring at the cellular level, despite continued neural input from the central nervous system.(16) This phenomenon may result from impaired electrical signal transmission, decreased sensitivity of the contractile apparatus to calcium ions (Ca^{2+}), or reduced calcium release from the sarcoplasmic reticulum. One of the primary mechanisms underlying impaired signal propagation is the disturbance of membrane repolarization, caused by an accumulation of potassium ions (K^+) in the extracellular space. During each contraction, K^+ exits the muscle fiber, and excessive extracellular accumulation disrupts the resting membrane potential, impairing the generation of subsequent action potentials.(17) The contractile apparatus of skeletal muscle, composed of proteins such as actin, myosin, and troponin, is activated by the presence of Ca^{2+}, which initiates muscle contraction. However, during exercise, increased concentrations of hydrogen ions (H^+) lead to intracellular acidification, reducing troponin's affinity for calcium and thereby impairing the activation of the contractile machinery. Additionally, accumulation of inorganic phosphate (Pi) may bind to Ca^{2+} or directly alter the conformation of contractile proteins, further diminishing their sensitivity to calcium.(18) Repeated contractions may also lead to fatigue of the calcium release system. This is associated with depletion of calcium stores in the sarcoplasmic reticulum and reduced efficiency of ryanodine receptors (calcium channels). Furthermore, changes in the intracellular environment—such as a decrease in pH—can inhibit calcium release mechanisms and exacerbate fatigue.(19) Peripheral fatigue may also result from diminished availability of energy substrates. Deficiencies in ATP and phosphocreatine (PCr) impair the activity of ion pumps such as Na^+/K^+-ATPase and Ca^{2+}-ATPase, disrupting both muscle fiber relaxation and the capacity to sustain repeated contractions.(20) Following intense or eccentric exercise, structural damage to muscle tissue may also occur. Micro-injuries to contractile proteins (actin and myosin), damage to the cell membrane and cytoskeletal elements, as well as elevated oxidative stress and inflammatory responses, may all contribute to reduced contractile efficiency or even complete functional impairment of the affected motor units.(21, 22)

The Impact of Fatigue on Motor Coordination

Motor coordination is a fundamental component of motor abilities, defined as the capacity to perform complex, precise, and purposeful movements through the effective cooperation of the nervous and muscular systems. Sport climbing, as a discipline that requires a high level of bodily control, strongly relies on various aspects of coordination, which are essential for effective and safe navigation of routes with diverse technical demands.(23) Several types of coordination can be distinguished in the literature, each playing a significant role in climbing performance. Intramuscular coordination refers to the ability to activate the appropriate number of motor units within a single muscle at the right time and intensity. In climbing, this allows for precise force regulation during gripping and maintaining isometric tension, which is crucial when hanging on small holds.(24) Intermuscular coordination involves the cooperation of muscle groups, including agonists, antagonists, and synergists, to execute fluid and energy-efficient complex movement sequences. Climbing demands a high degree of synchronization among these muscle groups, particularly during dynamic movements and changes in direction.(25) Visuomotor coordination enables the integration of visual stimuli with corresponding motor responses. In climbing, it plays a key role in planning movement trajectories and adapting to environmental changes, such as unexpected shifts in body position or grip availability.(26) Postural coordination, or balance control, is the ability to maintain or restore body stability in various positions. This is particularly important when standing on small footholds, navigating overhanging formations, or holding static, balance-intensive positions.(27) Kinesthetic coordination, defined as the ability to perceive one's own body position and movement without visual input, is essential for controlling foot pressure or identifying holds outside the climber's field of vision, especially during more challenging movement sequences.(28)

Reaction coordination refers to the ability to produce a rapid and appropriate motor response to a stimulus. This aspect is especially critical during dynamic sequences or in belaying, where immediate and precise reactions can prevent falls or mitigate their consequences.(6)

Deficiencies in any of these coordination aspects can reduce movement efficiency, increase energy expenditure, and elevate injury risk—particularly under fatigue or competition-related stress. For this reason, the development and evaluation of motor coordination are crucial elements of both climbing-specific training and functional diagnostics for athletes.(29)

Both peripheral and central fatigue can significantly affect motor coordination, reducing the fluidity, precision, and effectiveness of movements. In practice, this translates into delayed reactions, inaccurate judgment of hold distances, improper force application, and decreased postural stability. These impairments may lead to overload injuries, microtraumas, and more serious injuries resulting from falls or slips.(30) Physiologically, fatigue causes decreased excitability of motor neurons, impaired sensory information processing, and disrupted motor unit recruitment, all negatively impacting precise movement control. The effect of fatigue on muscular coordination has been extensively studied in the context of climbing as well as other sports that demand precision, strength, endurance, and concentration. Forestier et al. (1998) assessed the impact of fatigue on multi-joint movement coordination, demonstrating that fatigue leads to reorganization of activation patterns—from flexible and integrated movement sequences toward more rigid and simplified motor patterns. This may represent a compensatory mechanism aimed at maintaining performance despite limited physiological resources.(31) Similar findings were reported by Turpin et al. (2011), who observed adaptive changes in muscle coordination following fatigue, enabling maintenance of movement efficiency despite diminished muscle function.(32) However, the capacity for such adaptation appears to be related to the athlete's experience level. Aune (2008) showed that experienced table tennis players could adjust their movement patterns in response to fatigue, preserving spatial accuracy, whereas less experienced players exhibited significant deterioration in movement precision.(33) In the context of climbing, studies focusing on experienced climbers revealed that fatigue leads to decreased movement fluidity and an increased number of hand position corrections.(34) Moreover, differences in fatigue response are also evident at the level of nervous system modulation. More experienced climbers better regulate grip force and its development rate, and report lower levels of perceived stress and anxiety, which may serve as protective mechanisms against the adverse effects of fatigue. The findings emphasize the importance of incorporating fatigue-mimicking elements into climbing training—both physical and psychological.(35) Simulating such conditions during training can help develop compensatory mechanisms and increase resistance to coordination decline under exertion. This approach may also contribute to reducing injury risk and improving movement efficiency in varying load conditions. (36)

The Impact of Fatigue on Climbing Technique

Climbing technique is often underestimated by beginners who believe that muscular strength alone is sufficient for success in climbing. However, as the difficulty and variety of climbing routes increase, greater attention must be paid to technical aspects. Climbing technique encompasses a set of motor skills that enable the execution of deliberate and controlled movements, optimal use of strength, and maintenance of precision and proper balance, allowing climbers to complete routes with minimal effort and reduced risk of injury.(37) The negative impact of fatigue on climbing technique has been supported by scientific research. Yu et al. (2023) assessed changes in grip strength and hang time on a bar after a 24-hour climbing marathon, observing an average decline in grip strength of 14.7–15.1% and a reduction in hang time by 71.2%.(38) Ferrara et al. (2020) compared advanced climbers with amateurs and found that experienced climbers maintained finger strength and muscle activation patterns, suggesting effective movement strategies despite fatigue.(39) Walsh et al. (2023) demonstrated that forearm muscle fatigue did not affect movement fluidity but significantly increased the likelihood of falling, indicating that climbers may compensate for fatigue by preserving movement smoothness.(34) It is also important to note that the effect of fatigue on technique varies depending on the climbing style. In bouldering, characterized by short, powerful moves, precision and economy of movement are critical, and fatigue quickly leads to technical errors.(40) In contrast, in multi-pitch climbing, where endurance is more important, the ability to maintain technique quality over prolonged periods is crucial for both efficiency and safety. (3) Experienced climbers often compensate for the negative effects of fatigue through technique automation, better energy management, and more economical movement patterns. For example, they utilize rest positions more effectively and engage their legs more efficiently, allowing them to conserve arm and forearm strength. This capacity is linked to their greater experience and ability to adapt technique to changing conditions. (35) Fatigue also impairs decision-making abilities, leading to increased impulsivity and poorer risk assessment, especially under high psychological stress conditions typical in lead climbing on difficult routes. Consequently, this can result in technical errors and potentially hazardous situations.(41) Additionally, Pijpers (2007) found that fatigue may distort climbers' perception of their own capabilities, such as maximal reach. Participants perceived their reach as reduced, even though it remained unchanged in reality. Such misperception can lead to poor decisions and less effective movements, thereby increasing the risk of injury.(42)

The Risk of Injury Associated with Fatigue

Climbing is a high-risk sport, primarily due to the specific nature of its movements and the intense load placed on the upper limbs. The most common, though generally less serious, injuries include abrasions and bruises. These can be particularly problematic when located on the hands, often preventing athletes from training until fully healed. Finger injuries are reported by as many as 30–40% of climbers, and typically involve overload of the finger flexor tendons, pulley ruptures, and tendonitis, especially in the fingers and wrists (approximately 20–25% of cases).(43) The shoulder joint, due to its complex structure and wide range of motion, is also susceptible to overuse and strain—particularly in the rotator cuff region. Injuries resulting from falls, wall impacts, or belaying errors can lead to sprains, dislocations, or even fractures.(44) Climbers practicing bouldering are especially at risk, as unexpected falls can cause lower limb injuries such as ankle sprains or knee joint damage.(45) Belaying errors are a major risk factor, accounting for approximately 20% of all rope climbing accidents, whether in lead or top-rope climbing.(46) Fatigue significantly increases the risk of injury. Reduced grip control elevates the likelihood of microtrauma and overload, while impaired movement precision contributes to technical errors that increase strain on muscles and joints. This often results in compensatory overuse, potentially leading to inflammation and soft tissue damage.(47) Fatigue also negatively affects proprioception and spatial perception—leading to misjudgment of hold distances and difficulty maintaining balance and stability. This raises the risk of falling off the wall and suffering mechanical injuries.(48) Studies show that central (neurological) fatigue slows reaction times and lowers muscle tone, further increasing the chance of suboptimal body positioning and injury upon impact with the wall. Additionally, fatigue is associated with a lower pain threshold and a subjective sense of diminished motor control, making injuries more likely.(49) Vieira et al. (2024) demonstrated that post-climbing fatigue impairs grip control and increases the risk of decision-making errors. It is also important to consider the role of the central nervous system. Under fatigue, the ability to efficiently process sensory input declines, which impairs concentration and decision-making quality. Electromyography (EMG) studies have shown disruptions in muscular synchronization and delayed recruitment of motor units, contributing to loss of movement precision and uncoordinated actions. While experienced climbers are sometimes able to compensate for fatigue by adjusting movement patterns, these mechanisms are limited and tend to fail under increasing physical stress.(50)

Strategies to Prevent the Negative Effects of Fatigue

Fatigue can lead to a range of adverse outcomes, posing a threat to both the health and safety of climbers. To mitigate its effects, it is essential to implement well-structured training and recovery strategies.(51) A fundamental aspect of effective prevention is a well-designed training plan based on the principles of progression and periodization. Gradually increasing the intensity and volume of training sessions allows the body to adapt to higher loads. Preventing overuse injuries is particularly important and can be achieved through strategic variation of training stimuli and incorporating recovery phases.(52) Strength training has also been shown to reduce injury risk by increasing maximal strength and muscular endurance.(53) Recovery is a critical component of managing training loads. It is during this phase that the body replenishes energy stores and repairs muscle microdamage. Between climbing bouts, rest intervals of 2 to 5 minutes are recommended, while rest days between training sessions should last 24 to 48 hours, depending on training intensity.(54) Additionally, a deload week with reduced intensity and volume should be introduced approximately every six weeks.(55) Sleep plays a vital role in recovery, with at least 7 hours per night recommended to support muscle repair and nervous system regeneration.(56) Active recovery methods should also be employed—studies suggest that light climbing is more effective for recovery than passive rest or gentle walking. Light exercise increases circulation, enhances metabolite clearance, and supports repair processes.(57) Nutrition is another essential aspect. The diet should be balanced and aligned with the athlete's energy demands. Special attention should be paid to adequate protein intake—approximately 1.6 to 2.0 g/kg of body weight—as well as sufficient carbohydrate availability and proper hydration.(58) Additional recovery methods such as foam rolling, massage, and contrast baths (alternating hot and cold) may help reduce muscle tension, enhance blood flow, and accelerate post-exercise recovery.(59)

Modern approaches to fatigue management also include monitoring the athlete's condition. Overtraining may manifest as chronic fatigue, reduced performance, prolonged muscle soreness, mood disturbances, and increased susceptibility to injuries, even with continued training. Several tools exist for objective fatigue monitoring.(60) One such tool is resting heart rate—an increase of 5–10 beats per minute may indicate insufficient recovery. A reduction in heart rate variability (HRV) also reflects nervous system fatigue and autonomic imbalance.(61, 62)

Declines in grip strength or hang time can provide further insights. In addition to objective measures, subjective tools such as the Rating of Perceived Exertion (e.g., Borg scale) and questionnaires like DALDA can be valuable in assessing fatigue levels.(63-65) An important aspect of long-term prevention is the individualization of both training and recovery processes. Variability in recovery capacity among athletes necessitates ongoing monitoring and the adjustment of training loads to the athlete's current condition.(66) Lastly, psychological recovery should not be overlooked. Modern sports science increasingly emphasizes the importance of interventions that support the nervous system, such as breathing exercises, mindfulness, or meditation. Implementing these techniques can help manage stress, improve sleep quality, and shorten the time needed for complete recovery.(67)

Conclusions

Fatigue, both central and peripheral, significantly increases the risk of injuries in climbers. Physiological changes affecting motor control, perception, and movement coordination reduce movement efficiency and increase the likelihood of technical errors. As a result, the risk of falling or executing incorrect movements rises, potentially leading to injury.(9) To mitigate the negative effects of fatigue, carefully planned training and recovery strategies are essential. Coaches and athletes should systematically monitor training loads, symptoms of overtraining, and the recovery process. Recommended strategies include active recovery, heart rate variability (HRV) tracking, grip strength analysis, and the use of standardized fatigue assessment tools such as the Borg Scale or the DALDA questionnaire.(61, 64) Additionally, there is a strong need for ongoing education of climbers and coaches in the physiology of fatigue and fatigue-monitoring methods. Mental fatigue also plays a critical role, affecting decision-making, concentration, and motivation under stress.(68) Modern technologies, including wearable devices and mobile applications, can assist in the daily monitoring of fatigue and recovery. An individualized approach to training and recovery is crucial, as athletes differ in their tolerance to load, recovery time, and fatigue response.(69)

There remains a clear need for more specific research into fatigue-related motor impairments and injury risks in climbing, particularly among beginners. Many current findings are extrapolated from other populations and sports disciplines. Experimental studies on the effectiveness of different recovery strategies, personalized algorithms for early detection of overtraining, and climbing-specific monitoring tools are urgently needed. An interdisciplinary approach — integrating physiology, sport psychology, physiotherapy, and strength & conditioning — will be vital to developing effective injury prevention and performance enhancement strategies in climbing.

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