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STRESS FRACTURES IN ATHLETES - A MULTIFACTORIAL APPROACH TO DIAGNOSIS, TREATMENT, AND PREVENTION

Wiktor Rolski *(Corresponding Author, Email: rolskiwiktor@gmail.com)*
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0005-1439-4842

Aleksandra Anna Purpura
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0006-3893-7730

Zuzanna Przybylska
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0001-3329-4602

Paulina Michalska
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0007-4141-5906

Bartłomiej Przystaś
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0009-6121-3839

Magdalena Grzechowiak
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0001-8486-0352

Sebastian Podeszwa
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0000-2973-5324

Mikołaj Piotr Hobot
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0001-2829-6005

Gabriela Patrycja Dobosz
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0009-4012-9101

Paweł Michalski
Municipal Combined Hospital in Częstochowa, Częstochowa, Poland
ORCID ID: 0009-0002-8935-7171

ABSTRACT

Background: Stress fractures are common overuse injuries in athletes, resulting from repetitive mechanical loading and microdamage accumulation. Their development is multifactorial, involving biomechanical, metabolic, and behavioral factors. Increasing attention is being paid to data-driven training management and digital monitoring tools in injury prevention.
Aim: To review current approaches to the diagnosis, treatment, and prevention of stress fractures in athletes, with emphasis on multifactorial risk models and technology-supported workload management.
Materials and Methods: A narrative review was conducted using PubMed and Google Scholar databases. Original studies and reviews involving athletes were analyzed, focusing on diagnostic strategies, treatment approaches, and preventive frameworks.
Results: Stress fractures predominantly affect the lower extremities, especially the tibia and metatarsal bones. Their pathogenesis reflects an imbalance between mechanical load and bone adaptation, often linked to training errors, low bone mineral density, and hormonal disturbances. MRI is the most sensitive diagnostic modality. Management depends on fracture location and risk classification. Emerging evidence highlights the role of individualized workload monitoring and wearable technologies in reducing injury risk.
Conclusions: Stress fractures require an interdisciplinary approach integrating clinical management with technological and behavioral strategies. Data-driven workload monitoring and metabolic optimization may improve prevention and athlete well-being, with potential implications for broader health management and policy in sport systems.

KEYWORDS

Stress Fractures, Bone Stress Injuries, Diagnosis, Treatment, Prevention, Return to Sport

CITATION

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1. Introduction

Stress fractures are a significant problem in sports medicine and represent one of the most common overuse injuries of the skeletal system. They result from repetitive submaximal mechanical loading, leading to the accumulation of microdamage within bone structure, which may ultimately progress to complete fracture [1,2]. This process results from an imbalance between bone resorption and formation, characterized by increased osteoclastic activity relative to osteoblastic activity [3].

Stress fractures account for approximately 10–20% of all sports-related injuries, with incidence rates reaching up to 20% among elite athletes. They predominantly affect young, physically active individuals, particularly long-distance runners, track and field athletes, and military recruits [4,5]. In runners, these injuries are especially common due to the repetitive nature of mechanical loading applied to the skeletal system [5].

The lower extremity is the most common location of stress fractures, particularly involving the tibia, metatarsal bones, and femur [6]. It is estimated that 80–95% of all stress fractures occur in this anatomical region. The location of injury is closely related to the type of physical activity and the specific biomechanical loads involved [4].

The etiology of stress fractures is multifactorial and includes both extrinsic and intrinsic factors. Extrinsic factors primarily involve training errors, such as sudden increases in training volume or intensity, inappropriate footwear, and changes in training surface [2,5]. Intrinsic factors include female sex, low bone mineral density, hormonal disturbances, and inadequate nutritional habits [3,6]. Particular attention has been given to relative energy deficiency in sport (RED-S) and the female athlete triad, both of which significantly increase the risk of stress fractures [4].

Vitamin D deficiency is also recognized as an important risk factor, as it affects bone metabolism and mechanical strength. Evidence indicates that low serum 25(OH)D levels are associated with an increased risk of stress fractures and impaired bone mineralization [7]. Furthermore, vitamin D plays a crucial role in regulating bone metabolism and muscle function, and its deficiency is common among athletes. Adequate supplementation with vitamin D and calcium has been shown to reduce the incidence of these injuries [7].

The clinical presentation of stress fractures typically develops gradually and typically includes localized pain that initially occurs during physical activity and may later be present at rest [1,2]. Due to the nonspecific nature of symptoms and the limited sensitivity of radiographic imaging in the early stages, diagnosis is often delayed [2]. Currently, magnetic resonance imaging (MRI) is considered the most sensitive diagnostic modality, allowing detection of changes at the stage of bone stress reaction [1,2,3].

In recent years, increasing attention has been given to the role of modern technologies, including wearable devices and athlete monitoring systems, in the assessment and prevention of overuse injuries [24]. These approaches enable continuous tracking of training load and biomechanical stress, providing new opportunities for early detection and individualized risk management.

Despite the growing number of studies on stress fractures, significant gaps remain in the standardization of diagnostic, therapeutic, and preventive strategies. In particular, there is a lack of high-quality methodological studies, highlighting the need for further research in this field [4].

The aim of this study was to provide a comprehensive overview of current approaches to the diagnosis, treatment, and prevention of stress fractures in athletes, with particular emphasis on workload management and emerging technologies in injury monitoring.

2. Methodology

2.1. Study Design

This study was conducted as a narrative review aimed at synthesizing current evidence on the diagnosis, treatment, and prevention of stress fractures in athletes.

2.2. Literature Search Strategy

A structured literature search was performed using PubMed and Google Scholar databases, including studies published up to 2025.

The following keywords and their combinations were used:

"stress fractures", "bone stress injury", "fatigue fractures", "sports injuries", "diagnosis", "treatment", "prevention", "risk factors", and "return to sport".

Boolean operators ("AND", "OR") were applied to refine the search. Additionally, reference lists of relevant articles were manually screened to identify further studies.

2.3. Inclusion and Exclusion Criteria

The review included:

- original research articles,
- systematic reviews and meta-analyses,
- studies involving athletes and physically active populations.

Studies focusing on pathophysiology, epidemiology, diagnosis, treatment, and prevention of stress fractures were considered.

The following were excluded:

- animal studies,
- conference abstracts and opinion-based articles,
- publications not directly related to the topic.

2.4. Study Selection

Titles and abstracts of identified studies were screened, followed by full-text evaluation of eligible articles. Duplicate records were removed.

The final selection was based on relevance, methodological quality, and applicability to sports-related stress fractures.

2.5. Data Analysis

A qualitative synthesis approach was applied. Findings from selected studies were compared and integrated to identify key patterns related to diagnosis, treatment strategies, and prevention of stress fractures.

Special attention was given to factors influencing return to sport and injury risk.

3. Results

3.1. Pathophysiology

Stress fractures are considered a continuum of bone stress injuries resulting from repetitive submaximal loading that exceeds the bone's adaptive capacity. This process reflects an imbalance between mechanical loading applied to bone tissue and its ability to adapt. Bone is a dynamic tissue that continuously undergoes remodeling in response to mechanical stimuli, allowing it to adapt to changing loading conditions. This process involves the coordinated activity of osteoclasts, responsible for bone resorption, and osteoblasts, responsible for new bone formation [8].

Under physiological conditions, repetitive loading leads to an adaptive increase in bone strength. However, when the intensity or frequency of loading exceeds the regenerative capacity of bone tissue, structural microdamage accumulates. This results in a predominance of resorptive processes over bone formation, leading to progressive weakening of bone structure and the development of stress fractures [8,9].

A key stage in the pathogenesis is the so-called bone stress reaction, which represents an early phase of injury. At this stage, increased bone remodeling and metabolic changes occur within the affected tissue, which may be detected by imaging modalities before the appearance of a visible fracture line. With continued mechanical loading, this process may progress to a complete stress fracture [9].

The characteristics of mechanical stimuli also play a crucial role. Bone adaptation depends not only on the magnitude of loading but also on its dynamics, frequency, and number of cycles. Dynamic mechanical loading has been shown to be essential for stimulating anabolic processes in bone, whereas excessive loading may lead to structural damage. A rapid increase in training load may impair proper bone adaptation, thereby increasing the risk of stress fractures.

From a biomechanical perspective, this process can be explained by the bone's capacity to adapt to mechanical stress. However, when the adaptive threshold is exceeded, structural destabilization occurs, resulting in increased susceptibility to injury [10].

It is important to distinguish stress fractures from insufficiency fractures, which occur when normal physiological loads are applied to bone with reduced mechanical strength. In stress fractures, bone tissue is initially normal, and the primary pathogenic factor is chronic mechanical overload [11].

Additionally, systemic factors such as hormonal disturbances, low bone mineral density, and menstrual dysfunction may contribute to reduced adaptive capacity of bone tissue. These factors are particularly significant in female athletes, who demonstrate an increased susceptibility to stress fractures [11].

In summary, the pathophysiology of stress fractures is a complex process involving the interaction between mechanical loading, biomechanical properties of bone, and metabolic factors. The key mechanism underlying stress fracture development is a disruption of the balance between microdamage accumulation and bone remodeling, influenced by both mechanical loading patterns and systemic factors.

3.2. Epidemiology

Stress fractures represent a substantial proportion of overuse injuries in athletes, with incidence varying depending on sport type, training intensity, and population characteristics. Their occurrence is strongly influenced by repetitive loading patterns, particularly in endurance sports such as long-distance running [9].

Available data indicate that stress fractures constitute a substantial proportion of overuse injuries in sport. Systematic analyses emphasize that their occurrence is influenced by multiple factors, including training load characteristics and individual athlete-related factors [12].

More detailed insights are provided by population-based studies. In an analysis of collegiate athletes, the incidence was reported to be approximately 5.70 cases per 100,000 athlete exposures, with the highest rates observed in sports such as cross-country running, track and field, and gymnastics [13]. These findings reflect the impact of repetitive mechanical loading, which leads to the accumulation of microdamage within bone tissue.

Stress fractures most commonly occur in the lower extremities, particularly in the metatarsal bones and tibia, which are highly susceptible to repetitive loading during dynamic activities [9,13]. Notably, sex-related differences have also been observed, with female athletes demonstrating a higher susceptibility to these injuries, as confirmed by both epidemiological studies and analyses of specific athletic populations [13].

Additional epidemiological data are derived from studies conducted in specific athlete groups. Among long-distance female runners, an increased incidence of stress fractures has been reported, particularly in individuals with menstrual disturbances and inadequate energy intake, highlighting the importance of metabolic and hormonal factors [14].

Overall, epidemiological evidence indicates that stress fractures are strongly associated with repetitive loading patterns and are particularly prevalent in sports characterized by high-impact and endurance demands.

3.3. Risk Factors

The etiology of stress fractures is multifactorial, involving a complex interaction between intrinsic and extrinsic factors that collectively influence bone loading and adaptive capacity [12].

Among intrinsic factors, disturbances in bone metabolism and reduced bone mineral density play a key role. In a prospective study conducted among highly trained female runners, low bone mineral density in the lumbar spine was identified as the strongest predictor of stress fractures [15]. In particular, values below 81.1% of the age-matched reference value (YAM) were associated with a significantly increased risk of injury.

Additionally, reduced bone mass and decreased muscle mass are important contributors, as they impair shock absorption and compromise musculoskeletal stability [15]. In populations of long-distance female runners, previous injuries, menstrual disturbances, and inadequate nutritional habits have also been shown to significantly increase the risk of stress fractures [14]. These findings highlight the importance of energy balance and proper hormonal function in maintaining bone health.

Anatomical and biomechanical factors are also relevant, including malalignment of the lower limbs and altered movement mechanics, which may lead to uneven force distribution and localized bone overload [12].

Extrinsic factors are primarily related to training characteristics. In particular, a sudden increase in training intensity or volume, as well as a high frequency of competition, may lead to excessive bone loading and increased risk of stress fractures [12,9].

It has also been demonstrated that the preparatory period is associated with a higher risk of injury compared to the competitive season, likely due to rapid increases in training load combined with insufficient physiological adaptation [13].

Lifestyle-related factors are also important, including inadequate energy intake and insufficient recovery, both of which may impair the body’s ability to repair microdamage within bone tissue [14].

Contemporary understanding of stress fracture pathogenesis emphasizes its multifactorial nature. The risk of injury increases significantly when multiple adverse factors coexist, highlighting the importance of a multifactorial and individualized approach to risk assessment and prevention [12,15].

Therefore, stress fractures should be considered as the result of an imbalance between microdamage accumulation and the regenerative capacity of bone tissue, which forms the basis of the current understanding of their pathophysiology.

3.4. Diagnosis

The diagnosis of stress fractures requires an integrated approach combining clinical evaluation and imaging, as early-stage symptoms are often nonspecific and may mimic other musculoskeletal conditions [16,17].

The most common symptom of a stress fracture is gradually increasing, localized pain, initially occurring only during physical activity and, with progression, also at rest. Unlike acute injuries, patients are usually unable to identify a specific moment of onset, which often delays diagnosis [17]. Particular attention should be paid to a history of sudden increases in training intensity or volume, changes in the type of physical activity, and previous overuse injuries. The presence of predisposing factors, such as metabolic or hormonal disturbances and nutritional deficiencies, should also be considered.

On physical examination, localized tenderness over the affected bone is the most common finding and typically correlates with the site of injury. In some cases, soft tissue swelling or slight thickening of the affected area may be observed. Functional tests, such as the single-leg hop test or other provocation tests, may reproduce symptoms and suggest the presence of an overuse injury [17]. However, it should be emphasized that clinical findings are often nonspecific, necessitating thorough differential diagnosis.

The differential diagnosis of lower limb pain in athletes includes a wide range of conditions, such as medial tibial stress syndrome (MTSS), tendinopathies, muscle injuries, chronic exertional compartment syndrome, as well as vascular and neurological disorders [16]. Accurate differentiation is essential for appropriate therapeutic management. This broad differential diagnosis reflects the nonspecific nature of clinical presentation and highlights the importance of integrating clinical findings with imaging results [16].

Imaging studies play a key role in confirming the diagnosis of stress fractures. Conventional radiography (X-ray) is typically the first-line imaging modality due to its availability and low cost; however, its sensitivity in detecting early changes is limited. In the initial stages, radiographic findings may remain normal for several weeks, while characteristic features such as periosteal reaction, cortical thickening, or a fracture line appear only in more advanced stages [18].

Magnetic resonance imaging (MRI) is currently considered the gold standard in the diagnosis of stress fractures due to its high sensitivity and specificity, allowing detection of early bone stress reactions before structural bone damage occurs [18,19]. It enables detection of bone marrow edema and periosteal reactions at the initial phase of the disease process, allowing for early diagnosis and timely intervention [18,19]. Moreover, MRI allows precise assessment of lesion location and extent, as well as differentiation between stress reactions and complete fractures. Comparative studies have shown that MRI has the highest sensitivity among available imaging modalities, outperforming computed tomography and bone scintigraphy [18,19].

Computed tomography (CT) is primarily useful for assessing structural bone changes, particularly cortical integrity, and for identifying fracture lines. However, its role in early diagnosis is limited, as it does not allow visualization of bone marrow edema, which is a key feature of early stress injury [19]. It may, however, be useful in differential diagnosis, especially when neoplastic or other bone pathologies are suspected.

Bone scintigraphy, despite its high sensitivity, currently has limited use in the diagnosis of stress fractures. This is due to its low specificity, as increased tracer uptake may also be observed in other pathological conditions such as infections or neoplasms. Additionally, it involves exposure to ionizing radiation [18].

Early and accurate diagnosis is essential to prevent progression to complete fracture, optimize treatment strategies, and facilitate safe and timely return to physical activity [18]. Prompt implementation of appropriate diagnostic procedures helps limit lesion progression, reduce complication risk, and shorten time to return to physical activity. In clinical practice, it is emphasized that the diagnostic approach should be individualized, taking into account the location of the injury, the stage of the lesion, and patient-specific characteristics [18].

3.5. Classification

The classification of stress fractures is essential for determining injury severity, guiding management strategies, and predicting clinical outcomes, including return to physical activity [20]. Currently, particular importance is attributed to imaging-based classifications, especially those utilizing magnetic resonance imaging (MRI), which allows evaluation of the full spectrum of bone stress injuries [20].

Stress fractures do not represent a uniform clinical entity but rather a continuum of changes, ranging from early stress reactions to complete fractures with cortical disruption. On MRI, this process is reflected by a gradual progression of findings, from periosteal and bone marrow edema to the presence of a fracture line [20]. In clinical practice, stress fractures are also classified as low-risk and high-risk based on their anatomical location and potential for complications. High-risk fractures, such as those involving the femoral neck, anterior tibia, and navicular bone, are associated with delayed healing, nonunion, or progression to complete fracture, whereas low-risk fractures generally respond well to conservative treatment [1,2].

The most commonly used system is a four-grade MRI classification, which considers the extent of bone marrow involvement and the presence of structural bone damage. Grade 1 is characterized by mild edema visible on T2-weighted images without changes on T1-weighted images. Grade 2 involves more pronounced edema without T1 abnormalities. Grade 3 is defined by edema visible on both T2- and T1-weighted images, indicating more advanced injury, whereas Grade 4 corresponds to a complete stress fracture with a visible fracture line [20]. Higher MRI grades have been shown to be associated with significantly longer return-to-sport times, underscoring the clinical relevance of this classification. In addition, classification systems support clinical decision-making by identifying injuries that require more intensive management or prolonged recovery strategies [20].

3.6. Location

A clinically important distinction is the classification of stress fractures into low- and high-risk categories, which directly influences therapeutic decision-making and prognosis [21,22]. Low-risk fractures are typically located in well-vascularized regions subjected predominantly to compressive forces, thereby promoting healing. These include, among others, the posteromedial tibia, femoral shaft, metatarsal shafts, and calcaneus [21,22].

In contrast, high-risk fractures occur in areas with limited blood supply or exposed to tensile forces and include the anterior tibial cortex, base of the fifth metatarsal, navicular bone, and the lateral aspect of the femoral neck [21,22]. These characteristics contribute to impaired healing potential and a higher risk of complications, including delayed union, nonunion, and complete fracture [21,22].

In clinical practice, location-specific classification systems are also used, such as the Torg classification for fifth metatarsal fractures and the Saxena classification for navicular stress fractures, which allow for more precise assessment of injury severity, healing potential, and risk of complications. Combining imaging-based and clinical classification systems enables more accurate treatment planning and prediction of return-to-sport timelines [21,22].

The distribution of stress fractures within the skeletal system is closely related to biomechanical loading patterns and the specific nature of physical activity. The vast majority of injuries involve the lower extremities, accounting for up to 95% of cases in athletes [21,22], which reflects the repetitive weight-bearing loads characteristic of most sports disciplines. The tibia is the most frequently affected bone, representing up to 50% of cases, followed by the metatarsals, femoral neck, and tarsal bones [21,22].

High-risk locations, such as the base of the fifth metatarsal and the navicular bone, are of particular clinical importance due to their increased propensity for delayed union. In femoral neck stress fractures, a distinction is made between compression-type and tension-type injuries, with the latter associated with a significantly higher risk of complications, including displacement and avascular necrosis of the femoral head, often requiring urgent surgical management [21,22].

Stress fractures of the pelvis, including those involving the sacrum and pubic rami, although less common, are clinically significant due to diagnostic challenges and nonspecific symptom presentation [21,22].

In contrast to lower extremity injuries, stress fractures of the upper extremity are less common and demonstrate greater variability in location. Their occurrence is closely related to the specific demands of the sport and the pattern of repetitive loading [23].

Clavicular stress fractures may involve the medial portion or present as distal clavicular osteolysis due to repetitive microtrauma of the acromioclavicular joint [23]. Scapular stress fractures may affect various structures, including the acromion and coracoid process, and are typically associated with overload of the shoulder girdle musculature [23].

Rib stress fractures occur in characteristic locations depending on muscle forces and rotational loading, particularly in athletes performing repetitive trunk rotation [23].

Humeral stress fractures may involve both the proximal epiphysis, commonly seen in young athletes, and the shaft, often related to torsional and bending forces [23]. Special attention is given to classifications of olecranon stress fractures, which consider skeletal maturity and morphological characteristics, both of which have important clinical implications [23].

In summary, classification and anatomical location of stress fractures represent complementary elements in injury assessment, providing essential information for risk stratification, treatment selection, and return-to-sport decision-making. Their combined consideration allows for more accurate evaluation of injury severity, estimation of complication risk, and optimization of therapeutic management, which is particularly important in athletic populations.

3.7. Role of Technology in Monitoring and Prevention of Stress Fractures

Recent advances in wearable technology have significantly expanded the possibilities for objective monitoring of biomechanical loads and supporting prevention strategies for overuse injuries, including stress fractures [24]. Wearable sensors enable continuous, non-invasive data collection in real-world conditions, overcoming the limitations of traditional laboratory-based biomechanical assessments [24]. These systems can provide detailed information on movement patterns, loading characteristics, and training responses, which are critical in understanding the mechanisms underlying bone stress injuries.

A key application of wearable technology in sports medicine is the monitoring of training workload. Workload represents a combination of external load (e.g., distance, impacts, accelerations) and internal load (e.g., physiological response), both of which are associated with injury risk. Modern wearable devices, such as inertial measurement units (IMUs), GPS systems, and heart rate monitors, allow for longitudinal tracking of these variables in athletic populations [25]. This enables practitioners to identify potentially harmful training patterns, such as sudden increases in load or insufficient recovery, which are strongly associated with the development of stress-related injuries [25].

Beyond general workload monitoring, recent research has focused on the direct estimation of biomechanical forces acting on bone tissue. Traditional surrogate metrics, such as ground reaction forces, have been shown to poorly reflect internal tissue loading. In response, novel approaches combining wearable sensor data with biomechanical modeling and machine learning algorithms have been developed to estimate tibial bone forces more accurately [26]. These methods represent a significant step toward individualized injury risk assessment by enabling subject-specific estimation of internal bone loading, which cannot be directly measured using traditional approaches [26].

Further advancements have demonstrated that wearable systems can estimate tibial bone forces in real-world running conditions with relatively high accuracy. For example, multi-sensor configurations integrating pressure-sensing insoles and shoe-mounted IMUs have been shown to estimate peak tibial forces with low error margins compared to laboratory-based measurements [27]. This provides a practical framework for real-time monitoring of bone loading, supporting data-driven training adjustments and more precise workload management strategies in athletic populations [27].

Despite their promising potential, wearable technologies remain in a developmental stage in the context of injury prevention. Challenges include data variability, the need for standardized protocols, and limited evidence directly linking wearable-derived metrics to injury outcomes [24]. Nevertheless, current evidence remains limited, particularly regarding the direct translation of wearable-derived metrics into validated injury prediction models, highlighting the need for further longitudinal and application-oriented research [24]. As these technologies continue to evolve, they have the potential to support personalized, data-driven approaches to injury prevention and training optimization, contributing to the development of more effective and sustainable sports systems.

3.8. Prevention of Stress Fractures

Stress fractures represent the final stage of an overuse process resulting from an imbalance between cumulative mechanical loading and the bone's capacity for adaptation and repair [28]. Therefore, effective prevention requires a comprehensive and individualized approach integrating biomechanical, physiological, and training-related factors.

One of the most important elements of prevention is appropriate management of training load. Increasing evidence indicates that bone stress injuries develop when repetitive loading exceeds the adaptive capacity of bone tissue, particularly in the presence of rapid changes in training intensity or volume [29]. These so-called "load errors" are considered one of the most significant modifiable risk factors. Sudden "spikes" in workload are especially harmful, as they promote the accumulation of microdamage and increase the risk of injury [28,29].

Workload can be understood as the interaction between the magnitude, frequency, and number of loading cycles applied to bone tissue. Importantly, there is no single optimal workload; rather, it exists within an individualized range depending on factors such as bone quality, training history, and physiological condition [29]. While gradual progression of training load is recommended, universal rules such as the 10% increment rule are not always applicable and should be adapted to the individual athlete [29].

Within training structure, the relationship between volume and intensity is particularly important. An increase in training volume has been associated with a progressive rise in injury risk, whereas increases in intensity may result in a disproportionately greater increase in stress fracture risk [29]. For this reason, it is generally recommended to prioritize volume progression before introducing higher training intensity. Adequate recovery periods and proper training periodization are essential, as they restore bone mechanosensitivity and prevent excessive accumulation of fatigue-related damage [29].

Beyond external workload parameters, individual tolerance to loading is increasingly recognized as a key factor in injury prevention. A growing body of literature emphasizes the concept of training load capacity, defined as an individual's ability to tolerate mechanical stress without developing injury [30]. This capacity is dynamic and influenced by multiple intrinsic and extrinsic factors, including bone mineral density, hormonal status, nutrition, biomechanics, and psychological stress. These factors interact cumulatively, forming an individualized risk profile that determines susceptibility to bone stress injuries. Consequently, prevention strategies should adopt a holistic and patient-centered approach rather than focusing on isolated risk factors [30].

Proper neuromuscular and biomechanical preparation is also a key component of prevention. Strength training enhances the ability of muscles to absorb and redistribute mechanical loads, thereby reducing stress transmitted directly to bone tissue [29]. Optimization of movement patterns, including modifications of running technique such as increased cadence, may further decrease ground reaction forces and cumulative skeletal loading [29]. Additionally, incorporating low-impact cross-training activities, such as swimming or cycling, can reduce repetitive loading while maintaining cardiovascular fitness [29].

Preventive strategies should also include appropriate training structure and early athletic development. Periodization, including planned variations in load and intensity, allows for adequate recovery and adaptation. Furthermore, exposure to multidirectional and high-impact activities during early development has been shown to enhance skeletal robustness and may reduce future injury risk [29].

In addition to mechanical factors, metabolic and physiological determinants play a critical role in bone health. Adequate nutritional intake is essential for maintaining bone mineral density and structural integrity. Higher intake of calcium, vitamin D, and dairy products has been associated with a significantly reduced risk of stress fractures [31]. Protein intake and adequate mineral supply further contribute to optimal bone metabolism and strength [31].

Vitamin D is of particular importance, as its deficiency represents an independent risk factor for stress fractures. Individuals with low serum 25(OH)D levels have been shown to have a significantly increased risk of injury, likely due to disturbances in calcium-phosphate homeostasis and impaired bone mineralization [32]. Maintaining adequate vitamin D levels may therefore play a crucial role in prevention.

Hormonal balance is another critical determinant of bone health. Conditions such as relative energy deficiency in sport (RED-S) and the female athlete triad are associated with decreased bone mineral density and increased susceptibility to stress fractures [33]. Energy deficiency and menstrual dysfunction contribute to increased bone resorption and reduced bone strength, highlighting the importance of comprehensive medical and nutritional assessment in athletes.

Modern sports practice increasingly incorporates athlete monitoring systems that combine external load metrics, internal physiological responses, and subjective measures of well-being. Although direct quantification of tissue-level loading remains challenging, these systems provide useful surrogate indicators that support individualized load management and early identification of maladaptive patterns [34]. Continuous monitoring allows early identification of maladaptive loading patterns and facilitates timely adjustments in training and recovery.

Despite advances in prevention strategies, several challenges remain, including the lack of standardized workload thresholds, inter-individual variability in response to training, and limitations in accurately quantifying tissue-level loading. Nevertheless, current evidence supports a multifactorial and individualized approach that integrates workload management, biomechanical optimization, nutritional support, and continuous monitoring as the foundation of effective stress fracture prevention.

3.9. Treatment

The management of stress fractures in athletes represents a significant clinical challenge and should be tailored to the location of the injury, its severity, and its classification as either low- or high-risk. The primary goal of treatment is to achieve complete bone healing and enable a safe return to sport at the pre-injury level [21]. In clinical practice, low-risk fractures are typically managed conservatively, whereas high-risk fractures more often require surgical intervention due to the increased risk of complications and treatment failure [21].

Conservative management includes activity modification, load reduction, temporary immobilization, and gradual return to physical activity. It remains the mainstay of treatment in many cases of stress fractures [21]. This approach allows effective healing and return to sport in the majority of patients, particularly in low-risk locations [35]. Conservative treatment in tibial stress fractures is generally associated with high return-to-sport rates; however, a notable proportion of cases may require prolonged recovery or fail initial management [35]. Return-to-sport time in this group varies widely, ranging from approximately 1 to 6 months, depending on injury severity and location [35].

Similar outcomes are observed in other low-risk lower extremity fractures, such as those involving the posteromedial tibia or metatarsal shafts, where return to sport typically occurs within 4 to 12 weeks [21].

In contrast, high-risk fractures, such as those involving the navicular bone, anterior tibial cortex, or base of the fifth metatarsal, are more frequently treated surgically to reduce the risk of delayed union and nonunion [21]. A meta-analysis of navicular stress fractures reported an average return-to-sport time of approximately 4.17 months following surgical treatment and 4.67 months following conservative treatment, with comparable return-to-sport rates [36].

In fractures of the base of the fifth metatarsal, surgical treatment demonstrates a clear advantage over conservative management, with higher union rates (87% vs. 56%) and shorter healing time (13.1 vs. 20.9 weeks) [37]. Moreover, surgical management is associated with a lower risk of complications, including nonunion, which may occur in up to 33% of conservatively treated cases [37].

Return to sport is a key outcome measure used to evaluate treatment effectiveness. Available evidence indicates that return-to-sport rates are generally high regardless of treatment modality; however, differences are observed in recovery time and complication risk [35,37]. In fifth metatarsal base fractures, return to sport approaches 100% in both surgical and conservative groups; however, surgical treatment allows a faster return, averaging approximately 10 weeks to any level of activity and 14.5 weeks to pre-injury performance level [37].

In navicular fractures, return to sport typically occurs within 4–5 months regardless of treatment modality, highlighting the importance of injury location in determining recovery time [36]. In tibial stress fractures, return-to-sport time ranges from several weeks to several months, with surgical treatment associated with lower failure rates, whereas conservative treatment demonstrates greater variability in outcomes [35].

For olecranon stress fractures, both surgical and conservative approaches can result in high return-to-sport rates, although the average time to return is approximately 4–6 months, again emphasizing the importance of fracture location [38,39].

Overall, both surgical and conservative treatments allow return to sport in most patients; however, treatment selection should be individualized based on fracture characteristics. In high-risk fractures, surgical treatment is often associated with higher union rates, shorter healing times, and lower complication rates, resulting in a more predictable recovery course [21,37]. In contrast, although conservative treatment is effective in selected cases, it carries a higher risk of treatment failure and may necessitate secondary surgical intervention [35].

The effectiveness of treatment and time to return to sport are influenced by multiple factors, including fracture location, severity, treatment method, and individual patient characteristics [21]. Properly conducted rehabilitation and early detection of stress-related changes are also critical, as they may shorten recovery time and reduce the risk of recurrence [21]. Return-to-sport decisions should be based on the resolution of symptoms and the ability to perform activity without pain, followed by a gradual and supervised progression of loading [1,2].

4. Discussion

Stress fractures represent a complex clinical problem, requiring a multifaceted approach to their pathogenesis, diagnosis, and treatment. The available literature indicates that the key mechanism underlying these injuries is an imbalance between mechanical loading and the adaptive capacity of bone tissue, leading to the accumulation of microdamage and progression from a stress reaction to a complete fracture [1,3,8,9]. Contemporary perspectives emphasize the dynamic and multifactorial nature of this process, involving biomechanical, metabolic, and hormonal factors.

Epidemiological studies indicate a predominance of stress fractures in the lower extremities, reflecting the nature of loading in endurance sports [9,13]. Structures such as the tibia and metatarsal bones are particularly susceptible due to repetitive high-cycle loading. Significant sex-related differences have also been observed, with a higher risk in female athletes, likely associated with hormonal factors and RED-S [13,14,33]. These findings are consistent with the current multifactorial model, which assumes a synergistic interaction between intrinsic and extrinsic factors in injury development [12,15].

Magnetic resonance imaging plays a crucial role in the diagnosis of stress fractures, as it enables early detection of bone stress injuries prior to the appearance of a fracture line [18,19]. The high sensitivity of MRI and its ability to assess injury severity contribute to improved prognosis and optimization of therapeutic strategies. In contrast, the limited sensitivity of conventional radiography in early stages may lead to diagnostic delays, highlighting the need for advanced imaging techniques [1,18].

Available evidence indicates that the choice of therapeutic strategy should be closely related to fracture location and classification as low- or high-risk [21,22]. Conservative treatment remains the first-line approach for low-risk fractures and allows return to sport in most patients; however, it is associated with a significant rate of treatment failure in certain locations, such as the tibia [35]. Surgical treatment, on the other hand, is indicated in high-risk fractures and is associated with higher union rates and a more predictable clinical course, particularly in fractures of the base of the fifth metatarsal [37].

One of the most important clinical outcomes is time to return to sport, which serves as a key indicator of treatment effectiveness. Available data indicate that return to sport is achievable in most patients; however, it depends on fracture location and severity, and differences exist in recovery time and complication risk [35,36,37]. In some locations, such as the navicular bone, return-to-sport time is similar between treatment methods, whereas in others, such as the base of the fifth metatarsal, surgical treatment allows a faster return to activity [36,37]. This highlights the need for individualized therapeutic decision-making and consideration of injury-specific factors.

The findings also emphasize the key role of prevention, which should be an integral component of sports medicine practice. Proper management of training load is particularly important, as sudden increases in intensity or volume represent major risk factors for stress fractures [24,28,29]. This reflects a contemporary shift toward individualized and data-driven workload management models, which emphasize the balance between external load and individual load capacity.

Nutritional and metabolic factors also play a crucial role. Adequate intake of calcium, vitamin D, and energy contributes to maintaining bone mineral density and reducing injury risk [31,32]. Vitamin D deficiency, in particular, has been strongly associated with increased risk of stress fractures, as confirmed by prospective studies [32]. Hormonal factors, including disturbances related to RED-S, are equally important, as they contribute to reduced bone density and increased susceptibility to injury [33].

Despite the increasing number of studies on stress fractures, significant limitations remain in the available literature. In particular, heterogeneity of study populations, methodological differences, and the lack of standardized diagnostic and therapeutic protocols limit direct comparison of results and formulation of clear clinical recommendations [4,21]. Additionally, many studies are retrospective or involve small sample sizes, which reduces their level of evidence.

From a practical perspective, the findings of this study highlight the importance of a comprehensive approach to the diagnosis, treatment, and prevention of stress fractures. Early diagnosis, appropriate classification, and individualized treatment strategies enable optimization of therapeutic outcomes and reduction of time to return to sport. At the same time, implementation of preventive strategies, including training load management and optimization of metabolic factors, is essential for reducing the incidence of these injuries.

In conclusion, stress fractures should be considered as the result of a complex interaction between biomechanical, metabolic, and training-related factors. Effective management requires an interdisciplinary approach and further research aimed at standardizing diagnostic and therapeutic protocols, which may contribute to improved treatment outcomes and athlete safety.

5. Conclusions

Stress fractures represent a significant problem in sports medicine and result from an imbalance between mechanical loading and the adaptive capacity of bone tissue, leading to the accumulation of microdamage and progression to complete fracture. The risk of their occurrence is multifactorial and includes both extrinsic factors, such as training errors and sudden increases in training load, and intrinsic factors, including low bone mineral density, hormonal disturbances, and inadequate nutritional habits. The most common location of stress fractures is the lower extremity, particularly the tibia and metatarsal bones, which reflects the repetitive loading patterns characteristic of endurance sports.

Magnetic resonance imaging is the diagnostic modality of choice for stress fractures, enabling early detection of bone stress injuries and accurate assessment of their severity, which is crucial for prognosis and therapeutic decision-making [1,18,19]. The choice of treatment should depend on fracture location and its classification as low- or high-risk. Conservative management is preferred for low-risk fractures, whereas surgical treatment is indicated in high-risk cases, where it provides higher union rates and a more predictable clinical course. Return to sport is achievable in most patients; however, recovery time depends on fracture location, severity, and the treatment modality applied. In selected cases, surgical intervention may accelerate return to sport and reduce the risk of complications.

Effective prevention of stress fractures requires a comprehensive approach, including optimal training load management, adequate nutrition, and maintenance of proper hormonal balance, with particular emphasis on the role of vitamin D and calcium. Early identification of risk factors and implementation of preventive strategies may significantly reduce the incidence of these injuries and shorten time to return to physical activity. Despite the growing body of evidence, there remains a need for further high-quality studies to standardize diagnostic, therapeutic, and preventive strategies for stress fractures in athletes.

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