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Management and Prevention of Bone Stress Injuries in Long-Distance Runners

Humans are structurally and physiologically developed for long-distance running, which likely evolved during our time as hunters and gatherers. Although the ability to hunt and gather is no longer an evolutionary requirement, many people continue to run long distances today to take advantage of the well-known health and wellness benefits of endurance exercise. Unfortunately, distance running also carries the risk of developing overuse injuries, which in bone consist of bone stress injury (BSI). A BSI represents the inability of bone to withstand repetitive mechanical loading, which results in structural fatigue and localized bone pain and tenderness. Bone stress injuries occur along a pathology continuum beginning with stress reactions, which can progress to stress fractures and, ultimately, complete bone fractures. The purpose of this commentary is to discuss management and prevention options for BSIs in runners. In doing so, information is provided on the pathophysiology, epidemiology, risk factors, clinical diagnosis, and classification of BSIs.

SYNOPSIS: Bone stress injury (BSI) represents the inability of bone to withstand repetitive loading, which results in structural fatigue and localized bone pain and tenderness. A BSI occurs along a pathology continuum that begins with a stress reaction, which can progress to a stress fracture and, ultimately, a complete bone fracture. Bone stress injuries are a source of concern in long-distance runners, not only because of their frequency and the morbidity they cause but also because of their tendency to recur. While most BSIs readily heal following a period of modified loading and a progressive return to running activities, the high recurrence rate of BSIs signals a need to address their underlying causative factors. A BSI results from disruption of the homeostasis between microdamage formation and its removal. Microdamage accumulation and subsequent risk for development of a BSI are related both to the load applied to a bone and to the ability of the bone to resist load. The former is more amenable to intervention and may be modified by interventions aimed at training-program design, reducing impact-related forces (eg, instructing an athlete to run "softer" or with a higher stride rate), and increasing the strength and/or endurance of local musculature (eg, strengthening the calf for tibial BSIs and the foot intrinsics for BSIs of the metatarsals). Similarly, malalignments and abnormal movement patterns should be explored and addressed. The current commentary discusses management and prevention of BSIs in runners. In doing so, information is provided on the pathophysiology, epidemiology, risk factors, clinical diagnosis, and classification of BSIs.

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PATHOPHYSIOLOGY OF BSI

The pathophysiology underlying BSI remains somewhat speculative; however, there is growing consensus that it involves an imbalance between load-induced microdamage formation and its removal. A theoretical model is presented in **FIGURE 1**. The skeleton is exposed to mechanical loading during running, which causes bones to deform. The amount of deformation depends on the load magnitude and ability of bone to resist deformation, and is often expressed as strain. Strain refers to the change in length per unit length of a bone. It is a unitless value; however, because it is small for bone, it is often expressed as microstrain ($\mu\varepsilon$). Attachment of strain gauges to the tibia in select individuals has demonstrated compressive and tensile bone strains of 417 to 2456 $\mu\varepsilon$ during running.[1] While the safety factor between these strains and those required to break cortical bone in tension is large (7300 $\mu\varepsilon$),[6] strains below the level required for fracture are capable of generating microscopic damage (termed *microdamage*) (**FIGURE 2A**).

Microdamage formation is threshold dependent, with the threshold for its formation depending on the interac-

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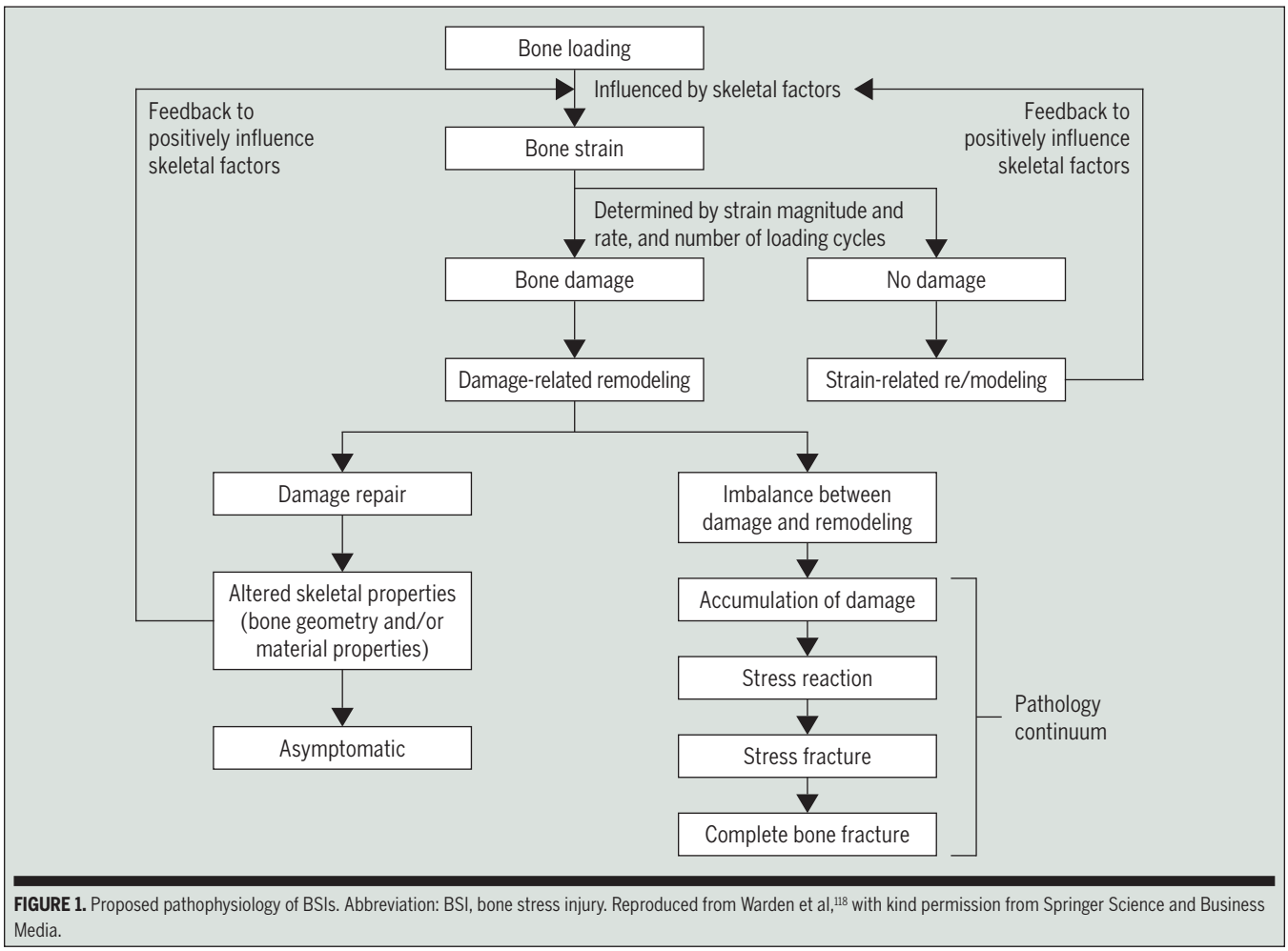

FIGURE 1. Proposed pathophysiology of BSIs. Abbreviation: BSI, bone stress injury. Reproduced from Warden et al,[118] with kind permission from Springer Science and Business Media.

tion between the number of bone strain cycles, strain magnitude, and the speed at which strain is introduced (strain rate). Once the threshold for microdamage has been surpassed, further increases in bone strain cycles, magnitude, and/or rate result in additional damage. The damage is a natural and useful phenomenon, as it not only helps dissipate energy that may create a fracture but also serves as a stimulus for targeted remodeling (**FIGURE 2B**). Targeted remodeling refers to site-specific remodeling targeted on areas of damage (possibly via osteocyte apoptosis[99]), which contrasts the hormonally driven nontargeted (stochastic) remodeling responsible for releasing calcium into the circulation.[20] Targeted remodeling involves activation of remodeling units, consisting of an advancing front of bone-resorbing osteoclasts followed by rows of bone-forming osteoblasts. The osteoclasts tunnel toward and remove the damaged tissue, whereas the trailing osteoblasts deposit layers of new bone to create a new bone structural unit. Targeted remodeling maintains homeostasis between microdamage formation and its removal to preserve skeletal mechanical competence, as well as reduces tissue age and enables bone to adapt over time to meet changing demands. The adaptation effectively decreases bone strain for a given load,[119,120] so that greater loads can be tolerated before surpassing the threshold for microdamage formation.

Remodeling normally removes damage approximately as fast as it occurs, and a reserve of additional remodeling units can be activated in response to increased microdamage formation. Thus, changes in loading that result in an increase in bone strain cycles, magnitude, and rate can generally be tolerated. However, remodeling is time dependent, and the time required to reach a new equilibrium following a disturbance is in the order of 1 remodeling period, which is approximately 3 to 4 months in cortical bone.[46] If insufficient time is given to adapt to a new mechanical stimulus, progressively more damage may form as a result of a positive feedforward loop between remodeling and damage formation. The feedforward loop results from the fact that resorption precedes formation in the remodeling process, so that an increase in the number of currently active remodeling units results in a localized reduction in bone mass. The net result is a local-

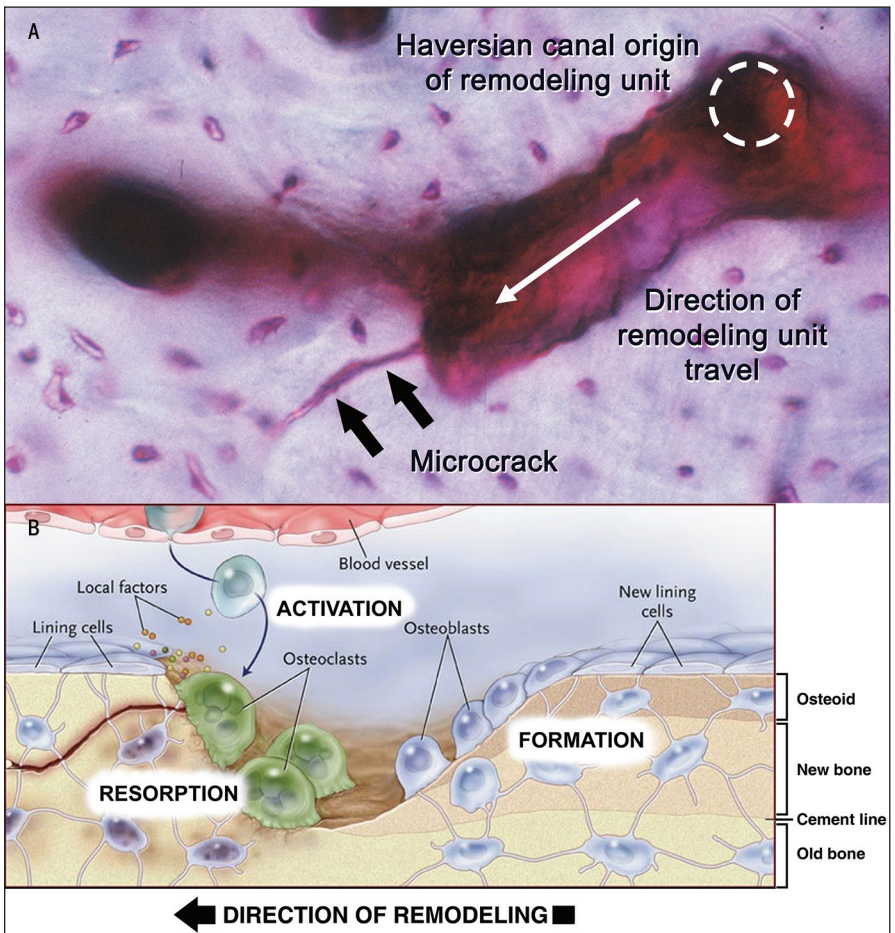

FIGURE 2. Bone microdamage and targeted remodeling. (A) A microcrack is visible in this basic fuchsin-stained histological section of cortical bone. A stimulus (possibly osteocyte apoptosis) has triggered targeted remodeling by a remodeling unit that is advancing toward the damage from a nearby Haversian canal. Reproduced from Warden et al,[117] with permission. Copyright © 2009 Elsevier. (B) Schematic representation of part of a remodeling unit performing targeted remodeling. A microcrack has activated osteoclast precursors to differentiate and form an advancing resorptive front of osteoclasts that tunnel toward the microcrack to remove the damage. The resorbed bone is subsequently replaced with osteoid (unmineralized bone matrix) by bone-forming osteoblasts, which is subsequently mineralized over time to form new bone. Osteoblasts that get trapped in the new bone turn into osteocytes, whereas those on the bone surface turn quiescent to become new bone-lining cells. Reproduced from Canalis et al,[21] with permission from Massachusetts Medical Society. Copyright © 2007 Massachusetts Medical Society.

ized reduction in the energy-absorbing capacity of the bone, which potentiates further damage formation. Accumulating microdamage may coalesce to initiate the BSI pathology continuum, which includes stress reactions, stress fractures, and, ultimately, complete fracture. Stress reactions are characterized by increased bone turnover associated with periosteal and/or marrow edema, whereas stress fractures have the addition of a discernible fracture line.

EPIDEMIOLOGY OF BSI

As the pathophysiology of BSI involves repetitive mechanical loading, it is not surprising that it frequently occurs in response to the skeletal loading introduced during long-distance running. Between one third and two thirds of competitive cross-country and long-distance runners have a history of BSI,[11,64] and the 1-year prospective incidence of BSI in competitive cross-country and track-and-field athletes ranges from 4.9% to 21.1%.[13,113] Of particular concern is the high recurrence rate of BSI. Half of track-and-field athletes report a history of BSI on more than 1 occasion, and 10.3% to 12.6% of cross-country and track-and-field athletes with a history of BSI sustain a subsequent BSI when prospectively followed for 1 to 2 years.[13,64]

Half of BSIs in long-distance runners occur in the tibial diaphysis, with the majority of other BSIs occurring in the femur, fibula, calcaneus, metatarsals, and tarsals.[18,64,113] However, BSIs in the pelvis and lumbar spine also occur in runners and should not be overlooked. The exact location of BSI development depends on how the individual loads his or her skeleton, with different running biomechanics influencing which bones are preferentially loaded and where strains occur within those bones. As an extreme example, long-distance runners typically use a rearfoot strike (RFS) pattern to preferentially load long bones (tibia, fibula, femur), whereas sprinters use a forefoot strike (FFS) pattern to introduce relatively greater loads to the bones of the feet. As a result of the differential bone loading, distance runners are at a greater risk of developing long-bone BSIs, whereas sprinters are more prone to BSIs of the tarsals and metatarsals.[13] Ultimately, BSIs can occur in any bone region and should be considered in the differential diagnosis of all overuse injuries in distance runners.

RISK FACTORS FOR BSI

To prevent BSI in runners and to develop appropriate management strategies when it does occur, an appreciation of contributing risk factors is required. Ideally, risk factors should be identified using prospective study designs that follow individuals longitudinally to determine which features assessed at baseline contribute to BSI development. However, it is very challenging to prospectively study BSI risk factors, as large numbers of individuals need to be fol-

lowed over lengthy periods to generate a sufficient number of BSIs for adequate statistical power. Large prospective studies have been performed in the military, where recruits present a captive audience and BSIs are more frequent, but similar studies in runners are rare. A popular alternative approach has been to use a retrospective, cross-sectional study design in which runners with a history of BSI are compared to matched controls. While cross-sectional studies have provided useful supplemental information regarding potential risk factors for BSI, they are limited in their ability to establish causal relationships.

Given the inherent difficulty in establishing risk factors for BSI in runners, many potential contributing factors remain unproven. However, considering its microdamage-centric pathophysiology, BSI can for the most part be viewed as occurring when the mechanical stimulus at a specific bone site is elevated beyond the threshold for microdamage formation. While the absolute threshold for microdamage formation is somewhat nebulous, microdamage forms in response to increasing bone strain magnitudes, rates, and cycles. As bone strain is dependent on the interaction between the load applied to a bone and the ability of the bone to resist deformation, risk factors for BSI can be grouped into 2 categories: factors modifying (1) the load applied to a bone and (2) the ability of a bone to resist load without damage accumulation (**FIGURE 3**).

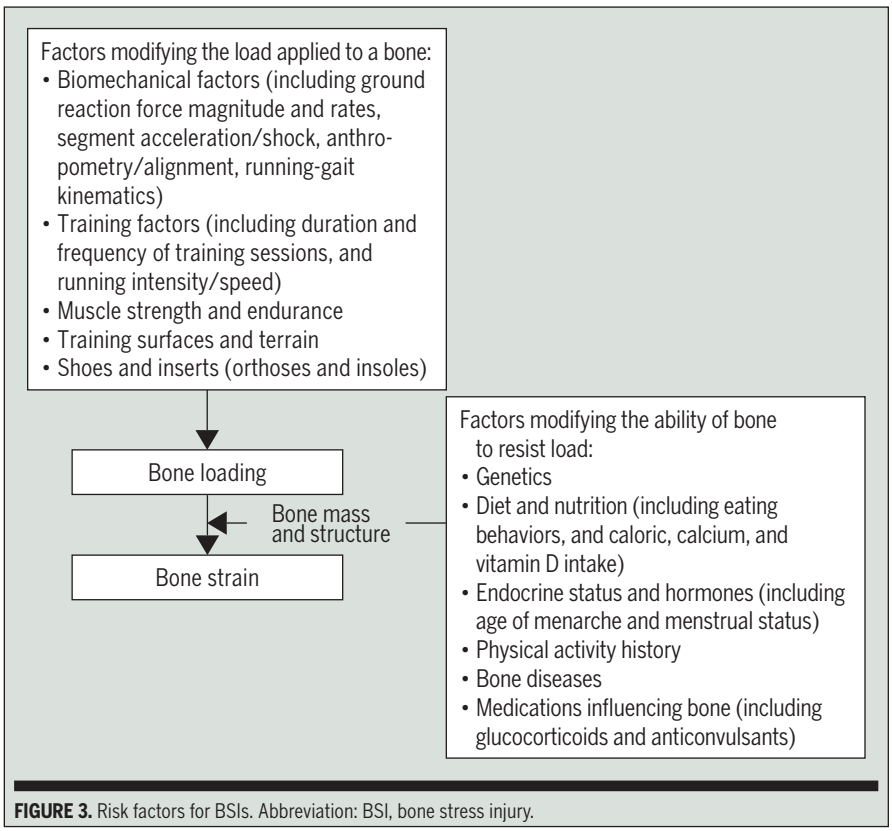

FIGURE 3. Risk factors for BSIs. Abbreviation: BSI, bone stress injury.

Factors Modifying the Load Applied to a Bone

The load applied to a bone during running represents the summation of external and internal forces, the components of which are magnitude, rate, frequency, duration, and direction. These components influence, respectively, the magnitude, rate, frequency, duration, and location of bone strain. Unfortunately, it is not currently possible to precisely measure the total load being applied to a bone, although subject-specific musculoskeletal models are being developed for this purpose. In the absence of an available measure of total bone loading during running, surrogate measures have been utilized, including measuring (1) bone strains by invasively attaching a strain gauge to a bone of interest, (2) bone acceleration (often referred to as *shock*) using an accelerometer, and (3) ground reaction forces (GRFs) obtained with a force platform. While each of these methods has limitations in defining the total load being applied to a bone, they have provided insight into the factors that influence BSI risk.

Biomechanical Factors Faulty biomechanics can contribute to BSI risk and can be divided into those related to abnormal forces and those related to abnormal motions. Increased forces on a normally aligned lower extremity can result in abnormal bone loading. Alternatively, normal forces applied to a malaligned lower limb can also abnormally load the skeleton. Having the combination of abnormal forces coupled with a malaligned lower limb is thought to further amplify BSI risk.

Runners with abnormal loading (high GRF magnitudes and rates, and accelerations during the early stance phase of running gait) are proposed to be at heightened risk of BSI. While variable evidence supports the magnitude of GRF impact peak as a discriminator between those with and without a BSI history,[10,29,54,86,87] individuals with a BSI history have greater GRF loading rates and peak accelerations.[87,100] Similarly, a preliminary prospective study by Davis et al[32] suggested that subjects who sustained a BSI had higher peak acceleration and vertical GRF loading rates prior to injury than matched controls. Torsional loads have also been associated with BSI history. Milner et al[86] reported significantly higher free moments in runners with a history of tibial BSI.

Abnormal movement patterns can also increase the risk of BSI. Static alignment is likely to influence movement

patterns and has been implicated in BSI development. For example, Williams et al[122,123] demonstrated that high-arched individuals exhibited reduced joint excursions and higher stiffness, and had a greater history of BSI. Other static variables reported to be related to BSI include increased external rotation range of motion of the hip,[44] leg-length discrepancy,[12] pes planus,[111] and pes cavus.[107] Individuals with a history of a BSI have been shown to have greater peak hip adduction, knee internal rotation, and peak rearfoot eversion in the frontal plane during running,[37,88,100] and may have less knee flexion in the sagittal plane.[87] These movement patterns have the potential to alter the magnitude and/or rate of bone loading. They may also alter the direction in which a bone is loaded and the subsequent distribution of strain within the bone. The net result may be increased loading of a less-accustomed bone site.

Training Factors Chronic introduction of high absolute load magnitudes, rates, and accelerations may reduce bone fatigue life, particularly when the number of loading cycles is high (ie, running long distances). However, the influence of these variables may be most prominent when runners attempt to progress their training. Increases in running speed increase GRFs and rates of introduction during heel-toe running gait,[55] whereas increases in the duration and/or frequency of running sessions increase the total number of bone-loading cycles. In the absence of a change in the load-bearing capacity of a bone, altered loading associated with large changes in training may contribute to microdamage accumulation and the generation of a BSI. There is evidence from military studies that individuals exposed to large changes in physical activity have heightened risk of BSI. For instance, recruits with a lesser history of regular physical activity prior to the commencement of standardized basic training (ie, those with larger changes in physical activity levels) are at a greater risk of developing BSI.[27,50,72,84,106] Although most athletes do not introduce changes in their running program and consequent bone-loading environment as extreme as those of military recruits, change is a frequent and required means of adaptation to achieve personal and competitive goals. Incrementing a running program too rapidly or frequently relative to a runner's usual activities is thought to be central to disrupting the balance between bone microdamage formation and removal.

Muscle Factors Training changes may independently contribute to BSI development, but the relative risk associated with the change may be compounded by muscle factors. An intimate mechanical relationship exists between muscle and bone, and it is hypothesized that muscle is protective rather than causative of BSI. During impact loading, muscle is believed to act as an active shock attenuator, helping to reduce loads as they are transmitted proximally along the kinetic chain. When muscles are dysfunctional (weakened, fatigued, or altered in their activation patterns), their ability to attenuate loads becomes compromised, potentially leading to increased loading on the skeleton. For instance, fatigue in laboratory studies caused a decrease in shock attenuation,[80,89] an increase in GRF loading rates and peak accelerations,[25,90] and an increase in bone strain magnitude and rate.[47,83] In addition, fatigue can lead to altered kinematics,[34] which may alter the direction in which a bone is loaded, resulting in increased bone strain at less-accustomed bone sites.[124] Further supporting the protective role of muscle in BSI development are prospective clinical studies demonstrating that BSI susceptibility is directly related to muscle size (girth and cross-sectional area)[4,9,12] and strength.[59]

Running Surface Bone loading and, subsequently, BSI risk may also be influenced by external factors such as running surface. Running surface has historically been considered a contributor to BSI risk. Harder surfaces (eg, asphalt/bitumen) have been hypothesized to increase loading compared to softer surfaces (eg, grass, rubber, and sand). However, the interaction between running surface and injury risk is complex. Runners alter their leg stiffness when running on surfaces of differing compliance, apparently to maintain a constant vertical excursion of their center of mass.[43] Leg stiffness decreases when running on stiffer surfaces to normalize, to some extent, GRF magnitude; however, GRF loading rates do appear to be systematically increased when running on surfaces that are less compliant.[36] Whether the increased loading rate associated with running on less-compliant surfaces contributes to BSI risk remains unclear, as large epidemiological studies of running injuries have failed to show an association between injuries and training surface after controlling for weekly running distance.[76,114] Ultimately, what may be important with regard to BSI risk is whether there has been a recent change in running surface to which the runner has yet to become accommodated. Changes may include increased running on (1) less-compliant surfaces (eg, changing from treadmill to overground running), which may increase bone strain magnitudes and rates[82]; (2) very compliant surfaces (eg, sand), which may increase energy expenditure and influence muscle-related risk factors and kinematics[97,98]; (3) downhill slopes, which may decrease shock attenuation[91] and increase loading magnitudes and rates[52]; and (4) altered terrain, which may alter kinematics to load less-accustomed skeletal sites.[125]

Shoes and Inserts The role of shoes and inserts (orthoses and insoles) on bone loading and BSI risk is a topic of ongoing debate. Located at the foot-ground interface, shoes and inserts act as filters that theoretically attenuate ground impact forces. In addition, they have the potential to influence motion of the foot and ankle and the subsequent mechanics proximally in the kinetic chain. Via these 2 mechanisms, shoes and inserts may influence bone loading and have an effect on BSI risk. In support, Gardner et al[50] found that military recruits who trained in shoes of advanced age (an indicator of

possible reduced shock-absorptive capacity) were at a greater risk of developing a BSI, and a recent systematic review concluded that orthoses reduced BSI risk during military training.[109] Whether the same benefits are observed in runners remains unclear, and recent work exploring the virtues of barefoot running has raised questions regarding the role of shoes in general injury prevention.[75]

Factors Influencing the Ability of the Bone to Resist Load Without Damage Accumulation

The amount and rate of strain when a load is applied to a bone depend on features of the applied load and also the ability of the bone to resist deformation in the direction of loading. For a given applied load, less-rigid bones experience greater strain at a faster rate than more-rigid bones and are therefore more susceptible to microdamage and BSI formation. Skeletal features that influence bone rigidity include the amount of bone material present (mass) and its distribution (structure), and there is strong evidence that both contribute to BSI risk. For instance, prospective studies have confirmed that BSI susceptibility is inversely related to bone mass and cross-sectional size.[8,9,12,27,51] While it is clear that reduced bone mass and size are risk factors for BSI, it is important to consider modifiable factors that may contribute to these skeletal characteristics. Three modifiable factors in runners that may impact the ability of bone to resist loading and contribute to BSI risk are physical activity history, energy availability, and calcium and vitamin D status.

Physical Activity History A longer history of physical activity appears to be protective against the development of a BSI.[27,50,72,84,106] An improved ability of the skeleton to resist loading likely contributes to the reduced BSI risk in individuals with a prior history of physical activity. The skeleton responds and adapts to mechanical loading in a site-specific manner to increase its rigidity in the direction of loading. It principally does this during the growing years by preferentially depositing small amounts of new bone on the outer periosteal surface at a distance from the bending axes. As the rigidity of a unit area of bone is proportional to the fourth power of its distance from a bending axis, the addition of a small amount of mass to the outer surface of a bone results in a disproportionate increase in bone strength. The net result is a decrease in the bone strain engendered in response to a given load and an increase in bone fatigue life. For instance, Warden et al[119] demonstrated using an animal model that a relatively moderate (less than 10%) increase in bone mass induced by mechanical loading resulted in a large (107-fold) increase in bone fatigue resistance due to the mass being distributed at a distance from the bending axis and reducing bone strain.

Energy Availability Gender factors contribute to BSI susceptibility, with females being at greater risk.[121] The cause for the higher incidence of BSIs in females appears to relate to the interrelationships between energy availability, menstrual function, and bone mass—otherwise known as the female athlete triad. While runners can have one or more components of the triad, low energy availability appears to be the central factor.[94] Low energy availability results from insufficient dietary intake to meet exercise energy expenditure. It can result from low dietary energy intake (whether inadvertent, intentional, or psychopathological) and/or excessive exercise energy expenditure. While complete discussion of the female athlete triad is beyond the scope of this commentary and has been covered comprehensively elsewhere,[94] the menstrual and skeletal changes associated with low energy availability reduce the ability of bone to resist load and/or impair its ability to repair microdamage. The net result is heightened BSI risk, particularly in elite female long-distance runners, where the difference between dietary energy intake and exercise energy expenditure is often small and the incidence of menstrual dysfunction is elevated.

Calcium and Vitamin D Status Calcium combines with phosphate to form hydroxyapatite crystals to endow bone with rigidity, whereas vitamin D contributes by promoting calcium absorption in the gut and reabsorption in the kidneys. Prospective studies provide evidence for roles of both low calcium and vitamin D in BSIs. Studying 18- to 26-year-old female distance runners, Nieves and colleagues[95] demonstrated that women who consumed less than 800 mg of calcium per day had nearly 6 times the BSI rate of those who consumed more than 1500 mg. In terms of vitamin D, Ruohola et al[104] found that male Finnish military recruits with a serum 25-hydroxyvitamin D concentration below a median level of 30.4 ng/mL had a greater risk for BSI. Additional support for the role of both calcium and vitamin D in mediating BSI risk was provided by a randomized controlled trial that demonstrated a 20% reduction in BSI incidence in female Navy recruits with suboptimal baseline daily calcium intake (300 mg) when they were supplemented with 2000 mg of calcium and 800 IU of vitamin D per day.[71] Overall, these data suggest that running athletes should ensure sufficient calcium and vitamin D intakes to meet or exceed the currently recommended dietary allowances of 1000 to 1300 mg and 600 IU (for individuals aged 14-50 years), respectively.[60]

CLINICAL DIAGNOSIS OF BSI

Based on our clinical experience, BSIs often present with a history consistent with overuse injury—the gradual onset of activity-related pain. As BSIs occur along a pathology continuum, signs and symptoms may vary depending on the point in the continuum at which the runner presents. An astute clinician may be able to diagnose the pathology at the stress reaction stage; however, some patients may not present until the pathology has progressed to a stress fracture, where there is actual cortical disruption. The earlier in the continuum a runner

presents and a diagnosis is made, the more likely it is that the pathology will respond quickly and favorably to management. Thus, bone as the tissue of origin of a runner's symptoms needs to be considered at all times during differential diagnosis to ensure prompt diagnosis and management.

A thorough history is the first step to the diagnosis of a BSI. In most instances, individuals with a BSI have a consistent and predictable history that centers on pain. At the start of the pathology continuum, pain is usually described as a mild, diffuse ache that occurs after a specific amount of running and at specific times during the running gait cycle (depending on which bone is afflicted and when it is loaded during running gait). The pain does not tend to resolve or "warm up" as the run continues, and only abates once running (bone loading) has ceased. As the initial pain often subsides soon after running is complete and is not present during rest, it is often ignored at first. However, with continued training and progression of the pathology, the pain may become more severe and localized, and occur at an earlier stage. It may also persist for longer periods following the completion of running and begin to be present during activities that involve lower levels of bone loading, such as walking. Eventually, the pain may result in running restriction or the need to cease training altogether. At this more advanced stage, any associated inflammatory response to the injury may also occasionally contribute to resting and night pain.

On physical examination, the most obvious feature of a BSI is localized bony tenderness. Certain bones (eg, the tibia, fibula, and metatarsals) lend themselves well to palpation because of their well-defined anatomical boundaries and the absence of overlying muscle. In these relatively subcutaneous bones, precise and thorough palpation is required, as tenderness may be very localized and adjacent areas completely pain free. Occasionally, redness, swelling, and warmth from an associated inflammatory reaction may also be felt, along with periosteal thickening and callus formation in longer-standing BSIs. Direct palpation is obviously not possible at deeper sites (eg, the femur and pars interarticularis of the spine), with symptoms at these sites possibly being provoked by specific bone-loading tests, such as hopping,[78] the fulcrum test for the femoral shaft,[63] or the 1-legged hyperextension test for the pars interarticularis.[61] However, the sensitivity and specificity of these bone-loading tests have either not been investigated or are disputed.[77] Likewise, the application of a vibrating tuning fork or therapeutic ultrasound for the clinical diagnosis of BSIs is not supported.[105]

Ultimately, runners who display clinical signs and symptoms of a possible BSI require imaging to confirm suspicions and to make a definitive diagnosis. Detailed discussion of BSI imaging is beyond the scope of the current commentary and has been discussed in detail elsewhere.[35,92] Briefly, in most clinical settings, plain radiographs remain the first line of imaging for BSI because of their low cost and wide availability; however, radiographs are limited by their planar nature and low spatial resolution, which contribute to extremely low sensitivity.[48,70] Computed tomography also lacks sensitivity,[48] but may be utilized in specific cases where demonstration of a fracture line may affect treatment. In contrast, bone scintigraphy has high sensitivity but is limited by low specificity[39,48] and extremely high ionizing radiation doses (equivalent to 2 years of background radiation). Of the imaging modalities currently available, magnetic resonance imaging is the modality of choice because of its superior contrast resolution, lack of exposure to ionizing radiation, and combined high sensitivity and specificity.[48,70]

CLASSIFICATION OF BSI

Injury classification systems may assist in grading pathology severity and in guiding management decisions and determining prognosis. Numerous classification systems have been reported for grading BSI.[85] While there is no universally accepted system, most classification systems for BSI utilize 1 or more of the following variables: symptoms, anatomical location, and imaging appearance.

Pain is the first variable to consider when classifying a BSI. It was once thought that imaging could be used to detect tissue changes associated with a BSI prior to the onset of symptoms and that early identification of these changes might reduce time lost from participation. It is common for imaging changes consistent with the presence of a BSI to be detected in asymptomatic individuals.[14,49,69,96] However, there is general consensus that imaging changes observed in asymptomatic individuals are incidental and of no clinical significance. For instance, 43% (9 of 21) of collegiate-level distance runners in one study exhibited changes in the tibial diaphysis consistent with a stress reaction, but none of the runners went on to develop symptoms in the succeeding 2 years, despite continuing to run at a high level.[14] Similarly, others have shown that imaging findings consistent with a BSI in asymptomatic individuals are of no prognostic value.[69,96] Thus, precautionary imaging to identify presymptomatic BSI changes does not appear to be indicated.

In runners who show changes in imaging that are consistent with their symptoms of a BSI, the anatomical location and imaging appearance of the pathology are important variables. Bone stress injuries can be dichotomized into either low- or high-risk groups according to their location (**TABLE 1**).[15,16] Low-risk BSIs predominantly occur on the compression side of the bone's bending axis and have a favorable natural history, in that recovery occurs with a low incidence of complications and without the need for aggressive intervention, such as surgery and/or prolonged modified weight bearing. In contrast, high-risk BSIs often occur on the tension side of a bone's bending axis, and present treatment challenges that demand specific attention because they

TABLE 1 Low- and High-Risk Bone Stress Injuries in Runners

Low Risk	High Risk
Posteromedial tibia	Femoral neck
Fibula/lateral malleolus	Anterior cortex of the tibia
Femoral shaft	Medial malleolus
Pelvis	Talus (lateral process)
Calcaneus	Navicular
Diaphysis of second to fourth metatarsals	Proximal diaphysis of the fifth metatarsal
	Base of second metatarsal
	Great-toe sesamoids

TABLE 2 Bone Stress Injury Grade According to Magnetic Resonance Imaging Appearance[45]

Grade	Management
1	Periosteal surface: mild to moderate edema on T2-weighted images Marrow: normal on T1- and T2-weighted images
2	Periosteal surface: moderate to severe edema on T2-weighted images Marrow: edema on T2-weighted images
3	Periosteal surface: moderate to severe edema on T2-weighted images Marrow: edema on T1- and T2-weighted images
4	Periosteal surface: moderate to severe edema on T2-weighted images Marrow: edema on T1- and T2-weighted images Clearly visible fracture line

are prone to delayed union or nonunion and/or are at high risk for progression to complete fracture.

In addition to classifying a BSI as either low or high risk according to anatomical location, a BSI can be categorized as either low or high grade according to its imaging appearance. A seminal magnetic resonance imaging grading system for BSIs is shown in **TABLE 2**,[45] with more recent grading systems yielding only slight variations. Grade 1 and 2 BSIs on the grading system can be grouped as low-grade BSIs, whereas grades 3 and 4 can be categorized as high-grade BSIs.[24]

The clinical utility of BSI grading systems may be in their prediction of recovery time. As one would expect, low-grade BSIs generally have a shorter recovery time because they are at an earlier stage in the pathology continuum. Using a prospective study design, Nattiv et al[93] recently demonstrated that return-to-sport time following low- and high-grade BSIs was 13.1 and 23.6 weeks, respectively. Dobrindt et al[38] obtained very similar data in their retrospective study. Interestingly, the later study also categorized low- and high-grade BSIs according to low and high risk. In doing so, Dobrindt et al[38] showed magnetic resonance imaging grade to be most prognostic in low-risk BSIs. Low-risk/low-grade BSIs had the most favorable outcome, with a return-to-sport time of 8.7 weeks. In contrast, low-risk/high-grade BSIs and all high-risk BSIs (irrespective of grade) had a return-to-sport time of around 20 weeks.

Combining knowledge regarding the anatomical location and imaging grade of BSIs provides a basis on which to formulate the management strategy and potential time to return to running. Generally speaking, BSIs at (1) low-risk sites with a low grade have the most favorable outcome and shortest time to return to running; (2) low-risk sites with a high grade need to be identified, as they can be expected to require a longer time to return to running; and (3) high-risk sites need to be carefully managed and can be expected to take longer for return to running, regardless of grade. However, it must be remembered that there is great variability in the return time to running between individuals with BSIs, even among those with BSIs within the same risk and grade levels. Thus, it is important to adhere to the mantra, "Treat the patient and not the X-ray."[65]

MANAGEMENT OF LOW-RISK BSI

Low-risk BSIs in runners represent relatively straightforward management problems in the sense that they readily heal without complication. A 2-phase approach consisting of modified activity followed by a gradual resumption of running forms the cornerstone of management. While the overarching goal is to return the athlete to his or her preinjury level of function in the shortest time possible without compromising tissue-level healing, it is generally acknowledged that there is more to the successful management of runners with a BSI. The high recurrence rate of BSIs indicates that a central goal for clinicians when managing low-risk BSIs should be to identify and modify potential risk factors for future BSIs. Using the concept that BSIs occur when the applied load exceeds the bone's ability to resist the load without microdamage accumulation, runners with a BSI require strategies to reduce the load being introduced and/or increase the load-bearing capacity of their skeleton.

Phase 1: Initial Management

Activity Modification There is no question that temporary discontinuation of running and the introduction of a variable period of modified activity are required in the initial management of low-risk BSIs to permit tissue-level healing and to pre-

vent pathology progression. However, the duration and extent of activity modification are highly variable and decided on an individual basis, using pain as the principal guiding variable. The presence of pain either during or after an activity indicates that the pathological site is being excessively loaded for the current stage of healing, and that loading needs to be titrated.

In the initial stages of BSI management, the goal of the athlete is to be pain free during and after usual activities of daily living (ADLs). Cushioned shoes and/or insoles may provide assistance in dissipating impact forces during ADLs in athletes with a rearfoot or leg BSI,[41,81] whereas stiff-soled shoes may be considered to reduce bending forces and symptoms in athletes with a BSI in the midfoot or forefoot.[5] Walking should be minimized to that essential to perform ADLs and limited to a normal gait pattern. If a normal gait pattern cannot be used or symptoms are produced either during or after walking, partial weight bearing using assistive gait devices (eg, double or single crutch, cane) should be considered. Alternatively, a pneumatic leg brace may be introduced to promote pain-free gait for BSIs of the fibula or posteromedial border of the tibia.[112] If a pain-free normal gait pattern cannot be achieved, a short period in a walking boot or of non–weight bearing may be considered. However, in each scenario, progression to unassisted pain-free gait should be sought as soon as possible.

Athletes need to be pain free not only during but also after activities. The presence of resting and/or night pain is a sign that the underlying pathology may have an inflammatory component. While resting pain does not typically require specific intervention, as it is usually short term and abates with activity modification, some athletes may consider nonsteroidal anti-inflammatory drugs or other analgesics. The use of these agents should be discouraged beyond a few days because of their ability to mask pain and subsequently influence activity progression, and because of the less favorable risk-to-benefit ratio of nonsteroidal anti-inflammatory drugs.[116] In particular, nonsteroidal anti-inflammatory drugs have the potential to impede tissue-level healing of BSIs when taken for prolonged periods.[67,74]

Identification and Initial Management of Potential Risk Factors The initial period following BSI diagnosis is a useful time to evaluate and begin addressing potential contributing factors, as it is often the time when an athlete gives the most attention. A detailed running and physical activity history is important. Consider not only usual and recent changes in running frequency, duration, and intensity, but also usual or new participation in physical activities beyond running. Bone stress injury risk reflects the sum of all bone loading, and loading from nonrunning activities may be enough to push an athlete beyond his or her injury threshold. Note should also be taken of any recent changes in running surfaces, shoes/inserts, or technique. By combining knowledge of recent running progressions with knowledge of lifelong physical activity history, it may be possible to provide a runner returning from a BSI with advice regarding future running-program design. For instance, novice runners with a minimal physical activity history may need to progress their training program at a slower rate to avoid overloading the skeleton and disrupting the homeostasis between microdamage formation and removal.

History taking in an injured runner should also assess factors influencing the ability of the runner's skeleton to resist loading. It is essential to obtain a history of the patient's general health, medications (including use of glucocorticoids and anticonvulsants), and personal habits to ensure that there are no factors that may influence bone health. A past history of BSI (and other bone injury) and current body mass index of less than 19 kg/m^2 are strong risk factors for BSI that require assessment and thorough exploration.[64,113] A full dietary history should be taken, with particular attention paid to possible deficits in energy intake and/or eating disorders, and calcium and vitamin D intake. There are numerous online calculators for estimating calcium and caloric intake, with exercising athletes requiring higher-than-recommended intakes for skeletal and body composition maintenance. A maternal family history of osteoporosis (low-trauma fractures) or low bone mineral density should be explored, and a detailed menstrual history should be taken in female runners, including their age of menarche and subsequent menstrual status. Identification of any issues of concern warrants appropriate referral when indicated, remembering that consultation for a BSI may be the first time that a runner's issues associated with the female athlete triad are identified.

In addition to history taking, initial assessment and management of potential factors that influence bone loading during running can be explored, even though running gait cannot typically be assessed until a later time. To guide the interventions and formulate an initial biomechanical impression of the athlete, it is important to gather as much circumstantial evidence as possible. Such evidence may come from recent videos of the athlete running; assessment of shoe wear pattern; a history of overuse injuries; a unilateral predominance; static posture and alignment; and hip, knee, and foot mechanics during nonpainful activities such as walking or single-leg squat. Depending on the individual athlete and the preliminary examination findings, initial biomechanical interventions can be introduced to maintain what the athlete already has or address suspected deficits. Activities can include muscle strength, endurance and control training, and interventions for muscle length and joint mobility. Key areas to consider include control, endurance, and strength at the hip, knee, and ankle; core stability; and strength of the intrinsic and extrinsic muscles of the foot. The activities may need to be modified to be pain free, and are often performed in non–weight bearing or partial weight bearing.

Maintenance of Physical Conditioning Maintaining conditioning during recovery from a BSI is important for a seamless return to running, as the athlete's pathology permits. Conditioning activities should be introduced early, as endurance-trained athletes experience declines in cardiovascular performance in as little as 2 weeks following training cessation.[28] There are multiple methods of maintaining cardiovascular fitness during recovery from a BSI, including cycling, swimming, deep-water running (DWR), and antigravity treadmill training (ATT). The latter 2 methods may be most specific to runners, as they more closely reproduce the neuromuscular recruitment patterns involved in running. Antigravity treadmill training is discussed in a later section, as it is not introduced until a runner is pain free during walking and ADLs. In the interim, DWR can be introduced as long as the athlete is pain free both during and after DWR sessions.

Deep-water running is performed in the deep end of a swimming pool, and makes use of buoyancy to provide 100% body-weight support. The runner mimics running on dry land without contacting the floor of the pool, with limb movements being resisted by the viscosity of the water and drag forces. Literature reviews have concluded that DWR introduces cardiovascular demands that are relatively close to those of real running when training at easy to moderate intensities, but that it is less effective at high intensities.[68,101] Thus, DWR is useful in maintaining and not necessarily increasing conditioning, except in less-conditioned runners. Use of a buoyancy vest or flotation belt reduces the energy demands of DWR, but promotes better specificity by encouraging a more "cross-country" style of gait, whereby the leg sweeps back at a large angle and the foot "pushes" down at the bottom of the stride.[68] Nevertheless, a limitation of DWR is that the running motion does not always mimic running on land, and there is increased resistance to all movements due to the hydrostatic properties of water.[68] Ultimately, DWR is useful during recovery from a BSI, as it can be used to maintain conditioning without excessively loading the pathological site, but it does not replace the need to progress to dry-land running when the pathology permits.

Accelerating Tissue-Level Healing It would be beneficial to provide an athlete with a means of accelerating the healing of a BSI, particularly if it also accelerated a return to running. While there are no proven methods of accelerating BSI healing, a number of candidate methods have been proposed. Low-intensity (less than 0.1 W/cm^2) pulsed ultrasound therapy currently has the greatest support, given its observed beneficial effects on complete bone fractures.[115] Low-intensity pulsed ultrasound has been effective in stimulating union in 98% and 94% of BSIs displaying delayed union and nonunion, respectively.[79] However, the benefits of low-intensity pulsed ultrasound on acute BSIs remain unclear. Although low-intensity pulsed ultrasound has preclinical[74] and anecdotal clinical[17,62] support in the management of acute BSIs, a pilot randomized clinical trial of low-intensity pulsed ultrasound effects on recovery following tibial BSI suggested no benefit.[103] Extracorporeal shockwave therapy and electromagnetic and capacitive coupled electric fields have also been considered as modalities for promoting BSI repair; however, studies of their effects have principally been limited to recalcitrant BSIs. One randomized controlled trial did study the effects of capacitive coupled electric fields on acute tibial BSIs, but was unable to demonstrate a generalized effect on time to return to activity.[7]

A number of pharmaceutical agents may facilitate BSI healing, yet their use is unlikely to receive regulatory approval due to the difficulty of establishing their efficacy in clinical trials of BSIs. Thus, their administration in runners with a BSI will likely remain off label. Bisphosphonates that impair osteoclast-mediated bone resorption have been explored as a potential therapy for BSI. Case series have reported rapid resolution of BSI symptoms with intravenous pamidronate or ibandronate[23,110]; however, this may not necessarily equate to enhanced tissue-level healing, with preclinical studies showing that bisphosphonates delay BSI healing by suppressing intracortical bone remodeling and damage removal.[66,108] In contrast, anabolic agents that more specifically target bone-forming activities may hold greater potential. Two such therapies are parathyroid hormone and antisclerostin antibody therapy. Parathyroid hormone, when administered intermittently, promotes osteoblastogenesis and osteoblast survival, whereas antisclerostin antibody therapy inhibits osteocyte secretion of sclerostin to facilitate Wnt signaling and subsequently promote osteoblast proliferation and function.[21] Both agents stimulate bone formation and accelerate fracture healing in preclinical models. Whether the same fracture-healing benefits carry over to humans and BSI is unknown, although an initial preclinical study suggested that parathyroid hormone therapy accelerated healing of experimentally induced BSIs.[108]

Phase 2: Return to Running

Beginning and Progressing Initial Running Graduated running programs are used in the management of low-risk BSIs to introduce controlled loading and facilitate a return to running in a timely yet safe manner. While loading is central to the development of low-risk BSIs, recovery is best met by a balance between rest from aggravating activities and performance of appropriate loading. Appropriate loading can be defined as loading that does not provoke BSI symptoms either during or after completion of an activity. Once a runner with a low-risk BSI becomes pain free during unassisted walking, the runner can start the gradual process of reintroducing running-related loads. While there is no established protocol for returning to running during recovery from a low-risk BSI, various programs have been developed based

TABLE 3 Graduated Running Program to Return a Runner to 30 Minutes of Pain-Free Running

Stage/Level	Description
0	Pre-entry to graduated running program
	Pain during walking in normal activities of daily living
1	Initial loading and jogging (50% normal pace) with increasing duration
A	Walk 30 minutes
B	Rest
C	Walk 9 minutes and jog 1 minute (3 repetitions)
D	Rest
E	Walk 8 minutes and jog 2 minutes (3 repetitions)
F	Rest
G	Walk 7 minutes and jog 3 minutes (3 repetitions)
H	Rest
I	Walk 6 minutes and jog 4 minutes (3 repetitions)
J	Rest
K	Walk 4 minutes and jog 6 minutes (3 repetitions)
L	Rest
M	Walk 2 minutes and jog 8 minutes (3 repetitions)
N	Rest
2	Running with increasing intensity
A	Jog 30 minutes
B	Rest
C	Run 30 minutes at 60% normal pace
D	Rest
E	Run 30 minutes at 60% normal pace
F	Rest
G	Run 30 minutes at 70% normal pace
H	Rest
I	Run 30 minutes at 80% normal pace
J	Rest
K	Run 30 minutes at 90% normal pace
L	Rest
M	Run 30 minutes at full pace
N	Rest
3	Running on consecutive days
A	Run 30 minutes at full pace
B	Run 30 minutes at full pace
C	Rest
D	Run 30 minutes at full pace
E	Run 30 minutes at full pace
F	Rest
G	Run 30 minutes at full pace
4	Return to running

on clinical experience. One program requires the athlete to be pain free for at least a week before beginning to run every other day for 2 weeks at half the athlete's usual pace and distance.[3] Thereafter, running distance and frequency are gradually increased over 3 to 6 weeks to the athlete's preinjury level. Once the athlete can run the usual training distance at the usual frequency, the pace is gradually increased. If the athlete experiences BSI symptoms at any time during incremental loading, running is ceased for at least 1 to 2 days and resumed at a lower level.

The above program provides general guidelines for resuming and progressing running activities; however, an example of a more prescriptive graduated running program to facilitate the return of a recreational runner to 30 minutes of running is provided in **TABLE 3**. The program consists of a pre-entry stage and 3 running stages. Once a patient is completely pain free for 5 consecutive days during usual activities, the patient may leave the pre-entry stage (stage 0) and commence deliberate progressive loading. Stage 1 introduces loading in 30-minute sessions, separated by rest days. Sessions in this stage consist of increasing durations of jogging (defined as running at 50% of normal pace) and decreasing durations of walking. The pace of running is progressed in stage 2 until the athlete can run for 30 minutes at the usual pace, with stage 3 consisting of running on 2 consecutive days followed by a rest day. The last stage incorporates individualized running until complete return to desired running activities.

Progress through each stage of the graduated running program is determined by BSI provocation. If an athlete is able to complete a session with no BSI symptoms and does not experience latent symptoms, the athlete can progress to the next level during the ensuing session. However, if BSI symptoms are experienced during a session or the athlete experiences latent symptoms, the athlete must stop the session and return to the last level that he or she was able to successfully complete at the next session. For example, if the athlete experienced symptoms while walking for 6 minutes and jogging for 4 minutes, the athlete would take a rest day, then walk for 7 minutes and jog for 3 minutes each at the next running session.

Using a graduated loading program that is strictly guided by pain to manage low-risk BSIs, the athlete and clinician

can facilitate recovery while being relatively confident that there would be no progression of the pathology. Of course, this requires the full understanding of the athlete regarding the appropriate progression through the program and adherence to the set pain levels. Patients with lower-grade BSIs may be able to progress more quickly through a graduated loading program, and the total duration of their program may be reduced from that outlined. Program duration should be based on the expected time course for recovery, which in turn is dependent on the classification of their BSI. Thus, all patients should perform individualized programs.

Antigravity Treadmill Training When available, an antigravity treadmill may initially be used in the place of overground running, as ATT may allow an athlete to run at higher intensities earlier during recovery, but with lower bone loading. Thereby, ATT can be used to maintain fitness while protecting the BSI site. Antigravity treadmills consist of a treadmill with an air-filled, pressure-controlled chamber that surrounds the lower half of the body from the waist down (**FIGURE 4**). Pressure in the chamber is modulated to unweight the runner in 1% increments so that the runner is running with between 100% and 20% body weight. Grabowski and Kram[53] found that certain combinations of velocity and body-weight support provided aerobic training similar to normal-weight running, but with less peak GRFs. Based on the data, if a person normally runs at 3 m/s with no body-weight support, he or she could run at 5 m/s with 43% body-weight support and achieve equal metabolic demand but decrease peak GRF by 32%.

Runners with a low-risk BSI can start ATT once pain free during walking and ADLs for at least a week. A typical starting point is to jog every other day 3 times for 5 minutes, with between 50% and 70% body weight and 1 minute of recovery between repetitions. This is performed for an initial week to acclimatize

FIGURE 4. Antigravity treadmill training. Reproduced with permission from AlterG, Inc.

to ATT while symptoms are monitored for provocation. How to progress from this initial stage is currently somewhat of an art rather than science, as there are few published protocols guiding ATT progression. However, a proposed progression is to increase, over the next 2 weeks, the duration of each run to a total of 20 to 30 minutes, body-weight percentage by 5% to 10%, and running speed.[24] Thereafter, as long as there are no BSI symptoms, the progression may continue until the athlete can run at the usual speed and duration with 90% body weight. Once this is achieved, ground running is introduced and relatively quickly progressed over a couple of weeks to normal durations and intensities.

Running Gait Retraining Despite a slow, progressive return-to-running program, the persistence of faulty mechanics may hinder the healing process or contribute to the elevated risk for a repeat injury. Therefore, it is important to identify and address any underlying mechanics when treating a runner with a BSI. Based on the hypothesis that bone loading is directly related to GRF and acceleration parameters, interventions that reduce GRFs and shock during running gait may represent a means of decreasing BSI risk. By reducing the magnitude and rate of bone loading, the number of loading cycles until microdamage accumulation and fatigue failure may be increased. A number of gait retraining techniques to reduce bone loading during running are currently being investigated, including the use of biofeedback, altering stride rate, and modifying initial contact.

Use of biofeedback from an accelerometer attached to the distal tibia has been described as a potential means of encouraging reductions in loading magnitude and rate. Crowell and colleagues[31] displayed tibial acceleration data in real time on a monitor in front of subjects running on an instrumented treadmill. Following a preliminary warm-up and baseline data-collection period, subjects were asked to "run softer" and reduce their peak positive acceleration by 50%. After 10 minutes of biofeedback followed by 10 minutes without biofeedback, 4 of 5 subjects had significantly reduced peak positive acceleration, and all subjects had reduced GRF impact peak and loading rates, demonstrating feasibility of the biofeedback technique. In a subsequent follow-up study, Crowell and Davis[30] provided accelerometer-based, real-time visual biofeedback to 10 runners with high peak positive tibial accelerations (greater than 8 *g*). After 8 training sessions over 2 weeks, there were significant reductions in peak positive acceleration and GRF loading rates. These changes, with the addition of a reduction in GRF impact peak, persisted for 1 month following feedback training completion, indicating short-term retention of the subjects' altered running form. How the subjects altered their gait to reduce tibial acceleration, the long-term permanence of the reduced acceleration, and whether the reduction in acceleration and subsequent GRF parameters alter BSI risk are areas of ongoing investigation.

Gait retraining using accelerometry biofeedback has shown promise and clinical translatability in reducing bone loading, as it does not require expensive equipment such as an instrumented treadmill. However, in the absence of accelerometry hardware, a simple alterna-

tive may be to increase a runner's stride rate above the runner's preferred rate. Increasing stride rate results in a proportional decrease in stride length (assuming a constant running speed) and positions the feet more underneath the center of mass at initial contact, with the knees and ankles in greater flexion and plantar flexion, respectively.[57] The net result is a reduction in vertical excursion and velocity of the center of mass, reduced peak hip adduction angle and moment, and reduced GRFs and tibial accelerations.[26,33,42,56-58] Changes in stride rate can be encouraged using a metronome, with increases of 10% or less above an athlete's preferred rate being adequate to reduce impact loading while maintaining or even reducing oxygen consumption.[22,56] An increase in stride rate and concomitant decrease in stride length increase the number of loading cycles experienced when running a given distance, potentially offsetting the benefit of stride-rate changes on BSI risk. However, the reduced loading magnitude associated with decreased stride length has been modeled to outweigh any potential detriment of the increased number of loading cycles.[40]

An alternative method of gait retraining to reduce impact loads has been to encourage a more FFS, rather than a heel or RFS pattern. Up to 89% of shod runners land with an RFS pattern,[73] possibly due to the thick, cushioned heel of modern running shoes. Landing with an RFS is associated with a defined impact peak in the vertical GRF during contact and a high rate of loading. In contrast, an FFS pattern eliminates the impact transient by reducing the effective mass at contact through eccentrically controlled dorsiflexion.[75] A potential means of promoting a more FFS pattern has been to have an athlete run barefoot or in a minimalist shoe. Barefoot running encourages a FFS pattern, as running barefoot with an RFS pattern results in very high loading rates and is typically uncomfortable.[2] In addition to encouraging an FFS pattern, barefoot running is associated with a shorter stride length and higher stride rate than typical shod running using an RFS pattern.[2] The net result is a reduction in the magnitude and rate of loading and, potentially, BSI risk. It is possible that a more FFS pattern may increase BSI risk in the metatarsals, due to greater bending forces. However, a natural barefoot landing is described typically as a very mild FFS, with the foot landing slightly plantar flexed and the heel slightly off the ground before it is actively lowered.[2] A low inclination of the foot at contact may reduce the bending moment on the metatarsals to reduce any potential elevation in BSI risk at this site. However, transitioning to minimal-footwear running should be done with caution. In a study by Ridge et al,[102] runners transitioning to minimalist shoes with little guidance more often developed metatarsal bone marrow edema than those remaining in their traditional shoes. Therefore, transitioning should be done slowly and be associated with a strengthening program of the calf and foot intrinsic muscles.

The benefit of the aforementioned gait retraining techniques remains an area of active inquiry, and the induction of running gait changes should not be taken lightly. Runners have typically been running with their particular gait pattern for many years, and the ability of a runner's musculoskeletal system to adapt to the nuances of their particular gait should not be underestimated. However, a history of repeat BSI and the accumulating loss of running time are signs that gait retraining should be considered. In doing so, it must be remembered that when inducing a change in gait, there is always the potential of altering injury risk at an alternative site. Thus, transitioning to a new running gait should be performed slowly and may be benefited by a preconditioning program.

Running Program Design Incrementing a running program too rapidly or frequently relative to a runner's usual activities can contribute to the generation of a BSI by upsetting the balance between bone microdamage formation and its removal. Unfortunately, there is no accepted algorithm for how much an individual can modify a running program before excessively heightening the risk of BSI. The historical rule of thumb has been to change a running program by no more than 10% per week to reduce injury risk; however, this "rule" is not generalizable on an individual basis, as different runners are able to tolerate more or less change before developing an injury.[19] In order to provide a runner returning from a BSI with appropriate advice with regard to the design and advancement of a running program, it is important that the runner recall as much as possible about the preinjury training regime. This should include information on changes in any feature that may have altered the load being introduced to the skeleton, including training intensity, duration, frequency, type, surface, technique, shoes, and so on. In addition, recovering runners should be encouraged to maintain a training diary containing these data to not only track running progress but also to provide reliable data regarding the running program for future reference. There are numerous useful apps for mobile devices that can semi-automatically collect some of these data. In addition to limiting the magnitude and number of running variables changed at any given time, the use of cyclic training methods should be encouraged. Cyclic training may involve the introduction of rest periods into a training program, or the replacement of overground running sessions with lower bone-loading running activities, such as DWR and ATT. This may involve a monthly regime of 3 weeks of running and 1 week of no or low-load activities.

MANAGEMENT OF HIGH-RISK BSI

Most BSIs are low risk in that they readily heal without complication or specific intervention. However, BSIs at some sites present diagnostic and management challenges

TABLE 4 Common Initial Management Approaches for High-Risk Bone Stress Injuries in Runners

Stress Fracture Site	Management
Femoral neck	Undisplaced—initial bed rest until passive hip movement is pain free, followed by non–weight bearing on crutches until radiological evidence of healing. Then, progressive resumption of weight bearing and running Displaced—surgical fixation
Anterior cortex of the tibia	Non–weight-bearing cast immobilization or surgical intervention (intramedullary rod fixation or anterior tension plate banding)
Medial malleolus	Non–weight-bearing cast immobilization for 6 weeks or surgical fixation
Talus (lateral process)	Non–weight-bearing cast immobilization for 6 weeks. Excision of lateral process through fracture line for longstanding symptomatic bone stress injuries
Navicular	Non–weight-bearing cast immobilization for 6 weeks
Proximal diaphysis of the fifth metatarsal	Non–weight-bearing cast immobilization for 6 weeks or percutaneous screw fixation
Base of second metatarsal	Non–weight-bearing cast immobilization for 4 to 6 weeks
Great-toe sesamoids	Non–weight bearing for 4 weeks

because they are difficult to diagnose, resulting in delays in diagnosis, prone to delayed union or nonunion, and/or at high risk for progression to complete fracture. Specific sites for these high-risk BSIs and their typical management based on our collective clinical experience are detailed in **TABLE 4**. Management ranges from prolonged modified activity to non–weight bearing, with or without a cast and/or surgical fixation. Factors determining management choice include BSI location, presence or absence of a cortical defect on imaging, duration of symptoms and/or the pathology, and running level (elite versus novice).

A return to weight-bearing and running activities following high-risk BSI typically requires a greater degree of tissue-level healing to minimize the risk of pathology progression. In most cases, return to activity can occur when imaging studies are consistent with cortical bridging or healing and the athlete is asymptomatic on weight bearing and palpation (when possible). However, at some locations (ie, tarsal navicular) or in the absence of a cortical defect at initial presentation, repeat imaging is not informative, and return-to-activity decisions are based on the absence of symptoms following completion of the initial mandatory management. Until the green light is given to begin and progress weight-bearing activities, interventions should focus on the identification and management of potential risk factors, when possible, and maintenance of physical conditioning. The latter is particularly important, as immobilization and restriction of running activities are typically prolonged with high-risk BSIs. Once running is permitted, progression follows that described for low-risk BSIs.

CONCLUSION

Bone stress injuries result from disruption of the homeostasis between microdamage formation and its removal, and remain a source of concern for long-distance runners and clinicians alike because of the morbidity they cause and their relatively high rate of recurrence. Risk for a BSI relates to both the load applied to a bone and the ability of the bone to resist load, with the former being most amenable to intervention. While most BSIs readily heal following a period of modified loading and a progressive return to running activities, the high recurrence rate of BSIs signals a need to address underlying reasons for their occurrence. In particular, there is a need to look beyond changes in training as the sole cause of BSIs. Interventions aimed at reducing the loads applied to the skeleton may include techniques to reduce impact-related forces (eg, instructing an athlete to "run softer" or with a higher stride rate) and increase the strength and/or endurance of local musculature (eg, the calf for tibial BSIs and foot intrinsics for BSIs of the metatarsals). Similarly, malalignments and abnormal movement patterns should be explored and addressed. Also, the ability of the skeleton to resist loading should not be ignored, despite the greater difficulty of intervention. In particular, elite female long-distance runners exhibiting signs and/or symptoms of the female athlete triad need appropriate multidisciplinary management.

REFERENCES

1. Al Nazer R, Lanovaz J, Kawalilak C, Johnston JD, Kontulainen S. Direct in vivo strain measurements in human bone—a systematic literature review. *J Biomech*. 2012;45:27-40. http://dx.doi.org/10.1016/j.jbiomech.2011.08.004
2. Altman AR, Davis IS. Barefoot running: biomechanics and implications for running injuries. *Curr Sports Med Rep*. 2012;11:244-250. http://dx.doi.org/10.1249/JSR.0b013e31826c9bb9
3. Andrish JT. The leg. In: DeLee JC, Drez D, eds. *Orthopaedic Sports Medicine: Principles and Practice*. Philadelphia, PA: W.B. Saunders; 1994:1603-1631.
4. Armstrong DW, 3rd, Rue JP, Wilckens JH, Frassica FJ. Stress fracture injury in young military men and women. *Bone*. 2004;35:806-816. http://dx.doi.org/10.1016/j.bone.2004.05.014
5. Arndt A, Westblad P, Ekenman I, Lundberg A. A comparison of external plantar loading and in vivo local metatarsal deformation wearing two different military boots. *Gait Posture*. 2003;18:20-26. http://dx.doi.org/10.1016/S0966-6362(02)00191-1
6. Bayraktar HH, Morgan EF, Niebur GL, Morris GE, Wong EK, Keaveny TM. Comparison of the elastic and yield properties of human femoral trabecular and cortical bone tissue. *J Biomech*. 2004;37:27-35. http://dx.doi.org/10.1016/S0021-9290(03)00257-4
7. Beck BR, Matheson GO, Bergman G, et al. Do capacitively coupled electric fields accelerate tibial stress fracture healing? A randomized controlled trial. *Am J Sports Med*. 2008;36:545-553. http://dx.doi.org/10.1177/0363546507310076
8. Beck TJ, Ruff CB, Mourtada FA, et al. Dual-energy X-ray absorptiometry derived structural geometry for stress fracture prediction in male

U.S. Marine Corps recruits. *J Bone Miner Res*. 1996;11:645-653. http://dx.doi.org/10.1002/jbmr.5650110512
9. Beck TJ, Ruff CB, Shaffer RA, Betsinger K, Trone DW, Brodine SK. Stress fracture in military recruits: gender differences in muscle and bone susceptibility factors. *Bone*. 2000;27:437-444.
10. Bennell K, Crossley K, Jayarajan J, et al. Ground reaction forces and bone parameters in females with tibial stress fracture. *Med Sci Sports Exerc*. 2004;36:397-404.
11. Bennell KL, Malcolm SA, Thomas SA, et al. Risk factors for stress fractures in female track-and-field athletes: a retrospective analysis. *Clin J Sport Med*. 1995;5:229-235.
12. Bennell KL, Malcolm SA, Thomas SA, et al. Risk factors for stress fractures in track and field athletes. A twelve-month prospective study. *Am J Sports Med*. 1996;24:810-818.
13. Bennell KL, Malcolm SA, Thomas SA, Wark JD, Brukner PD. The incidence and distribution of stress fractures in competitive track and field athletes. A twelve-month prospective study. *Am J Sports Med*. 1996;24:211-217.
14. Bergman AG, Fredericson M, Ho C, Matheson GO. Asymptomatic tibial stress reactions: MRI detection and clinical follow-up in distance runners. *AJR Am J Roentgenol*. 2004;183:635-638. http://dx.doi.org/10.2214/ajr.183.3.1830635
15. Boden BP, Osbahr DC. High-risk stress fractures: evaluation and treatment. *J Am Acad Orthop Surg*. 2000;8:344-353.
16. Boden BP, Osbahr DC, Jimenez C. Low-risk stress fractures. *Am J Sports Med*. 2001;29:100-111.
17. Brand JC, Jr., Brindle T, Nyland J, Caborn DN, Johnson DL. Does pulsed low intensity ultrasound allow early return to normal activities when treating stress fractures? A review of one tarsal navicular and eight tibial stress fractures. *Iowa Orthop J*. 1999;19:26-30.
18. Brukner P, Bradshaw C, Khan KM, White S, Crossley K. Stress fractures: a review of 180 cases. *Clin J Sport Med*. 1996;6:85-89.
19. Buist I, Bredeweg SW, van Mechelen W, Lemmink KA, Pepping GJ, Diercks RL. No effect of a graded training program on the number of running-related injuries in novice runners: a randomized controlled trial. *Am J Sports Med*. 2008;36:33-39. http://dx.doi.org/10.1177/0363546507307505
20. Burr DB. Targeted and nontargeted remodeling. *Bone*. 2002;30:2-4.
21. Canalis E, Giustina A, Bilezikian JP. Mechanisms of anabolic therapies for osteoporosis. *N Engl J Med*. 2007;357:905-916. http://dx.doi.org/10.1056/NEJMra067395
22. Cavanagh PR, Williams KR. The effect of stride length variation on oxygen uptake during distance running. *Med Sci Sports Exerc*. 1982;14:30-35.
23. Chambers SA, Clarke A, Wolman R. Treatment of lumbar pars interarticularis stress injuries in athletes with intravenous bisphosphonates: five case studies. *Clin J Sport Med*. 2011;21:141-143. http://dx.doi.org/10.1097/JSM.0b013e31820f8f62
24. Chen YT, Tenforde AS, Fredericson M. Update on stress fractures in female athletes: epidemiology, treatment, and prevention. *Curr Rev Musculoskelet Med*. 2013;6:173-181. http://dx.doi.org/10.1007/s12178-013-9167-x
25. Clansey AC, Hanlon M, Wallace ES, Lake MJ. Effects of fatigue on running mechanics associated with tibial stress fracture risk. *Med Sci Sports Exerc*. 2012;44:1917-1923. http://dx.doi.org/10.1249/MSS.0b013e318259480d
26. Clarke TE, Cooper LB, Hamill CL, Clark DE. The effect of varied stride rate upon shank deceleration in running. *J Sports Sci*. 1985;3:41-49. http://dx.doi.org/10.1080/02640418508729731
27. Cosman F, Ruffing J, Zion M, et al. Determinants of stress fracture risk in United States Military Academy cadets. *Bone*. 2013;55:359-366. http://dx.doi.org/10.1016/j.bone.2013.04.011
28. Coyle EF, Martin WH, 3rd, Sinacore DR, Joyner MJ, Hagberg JM, Holloszy JO. Time course of loss of adaptations after stopping prolonged intense endurance training. *J Appl Physiol Respir Environ Exerc Physiol*. 1984;57:1857-1864.
29. Crossley K, Bennell KL, Wrigley T, Oakes BW. Ground reaction forces, bone characteristics, and tibial stress fracture in male runners. *Med Sci Sports Exerc*. 1999;31:1088-1093.
30. Crowell HP, Davis IS. Gait retraining to reduce lower extremity loading in runners. *Clin Biomech (Bristol, Avon)*. 2011;26:78-83. http://dx.doi.org/10.1016/j.clinbiomech.2010.09.003
31. Crowell HP, Milner CE, Hamill J, Davis IS. Reducing impact loading during running with the use of real-time visual feedback. *J Orthop Sports Phys Ther*. 2010;40:206-213. http://dx.doi.org/10.2519/jospt.2010.3166
32. Davis IS, Milner CE, Hamill J. Does increased loading during running lead to tibial stress fractures? A prospective study. *Med Sci Sports Exerc*. 2004;36:S58.
33. Derrick TR, Hamill J, Caldwell GE. Energy absorption of impacts during running at various stride lengths. *Med Sci Sports Exerc*. 1998;30:128-135.
34. Dierks TA, Davis IS, Hamill J. The effects of running in an exerted state on lower extremity kinematics and joint timing. *J Biomech*. 2010;43:2993-2998. http://dx.doi.org/10.1016/j.jbiomech.2010.07.001
35. Dixon S, Newton J, Teh J. Stress fractures in the young athlete: a pictorial review. *Curr Probl Diagn Radiol*. 2011;40:29-44. http://dx.doi.org/10.1067/j.cpradiol.2009.12.001
36. Dixon SJ, Collop AC, Batt ME. Surface effects on ground reaction forces and lower extremity kinematics in running. *Med Sci Sports Exerc*. 2000;32:1919-1926.
37. Dixon SJ, Creaby MW, Allsopp AJ. Comparison of static and dynamic biomechanical measures in military recruits with and without a history of third metatarsal stress fracture. *Clin Biomech (Bristol, Avon)*. 2006;21:412-419. http://dx.doi.org/10.1016/j.clinbiomech.2005.11.009
38. Dobrindt O, Hoffmeyer B, Ruf J, et al. Estimation of return-to-sports-time for athletes with stress fracture – an approach combining risk level of fracture site with severity based on imaging. *BMC Musculoskelet Disord*. 2012;13:139. http://dx.doi.org/10.1186/1471-2474-13-139
39. Dobrindt O, Hoffmeyer B, Ruf J, et al. Blinded-read of bone scintigraphy: the impact on diagnosis and healing time for stress injuries with emphasis on the foot. *Clin Nucl Med*. 2011;36:186-191. http://dx.doi.org/10.1097/RLU.0b013e318208f0e6
40. Edwards WB, Taylor D, Rudolphi TJ, Gillette JC, Derrick TR. Effects of stride length and running mileage on a probabilistic stress fracture model. *Med Sci Sports Exerc*. 2009;41:2177-2184. http://dx.doi.org/10.1249/MSS.0b013e3181a984c4
41. Ekenman I, Milgrom C, Finestone A, et al. The role of biomechanical shoe orthoses in tibial stress fracture prevention. *Am J Sports Med*. 2002;30:866-870.
42. Farley CT, González O. Leg stiffness and stride frequency in human running. *J Biomech*. 1996;29:181-186. http://dx.doi.org/10.1016/0021-9290(95)00029-1
43. Ferris DP, Louie M, Farley CT. Running in the real world: adjusting leg stiffness for different surfaces. *Proc Biol Sci*. 1998;265:989-994. http://dx.doi.org/10.1098/rspb.1998.0388
44. Finestone A, Shlamkovitch N, Eldad A, et al. Risk factors for stress fractures among Israeli infantry recruits. *Mil Med*. 1991;156:528-530.
45. Fredericson M, Bergman AG, Hoffman KL, Dillingham MS. Tibial stress reaction in runners. Correlation of clinical symptoms and scintigraphy with a new magnetic resonance imaging grading system. *Am J Sports Med*. 1995;23:472-481. http://dx.doi.org/10.1177/036354659502300418
46. Frost HM. Tetracycline-based histological analysis of bone remodeling. *Calcif Tissue Res*. 1969;3:211-237.
47. Fyhrie DP, Milgrom C, Hoshaw SJ, et al. Effect of fatiguing exercise on longitudinal bone strain as related to stress fracture in humans. *Ann Biomed Eng*. 1998;26:660-665.
48. Gaeta M, Minutoli F, Scribano E, et al. CT and MR imaging findings in athletes with early tibial stress injuries: comparison with bone scintigraphy findings and emphasis on cortical abnormalities. *Radiology*. 2005;235:553-561. http://dx.doi.org/10.1148/radiol.2352040406
49. Gaeta M, Minutoli F, Vinci S, et al. High-resolution CT grading of tibial stress reactions in distance runners. *AJR Am J Roentgenol*. 2006;187:789-793. http://dx.doi.org/10.2214/AJR.05.0303
50. Gardner LI, Jr., Dziados JE, Jones BH, et al. Prevention of lower extremity stress fractures: a controlled trial of a shock absorbent insole. *Am J Public Health*. 1988;78:1563-1567.

51. Giladi M, Milgrom C, Simkin A, et al. Stress fractures and tibial bone width. A risk factor. *J Bone Joint Surg Br*. 1987;69:326-329.

52. Gottschall JS, Kram R. Ground reaction forces during downhill and uphill running. *J Biomech*. 2005;38:445-452. http://dx.doi.org/10.1016/j.jbiomech.2004.04.023

53. Grabowski AM, Kram R. Effects of velocity and weight support on ground reaction forces and metabolic power during running. *J Appl Biomech*. 2008;24:288-297.

54. Grimston SK, Engsberg JR, Kloiber R, Hanley DA. Bone mass, external loads, and stress fracture in female runners. *J Appl Biomech*. 1991;7:293-302.

55. Hamill J, Bates BT, Knutzen KM, Sawhill JA. Variations in ground reaction force parameters at different running speeds. *Hum Mov Sci*. 1983;2:47-56. http://dx.doi.org/10.1016/0167-9457(83)90005-2

56. Hamill J, Derrick TR, Holt KG. Shock attenuation and stride frequency during running. *Hum Mov Sci*. 1995;14:45-60. http://dx.doi.org/10.1016/0167-9457(95)00004-C

57. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. *Med Sci Sports Exerc*. 2011;43:296-302. http://dx.doi.org/10.1249/MSS.0b013e3181ebedf4

58. Hobara H, Sato T, Sakaguchi M, Nakazawa K. Step frequency and lower extremity loading during running. *Int J Sports Med*. 2012;33:310-313. http://dx.doi.org/10.1055/s-0031-1291232

59. Hoffman JR, Chapnik L, Shamis A, Givon U, Davidson B. The effect of leg strength on the incidence of lower extremity overuse injuries during military training. *Mil Med*. 1999;164:153-156.

60. Institute of Medicine. Dietary Reference Intakes for Calcium and Vitamin D. Washington, DC: National Academy of Sciences; 2010.

61. Jackson DW, Wiltse LL, Dingeman RD, Hayes M. Stress reactions involving the pars interarticularis in young athletes. *Am J Sports Med*. 1981;9:304-312.

62. Jensen JE. Stress fracture in the world class athlete: a case study. *Med Sci Sports Exerc*. 1998;30:783-787.

63. Johnson AW, Weiss CB, Jr., Wheeler DL. Stress fractures of the femoral shaft in athletes—more common than expected. A new clinical test. *Am J Sports Med*. 1994;22:248-256. http://dx.doi.org/10.1177/036354659402200216

64. Kelsey JL, Bachrach LK, Procter-Gray E, et al. Risk factors for stress fracture among young female cross-country runners. *Med Sci Sports Exerc*. 2007;39:1457-1463. http://dx.doi.org/10.1249/mss.0b013e318074e54b

65. Khan KM, Tress BW, Hare WS, Wark JD. Treat the patient, not the X-ray: advances in diagnostic imaging do not replace the need for clinical interpretation. *Clin J Sport Med*. 1998;8:1-4.

66. Kidd LJ, Cowling NR, Wu AC, Kelly WL, Forwood MR. Bisphosphonate treatment delays stress fracture remodeling in the rat ulna. *J Orthop Res*. 2011;29:1827-1833. http://dx.doi.org/10.1002/jor.21464

67. Kidd LJ, Cowling NR, Wu AC, Kelly WL, Forwood MR. Selective and non-selective cyclooxygenase inhibitors delay stress fracture healing in the rat ulna. *J Orthop Res*. 2013;31:235-242. http://dx.doi.org/10.1002/jor.22203

68. Killgore GL. Deep-water running: a practical review of the literature with an emphasis on biomechanics. *Phys Sportsmed*. 2012;40:116-126. http://dx.doi.org/10.3810/psm.2012.02.1958

69. Kiuru MJ, Niva M, Reponen A, Pihlajamäki HK. Bone stress injuries in asymptomatic elite recruits: a clinical and magnetic resonance imaging study. *Am J Sports Med*. 2005;33:272-276. http://dx.doi.org/10.1177/0363546504267153

70. Kiuru MJ, Pihlajamäki HK, Hietanen HJ, Ahovuo JA. MR imaging, bone scintigraphy, and radiography in bone stress injuries of the pelvis and the lower extremity. *Acta Radiol*. 2002;43:207-212. http://dx.doi.org/10.1034/j.1600-0455.2002.430222.x

71. Lappe J, Cullen D, Haynatzki G, Recker R, Ahlf R, Thompson K. Calcium and vitamin D supplementation decreases incidence of stress fractures in female Navy recruits. *J Bone Miner Res*. 2008;23:741-749. http://dx.doi.org/10.1359/jbmr.080102

72. Lappe JM, Stegman MR, Recker RR. The impact of lifestyle factors on stress fractures in female Army recruits. *Osteoporos Int*. 2001;12:35-42. http://dx.doi.org/10.1007/s001980170155

73. Larson P, Higgins E, Kaminski J, et al. Foot strike patterns of recreational and sub-elite runners in a long-distance road race. *J Sports Sci*. 2011;29:1665-1673. http://dx.doi.org/10.1080/02640414.2011.610347

74. Li J, Waugh LJ, Hui SL, Burr DB, Warden SJ. Low-intensity pulsed ultrasound and nonsteroidal anti-inflammatory drugs have opposing effects during stress fracture repair. *J Orthop Res*. 2007;25:1559-1567. http://dx.doi.org/10.1002/jor.20461

75. Lieberman DE, Venkadesan M, Werbel WA, et al. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*. 2010;463:531-535. http://dx.doi.org/10.1038/nature08723

76. Marti B, Vader JP, Minder CE, Abelin T. On the epidemiology of running injuries. The 1984 Bern Grand-Prix study. *Am J Sports Med*. 1988;16:285-294.

77. Masci L, Pike J, Malara F, Phillips B, Bennell K, Brukner P. Use of the one-legged hyperextension test and magnetic resonance imaging in the diagnosis of active spondylolysis. *Br J Sports Med*. 2006;40:940-946; discussion 946. http://dx.doi.org/10.1136/bjsm.2006.030023

78. Matheson GO, Clement DB, McKenzie DC, Taunton JE, Lloyd-Smith DR, MacIntyre JG. Stress fractures in athletes. A study of 320 cases. *Am J Sports Med*. 1987;15:46-58.

79. Mayr E, Frankel V, Rüter A. Ultrasound – an alternative healing method for nonunions? *Arch Orthop Trauma Surg*. 2000;120:1-8.

80. Mercer JA, Bates BT, Dufek JS, Hreljac A. Characteristics of shock attenuation during fatigued running. *J Sports Sci*. 2003;21:911-919. http://dx.doi.org/10.1080/0264041031000140383

81. Milgrom C, Finestone A, Ekenman I, Simkin A, Nyska M. The effect of shoe sole composition on in vivo tibial strains during walking. *Foot Ankle Int*. 2001;22:598-602.

82. Milgrom C, Finestone A, Segev S, Olin C, Arndt T, Ekenman I. Are overground or treadmill runners more likely to sustain tibial stress fracture? *Br J Sports Med*. 2003;37:160-163.

83. Milgrom C, Radeva-Petrova DR, Finestone A, et al. The effect of muscle fatigue on in vivo tibial strains. *J Biomech*. 2007;40:845-850. http://dx.doi.org/10.1016/j.jbiomech.2006.03.006

84. Milgrom C, Simkin A, Eldad A, Nyska M, Finestone A. Using bone's adaptation ability to lower the incidence of stress fractures. *Am J Sports Med*. 2000;28:245-251.

85. Miller T, Kaeding CC, Flanigan D. The classification systems of stress fractures: a systematic review. *Phys Sportsmed*. 2011;39:93-100. http://dx.doi.org/10.3810/psm.2011.02.1866

86. Milner CE, Davis IS, Hamill J. Free moment as a predictor of tibial stress fracture in distance runners. *J Biomech*. 2006;39:2819-2825. http://dx.doi.org/10.1016/j.jbiomech.2005.09.022

87. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc*. 2006;38:323-328. http://dx.doi.org/10.1249/01.mss.0000183477.75808.92

88. Milner CE, Hamill J, Davis IS. Distinct hip and rearfoot kinematics in female runners with a history of tibial stress fracture. *J Orthop Sports Phys Ther*. 2010;40:59-66. http://dx.doi.org/10.2519/jospt.2010.3024

89. Mizrahi J, Verbitsky O, Isakov E. Fatigue-induced changes in decline running. *Clin Biomech (Bristol, Avon)*. 2001;16:207-212.

90. Mizrahi J, Verbitsky O, Isakov E. Fatigue-related loading imbalance on the shank in running: a possible factor in stress fractures. *Ann Biomed Eng*. 2000;28:463-469.

91. Mizrahi J, Verbitsky O, Isakov E. Shock accelerations and attenuation in downhill and level running. *Clin Biomech (Bristol, Avon)*. 2000;15:15-20.

92. Moran DS, Evans RK, Hadad E. Imaging of lower extremity stress fracture injuries. *Sports Med*. 2008;38:345-356.

93. Nattiv A, Kennedy G, Barrack MT, et al. Correlation of MRI grading of bone stress injuries with clinical risk factors and return to play: a 5-year prospective study in collegiate track and field athletes. *Am J Sports Med*. 2013;41:1930-1941. http://dx.doi.org/10.1177/0363546513490645

94. Nattiv A, Loucks AB, Manore MM, Sanborn CF, Sundgot-Borgen J, Warren MP. American College of Sports Medicine position stand. The female athlete triad. *Med Sci Sports Exerc*. 2007;39:1867-1882. http://dx.doi.org/10.1249/mss.0b013e318149f111

95. Nieves JW, Melsop K, Curtis M, et al. Nutritional factors that influence change in bone density and stress fracture risk among young female cross-country runners. *PM R*. 2010;2:740-750; quiz 794. http://dx.doi.org/10.1016/j.pmrj.2010.04.020

96. Niva MH, Mattila VM, Kiuru MJ, Pihlajamäki HK. Bone stress injuries are common in female military trainees: a preliminary study. *Clin Orthop Relat Res*. 2009;467:2962-2969. http://dx.doi.org/10.1007/s11999-009-0851-5

97. Pinnington HC, Dawson B. The energy cost of running on grass compared to soft dry beach sand. *J Sci Med Sport*. 2001;4:416-430.

98. Pinnington HC, Lloyd DG, Besier TF, Dawson B. Kinematic and electromyography analysis of submaximal differences running on a firm surface compared with soft, dry sand. *Eur J Appl Physiol*. 2005;94:242-253. http://dx.doi.org/10.1007/s00421-005-1323-6

99. Plotkin LI. Apoptotic osteocytes and the control of targeted bone resorption. *Curr Osteoporos Rep*. 2014;12:121-126. http://dx.doi.org/10.1007/s11914-014-0194-3

100. Pohl MB, Mullineaux DR, Milner CE, Hamill J, Davis IS. Biomechanical predictors of retrospective tibial stress fractures in runners. *J Biomech*. 2008;41:1160-1165. http://dx.doi.org/10.1016/j.jbiomech.2008.02.001

101. Reilly T, Dowzer CN, Cable NT. The physiology of deep-water running. *J Sports Sci*. 2003;21:959-972. http://dx.doi.org/10.1080/0264041031000141368

102. Ridge ST, Johnson AW, Mitchell UH, et al. Foot bone marrow edema after a 10-wk transition to minimalist running shoes. *Med Sci Sports Exerc*. 2013;45:1363-1368. http://dx.doi.org/10.1249/MSS.0b013e3182874769

103. Rue JP, Armstrong DW, 3rd, Frassica FJ, Deafenbaugh M, Wilckens JH. The effect of pulsed ultrasound in the treatment of tibial stress fractures. *Orthopedics*. 2004;27:1192-1195.

104. Ruohola JP, Laaksi I, Ylikomi T, et al. Association between serum 25(OH)D concentrations and bone stress fractures in Finnish young men. *J Bone Miner Res*. 2006;21:1483-1488. http://dx.doi.org/10.1359/jbmr.060607

105. Schneiders AG, Sullivan SJ, Hendrick PA, et al. The ability of clinical tests to diagnose stress fractures: a systematic review and meta-analysis. *J Orthop Sports Phys Ther*. 2012;42:760-771. http://dx.doi.org/10.2519/jospt.2012.4000

106. Shaffer RA, Brodine SK, Almeida SA, Williams KM, Ronaghy S. Use of simple measures of physical activity to predict stress fractures in young men undergoing a rigorous physical training program. *Am J Epidemiol*. 1999;149:236-242.

107. Simkin A, Leichter I, Giladi M, Stein M, Milgrom C. Combined effect of foot arch structure and an orthotic device on stress fractures. *Foot Ankle*. 1989;10:25-29.

108. Sloan AV, Martin JR, Li S, Li J. Parathyroid hormone and bisphosphonate have opposite effects on stress fracture repair. *Bone*. 2010;47:235-240. http://dx.doi.org/10.1016/j.bone.2010.05.015

109. Snyder RA, DeAngelis JP, Koester MC, Spindler KP, Dunn WR. Does shoe insole modification prevent stress fractures? A systematic review. *HSS J*. 2009;5:92-98. http://dx.doi.org/10.1007/s11420-009-9114-y

110. Stewart GW, Brunet ME, Manning MR, Davis FA. Treatment of stress fractures in athletes with intravenous pamidronate. *Clin J Sport Med*. 2005;15:92-94.

111. Sullivan D, Warren RF, Pavlov H, Kelman G. Stress fractures in 51 runners. *Clin Orthop Relat Res*. 1984:188-192.

112. Swenson EJ, Jr., DeHaven KE, Sebastianelli WJ, Hanks G, Kalenak A, Lynch JM. The effect of a pneumatic leg brace on return to play in athletes with tibial stress fractures. *Am J Sports Med*. 1997;25:322-328.

113. Tenforde AS, Sayres LC, McCurdy ML, Sainani KL, Fredericson M. Identifying sex-specific risk factors for stress fractures in adolescent runners. *Med Sci Sports Exerc*. 2013;45:1843-1851. http://dx.doi.org/10.1249/MSS.0b013e3182963d75

114. Walter SD, Hart LE, McIntosh JM, Sutton JR. The Ontario cohort study of running-related injuries. *Arch Intern Med*. 1989;149:2561-2564.

115. Warden SJ. A new direction for ultrasound therapy in sports medicine. *Sports Med*. 2003;33:95-107.

116. Warden SJ. Prophylactic use of NSAIDs by athletes: a risk/benefit assessment. *Phys Sportsmed*. 2010;38:132-138. http://dx.doi.org/10.3810/psm.2010.04.1770

117. Warden SJ, Burr DB, Brukner PD. Repetitive stress pathology: bone. In: Magee DJ, Zachazewski JE, Quillen WS, eds. *Pathology and Intervention in Musculoskeletal Rehabilitation*. St Louis, MO: Elsevier/Saunders; 2009:685-705.

118. Warden SJ, Burr DB, Brukner PD. Stress fractures: pathophysiology, epidemiology, and risk factors. *Curr Osteoporos Rep*. 2006;4:103-109.

119. Warden SJ, Hurst JA, Sanders MS, Turner CH, Burr DB, Li J. Bone adaptation to a mechanical loading program significantly increases skeletal fatigue resistance. *J Bone Miner Res*. 2005;20:809-816. http://dx.doi.org/10.1359/JBMR.041222

120. Warden SJ, Mantila Roosa SM, Kersh ME, et al. Physical activity when young provides lifelong benefits to cortical bone size and strength in men. *Proc Natl Acad Sci U S A*. 2014;111:5337-5342. http://dx.doi.org/10.1073/pnas.1321605111

121. Wentz L, Liu PY, Haymes E, Ilich JZ. Females have a greater incidence of stress fractures than males in both military and athletic populations: a systemic review. *Mil Med*. 2011;176:420-430. http://dx.doi.org/10.7205/MILMED-D-10-00322

122. Williams DS, 3rd, McClay IS, Hamill J. Arch structure and injury patterns in runners. *Clin Biomech (Bristol, Avon)*. 2001;16:341-347.

123. Williams DS, McClay IS, Hamill J, Buchanan TS. Lower extremity kinematic and kinetic differences in runners with high and low arches. *J Appl Biomech*. 2001;17:153-163.

124. Yoshikawa T, Mori S, Santiesteban AJ, et al. The effects of muscle fatigue on bone strain. *J Exp Biol*. 1994;188:217-233.

125. Zahger D, Abramovitz A, Zelikovsky L, Israel O, Israel P. Stress fractures in female soldiers: an epidemiological investigation of an outbreak. *Mil Med*. 1988;153:448-450.

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