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Tibial Stress Fractures in Runners & Associated Risk Factors

**Bone & Stress Fractures:**

Bone is a metabolically dynamic tissue that reacts to the demands placed on it. Imposing stress on a bone leads to activation of osteoclasts, which resorb bone, and osteoblasts, which form new bone and remodel the tissue. This stress is necessary for bone to maintain normal strength. If stress is imposed too frequently, the osteoclast activity can outpace the osteoblast activity, leading to accumulated micro-fracture and a stress fracture can occur.1,2 A fatigue curve demonstrates the optimal balance between the amount of stress applied to a structure and the number of repetitions the structure can withstand in relation to potential for injury.3

Stress fractures are a common injury in the athletic population, reported to account for 10% of all injuries.2  The demographic with the largest reports is runners, in which stress fractures account for 4.4%-15.6% of all running injuries.2 The tibia is the most common site and has been estimated to account for 49.1% of all stress fractures, most commonly affecting the posteromedial surface.2,4 There are many reasons why stress fractures with an emphasis on prevention deserve attention. Two major factors are that the recovery typically involves 6-8 weeks of rest and rehabilitation and the recurrence rate of stress fractures can be as high as 36%.4

The etiology for stress fractures is multifactorial and many risk factors have been identified.1 It is important to consider all of the risk factors, as each individual presenting with a stress fracture will likely present with their own unique subset of these risk factors, which likely differ from another individual. This complicates both treatment and research efforts for gaining further understanding of stress fractures. Therefore, it is important to use an applied anatomical and biomechanical perspective when examining the risk factors that have been suggested in combination with the findings in the current evidence. This literature review includes a comprehensive exploration of risk factors for tibial stress fractures in runners with an emphasis on anatomical and biomechanical variables, some of which lend to intervention implications.

**Metabolic and Activity-Based Risk Factors:**

 Stress fractures are an injury to the bone and anything that weakens bone tissue will in turn predispose one to a stress fracture. For example, lower bone mineral density (BMD) and metabolic disorders and diseases that decrease BMD increase risk of fracture. Further, the “female athlete triad”, including disordered eating, amenorrhea, and osteoporosis, is associated with stress fractures, as well as increased age at first menarche.2 Further, nutritional factors such as low calcium intake and a low-fat diet have been associated as well.

 It has been estimated that over 60% of running injuries can be attributed to training errors.3 This is a factor of utmost importance in stress fracture etiology and should be a definite focus of intervention, as well. Training errors include poor fitness, poor diet, and sudden increase in frequency, duration, mileage, or speed of running.2 Additionally, excessive dose of training, poor footwear, and irregular terrain are also contributors to stress fracture risk.5

**Anatomical Factors: Bone Structure & Lower Extremity Alignment**

Smaller cross-sectional area and smaller area moment of inertia of the tibia could lead the bone to lowered ability to resist stress and increased risk of tibial stress fracture. These associations have conflicting evidence, with confirming evidence in a sample of males, but a similar study with female runners did not detect a significant association.6

 Two anatomical factors that have been significantly associated with stress fractures include leg length discrepancy and calf muscle girth. A prospective study by Bennell et al. found that female athletes with a leg length discrepancy were twice as likely to develop stress fractures as compared to female athletes without stress fractures. Additionally, they found a significant relationship with decreased calf girth, adjusted for size, and stress fracture frequency, where for every 1-cm decrease in calf girth, the stress fracture risk increase fourfold.7 As muscular contraction conceptually counteracts joint loading from the ground reaction force, it is logical that greater muscle size and strength could be protective against stress fracture and that the plantarflexor muscle group could protect the tibia from harmful loading.8,2

Further, various alignments of the lower extremity have been implicated as risk factors for tibial stress fracture, including varus lower extremity alignment, pes cavus, and pes planus.9 The varus lower extremity alignment includes genu varus, tibial varum, subtalar varus, and forefoot varus.6 Tibial varum is implicated as this alignment could lead to greater bending moments when the tibia undergoes compressive loading, increasing tensile and compressive forces on either side of the tibia. Additionally, it is hypothesized that the varus alignment throughout the lower extremity is a rigid alignment with decreased time for deformation and shock absorption, thus placing the individual at greater risk for boney injury including stress fractures.2 This rationale similarly extends to pes cavus.2 Pes planus involves greater activity of the posterior tibialis muscle and allows for greater soft tissue shock absorption. However, excessive activity of this muscle could lead to muscular fatigue reducing the force protection of bone and increasing risk for boney injury. Despite both of these possible associations, in a recent systematic review, Barnes et al. found no conclusive evidence for foot type being associated with tibial stress injuries.10

Nearly all of these alignment factors have contradictory evidence in the literature and ultimately studies have been inconclusive.6 This leads to the conclusion for either a need for more evidence, or more likely, a reinforcement of the concept that what might act as a risk factor for one particular person may prove to be benign or even protective in another person.

**Biomechanical Factors:**

Loading Rates and Ground Reaction Forces:

Recently, vertical loading rates and ground reaction forces (GRF) have been investigated in relation to tibial stress fractures.11 These important kinetic variables quantify aspects of the collision of the lower extremity with the ground. They can be visualized by examining a plot of the vertical ground reaction force (GRF) over time in stance phase of running, as demonstrated in Figure 1. Some key components in this plot include the GRF, impact peak, propulsion peak, and vertical loading rates. The GRF is an approximate measure of the vertical loading of the lower-extremity. A rearfoot striking pattern, which the majority of American runners employ, includes the two peaks seen on this graph. These include the impact peak, the initial peak for approximately the first 10-30ms of stance, and the propulsion peak, the second peak through the remainder of stance.3 The impact peak varies per person but has been estimated to be 1.5 to 5 times a person’s body weight.3 Finally, vertical loading rates refer to the slope from foot strike to the top of the impact peak. Both instantaneous and average loading rates are kinetic variables often investigated and they indicate how rapidly the GRF rises during this time.11 Frequently loading rates are measured using 20%-80% of the period between foot strike and impact peak to capture the most linear portion.6

It has been suggested that higher GRF and loading rates could lead to increased stress fracture risk and that in a group of individuals all performing the same task, those who develop a stress fracture either are more vulnerable to loading or are experiencing more severe loading than their uninjured counterparts.11 Further, it is possible that higher loading rates lead to increased internal strain rate in bone lesser ultimate strength of bone over repeated exposures, which is similar to what has been suggested in mechanical testing of bones tolerance for fatigue.

Many studies regarding loading rates and other risk factors involve a retrospective design, searching for differences between a group of individuals who have a tibial stress fracture history compared to age and mileage matched controls who do not have a history of tibial stress fracture. A recent review by Zadpoor et al. investigated the relationship between lower extremity stress fractures and GRF-related variables. 10 of the 13 studies included in this review focused on tibial stress fractures and the majority involved a subject group of female runners.11 The review performed a meta-analysis and found that there was no significant difference in vertical GRF peak between the stress fracture group and the control group, but the average vertical loading rates (AVLR) and instantaneous vertical loading rates (IVLR) were both significantly higher in the stress fracture group. These relationships all remained unchanged when the meta-analysis was performed with only the tibial stress fracture groups.11

These consistent results suggest that increased loading rate is a risk factor for tibial stress fracture. When investigating loading, it is important to consider both external and internal loading on bones. The external loading is the ground imposing a stress on the lower extremity at collision and traveling up the joints, represented by the GRF and associated loading variables. However, the internal loading involves the soft tissue forces including muscles, tendons, and ligaments, and it can be more difficult to quantify. There is less available evidence on these internal loading factors, but they should not be forgotten when targeting external loading variables in intervention.

Tibial Acceleration, Tibial Shock, and Lower Extremity Stiffness:

Two studies have demonstrated that the aforementioned increased loading rates are significantly, positively correlated to peak tibial acceleration during running.6 A recent study compared 20 runners with a tibial stress fracture history to 20 matched control runners evaluating a wide range of kinetic and kinematic variables. Using an accelerometer to measure peak positive acceleration (PPA) of the tibia to represent peak tibial shock, they found significantly greater PPA in the group with a tibial stress fracture history. This is an important relationship to establish and confirm, as it establishes a relationship between loading rates and PPA and it also implies there are multiple possible screening tools to determine high risk in runners. One can use GRF data collected from a force plate, or one can utilize a tibial accelerometer.

Theoretically, if the lower extremity undergoes greater change in range of motion, the time for deformation will increase, attenuating shock and possibly decreasing GRF and loading rates. This relationship has been demonstrated in jumping and landing studies but there are mixed results in evaluating excursion and stiffness in runners, possibly related to varying study designs.8,6 One recent cross-sectional study found that sagittal plane knee stiffness during impact peak was higher in a group of runners with tibial stress fracture history. Further, stiffness was positively correlated with greater tibial shock, supporting that stiffness could be an early stance risk factor for tibial stress fractures.6,12

Sagittal Plane Bending:

Internal and external loading of the tibia during running is not currently well understood.8,10 Although these forces change throughout the gait cycle, two predominant external forces that are agreed to be involved in tibial loading include an axial compressive force and a posteriorly directed shear force. Further, a predominant internal force imposed largely by the plantarflexor muscle group has been suggested, which involves a compressive force and an anteriorly directed shear force.10 Both of these contribute to the loading the tibia experiences. However, recent research studies, both involving ten healthy male runners, have argued opposite responses of the tibia. One study suggests the resultant loading compresses and bends the distal portion of the tibia posteriorly, whereas, another study suggests the distal portion of the tibia moves anteriorly in response to this compressive and bending load.8,13 Both studies used experimental modeling techniques for estimation, which is possibly a contributor to the different results.8,13 Clearly more research needs to be done to comprehensively evaluate internal and external loading of the tibia and associated bending in running. However, common to both of these studies is the hypothesis that the factors causing injury are occurring during mid-stance, as opposed to impact peak, which is different from loading rates.

Free Moments, Rearfoot Eversion, and Hip Adduction:

Although tibial stress fractures are most commonly classified by location and not shape, there exists evidence that some tibial stress fractures are spiral fractures.14 This spiral shape implies that there are additional forces to the axial and shear forces imposed on the tibia and that torsion may be a contributor to tibial stress fracture incidence.14 An indirect measure of this torque is “free moment” (FM), which is defined as the torque about a vertical axis that is a result of friction between the foot and the ground during stance phase of gait.14 Colloquially, the free moment can be thought of as the resistance to toeing in or out, where adduction FM resists toeing out and abduction FM resists toeing in. Therefore, the greater the FM, the greater the torque acting on the tibia, presumably, as again this is an indirect measure.14

Existing evidence links FM to pronation and rearfoot eversion.14,15 An additional study investigated FM in relation to tibial stress fracture history. In a cross-sectional study comparing 25 female runners with a history of tibial stress fracture to 25 age and mileage matched female runners, they found that all FM variables were significantly greater in the group with history of tibial stress fracture. These FM variables included maximum Adduction FM (ADDFM), FM at peak braking force (FMBRAK), and absolute peak FM (ABSFM). No difference in Impulse (IMP) was found between groups. ABSFM had the highest values and a large effect size (0.99). Further, through a binary logistic regression, the authors determined the ABSFM serves as a good predictor, successfully predicting 66% of tibial stress fracture history cases.14 These significant differences in FM variables indicate that higher torque values imposed on the tibia may be associated with tibial stress fractures, and further that the magnitude of this torque may be more important in this association than the direction.14

 Additional biomechanical factors during stance phase of running can offer valuable insight to injury risk, as altered kinematics can lead to altered loading patterns, so that even normal external loads can lead to injury.15 Two kinematic factors associated with tibial stress fracture include increased peak hip adduction (HADD) and increased rearfoot eversion (RFEV). Increased RFEV has been associated with excessive pronation, FM, and may impose greater torsion on the tibia, as explored above.4,9 A small recent study found increased peak HADD and internal rotation in the first half of stance in runners with history of tibial stress fracture.15 A more extensive, cross-sectional study evaluated 29 female runners with a tibial stress fracture history as compared to 29 matched controls, all rear foot strikers, evaluating frontal and transverse plan motions at the ankle, tibia, knee, and hip. They found, overall, that the kinematics of stance phase were significantly different between these two groups, and they found that peak HADD and peak RFEV were significantly greater in the tibial stress fracture group. They did not find significant differences between tibial internal rotation, peak knee angles, or hip internal rotation. They did not find any significant differences in these kinematic variables at impact peak.15 Interestingly, these variables were significant during overall stance phase, which is different than other risk factors such as loading rates at impact peak and sagittal bending moments at mid-stance.

An interesting study by Pohl et al. evaluated many of the above-explored biomechanical risk factors in female runners. The results of their study confirmed suggested associations of greater VALR, VILR, PPA, FM, HADD, and RFEV in a group of runners with tibial stress fracture history compared to controls. Further, they performed a Nagelkerke statistical test, which revealed that nearly 50% of the variance between the tibial stress fracture and control group was accounted for my combined HADD, FM, and RFEV and this model successfully classified 83% of injured runners. In addition, the loading rate variables such as VILR did not improve the predictive ability of the group.4

Fatigue:

An additional factor purported to play a role in changing mechanics is fatigue. Often research studies are conducted with a limited amount of running and they do not assess effects of longer duration exercise. However, after given period of running, muscles begin to fatigue, which leads to increased energy transmitted to the surrounding bones.11 One retrospective study found that after 45 minutes of running, a group of runners with tibial stress fracture history had higher GRF increases than that of a matched control group.11 Another study by Clansey et al. investigated the effect of fatigue on biomechanical factors that have been associated with tibial stress fractures in experienced distance runners. They evaluated the mechanics at three times, with a 20-minute segment of running at lactate threshold speed in between each. Rate of Perceived Exertion (RPE) reports confirmed that fatigue was increasing through these runs. Corresponding vertical impact peak and peak tibial acceleration were not significantly affected.16 Yet, corresponding significant increases were found in peak RFEV, peak FM, and vertical force loading rates, as well as peak axial head acceleration.16 This has large clinical implications and fatigue should certainly be considered in prevention and intervention strategies.

**Limitations & Conclusions:**

There are many limitations in approaching tibial stress fracture risk factors in the retrospective manner that the majority of the existing evidence uses. For example, after their recovery from the injury it is possible that these individuals modified their gait pattern to prevent re-injury. Only one study by Bennell et al. evaluated tibial stress fracture prospectively, and more studies of this nature in the future would provide for stronger research.7 Further, a number of research studies have used a standardized gait speed, which is also suggested to effect normal running style, and few studies identified evaluate the effect of fatigue. Additionally, the limited sample of relatively homogenous young adults and short period of time for cross-sectional studies both contribute to the limited amount of definitive conclusions that can be made. Lastly, data collection and measurement methods, particularly of variables difficult to measure such as tibial loading, introduce an amount of error.

Despite these limitations, one can appreciate the many identified risk factors that have been associated with tibial stress fractures. Specifically looking at a few of the biomechanics, one can recognize various risk factors throughout the whole stance phase of gait from loading rates to sagittal bending to free moments. Further, recognizing the contribution of all areas of risk factors including metabolic, activity-related, anatomical, and biomechanical will allow for a complete evaluation of an individual presenting with a tibial stress fracture. Further targeting these risk factors in intervention strategies could plausibly lead to decreased re-injury rates and possibly early screening and prevention in the future.

Specific studies of intervention strategies for tibial stress fractures are limited, particularly as the main intervention is rest from running. However, in addition to modifying training errors, evidence has suggested that changing some of these biomechanical risk factors, could possibly lead to reduced injury.17,18 This can be targeted through strengthening exercises or external supports such as orthotics. Further, recently, it has been targeted through running gait retraining with feedback, involving retraining running mechanics to decrease abnormally high vertical loading rates or tibial acceleration rates.17,18,19 Some methods include increasing step frequency, modifying landing pattern, and learning to alter tibial acceleration.17,18,19,20 These retraining studies are very recent and little can be definitively concluded, but they do show promising evidence for future rehabilitation directions and possible reductions in recurring stress fractures.

Figures:

1.Zadpoor et al. 2011

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