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Bone Stress Injuries in Collegiate Distance Runners:
Review of Incidence, Distribution, and Risk Factors

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Professional Paper for the Degree of Master of Science

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Abstract

This literature review investigates the risk factors for bone stress injuries that apply to collegiate distance runners. Collegiate distance runners demonstrate high incidence rates of this type of injury and can suffer from a loss of training time. It is important to review the risk factors that apply to these athletes in order to mitigate the time lost to injury and optimize training. PubMed and Google Scholar were searched for original articles pertaining to risk factors associated with bone stress injuries and/or stress fractures. Results from these original articles demonstrate that this injury has many risk factors including biomechanical, biological, and environmental factors. Collegiate distance runners need to be assessed on the basis of these risk factors so that they may mitigate their risk of bone stress injury and optimize their training time. This paper concludes with practical recommendations for collegiate distance runners to take into consideration that may decrease the risk of stress fracture.

Introduction

Bone stress injuries (BSI) are a common relative overload injury found in runners, military, and other sport populations where repetitive loads are experienced by the musculoskeletal system. Reports have shown that up to 20% of musculoskeletal injuries sustained by these populations are BSI [30,78]. BSI is on a continuum of severities, beginning with stress reactions and progressing to stress fractures (SF) [107]. Researchers suggest that although studies done on military populations have contributed to the understanding of this continuum of BSI and subsequent SF, collegiate distance runners are a population that needs to be assessed separately due to differences in training and other risk factors. Matheson et al. 2005 provided descriptive data from 320 cases of bone-scan positive stress fractures in athletes from different sports and found that 221 stress fractures were in runners (69%). Ardent et al. 2003 performed a retrospective review of SF in college athletes at a single institution between the years 1990 and 1999 and found that cross country and distance runners had the highest rates of SF among all the sports studied. In a more recent study, Rizzone et al. 2017 studied rates of SF among NCAA athletes in 25 different sports between the years 2004 to 2014. Throughout this 10-year period, 671 SF were reported and the highest rates of SF were found in women's cross country and outdoor track and men's cross country. This study also looked at restriction of participation in athletes who had a SF and found about two thirds of these athletes needed to miss 3 or more weeks of training. The high restriction of participation rates indicate that it is important to assess an athlete's risk of SF to minimize time away from practice. The conclusions from these studies speculate that the repetitive, submaximal loading placed on the musculoskeletal system and increase the runner's risk of SF [48].

Popp et al. 2016 suggest that bone structure and anatomic alignment contribute significantly to a runner's overall risk of SF [81]. Milner et al. 2006 suggest that loading rates and tibial shock contribute significantly to a runner's risk of SF [34]. Matheson et al. 2006 found incidence rates that varus malalignment was present in a majority of runners with SF [33]. The musculoskeletal system experiences external vertical loading forces between 2.5 to 2.8 times the body weight during running [62]. External forces, i.e, ground reaction forces, and internal forces i.e., muscles and ligaments acting on the bone, create forces on bone. Milner et al. 2006 also suggest that aberrant kinematics of the knee, hip, and ankle are biomechanical characteristics that may predispose a distance runner to an increased risk of SF [72]. It is thought that a difference in kinematics may increase loading rates in the lower extremities, increasing the risk of SF. A review of biomechanical factors is important to assessing the risk of BSI and SF among collegiate distance runners.

The high energy and metabolic demands of collegiate distance running are suggested reasons this sport is correlated with a high rate of BSI compared to other college sports [102]. Tenforde et al. 2017 associated the female athlete triad to the development of BSI, and of the 16 college sports they investigated, cross country runners had the highest number of BSIs [102]. The female athlete triad is composed of three components: low energy availability, menstrual dysfunction, and low bone mineral density [102]. In Tenforde et al.'s 2017 study, athletes were classified by low risk, moderate risk, and high risk for sustaining a BSI based on criteria formed from the female athlete triad definition [102]. Cross country runners contributed the largest percent of athletes at a high risk for BSI [102]. Tenforde et al. 2017 illuminates the high risk of BSI in collegiate cross-country runners compared to other sports and suggests low energy availability as the underlying biological risk factor for BSI [102]. It also demonstrates that BSI is cumulative in nature and encompasses risk factors that begin in high school, e.g. delayed menarche. Tenforde et al. 2017 conclude that assessing college athletes, especially distance runners, for risk factors associated with the triad, including risk factors that begin in high school or earlier, is important for identifying collegiate athletes at high risk for sustaining SF [102].

The IOC (International Olympic Committee) in 2005 defined the female athlete triad as the combination of disordered eating (DE) and irregular menstrual cycles that leads to a decrease in estrogen and other hormones, resulting in low bone mineral density. In 2007 the definition changed to the relationship between energy availability, menstrual function, and bone health. Tenforde et al. 2017 and other researchers have studied energy availability as the underlying, etiological component of the triad, as it supports the basic metabolic functions [21, 48, 102]. In 2007, the triad has been reworked into the relative energy deficiency in sport (RED-S) and encompasses more than the female athlete triad definition to include other physiological dysfunctions that occur from an energy deficiency in sport as well as both sexes [48]. Vitamin D and calcium deficiencies have been suggested to be risk factors for SF in distance runners. Kim et al. 2016 found an inverse relationship between vitamin D levels and time lost to BSI in NCAA division 1 distance runners. Higher levels of vitamin D were associated with fewer days lost to BSI, demonstrating a possible protective effect of vitamin D on BSI. Lappe et al. 2008 found calcium and vitamin D supplementation decreases the incidence of SF in female Navy recruits, suggesting that when supplemented together, calcium and vitamin D may have a protective effect on BSI [55]. These are important considerations when assessing a collegiate distance runner's risk of SF due to the high risk of low energy availability, low vitamin D levels, and low calcium consumption.

Due to BSI and SF being overuse injuries, it is important review the relationship between overtraining and this injury. Soligard et al. 2016 suggest that poor management of training loads can increase the risk of overuse injuries such as BSI through a variety of mechanisms [94]. One of these mechanisms is the excessive micro damage in bone tissue that exceeds the bone's load bearing capacity to adapt or insufficient recovery between loading cycles [54, 94]. Collegiate distance runners' training loads may be increased inappropriately, leading to excessive microdamage with insufficient amounts of recovery between loading [94]. Clansey et al. 2012 investigated the effect of fatigue on running mechanics associated with tibial stress fractures (TSF). This study found that following acute bouts of fatigue, biomechanical characteristics previously shown to be associated with an increased risk of TSF, rearfoot eversion and vertical force loading rates, had increased [19]. These studies show the importance of investigating training load among collegiate distance runners as a potential risk factor for BSI and SF. In addition to training load, other factors such as oral contraceptives and running shoe type will be reviewed as they are speculated to have an influence on the increased risk of BSI and SF.

Statement of Problem

Collegiate distance runners are a population at high risk of BSI and SF due to the nature of the sport, the natural selection of lean athletes, and the multi season, fall cross country, winter track, and spring track, aspect of collegiate distance running. Other studies have associated it with various risk factors, such as biomechanical insufficiencies and low energy availability. Based on the high incidence rates of BSI and SF among collegiate distance runners, it is important to review the risk factors that have been associated with BSI and SF so that high risk individuals can be identified prior to the development of injury. Risk factors that will be reviewed include, but are not limited to, biological characteristics of the athlete such as energy availability and the subsequent effect on hormones and bone mineral density, biomechanical characteristics, as well as training loads, shoe type, and oral contraceptives. Reviewing these risk factors may illuminate gaps in the current literature where future studies can be performed in order to fill the gaps. By decreasing the risk of BSI and SF, collegiate distance runners may be able to focus their time training and competing.

Significance of Study

The purpose of this paper is to review original research articles that study the biological, biomechanical, and environmental risk factors for BSI and SF in collegiate distance runners. This may aid practitioners and athletes in the avoidance of injury, as well as identifying where further research may contribute. Pathology, incidence rates, and distribution rates in collegiate distance runners will be further reviewed. Due to the detrimental consequences that SF have on training time and competing for collegiate distance runners, having the knowledge of the risk factors is important in managing them so the athlete can optimize time training and competing.

Limitations

One of the largest limitations of this literature review is the limited number of studies using collegiate distance runners as the subjects. Using recreational runners as subjects to study SF risk factors may not give a full understanding of how these risk factors apply to collegiate distance runners because of the training discrepancy. Studies using "competitive" or "elite" distance runners provide adequate subject cohorts to extract risk factor information due to the level of training intensity performed. Self-reported scores in studies, for example energy availability, are speculated to be underreported, and may underestimate the true prevalence of low energy availability among collegiate distance runners. Convenient sampling by using subjects from one institution is a limitation due to the small sample size, and often lack of diversity. Female distance runners on hormonal treatment, e.g. birth control, were typically excluded from results pertaining to hormonal dysfunction, decreasing the sample size and possibly inaccurately representing results on hormonal dysfunction as a stress fracture risk factor.

Definition of Terms

Bone Stress Injury (BSI) – continuum of overuse/fatigue related injury including stress reaction and stress fracture; occurs when bone is unable to withstand repetitive weight bearing activity; micro trauma accrued in bone exceeds remodeling rate of bone [107]

Stress Reaction (SR) – early BSI characterized by localized pain that has gradual onset and increasing pain with continued loading; characterized by increased bone turnover (increase in bone resorption relative to bone formation); bone marrow edema in periosteal bone (swelling of marrow due to excess fluid) in response to accumulation of micro damage; pain initially felt following training, but if loading continues, pain can be felt during training [107]

Stress Fracture (SF) –stress reaction progresses to micro-fracture of cortical bone discernible on magnetic resonance imaging technology (MRI); pain felt during training [107]

Bone Turnover – difference between bone resorption and bone formation during bone remodeling [107]

Distance runner - athlete competing in a race 800 meters or longer [2,9]

Female Athlete Triad (2014) – medical condition often observed in physically active girls and women and involved three components: 1) low energy availability (EA) with or without disordered eating (DE), 2) menstrual dysfunction, 3) low bone mineral density (BMD) [46]

Relative Energy Deficiency in Sport (RED-S) (2014) – syndrome affecting not only energy availability, menstrual function, and bone health, but also metabolic rate, immunity, protein synthesis, cardiovascular and psychological health [70]

Energy Availability (EA) – balance between dietary energy intake (EI) and energy expenditure relative to fat free mass that is the underlying etiological factor needed to maintain homeostasis, proper metabolic functions, and overall health [70]

Low EA – negative energy balance when either energy intake is decreased or exercise load is increased; causes adjustments in bodily systems needing to decrease energy expenditure, leading to disruptions in hormonal and metabolic functions [102]

Delayed menarche – lack of menarche by age 15 [83,102]

Amenorrhea – absence of three or more consecutive menstrual cycles post-menarche [83,102]

Oligomenorrhea – menstrual cycle length greater than 45 days [83,102]

Eumenorrhea – normal/regular menstrual cycles; greater than 10 menstrual cycles per year

Disordered Eating (DE) – consists of restrictive eating behaviors that do not necessarily reach the level of clinical eating disorder; typically measured by questionnaires (Eating Attitudes Test – 26, Eating Disorder Inventory) assessing health, weight, dieting, and body image [16]

Eating Disorders (ED) – spectrum ranging from DE to subclinical ED to clinical ED; anorexia nervosa (restriction of all food), bulimia nervosa (binge and purge of food) as defined by the DSM-V.

Oral Contraceptives (OC) – exogenous estrogen and/or progestin taken orally in the form of a pill [22]

Bone Mineral Density (BMD) – measurement of quality of bone; measured using dual energy X-ray absorptiometry (DEXA scan); units expressed in grams per squared centimeter [73]

Biomechanics – study of the mechanical laws relating to the movement or structure of the human body

Ground Reaction Force (GRF) – primary descriptive component in analysis of support phase of running; provides descriptive information concerning magnitude, direction, and point of application of impact force; measured using force platform; measurement expressed in times body weight [13,15]

External Load – external stimulus applied to athlete that is measured independently of internal characteristics; measuring involves quantifying training load; e.g. GRF [100, 117]

Internal Load – individual response to external load; measured by assessing internal physiological and psychological response to external load; muscle, tendons, ligaments responding to external forces contribute to internal force bones experience [100, 117]

Vertical Loading Rate (VLR) – slope or magnitude of the vertical GRF curve; relationship between foot strike and vertical impact peak; indication of how fast the vertical GRF rises to the first peak [68, 117]

Tibial Shock – measure of load applied to lower extremity; determined as the highest acceleration measurement during the stance phase [68]

Hip Adduction – biomechanical characteristic; distal joint extends towards midline creating larger angle than normal at proximal joint causing pelvis to drop [75, 92]

Review of Literature

BSI Pathology

Wolff's law states that intermittent forces applied to bone stimulate remodeling so that it may withstand high stress environments via adaptive homeostasis[50,99]. When bone experiences an increase in applied stress that outpaces the bone's ability to adapt, micro-damage develops at a site where bone resorption has occurred. Following resorption, new bone formation takes place, but at a slower rate. This discrepancy between resorption and formation of new bone following an increase in stress results in the accumulation of micro-damage at a site in the bone, leading to BSI unless the abusive loading patterns are mitigated. The severity of BSI falls on a spectrum beginning with a stress reaction, characterized by an increase in bone turnover and periosteal edema and bone marrow edema, depicted in Figure 1. Periosteal edema and bone marrow edema occurs in response to the accumulation of damage to the bone and increases fluid in the bone marrow, causing swelling [103]. If diagnosis is prolonged and the micro damage continually exceeds bone remodeling, the injury becomes what is called a stress fracture (SF). The gold standard for diagnosis of a SF is magnetic resonance imaging (MRI) [69]. SF's have a discernible fracture line visible using MRI technology and can develop into complete bone fractures that need surgical intervention if left undiagnosed and untreated. For the purpose of this paper, focus will be on the illustration of the pathology continuum where an imbalance exists between damage and remodeling due to bone loading.

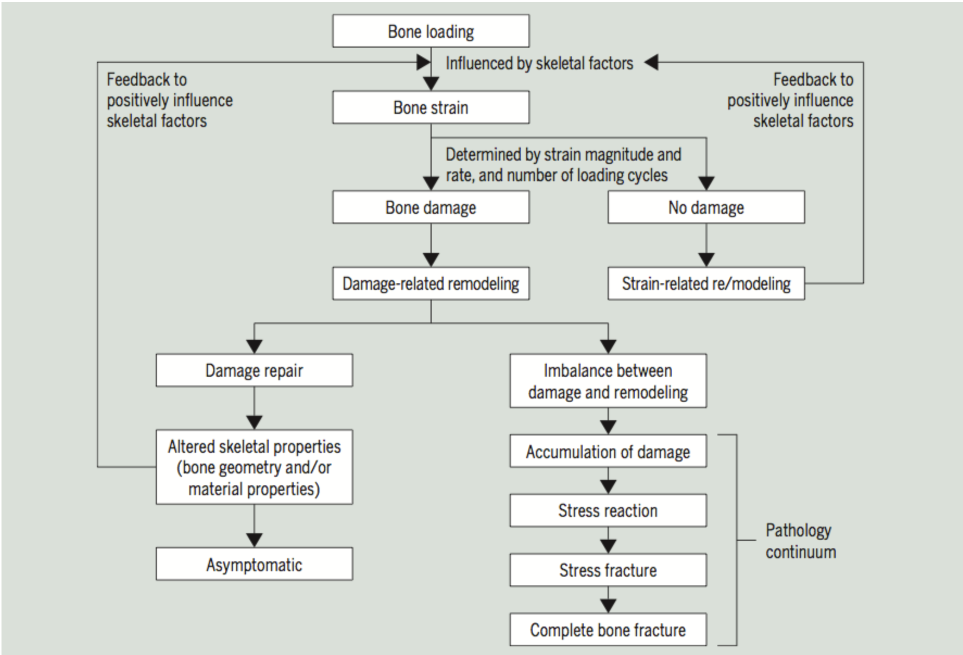

Figure 1. Pathophysiology of BSIs. Adapted from Management and Prevention of Bone Stress Injuries in Long-Distance Runners. By Warden, Davis, & Fredericson, *2014, The Journal of Orthopaedic and Sports Physical Therapy, 44(10), 749-765.* 2014 by Journal of Orthopaedic & Sports Physical Therapy.

Incidence and Distribution Rates

Reviewing the incidence rates of stress fractures in collegiate distance runners is important know in order to appreciate the magnitude of the issue. Distribution sites are also important to investigate to identify risk factors specific to the highly affected areas. Bennell et al. 1996 performed a twelve-month prospective study on the incidence and distribution of SF among competitive track and field athletes [10]. It was found among the 112 competitive track and field subjects, 53 females and 58 males, 20 athletes sustained 26 SF in the 12-month period, an overall incidence rate of 21.1%. This study found a greater number of SF among long distance runners compared to other track and field event groups. The distribution of injury site showed 46% of stress fractures occurred in the tibia, 15% in the navicular, and 12% in the fibula. These high incidence rates in collegiate distance runners and high distribution rates among the lower extremities suggest a further investigation of risk factors that predispose this athletic population to SF. It is also suggested that biomechanical characteristics associated with tibial stress fractures need to be identified due to the highest rate of incidence found in the tibia.

Ardent et al.2003 performed a retrospective review of SF in college athletes at a single institution between the years 1990 and 1999 [2]. It was found that cross country and distance runners had the highest rates of SF among all the sports studied. Distance runner was defined as an athlete competing in 800-meters or greater. Female cross country runners exhibited the highest rate of incidence of SF (6.4%) compared to other sports, e.g. women's gymnastics (4.29%). Men's cross country also showed the highest rates of SF (3.89%) in comparison to other sports, e.g. men's basketball (2.86%). Distribution rates found that the tibia was the most common site of SF (37%), however, the foot as an anatomic region, including the metatarsal and navicular bones, exhibited the greatest percentage of SF (44%).

Rizzone et al. 2017 conducted a descriptive, epidemiological study among NCAA athletes over 10 years (2004 to 2014) and found the highest rates of SF were among women's cross country and outdoor track and men's cross country [86]. Comparing rates by sex, the rates were higher for women's cross country, indoor and outdoor track compared to men's cross country, indoor and outdoor track. Distribution rates showed a higher rate in metatarsals (37.9%), followed by the tibia (21.9%). Restriction of participation rates showed 46.8% of SF caused athletes to miss 21 days or more of participation in their sport and 20.7% of SF were season ending. The high restriction of participation rates suggest negative consequences to the distance runner's training and competition schedule [86]. About two thirds of the athletes who sustained a stress fracture needed to miss 3 or more weeks of training [86]. Results from this study show a high risk of SF among cross country and track athletes compared with other athletes and a higher risk in females compared to males [86]. These results are consistent with previous studies and indicate a need to assess the risks that cause SF in collegiate distance runners. Rizzone et al. 2017 suggest that these high incidence, restriction, and distribution rates are due to the nature of training and the high loads of repetitive impact.

Matheson et al. 2006 analyzed 320 cases of positive bone scans for SF in athletes. Distribution rates showed the tibia as the most frequent site of SF (49.1%) and tarsals as the second most frequent site (25.3%), similar to results from Bennel et al. 1996 [10, 33]. Other sites of SF were the metatarsals (8.8%), femur (7.2%), fibula (6.6%), pelvis (1.6%), sesamoids (0.9%), and back (0.6%) [33]. Two hundred and twenty one athletes of the 320 cases of SF positive bone scans were runners [33]. Although studies may show different rates of distribution of SF, the tibia, tarsals, and metatarsals are the most common sites, indicating the importance of reviewing biomechanical factors associated with these sites of injury.

Role of Ground Reaction Forces

The body experiences external vertical ground forces 2.5 to 2.8 times the body weight during running with each foot strike and approximately 1000 foot strikes occur during 1 mile of running [24, 68]. Ground reaction forces are the external loads the runner experiences and the muscles, tendons, and ligaments responding to these external forces contribute to the internal forces that the bone experience [117]. As the speed of running increases, the external forces create greater internal forces on the bones that may increase a runners risk of injury [69, 117]. Davis et al. 2004 performed a study looking at the difference in loading rates between runners who developed a running-related injury and those who remained uninjured [24]. Loading rate is defined as the rate of rise of the vertical ground reaction force curve [24]. Loading rates are in magnitude of 65 to 120 body weights per second, depending on the speed of running [24]. Tibial stress fracture (TSF) was one of the running-related injuries that runners sustained during this study. Results demonstrated that the group of runners who sustained a running-related injury had increased loading rates compared to the runners who remained uninjured. Davis et al. 2004 concluded that runners displaying increased loading rates have an amplified risk of developing a running-related injury, which includes SF [24]. This is important to note for collegiate distance runners who may display higher loading rates and increase their risk of sustaining a SF.

In addition to examining the relationship between loading rates and injury risk researchers have shown that ground reaction forces increase as running speed increases. Based on Davis et al.'s 2004 results displaying that higher loading rates may place a runner at an increased risk of developing a SF, examining the relationship between speed and GRF is important for collegiate distance runners who perform training runs at high speeds [24]. Keller et al. performed a study investigating whether ground reaction forces (GRF) would increase linearly at running speeds greater than 5 m/s. Thirteen male and 10 female recreationally active subjects participated in this study.

Females			*Males*		
Speed ($\pm$ 0.2 m s^{-1})	*Thrust max. force (F_z, BW)*	*Loading rate (G_z, BW s^{-1})*	*Speed ($\pm$ 0.2 m s^{-1})*	*Thrust max. force (F_z, BW)*	*Loading rate (G_z, BW s^{-1})*
1.5 (*n* = 50)	1.15 (0.10)	7.77 (1.78)	1.5 (*n* = 65)	1.23* (0.10)	8.20 (1.84)
2.0 (*n* = 50)	1.36 (0.18)	11.5 (2.36)	2.0 (*n* = 64)	1.42* (0.14)	11.0 (2.29)
2.5 (*n* = 49)	1.73 (0.43)	14.6 (3.71)	2.5 (*n* = 65)	1.62 (0.24)	14.6 (2.46)
3.0 (*n* = 50)	2.11 (0.46)	16.9 (3.97)	3.0 (*n* = 61)	2.10 (0.50)	16.0 (3.30)
3.5 (*n* = 41)	2.36 (0.25)	19.1 (3.82)	3.5 (*n* = 37)	2.45 (0.28)	18.32 (3.36)
4.0 (*n* = 48)	2.33 (0.32)	19.6 (4.65)	4.0 (*n* = 58)	2.35 (0.48)	18.9 (4.85)
4.5 (*n* = 10)	2.54 (0.27)	23.7 (4.91)			
5.0 (*n* = 38)	2.28 (0.32)	22.3 (4.61)	5.0 (*n* = 60)	2.46* (0.33)	22.8 (4.51)
5.5 (*n* = 10)	2.13 (0.32)	22.5 (6.87)			
6.0 (*n* = 10)	2.45 (0.13)	30.0 (2.63)	6.0 (*n* = 67)	2.38 (0.28)	29.1 (15.2)
			6.5# (*n* = 26)	2.34 (0.23)	37.8 (29.3)
			7.0# (*n* = 17)	2.29 (0.19)	36.5 (22.5)
			8.0# (*n* = 3)	1.89 (0.49)	58.5 (37.6)

Table 1. Summary of vertical GRF variables (mean values) grouped by running speed and sex. Adapted from Relationship between vertical ground reaction force and speed during walking, slow jogging, and running. By Keller, Weisberger, Ray, Hasan, Shiavi, &Spengler, *1996, Clinical Biomechanics, 11(5), 253-295.* 1996 y Elsevier Science Limited.

Table 1 displays vertical thrust maximum force (F_z), vertical thrust maximum loading rate (G_z), and speed. For females, F_z increased linearly until a speed of 3.5 m/s was reached, after which it fluctuated between 2.13 and 2.54 with each increase in speed. G_z increased linearly until a speed of 4.5 m/s was reached in females. Male subjects demonstrated a similar trend in F_z as female subjects. F_z increased linearly until a speed of 3.5 m/s was reached, after which it showed values between 1.89 m/s and 2.46 m/s. Unlike female subjects, male subjects displayed a linear increase in G_z, where values increased linearly until a speed of 6.5 m/s was reached. Keller et al. further examined the relationship between GRF and running speeds, an important factor when assessing running injuries, and found that at running speeds above 3.5 m/s, vertical forces remained constant at approximately 2.5 times body weight. Due to the musculoskeletal system experiencing approximately 2.5 times the body weight during varying running speeds, there is speculation that collegiate distance runners with mechanical parameters that further increase GRF may increase these athletes' risk of sustaining a SF.

Varus Alignment May Increase Risk of Stress Fracture

In their study of incidence rates of SF, Matheson et al. 2006 also looked at potential biomechanical factors that may place collegiate distance running at an increased risk of SF [34]. Varus malalignment is a biomechanical factor that may influence the magnitude of forces imposed on the lower extremity [34]. It was found that varus malalignment was a frequent characteristic among athletes with SF for both males and females [34]. In an athlete with varus malalignment the tibia will experience greater bending forces during compressive loading [34]. This result indicates the importance of biomechanical alignment in the etiology of SF. Hughes et al. 2017 conducted a study on the biomechanical analysis of the foot and ankle and the influence on development of metatarsal SF in soldiers [46]. Results showed that soldiers displaying forefoot varus between 1 and 17 degrees had an 8.3:1 odds of developing a metatarsal SF [46]. This significant result demonstrates that soliders with a greater forefoot varus are more likely to develop metatarsal SF due to the alteration of the bone's ability to adapt to repetitive forces [46]. Runners are similar to soldiers in regards to the repetitive forces applied to the musculoskeletal system. Results from these studies provide important considerations for collegiate distance runners who may display varus malalignment and forefoot varus.

Retrospective studies have found that runners with a history of tibial stress fracture (TSF) have greater peak hip adduction (HADD) compared to runners without a history of TSF [75, 85]. Hip adduction occurs when the pelvis drops due to a large angle at the proximal joint created by the adduction, movement closer to the midline of the body, of the hip [36, 92]. Greater hip adduction has been suggested to place greater loading on the tibia during running [74]. Pohl et al. 2008 found that kinematic variables, such as HADD, were able to correctly predict a history of TSF is 83% of the cases looked at in this study [85]. Milner et al. 2008 also performed a retrospective study and found that runners with a previous TSF demonstrated greater HADD during the stance phase of running compared to runners without a previous TSF [75]. These results suggest that collegiate distance runners exhibiting greater HADD may be at an increased risk of sustaining a TSF. A prospective study should be performed to confirm these findings.

Biomechanical Characteristics Associated with Tibial Stress Fractures

Milner et al. 2006 retrospectively investigated biomechanical factors associated with tibial stress fractures (TSF) in female runners. Milner et al. 2006 suggest that bone structure and biomechanics contribute to an increased risk of SF [72]. Crossley et al. 2004 associated smaller tibial area moments of inertia with a higher incidence of SF in male runners, yet this biomechanical risk factor had not been determined in female distance runners [8]. Milner et al. 2006 conducted a cross-sectional study on subjects who participated in competitive running to determine whether differences in tibial bone structure and biomechanics existed between trained female distances runners with a history of TSF and those without a history of TSF [68]. The GRF variables measured are shown in Table 2 and include impact peak (IPEAK), vertical instantaneous and average loading rates (VILR, VALR), and anterior-posterior instantaneous and average loading rates during braking (BILR, BALR).

Ground Reaction Force	TSF	CTRL	Effect Size	*P* Value
IPEAK (BW)	1.84 (0.21)	1.70 (0.32)	0.51	0.057
VILR ($BW \cdot s^{-1}$)*	92.56 (24.74)	79.65 (18.81)	0.59	0.036
VALR ($BW \cdot s^{-1}$)*	78.97 (24.96)	66.31 (19.52)	0.56	0.041
BILR ($BW \cdot s^{-1}$)	20.35 (6.17)	19.29 (4.70)	0.19	0.272
BALR ($BW \cdot s^{-1}$)	8.54 (3.10)	8.37 (2.25)	0.07	0.420

Table 2. Mean ground reaction force variables for retrospective tibial stress fracture (TSF) group and control (CTRL) group. Adapted from Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners. By Milner, Ferber, Pollard, Hamill, & Davis, *2006, Medicine and Science in Sport and Exercise, 38(2), 323-328.* 2006 by American College of Sports Medicine.

The highlighted portions of Table 2 show the factors that were significantly higher in the group who had previous sustained TSF compared to the control group. These results indicate that distance runners who display higher loading rates may be at a higher risk for TSF than those who do not. There was also a trend toward significance for IPEAK, which indicates this may be important in determining an increased risk for SF due to the cumulative effect of slightly higher impacts over thousands of footstrikes. The highlighted portion of Table 3, peak positive acceleration (PPA), show a significant increase in the TSF group compared to the control group. Peak positive acceleration, also known as tibial shock, is a measure of load applied to the lower extremity [68]. Lieber et al. 1990 reported a strong correlation between vertical loading rates and tibial shock, suggesting it may be a variable associated with increased loading rates.

	TSF	CTRL	Effect Size	*P* Value
KEXC	33.1 (5.0)	34.8 (5.2)	0.34	0.147
ASTIF ($\times 10^{-2}$)*	4.31 (0.59)	4.59 (0.61)	−0.46	†
KSTIF ($\times 10^{-2}$)	4.88 (0.88)	4.46 (0.68)	0.54	0.054
PPA*	7.70 (3.21)	5.81 (1.66)	0.74	0.014
TIBAMI	11312 (2883)	12224 (2387)	−0.34	0.174
TIBVAR	6 (2)	6 (2)	−0.36	0.128

Table 3. Mean joint excursion, stiffness, and structural variables for retrospective tibial stress fracture (TSF) group and control (CTRL) group. Adapted from Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners. By Milner, Ferber, Pollard, Hamill, & Davis, *2006, Medicine and Science in Sport and Exercise, 38(2), 323-328.* 2006 by American College of Sports Medicine.

An increased PPA is suggested to be related to an increased likelihood of having a history of TSF. Milner et al. 2006 discuss tibial shock as providing a direct estimate of load acting on the tibia and may be a more sensitive discriminator of runners at higher risk of TSF, although, this speculation needs to be confirmed with a prospective study [68]. The conclusions drawn from this study are that TSF appear to be most related to loading rates and tibial shock, with respect to biomechanical factors [68]. Since TSF are fatigue fractures and loading rate is a factor associated with the fatigue of bone [68], this is an important consideration for collegiate distance runners who may display higher loading rates and increased tibial shock in response to the applied load and the magnitude of the load. Due to loading rates and tibial shock being associated with fatigue, the effect that fatigue has on biomechanical parameters and GRF is important to illuminate among collegiate distance runners.

The Effect of Fatigue on Biomechanical Properties and Ground Reaction Forces

An important aspect of collegiate distance training is performing runs at lactate threshold (LT)[16]. These training runs have been used as exercise protocols in studies examining the effects of fatigue on ground reaction forces and biomechanical parameters that may increase a runner's risk of sustaining a stress fracture. Clansey et al. 2012 aimed to investigate the acute effects of progressive fatigue on biomechanical parameters previously associated with tibial stress fracture (TSF) risk [19]. Twenty one highly trained male distance runners served as the subjects for this study. Subjects performed three gait analyses, before and after two 20 minute lactate threshold runs. Gait analyses were performed along a 15 meter runway at 4.5 m/s and LT runs were performed on a treadmill at their previously determined LT speed for 20 minutes.

Variable	Pre	Mid	Post	*P*	Effect Size
VALR ($BW \cdot s^{-1}$)	107.90 (25.29)	113.87 (31.56)	130.53 (39.60)^{a,b}	0.001	0.70
VILR ($BW \cdot s^{-1}$)	148.75 (39.13)	162.56 (44.88)	181.73 (54.73)^{a,b}	0.004	0.71
IP (BW)	2.21 (0.28)	2.32 (0.22)	2.41 (0.13)	0.096	0.98
Step length (m)	1.70 (0.05)	1.68 (0.09)	1.69 (0.06)	0.698	0.18
PHA (*g*)	1.04 (0.31)	1.17 (0.35)	1.30 (0.34)^{a,b}	0.001	0.80
PTA (*g*)	11.30 (2.15)	11.13 (2.13)	11.79 (1.77)	0.226	0.25
KEXC (°)	10.13 (2.64)	9.33 (2.06)	8.52 (1.91)	0.098	0.71
KSTIF ($N \cdot m \cdot kg^{-1}$)	0.12 (0.02)	0.13 (0.02)^{c}	0.13 (0.02)	0.174	0.50
FM	12.05 (2.39)	13.09 (2.40)^{c}	13.88 (2.60)^{b}	0.004	0.73
HADD (°)	12.72 (1.40)	12.94 (1.09)	13.24 (1.19)	0.702	0.40
RFEV (°)	16.78 (1.34)	19.11 (2.28)	20.68 (1.95)^{b}	0.036	2.37

Table 4. Stance phase variables during pre, mid, and post test conditions. Adapted from Effects of Fatigue on Running Mechanics Associated with Tibial Stress Fracture. By Clansey, Hanlon, Wallace, & Lake, *2012, Medicine and Science in Sports and Exercise, 44(10), 917-1923.* 2012 by American College of Sports Medicine.

The highlighted portions of Table 4 depict the variables demonstrating a significant difference. Vertical instantaneous and average loading rates (VILR, VALR) significantly increased from pre to mid and mid to post LT run. These higher loading rates have been associated with a history of TSF found in retrospective studies examining biomechanics and GRF's between runners with a history of TSF and those without a history[60]. Peak head acceleration (PHA), free moment (FM), and rearfoot eversion (RFEV) significantly increased from mid to post LT run, whereas PHA significantly increased from pre to mid and mid to post LT run. Clansey et al. speculates the increases in FM may be linked to the increases in RFEV due to the peripheral and central fatigue that changes the body's ability to maintain proper mechanical patterns. The significant increases in PHA with increasing fatigue indicates that there is less dampening of impact forces on the distal joints [19]. Clansey et al. 2012 report that the altered joint mechanics due to muscular fatigue may be the primary causes of increases in loading rates and PHA [19]. Clansey et al. 2012 conclude that previously identified biomechanical parameters associated with TSF are evident as levels of fatigue increase during a LT run [19]. This is an important consideration for collegiate distance runners who may display increases in these biomechanical parameters and perform training runs at their LT.

Influence of Bone Geometry on Bone Strength and Ground Reaction Forces

Researchers have identified two categories of factors that affect bone strength and factors that affect the external mechanical load on bone, that may place a collegiate distance runner at greater susceptibility to SF [81]. In a retrospective study, Popp et al. 2016 aimed to examine these two categories and find the differences in bone mineral density (BMD) and bone geometry between competitive female distance runners with and without SF [81]. These two parameters of bone strength, BMD and bone geometry, were then assessed relative to external mechanical loading between the SF group (SFX) and no SF group (NSFX). Subjects performed an exhaustive run on a high-speed, force-sensing motorized treadmill that collected GRF at each individual's predicted 5 kilometer pace. Total bone cross-sectional area and BMD were assessed to estimate bone strength. Muscle cross sectional area (MCSA) was assessed at the 66% site of the tibia since the calf muscle is the largest in this area.

Group	Parameter	Delta[a]	p-Value[a]	SFX n = 15 mean* (CI)		NSFX n = 15 mean* (CI)		p-Value	
				Left	Right	Left	Right	Left	Right
4%	Total area (mm^2)	52.0	0.18	931.2 (870.0, 992.4)	926.7 (868.0, 985.5)	988.9 (927.7, 1050)	969 (910.8, 1028.3)	0.19	0.31
	BMD (mg/mm^3)	4.7	0.70	321.2 (303.9, 338.5)	325.9 (306.4, 345.5)	319.8 (302.5, 337.1)	322.1 (302.5, 341.6)	0.91	0.78
	BSI ((mg/mm^4)/1,000,000)	2.5	0.72	96.2 (86.2, 106.1)	98.7 (87.9, 109.0)	101.3 (91.4, 111.2)	101.1 (89.8, 111.1)	0.47	0.80
15%	Total area (mm^2)	15.9	0.41	391.8 (362.9, 420.7)	393.3 (363.4, 423.3)	405.9 (377.0, 434.8)	409.9 (379.5, 439.4)	0.48	0.45
	Cortical area (mm^2)	14.04	0.01*	173.9 (165.1, 182.8)	174.5 (165.8, 183.3)	187.8 (179.0, 196.7)	188.6 (179.9, 197.3)	0.03*	0.03*
	Cortical density (mg/mm^3)	8.1	0.13	1162 (1153, 1171)	1159 (1151, 1167)	1169 (1161, 1178)	1168.2 (1160, 1177)	0.26	0.12
	SSIp (mm^3)	119.6	0.13	1369 (1249, 1489)	13,589 (1239, 1478)	1485 (1365, 1604)	1476 (1357, 1596)	0.17	0.17
	Section modulus (mm^3)	117.3	0.13	1320 (1203, 1437)	1317 (1198, 1437)	1439 (1322, 1556)	1431 (1312, 1551)	0.16	0.18
25%	Total area (mm^2)	12.1	0.34	335.8 (316.6, 355.1)	337.5 (316.8, 358.1)	345.1 (325.9, 364.3)	352.8 (332.2, 373.4)	0.50	0.30
	Cortical area (mm^2)	13.2	0.09	229.1 (217.9, 240.3)	230.7 (218.2, 243.1)	240.0 (228.8, 251.2)	245.8 (233.3, 258.2)	0.17	0.09
	Cortical density (mg/mm^3)	1.0	0.91	1202 (1192, 1211)	1199 (1189, 1211)	1203 (1194, 1213)	1200 (1189, 1211)	0.80	1.00
	SSIp (mm^3)	76.1	0.29	1380 (1273, 1488)	1408 (1293, 1522)	1440 (1333, 1547)	1500 (1385, 1614)	0.43	0.26
	Section modulus (mm^3)	89.0	0.22	1325 (1221, 1430)	1357 (1241, 1473)	1392 (1288, 1496)	1469 (1353, 1585)	0.37	0.18
33%	Total area (mm^2)	13.9	0.24	348.4 (331.4, 365.3)	355.4 (336.1, 374.8)	363.3 (346.3, 380.3)	369.2 (349.9, 388.6)	0.22	0.31
	Cortical area (mm^2)	13.0	0.14	268.8 (256.1, 281.6)	273.7 (259.0, 288.5)	282.0 (269.2, 294.7)	286.9 (272.1, 301.7)	0.15	0.21
	Cortical density (mg/mm^3)	0.8	0.91	1203 (1194, 1212)	1198 (1186.6, 1210.3)	1203 (1194, 1212)	1196.9 (1185, 1209)	1.00	0.85
	SSIp (mm^3)	84.6	0.20	1493 (1399, 1588)	1519 (1408, 1629)	1583 (1488, 1678)	1602 (1492, 1713)	0.19	0.29
	Section modulus (mm^3)	99.5	0.16	1452 (1353, 1552)	1495 (1378, 1612)	1560 (1460, 1660)	1590 (1473, 1708)	0.13	0.26
45%	Total area (mm^2)	24.0	0.07	395.4 (376.3, 414.6)	398.0 (367.6, 419.4)	417.5 (398.4, 436.7)	423.2 (401.7, 444.6)	0.11	0.10
	Cortical area (mm^2)	22.8	0.05*	302.1 (285.1, 319.2)	304.1 (285.2, 322.9)	322.6 (305.6, 339.7)	328.9 (310.0, 247.7)	0.01*	0.06
	Cortical density (mg/mm^3)	0.7	0.93	1189 (1178, 1200)	1189 (1176, 1201)	1190 (1179, 1202)	1186 (1173, 1199)	0.86	0.71
	SSIp (mm^3)	163.8	0.06	1714 (1592, 1836)	1722 (1580, 1864)	1868 (1746, 1990)	1886 (1744, 2028)	0.08	0.12
	Section modulus (mm^3)	191.0	0.03*	1692 (1571, 1811)	1681 (1534, 1829)	1860 (1740, 1980)	1891 (1743, 2038)	0.05*	0.05*
50%	Total area (mm^2)	22.6	0.13	412.7 (390.2, 435.1)	420.8 (397.4, 444.2)	438.1 (415.7, 460.5)	441.1 (417.7, 464.5)	0.12	0.22
	Cortical area (mm^2)	22.8	0.07	306.8 (288.1, 325.5)	312.5 (292.5, 332.5)	329.9 (311.2, 348.6)	334.2 (314.2, 354.1)	0.09	0.13
	Cortical density (mg/mm^3)	2.0	0.78	1183 (1172, 1194)	1176 (1163, 1188)	1186 (1175, 1196)	1177 (1164, 1190)	0.75	0.90
	SSIp (mm^3)	240.7	0.03*	1753 (1571, 1935)	1810 (1645, 1976)	2038 (1856, 2220)	2023 (1837, 2169)	0.03*	0.04*
	Section modulus (mm^3)	203.3	0.04*	1790 (1645, 1934)	1820 (1666, 1975)	2011 (1866, 2156)	2006 (1852, 2161)	0.04*	0.05*
66%	Total area (mm^2)	23.4	0.25	518.0 (486.9, 549.0)	519.9 (488.1, 551.8)	545.4 (514.4, 576.4)	537.0 (505.2, 568.8)	0.22	0.45
	Cortical area (mm^2)	18.1	0.12	302.7 (284.6, 320.8)	307.2 (289.2, 325.1)	319.3 (301.3, 337.4)	325.8 (307.9, 343.7)	0.20	0.15
	Cortical density (mg/mm^3)	8.3	0.22	1158 (1147, 1169)	1154 (1143, 1164)	1163 (1152, 1174)	1165 (1154, 1175)	0.48	0.14
	SSIp (mm^3)	231.3	0.07	2257 (2069, 2446)	2254 (2054, 2454)	2493 (2304, 2681)	2445 (2245, 2645)	0.08	0.18
	Section modulus (mm^3)	197.4	0.16	2302 (2091, 2512)	2320 (2104, 2536)	2511 (2300, 2722)	2476 (2260, 2692)	0.17	0.31
	Muscle CSA (mm^2)	396.4	0.03*	4852 (4582, 5121)	4884 (4608, 5160)	5215 (4945, 5484)	5327 (5051, 5603)	0.06	0.03*

Table 5. Tibial bone volumetric density, geometry, and estimated strength at seven measurement sites in female runners with (SFX) and without (NFSX) history of stress fracture. Adapted from

Bone strength estimates relative to vertical ground reaction force discriminates women runners with stress fracture history. By Popp, McDermott, Hughes, Baxter, Stovitz, & Petit, *2016, Bone, 94, 22-28.* 2016 by Elsevier Inc.

As seen in the highlighted portions of Table 5**,** The SFX group showed significantly lower cortical area at 15% and 45% sites in the tibia compared to the NSFX, suggesting that bone geometry plays a role in the development of stress fracture [81]. Section modulus (Zp) and polar strength strain index (SSIp) were indices of bone strength assessed in this study. Results also demonstrated that ZP and SSIp were significantly lower in the SFX group compared to the NSFX group at one or more mid-shaft tibia sites, suggesting that SF development could be higher in collegiate distance runners who have lower bone strength [81].

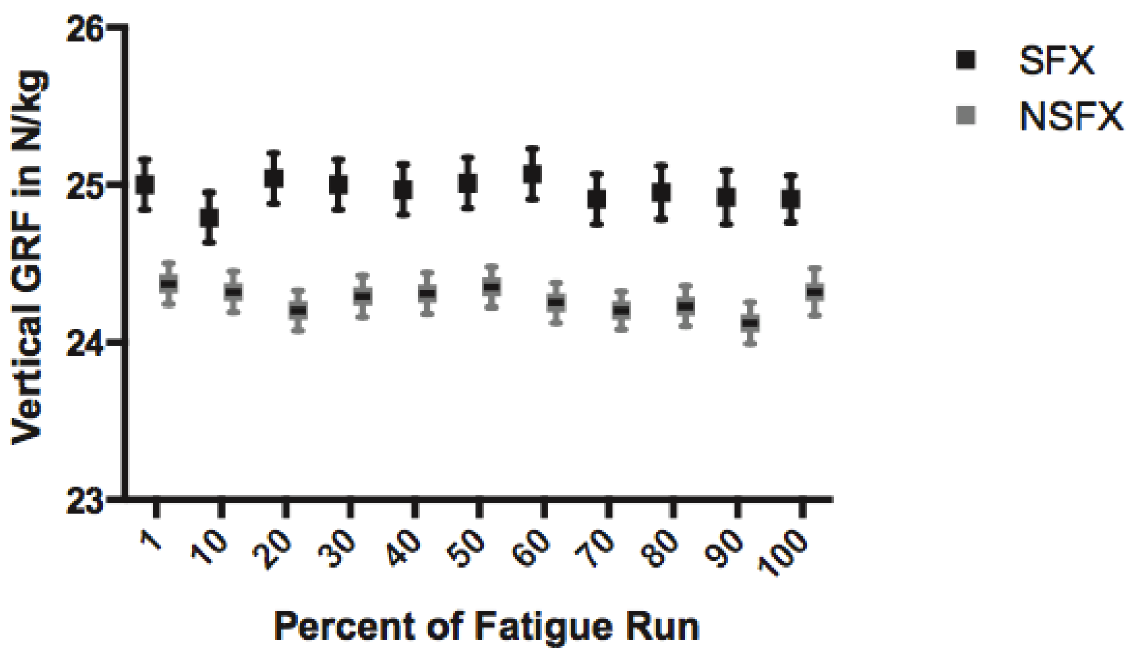

Figure 2. Mean active peaks vertical (pkZ) ground reaction forces (GRFs) between groups. Adapted from Bone strength estimates relative to vertical ground reaction force discriminates women runners with stress fracture history. By Popp, McDermott, Hughes, Baxter, Stovitz, & Petit, *2016, Bone, 94, 22-28.* 2016 by Elsevier Inc.

Throughout the entire run, the SFX group displayed higher pkz values compared to the NSFX group. Popp et al. 2012 chose to measure pkz GRF based on other research showing that pkz GRF provides an approximation of the load acting on the tibia during running [8]. Figure 2 shows that pkz GRFs were significantly higher in the SFX group compared to the NSFX group, indicating that runners with a history of SF display higher loading rates [81]. Table 6 shows that at the 45%, 50%, and 66% sites of the tibia the SFX group had significantly lower bone strength relative to mean pkz GRFs.

Group						
Site	SFX n = 15 mean* (CI)		NSFX N = 15 mean* (CI)		p-Value	
	Left	Right	Left	Right	Left	Right
15%	0.99 (0.89–1.09)	0.98 (0.88–1.07)	1.08 (1.00–1.16)	1.03 (0.98–1.17)	0.16	0.12
25%	0.60 (0.54–0.65)	0.60 (0.56–0.65)	0.63 (0.59–0.67)	0.66 (0.60–0.71)	0.37	0.11
33%	0.49 (0.45–0.52)	0.49 (0.46–0.52)	0.53 (0.50–0.55)	0.53 (0.50–0.57)	0.06	0.07
45%	0.41 (0.38–0.43)	0.40 (0.38–0.43)	0.46 (0.43–0.48)	0.46 (0.42–0.50)	0.006*	0.007*
50%	0.38 (0.34–0.41)	0.38 (0.36–0.41)	0.45 (0.41–0.49)	0.44 (0.40–0.48)	0.007*	0.02*
66%	0.37 (0.34–0.04)	0.37 (0.34–0.40)	0.41 (0.39–0.44)	0.42 (0.39–0.44)	0.03*	0.02*

Table 6. Relative bone strength in female runners with (SFX) and without (NSFX) a history of stress fracture, at six measurement sites. Adapted from Bone strength estimates relative to vertical ground reaction force discriminates women runners with stress fracture history. By Popp, McDermott, Hughes, Baxter, Stovitz, & Petit, *2016, Bone, 94, 22-28.* 2016 by Elsevier Inc.

These novel results suggest that runners with a history of SF experience greater loads in the tibia during running. Based on other research, such as Milner et al.'s 2006 findings, Popp et al. 2012 suggest that other mechanical characteristics associated with an increased SF risk, peak rearfoot eversion, peak hip adduction, and greater free moments, may increase the load experienced by the tibia during running [34, 81]. Popp et al. 2012 conclude that the strength deficits found in the SFX group at the mid-shaft of the tibia, 45%, 50%, 66%, is an important region of the tibia to identify individuals at high risk for TSF [81]. This study also illuminates the importance of assessing bone structure and strength relative to the external loads being placed on the tibia during running.

Relationship Between Training Volume and Risk of Stress Fracture

The pathology of a bone stress injury indicates that it occurs from overuse and the bone is unable to withstand the amount of load without adverse consequences [94]. The International Olympic Committee (IOC) recruited a group of researchers to review scientific evidence regarding the relationship between load and health in sport. Load was defined broadly as rapid changes in training and competition, heavy competition calendar, and psychological load. Load encompasses external and internal loads. External load refers to an external stimulus applied to the musculoskeletal system and results in physiological and psychological responses in the collegiate distance runner [94]. Internal load refers to the individual, internal physiological response to the external load [94]. This review of training load in sport illuminates the issue of needing to assess individual athletes' risk of injury along a continuum of adverse health outcomes [94]. SF is an adverse health outcome that occurs when training loads are poorly managed. If the external load is poorly managed, then the collegiate distance runner may experience increased internal loads that may cause adverse health outcomes, such as a SF [94].

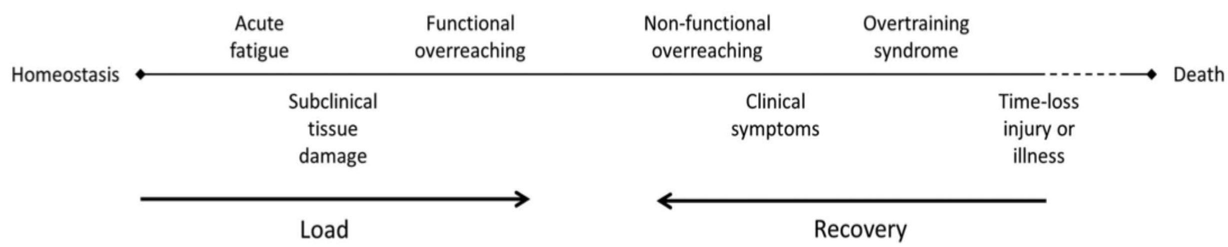

Figure 3. Well-being continuum. Adapted from How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. By Soligard, Schwellnus, Alonso, Bahr, Clarsen, Dijkstra, Gabbett, Gleeson, Hagglund, Hutchinson, Jans van Rensburg, Raftery, Budgett, Engebretsen, *2016, British Journal of Sports Medicine, 50(17), 1030-1041.* 2016 by British Journal of Sports Medicine.

Similar to Soligard et al.'s 2017 well being continuum shown in Figure 3, Lack et al. 2018 recreated a figure from a clinical perspective by Dye et al. 1999 regarding the envelope of function for tissue homeostasis and how it is affected by load and frequency of load [55, 94].

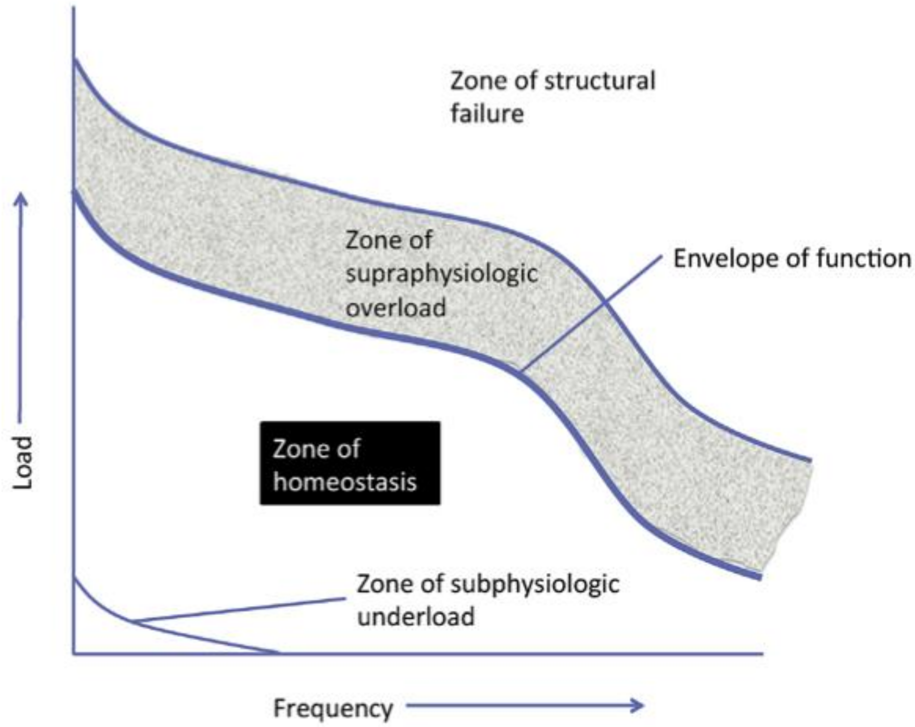

Figure 4. Representation of the zone of tissue homeostasis. Adapted from How to manage patellofemoral pain – Understanding the multifactorial nature and treatment options. By Lack, Neal, De Oliveira Silva, Barton, *2018, Physical Therapy in Sport, 32, 155-166.* 2018 by Elsevier Ltd.

Figure 4 demonstrates the relationship between an increasing load and increasing frequency that can cause a loss of tissue homeostasis and push the collegiate distance runner into a zone of structural failure, or overuse injury [94]. The risk of SF occurs when poorly managed training and/or competition loads lead to excessive microdamage due to the magnitude of training being beyond the tissue's load bearing capacity, forcing the runner to take time off [94]. Another mechanism that may increase the risk of SF in collegiate distance runners occurs when the recovery between loading cycles is insufficient [94], shown in Figure 5.

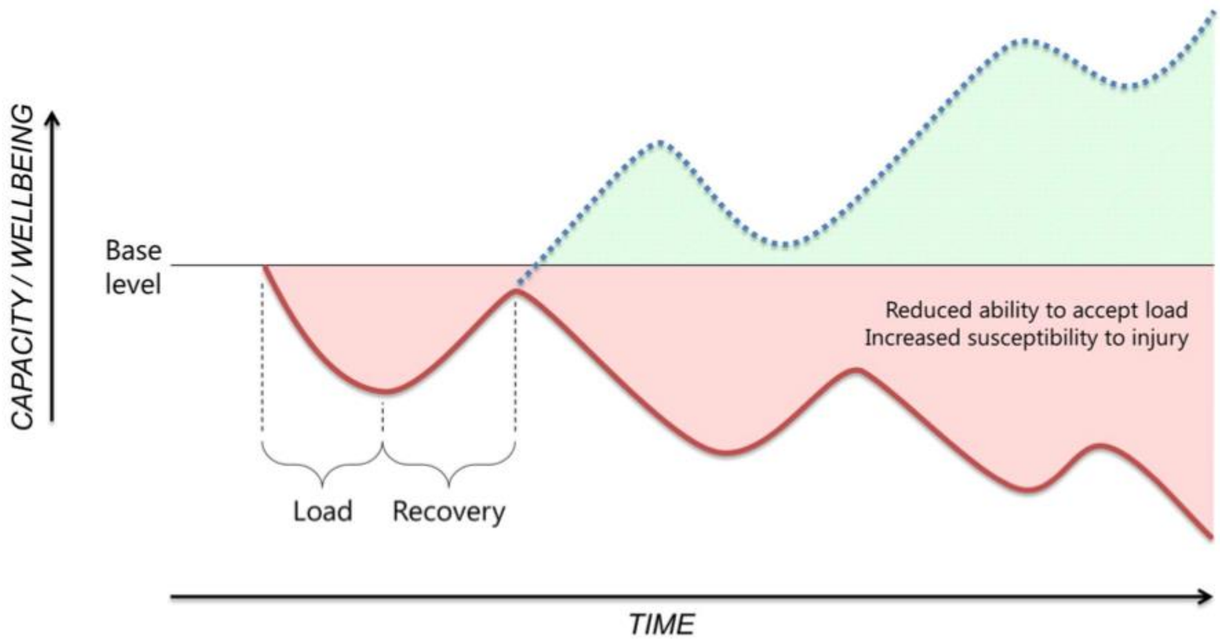

Figure 5. Biological maladaptation through cycles of excessive loading and/or inadequate recovery. Adapted from How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. By Soligard, Schwellnus, Alonso, Bahr, Clarsen, Dijkstra, Gabbett, Gleeson, Hagglund, Hutchinson, Jans van Rensburg, Raftery, Budgett, Engebretsen, *2016, British Journal of Sports Medicine, 50(17), 1030-1041.* 2016 by British Journal of Sports Medicine.

When the recovery between training loads are insufficient, there is a decreased capacity for the musculoskeletal system to bear the load and increases the risk of overuse injury, in this case a SF in collegiate distance runners can occur [94]. Soligard et al. 2017 suggest that the monitoring of athlete's external and internal loads can help explain changes in performance, increase the understanding of training responses, reveal fatigue, and ensure the proper level of load to minimize the risk of injury and illness from non-functional over-reaching and overtraining, as depicted in Figures 3-5.

An aspect of training that may have an influence on injury is acute to chronic workload ratio. Hulin et al. 2016 investigated this relationship between acute:chronic workload ratio and risk of injury in rugby players [47, 48]. This relationship remains to be examined in collegiate distance runners. Gabbett et al. 2016 explains this ratio as the most recent week's training (acute workload) to the 4 week rolling average of acute workloads (chronic workload) [36]. Chronic workload is associated with the development of fitness in the athlete, whereas acute workload is associated with the level of fatigue experienced in the athlete [36, 37]. An athlete is considered well prepared for training and has a decreased risk of injury if the ratio is between 0.8 and 1.3 [36]. Hulin et al. 2016 demonstrate in their study of rugby players that a very high ratio, greater than 2.11, was associated with an injury risk 2.3 times higher than a moderate ratio, 1.03 – 1.38 [48]. The novel finding that a high chronic workload combined with a moderate acute:chronic workload had a smaller risk of injury than a combination of a low chronic workload and moderate acute:chronic workload suggests a way to manage collegiate distance runners training programs to minimize risk of injury [47, 48]. The concept of tracking acute:chronic workloads in athletes, as described by Hulin et al. 2016, suggests that this may be a viable means to track workloads in an effort to decrease the risk of overuse injury, such as SF, in collegiate distance runners.

While Hulin et al. 2016 and Gabbett et al. 2016 provide a method for managing training loads, it is important to uncover the relationship between training volume and intensity and the risk of injury in collegiate distance runners [36, 37, 48]. Hrejlac et al. 2004 explain that overuse injuries can be linked to errors in training such as sudden increases in mileage and rapid change in training intensity [45]. Neilsen et al. 2014 conducted a 1 year prospective, cohort study on 874 healthy, novice runners to examine the relationship between injury and progression in weekly running distance [81]. Results demonstrated that runners increasing mileage by greater than 30% per week were at a greater risk of sustaining an overuse injury compared to the runners who increased mileage by 10% or less [81]. This study suggests a correlation between increases in running mileage and risk of injury.

Edwards et al. 2009 and Edwards et al. 2010 conducted studies examining the effects of stride length and running mileage on the probability of SF the effects of running speed, or intensity, on the probability of SF [28, 29]. Three daily running mileages of 3, 5, and 7 miles per day were investigated using a probabilistic model to determine the probability of failure in bone [29]. In addition to these three mileages, subjects were asked to perform running trials using their preferred stride length (PSL) and a stride length that was 10% less than PSL (-10%PSL). Edwards et al. 2010 found that a 10% reduction in stride length decreased the likelihood of tibial stress fracture (TSF), however, the probability of TSF increased as running mileage increased regardless of the stride length, seen in Figure 6.

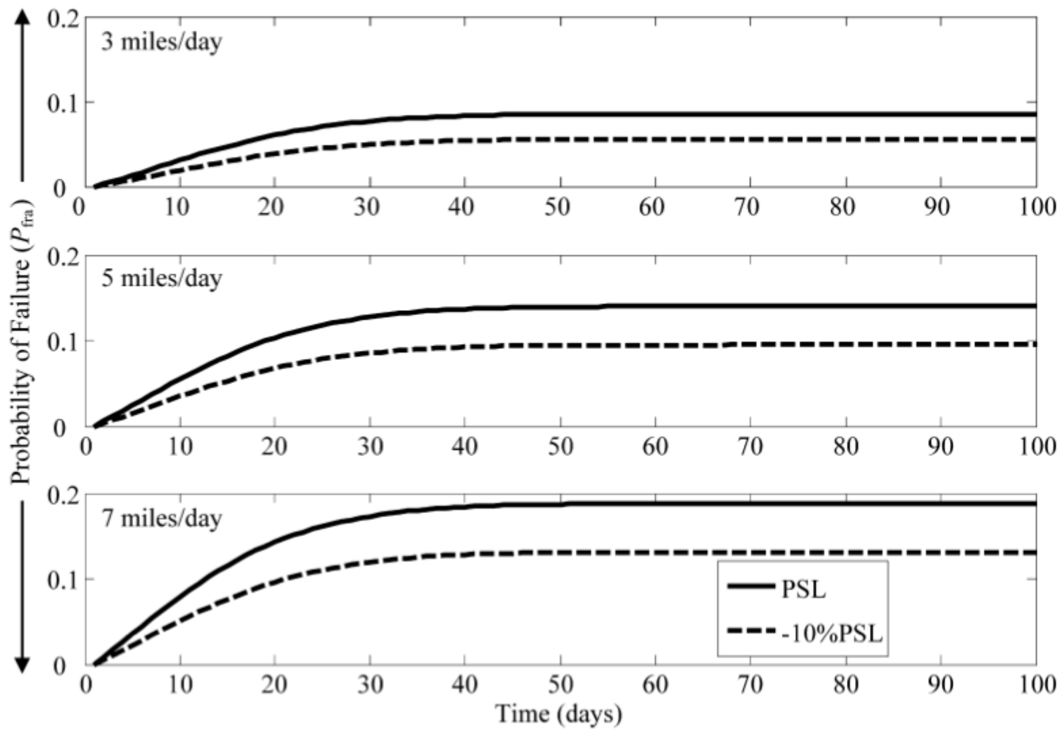

Figure 6. Average probabilities of failure for three different daily mileages across 100 days of training. Adapted from Effects of Stride Length and Running Mileage on a Probabilistic Stress Fracture Model. By Edwards, Taylow, Rudolph, Gillette, & Derrick, *2009, Medicine and Science in Sports and Exercise, 41(12), 2177-2184.* 2009 by American College of Sports Medicine.

Figure 6 demonstrates that the first 30 days is the most critical time point to address the risk of injury [29]. Edwards et al. 2009 investigated the effect of running speed on the probability of SF [28]. It was hypothesized that as running speed increases, the probability of SF would increase [28]. Figure 7 demonstrates that as running speed increased, the probability of failure increased significantly. Edwards et al. 2009 suggest that runner's risk of SF increase as weekly running mileage and running speed increase [28, 29]. The results from Edwards et al.'s 2009 and 2010 studies should be taken into consideration along with the concept of actue:chronic workload ratio to ensure the athlete's running mileage and running speed is systematically increased and does not exceed a ratio that may increase their risk of SF [28, 29, 36, 37] .

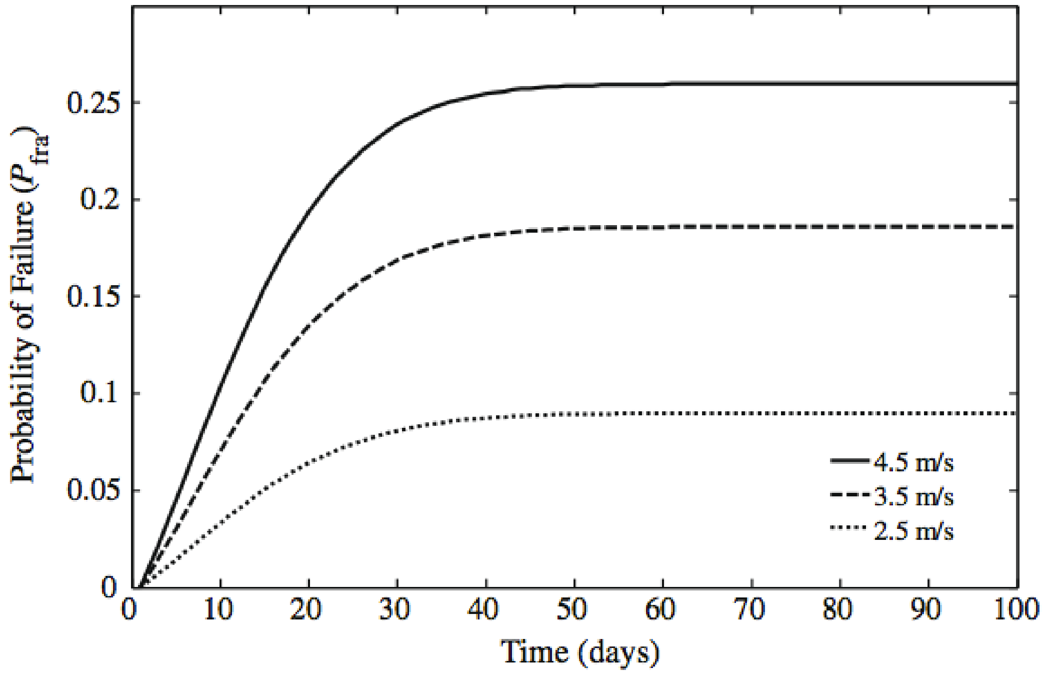

Figure 7. Average probabilities of failure for three different speeds across 100 days of training. Effects of running speed on probabilistic stress fracture model. By Edwards, Taylor, Rudolphi, Gillette, & Derrick, *2010, Clinical Biomechanics, 25(4), 372-377.* 2010 by Elsevier Ltd.

Interventions May Reduce Biomechanical Properties Associated with Stress Fracture

Milner et al. 2006 demonstrated that stress fractures in collegiate distance runners have been associated with high loading rates [71]. It is important to reduce these high loading rates in order to mitigate the risk of SF and loss of training time [71]. Gait retraining using real-time feedback offers a potential method to reduce high loading rates in collegiate distance runners that may decrease the risk of SF. Researchers have examined the effects of altering loading mechanics using a variety of methods that monitor loads and allows the subject to receive feedback regarding the load.

Crowell and Davis 2010 performed a study examining the efficacy of a gait retraining program on the reduction of tibial acceleration and lower extremity loading on athletes and recreational runners who displayed tibial accelerations above normal during running [23]. The gait retraining program consisted of 8 sessions in which an accelerometer was taped to the subject's distal tibia and displayed visual feedback to the subject on a monitor positioned in front of the treadmill. The signal displayed on the monitor from the accelerometer showed a line at approximately 50% of the tibial shock (PPA) which would reduce the PPA for the subjects and bring them within one standard deviation of the uninjured runners' PPA. These 8 sessions took place over a 2-week period and during each one, the subject was advised to keep their acceleration peaks below the line displayed from the accelerometer signal on the monitor. The variables measured include tibial shock (PPA), vertical instantaneous loading rate (VILR), vertical average loading rate (VALR), and vertical impact peak (VIP).

	PPA	VILR	VALR	VIP
Pre-training to post-training				
Percent difference	−48*	−34*	−32*	−19
Effect size	1.5	1.7	1.5	1.2
Pre-training to 1-month				
Percent difference	−44*	−30*	−27*	−20*
Effect size	1.4	1.7	1.3	1.3
Post-training to 1-month				
Percent difference	6.2	6.4	7.6	−1.3
Effect size	0.1	0.2	0.02	0.1

Table 7. Changes in GRF variables as a result of gait retraining. Adapted from Gait retraining to reduce lower extremity loading in runners. By Crowell & Davis, *2010, Clinical Biomechanics, 26(1), 78-83.* 2010 by Elsevier Ltd.

Table 7 shows significant decreases in PPA, VILR, and VALR from pre-training to post-training, as well as significant decreases in PPA, VILR, VALR, and VIP, from pre-training to the on- month follow-up data collected [23]. Crowell and Davis 2010 demonstrated that loading rates and tibial shock, two variables that have been previously associated with SF in runners, can be decreased using a gait retraining method [23]. This has practical implications for collegiate distance runners who may display higher loading rates and tibial shock and who could benefit from a gait retraining intervention to decrease their risk of SF associated with these high loading rates and tibial shock.

Similar to Crowell and Davis 2010, Willy et al. 2016 examined the efficacy of an in-field gait retraining program on reducing excessive impact forces and peak hip adduction among 30 runners who demonstrated a risk for tibial stress fracture [112]. Based on previous studies showing a relationship between high loading rates and history of tibial stress fracture [71], this study hypothesized that a reduction in step rate would decrease instantaneous and vertical loading rates

[112]. Runners who exhibited high impact forces were recruited as subjects and randomized into either a retraining group or control group. The retraining group increased step rate by 7.5%, cued by a wireless accelerometer, during 8 running trials.

Variable	Group	Baseline	Post	1MO	P value
Steps per minute (SPM)	RT	166.5 (160.1–172.9)	180.8*† (174.9–186.6)	180.6*† (174.1–187.1)	Group × time
	CON	166.7 (160.7–172.7)	169.7 (163.4–176.0)	168.6 (162.7–174.5)	< 0.0001
Instantaneous vertical load rate (bw/s)	RT	101.3 (96.0–106.5)	83.2*† (72.0–94.3)	83.5*† (73.1–93.9)	Group × time
	CON	108.0 (99.6–116.3)	104.5 (94.8–114.2)	102.6 (91.5–113.7)	0.034
Average vertical load rate (bw/s)	RT	75.6 (71.4–79.7)	61.3*† (53.9–68.6)	60.4* (53.4–67.5)	Group × time
	CON	77.2 (68.0–86.3)	79.2 (69.9–88.4)	74.8 (63.3–86.3)	0.007
Peak hip adduction (degrees)	RT	14.7 (12.6–16.8)	11.8* (9.7–13.9)	12.2* (9.9–14.5)	Group × time
	CON	11.8 (8.6–15.0)	13.0 (10.1–15.8)	12.7 (10.7–14.7)	0.005
Eccentric knee work per stance (J/kg*m)	RT	–0.33 (–0.39––0.28)	–0.24* (–0.28––0.2)	–0.26* (–0.3––0.22)	Group × time
	CON	–0.30 (–0.35––0.24)	–0.29 (–0.34––0.25)	–0.31 (–0.38––0.26)	< 0.0001
Eccentric knee work per km (J/kg*m)	RT	–144.8 (–166.7––123.0)	114.2* (–128.7––99.7)	–123.3* (–140.3––106.4)	Group × time
	CON	–129.8 (–149.2––110.3)	–130.9 (–149.6––112.3)	–140.9 (–161.8–120.0)	0.002

Table 8. Changes observed in variables from baseline, post intervention, and 1 month post intervention. Adapted from In-field gait retraining and mobile monitoring to address running biomechanics associated with tibial stress fracture. By Willy, Buchenic, Rogack, Ackerman, Schmidt, & Wilson, *2016, Scandanavian Journal of Medicine and Science in Sport, 26(2), 197-205.* 2015 by John Wiley & sons Ltd.

The retraining group (RT) demonstrated significant increases in step rate (SR) from baseline to post intervention and at 1-month post intervention, as well as a significant increase compared to the control group (CON), as shown in Table 8 [112]. With this increase in SR, RT demonstrated significant decreases in instantaneous and average vertical loading rates from baseline to post intervention and post intervention to 1-month post intervention, as well as a significant decrease compared to the CON group [112]. Peak hip adduction and eccentric knee work per stance and per km were significantly decreased in the RT group from baseline to post intervention and post intervention to 1-month post intervention. These results demonstrate the ability of a modest increase in SR of 7.5% to decrease biomechanical parameters that have been previously associated with SF [71,112]. These results also have implications for collegiate distance runners who may display high loading rates and hip adduction that suggest they are at an increased risk of SF [71, 83, 112]. By implementing this gait retraining intervention, it may decrease a collegiate distance runner's risk of SF by reducing variables associated with SF.

Crowell and Davis 2010 and Willy et al. 2016 suggest that gait retraining interventions using real-time feedback decrease loading rates and impact peaks, which have previously been associated with an increased risk of SF [24, 112]. The sound intensity of a runner's initial ground contact is another form of real time feedback that may reduce loading rates and impact peaks. Tate and Milner 2017, in a controlled, within session study design, examined the usefulness of sound intensity as real-time feedback for runners to decrease their loading rates and impact peaks [102]. Subjects performed running trials on the treadmill for 15 minutes while continuously receiving real-time visual feedback of sound intensity on an iPad. Subjects were then instructed to decrease the decibel level shown on the iPad as much as possible. After the gait retraining intervention, subjects performed 5 additional treadmill trials where they used the new running strategy they developed previously.

Variable	Baseline	After Gait Retraining	*P* Value	Change, %	Effect Size
VIP, BW	1.56 ± 0.31	1.13 ± 0.34	<.001†	−28	1.33
VILR, BW/s	95.48 ± 27.41	62.79 ± 22.35	.001†	−34	1.31
VALR, BW/s	69.09 ± 20.15	43.91 ± 16.14	<.001†	−36	1.39

Table 9. Changes observed in loading variables at baseline and after gait retraining. Adapted from Sound-Intensity Feedback During Running Reduces Loading Rates and Impact Peaks. By Tate & Milner, *2017, The Journal of Orthopaedic and Sports Physical Therapy, 47(8), 565-569.* 2017 by Journal of Orthopaedic & Sports Physical Therapy.

Table 9 displays a significant decrease in vertical impact peak, vertical average loading rate, and vertical instantaneous loading rate from baseline to post gait retraining [102]. Tate and Milner 2017 demonstrated that runners may be able to decrease their VILR, VALR, and VIP through a single session of sound intensity gait retraining [102]. This particular gait retraining intervention did not require specialized equipment and may be a practical suggestion for clinical settings such as an athletic training room at a University. Collegiate distance runners displaying high loading rates and impact peaks may benefit from this effective and simple gait retraining intervention.

Low Energy Availability is the Underlying Biological Risk Factor for Stress Fracture

The athlete triad has gone through several revisions to include what is considered a medical condition composed of low energy availability (EA), hormonal dysfunction, and low bone mineral density [75, 87, 105]. These three components have been associated with increased risks of injury and illness in athletes. Relative energy deficiency in sport (RED-S) has been the most recent revision of the athlete triad that encompasses more than EA, hormonal dysfunction, and

BMD and also includes other physiological consequences such as impaired metabolic rate, immunity, protein synthesis, cardiovascular system, and psychological health [75].

Collegiate distance runners show signs of low EA and subsequent BSI based on the athlete triad components [105]. EA is defined as the sufficient energy intake required to meet the energy cost of exercise and metabolic functions [75]. Tenforde et al. 2016 classified athletes into low, moderate, and high-risk categories for sustaining BSI based on criteria from the female athlete triad. Six criteria points were generated from an NCAA required pre participation form and a DXA scan. The athlete chose a numerical ranking between 0 and 2 based on the accuracy of the description of each criterion. A score of 0 to1 constituted a low risk, 2-5 a moderate risk, and greater than 6 a high risk for BSI.

Sport	No. of Athletes	Low Risk	Moderate Risk	High Risk
Basketball	9	9 (100)	0 (0)	0 (0)
Crew/rowing	30	27 (80)	3 (20)	0 (0)
Cross-country	47	24 (51)	16 (34)	7 (14.9)
Fencing	5	5 (100)	0 (0)	0 (0)
Field hockey	21	16 (76.2)	5 (23.8)	0 (0)
Gymnastics	16	7 (43.8)	9 (56.2)	0 (0)
Lacrosse	16	8 (50)	8 (50)	0 (0)
Sailing	3	2 (66.7)	1 (33.3)	0 (0)
Soccer	5	4 (80)	1 (20)	0 (0)
Softball	19	16 (84.2)	3 (15.8)	0 (0)
Swimming/diving	21	12 (57.1)	8 (38.1)	1 (4.8)
Synchronized swimming	11	9 (81.8)	1 (9.1)	1 (9.1)
Track[b]	4	4 (100)	0 (0)	0 (0)
Tennis	7	5 (71.4)	2 (28.6)	0 (0)
Volleyball	9	6 (66.7)	3 (33.3)	0 (0)
Water polo	16	15 (93.8)	1 (6.3)	0 (0)

Table 10. Number of athletes from each sport classified into low, moderate, and high risk for sustaining BSI. Adapted from Association of the Female Athlete Triad Risk Assessment Stratification to the Development of Bone Stress Injuries in Collegiate Athletes. By Tenforde, Carlson, Chang, Sainani, Shultz, Kim, Cutti, Golden, & Fredericson, *2017, The American Journal of Sports Medicine, 45(2), 302-310.* 2016 by the authors.

Table 10 shows cross country athletes had the highest risk of sustaining a BSI, based on criteria assessed [105]. Compared with cross country athletes categorized in low risk, cross country athletes in the moderate and high risk categories showed a 4-fold and 5.7 fold increased risk for BSI's, respectively [105]. Due to the high metabolic demands of collegiate distance running, Tenforde et al. 2017 concluded that assessing an athlete's risk of low EA can help to identify athlete's who are at a greater risk of BSI [105].

Bone mineral density (BMD) is an important component in assessing a distance runner's risk for SF [77]. Tenforde et al. 2017 investigated the effects of the criteria for the athlete triad on BMD [105]. Athletes were recruited from a single division 1 NCAA college and assessed for five criteria, self reporting scores for low EA with or without disordered eating/eating disorders (DE/ED), body mass index (BMI), delayed menarche, oligomenorrhea/amenorrhea, and prior stress reaction/stress fracture. Dual Energy X-ray absorptiometry (DXA) scans were used to collect data for total body (TB) and lumbar spine (LS) BMD. Of the 239 athletes participating in the study, 23 showed low BMD, with a Z-score of less than 1.0 for LS or TB BMD [105]. Sports characterized as low impact, such as distance running, synchronized swimming, and swimming had significantly lower BMD compared to sports characterized as high impact, such as gymnastics, volleyball, and basketball [105]. Low BMI and oligo/amenorrhea were the strongest predictors of low BMD [105]. These results present an important consideration when assessing a collegiate distance runner's risk of SF compared to other collegiate sports. Tenforde et al. 2017 demonstrated that collegiate cross country runners, compared to other sports, have a higher risk of SF based on criteria formed from the female athlete triad [105]. These criteria were then associated with low BMD [105].

Delayed Menarche Begins in High School and Increases Risk of Stress Fracture

Tenforde et al. 2017 identified female collegiate athletes as having a moderate risk of sustaining a stress fracture if menarche began between the ages of 15 and 16 years old and high risk if menarche began past the age of 16 [105]. These ages indicate that delayed menarche may increase the risk of SF and begins in high school. Based on the Tenforde et al.'s 2017 conclusions, delayed menarche is a biological factor that needs to be assessed since adolescence is a critical time for bone mineral accrual and can influence risk of SF later on in life [73, 74].

Rauh et al. 2014 performed a prospective study looking at the relationship between the female athlete triad and injury in high school distance runners [87]. Injury reports throughout the season were recorded, as well as eating attitude and behaviors, menstrual status, and bone mineral density. Primary amenorrhea was defined as no onset of menses by age 15 years. Of the 89 runners assessed, 38 high school distance runners (42.7%) sustained 65 running-related injuries during the season [87]. Runners who reported oligo/amenorrhea within the past year had a significantly older age of menarche compared to runners who were eumenorrheic [87]. This suggests that delayed menarche may affect menstrual regularity as these high school aged runners begin menses and increase their risk of menstrual irregularity in college [87]. Runners who had sustained an injury during the season reported significantly higher scores on the eating attitudes and behaviors assessments than non-injured runners, after adjusting for body mass index (BMI) [87]. Significantly lower BMD (spine, total hip, and whole-body) was observed in runners who had sustained an injury throughout the season compared to those runners who had not sustained an injury [87]. At the site of the tibia/fibula, there was a decrease in BMD between injured and non injured runners, although it was not statistically significant [87]. The results from this study are similar to the results found in Tenforde et al. 2017 that runners who reported menstrual dysfunction (oligo/amenorrhea, delayed menarche) and whose BMD was lower than normal for their age had an increased risk of injury compared to runners with normal menses and those who fell within the normal BMD range [87, 105].

Tenforde et al. 2015 performed a study examining the sex-specific risk factors for low BMD in adolescent runners [107]. It was hypothesized these adolescent runners would have sex-specific risk factors that influenced low BMD based on lower lean mass, low BMI, prior SF, menstrual variables, sport participation, disordered eating, and nutritional variables (calcium and vitamin D intake) [107]. Bone mineral density was measured at the lumbar spine (LS) and total body less head (TBLH).

Multivariable Linear Regression Analysis of Risk Factors to Lower BMD Z-Scores	
Girls	
LS	Lower A:G ratio, higher fat mass, lower height, current menstrual irregularity with history of fracture
TBLH	Lower A:G ratio, lower lean mass, later age of menarche, fewer cups of milk per day
Boys	
LS	Lower BMI Z-score,[b] belief that "thinner is faster"[c]
TBLH	Lower BMI Z-score,[b] belief that "thinner is faster,"[c] lower A:G ratio
Sex-specific risk factors for BMD Z-scores ≤–1	
Girls	BMI ≤17.5 kg/m^2, menstrual irregularity plus history of fracture
Boys	BMI ≤17.5 kg/m^2, belief that "thinner is faster"[c]

Table 11. Sex specific risk factors for lower BMD and low bone mass. Adapted from Identifying Sex-Specific Risk Factors for Low Bone Mineral Density in Adolescent Runners. By Tenforde, Fredericson, Sayres, Cutti, & Sainani, *2015, The American Journal of Sports Medicine, 43(6), 1494-1504.* 2015 by the authors.

Results in Table 11 demonstrate that females showing a lower android to gynoid (A:G) fat mass ratio, lower height, current menstrual irregularity, lower lean mass, later age of menarche, and a decreased intake of calcium and vitamin D, in the form of fewer cups of milk per day had lower BMD [107]. The results from the male adolescent runners demonstrated that lower BMI Z-scores, a belief that "thinner is faster", and a lower A:G fat mass ratio were significantly associated with lower BMD [107]. These results suggest the importance of identifying sex-specific risk factors that affect males' and females' risk of lower BMD, which has been seen to increase a runner's risk of SF [77, 107]. Tenforde et al. 2015 illuminated the male specific risk factors for lower BMD, which is a lower BMI and a belief that "thinner is faster" [107]. These male specific risk factors suggest that males are at an increased risk for low BMD if they display disordered eating tendencies [107].

Effect of Disordered Eating/Eating Disorders on Stress Fracture Risk

Tenforde et al. 2017 demonstrated that collegiate distance runners are a population of athletes at a high risk for low energy availability, which is postulated as the primary cause of the athlete triad and is the basis of RED-S [75, 105]. Low EA is linked to an increase risk of SF [105]. Disordered eating (DE) can be characterized as restricted eating behaviors that do not necessarily reach the level of a clinical eating disorder [20]. An example of restricted eating behaviors include lactose intolerance and gluten intolerance. Cobb et al. 2003 examined the relationship between disordered eating, menstrual irregularity, and bone mineral density in a randomized controlled trial among a cohort of competitive female distance runners [21]. Subjects filled out questionnaires regarding training volume in mileage per week during each competitive season (fall cross country, winter indoor track, spring outdoor track) and the off season (summer training) and answered questions regarding menstrual history. Nutrient intake was recorded using an expanded version of the 97-item National Cancer Institute Health Habits and History food frequency questionnaire. Eating Disorder Inventory (EDI) was used to screen for subclinical ED and included three subscales – drive for thinness, bulimic tendencies, and body dissatisfaction. BMD was recorded using DXA at the left proximal femur, spine, and total body.

Results from this study showed that 26% of the subjects were oligomenorrheic and 10% were amenorrheic [21]. The oligo/amenorrheic runners began menarche 1.2 years later, had 45% fewer menstrual cycles, and ran 18% more miles per week than the eumenorrheic runners [21]. DE was categorized as either normal EDI or elevated EDI based on the total scores on the three subscales. Subjects whose scores categorized them into elevated EDI reported 19% lower caloric intakes per day compared to those whose scores categorized them into normal EDI [21].

Characteristic	Menstrual Group Eumenorrheic (*N* = 58)	Oligo/Amenorrheic (*N* = 33)
EDI scores*		
Drive for thinness subscale (0–21)	3.3 ± 0.7	9.3 ± 1.4†
Bulimia subscale (0–21)	0.9 ± 0.2	2.3 ± 0.5‡
Body dissatisfaction subscale (0–27)	5.4 ± 0.8	9.3 ± 1.5‡
total (0–69)	9.6 ± 1.5	20.9 ± 3.0†
Daily nutrient intake		
Calories ($kcal \cdot d^{-1}$)	2241 ± 121	2219 ± 147
Fat (% of total calories)	18.7 ± 0.9	15.3 ± 1.0§
Protein (% of total calories)	16.3 ± 0.4	16.3 ± 0.5
Calcium (mg)	1418 ± 106	1437 ± 123
Fiber (g)	28.1 ± 2.2	32.0 ± 3.7
Vitamin C (mg)	283 ± 23	274 ± 28
Iron (mg)	22.2 ± 2.6	23.6 ± 2.1

Table 12. EDI scores and daily nutrient intake for eumenorrheic and oligo/amenorrheic menstrual groups. Adapted from Disordered Eating, Menstrual Irregularity, and Bone Mineral Density in Female Runners. By Cobb, Bachrach, Greendale, Marcus, Neer, Nieves, Sowers, Brown, Gopalakrishnan, Leutters, Tanner, Ward, & Kelsey, *2003, Medicine and Science in Sports and Exercise, 35(5), 711-719.* 2003 by American College of Sports Medicine.

	Menstrual Group Eumenorrheic (*N* = 58)	Oligo/Amenorrheic† (*N* = 33)
Spine BMD		
Observed	1.01 ± 0.013	0.94 ± 0.018‡
Adjusted*	1.00 ± 0.013	0.95 ± 0.019§
Total hip BMD		
Observed	1.00 ± 0.015	0.95 ± 0.020§
Adjusted*	1.00 ± 0.014	0.94 ± 0.020§
Whole body BMD		
Observed	1.12 ± 0.011	1.08 ± 0.015§
Adjusted*	1.11 ± 0.010	1.08 ± 0.015

Table 13. BMD for eumenorrheic and oligo/amenorrheic menstrual groups. Adapted from Disordered Eating, Menstrual Irregularity, and Bone Mineral Density in Female Runners. By Cobb, Bachrach, Greendale, Marcus, Neer, Nieves, Sowers, Brown, Gopalakrishnan, Leutters,

Tanner, Ward, & Kelsey, *2003, Medicine and Science in Sports and Exercise, 35(5), 711-719.* 2003 by American College of Sports Medicine.

Twenty-three subjects had elevated EDI scores and 65% were oligo/amenorrheic [21]. Only 25% of the 67 subjects with normal EDI scores were oligo/amenorrheic. Of the three subscales on the EDI, a drive for thinness had the strongest association with oligo/amenorrhea [21]. Once body weight and composition were adjusted for, results showed a significant decrease in spine BMD in subjects who had elevated EDI scores compared to subjects who had normal EDI scores [21]. Trends toward a significant decrease in hip BMD and whole-body BMD were seen as well [21]. These results, summarized in Tables 12 and 13, present important considerations when assessing eating attitudes and the risk for decreased BMD and subsequent BSI and SF in female collegiate distance runners [21]. Cobb et al. 2003 suggest that DE is associated with oligo/amenorrhea and DE is associated with low BMD in eumenorrheic runners [21]. This study suggests the significance of the three components of the athlete triad when assessing risk of low BMD that may suggest an increased risk of SF in collegiate distance runners [21].

Low Bone Mineral Density May Increase Risk of Stress Fracture

There are certain biological factors that increase a collegiate distance runner's risk of low BMD. Tenforde et al. 2015 has shown that there are sex-specific risk factors such as menstrual irregularity in females and disordered eating tendencies among males that increase the risk of low BMD [107]. Cobb et al. 2003 found that disordered eating and eating disorders can increase a runner's risk for low BMD by decreasing their energy availability [21]. These findings are similar to Tenforde et al.'s 2017 findings that DE/ED can increase the risk of menstrual irregularity [105]. While these studies have demonstrated the factors that contribute to a decrease in BMD, it is important to recognize and study the contribution of low BMD to the risk of SF.

Myburgh et al. 1990 performed a case-control study investigating the relationship between low bone mineral density (BMD) and incidence of stress fractures in athletes to determine if low BMD is an etiologic factor in the development of stress fractures [77]. Twenty-five athletes, 19 women and 6 men, who had been diagnosed with a lower extremity stress fracture were matched for sex, age, weight, height, and exercise history with 25 control athletes. Menstrual histories of the female subjects, daily dietary composition and intake of nutrients, estimated weekly intake portions of dairy products, and bone mineral density were assessed in these athletes. Results demonstrated that significantly more injured female subjects were experiencing menstrual irregularity compared to the control female subjects [77]. Significantly more control female subjects were using oral contraceptives compared to the injured female subjects, which suggests a potential link between oral contraceptive use and a decreased risk of stress fracture [22, 77]. The control athletes consumed significantly more calcium compared to the injured subjects and only 9 injured subjects met the recommended daily allowance (RDA) for calcium, whereas 14 of the control subjects met the RDA. The injured athletes consumed significantly less dairy products per week compared to the control athletes. This result suggests a significant relationship between calcium intake and risk of SF [77, 94].

Bone Mineral Density	Injured Subjects		Control Subjects		P Value
	Mean ± SD	Percentage	Mean ± SD	Percentage	
	g/cm^2		g/cm^2		
Spine (lumbar vertebrae 2 through 4)	1.014 ± 0.142	96	1.108 ± 0.131	104	0.02
Femoral neck	0.838 ± 0.091	94	0.898 ± 0.110	101	0.005
Ward triangle	0.670 ± 0.112	89	0.736 ± 0.089	98	0.01
Trochanter	0.690 ± 0.088	96	0.755 ± 0.115	105	0.01
Intertrochanteric space	1.083 ± 0.138	95	1.146 ± 0.157	100	0.06
Total proximal femur	0.932 ± 0.109	96	0.997 ± 0.133	103	0.02

Table 14. BMD at measurement sites for injured subjects and control subjects. Adapted from Low Bone Density is an Etiologic Factor for Stress Fracture in Athletes. By Myburgh, Hutchins, Fataar, Hough, & Noakes, *1990, Annals of Internal Medicine, 113(10), 754-759.* 1990 by American College of Physicians.

Table 14 demonstrates injured subjects had significantly less BMD in the lumbar spine and proximal femur compared to the control subjects, in particular the femoral neck and the Ward triangle [77]. Myburgh et al. 1990 showed a decrease in BMD at an appendicular site that is weight bearing, the femur, a site at which stress fractures occur [10, 34, 77]. These novel results demonstrate significant correlations between menstrual irregularity, dietary calcium intake, and bone mineral and the incidence of stress fracture [77]. Myburgh et al. 1990 present important considerations for collegiate distance runners who have a high incidence rate of stress fracture, which may indicate low BMD [77].

Role of Vitamin D and Calcium Deficiencies in Risk of Stress Fracture

An important consideration when assessing a collegiate distance runner's risk of BSI and SF is the mechanism and influence of vitamin D and calcium. Vitamin D is important during the period of high bone turnover and is absorbed through the diet as well as synthesized through conversion of 7-dehydrochelsterol to previtamin D3 by ultraviolet B from exposure to the sun [1]. When vitamin D is activated, calcium absorption is stimulated in the small intestine and can absorbed by bone [1]. Based on the mechanism of vitamin D and the influence it has on calcium absorption by bone, researchers suggest that it can have an influence on BMD and may decrease the risk of SF [1, 104].

Lovell et al. 2008 examined the vitamin D status and calcium intake of 18 female gymnasts, an athletic population with a high incidence rate of stress fracture due to the high loading rates and high training volumes, and examined the rate in bone stress injuries in these athletes [64]. Vitamin D levels were tested using the DiaSorin vitamin D assay and calcium intake was assessed using a standard food frequency questionnaire. Of the 18 gymnasts who participated in this study, only 3 had vitamin D levels greater than 75 nm/L, 15 gymnasts had levels below 75 mn/L and had their PTH levels tested [64]. The 15 gymnasts who had their PTH levels tested fell within the normal reference range, except for one who had a low PTH level. Thirteen gymnasts showed calcium intakes below the daily recommended intake of 1000 mg for 9 to 11 years old and 1300 mg for 12 to 18 years old. Lovell et al. 2008 also reviewed case notes of these 18 gymnasts from the previous year and found that 12 had been diagnosed with a stress reaction and 1 had been diagnosed with a stress fracture. These results indicate the importance of assessing calcium and vitamin D levels in athletic populations who demonstrate a high incidence rate of stress fractures [64]. Lovell et al. 2008 conclude that vitamin D and calcium supplementation is an important suggestion for athletes at a high risk for stress fracture [64].

Silk et al. 2015 conducted a randomized, double-blinded, placebo-controlled study on the effect of calcium and vitamin D supplementation on bone properties in male jockeys [93]. Male jockeys are a population of athletes who engage in caloric restriction and high volumes of physical activity due to the emphasis of leanness and low weight in their sport, similar to collegiate distance runners [93]. The treatment group received 800 mg of calcium and 400 IU of vitamin D3 in pill form. The control group received a cellulose placebo, also in pill form. Distal and proximal tibial bone properties were measured at baseline and 6 months using peripheral quantitative computed tomography. Blood borne markers for bone turn over, CTx a bone resorption marker and P1NP a bone formation marker, and vitamin D concentrations were measured as well.

	Unadjusted baseline values		ANCOVA six-months adjusted values						
	S group (n = 8) baseline Mean (SD)	P group (n = 9) baseline Mean (SD)	S group (n = 8) Adj Mean (SE)	P group (n = 9) Adj Mean (SE)	Adjusted Mean diff (SE)	% diff	Partial Eta² (η²)	95% CI	p-Value
4% distal tibia									
Trabecular density (mg cm²)	241.0 (28.1)	246.8 (33.9)	259.3 (5.6)	244.3 (5.3)	14.9 (7.8)	5.7%	0.23	−2.1 to 31.9	0.080
Trabecular content (mg mm)	227.0 (26.0)	211.4 (42.3)	220.8 (6.6)	220.8 (5.8)	−0.02 (9.1)	0.0%	0.00	−20.0 to 19.9	0.998
Trabecular area (mm²)	861.1 (160.2)	854.7 (126.7)	892.0 (49.7)	870.0 (18.5)	22.0 (27.4)	2.5%	0.05	−37.7 to 81.7	0.437
Total area (mm²)	1109.2 (81.7)	1044.0 (137.8)	1063.9 (15.9)	1090.0 (14.9)	−26.1 (22.8)	−2.5%	0.10	−75.8 to 23.6	0.275
Total density (mg cm²)	300.1 (29.0)	286.6 (40.9)	292.2 (8.0)	293.9 (7.6)	−1.7 (11.3)	−0.6%	0.00	−26.2 to 22.8	0.882
Bone strength index (mg² mm⁴)	100.1 (17.5)	86.6 (22.4)	90.6 (4.5)	96.5 (4.2)	−5.8 (6.4)	−6.4%	0.07	−19.7 to 8.1	0.380
66% proximal tibia									
Cortical content (mg mm)	296.5 (35.7)	293.8 (52.4)	318.3 (2.9)	297.1 (2.7)	21.1 (4.0)	6.6%	0.70	12.4 to 29.8	*<0.001*
Cortical area (mm²)	267.1 (29.3)	263.4 (43.8)	282.6 (2.3)	266.0 (2.2)	16.6 (3.2)	5.9%	0.69	9.6 to 23.5	*<0.001*
Cortical density (mg cm²)	1101.5 (24.7)	1113.4 (22.1)	1127.4 (2.5)	1112.9 (2.3)	14.5 (3.5)	1.3%	0.59	6.9 to 22.1	*0.001*
Total area (mm²)	492.2 (59.6)	519.8 (75.6)	524.6 (4.2)	503.4 (3.9)	21.2 (5.8)	4.0%	0.53	8.5 to 33.9	*0.003*
Cortical thickness (mm)	4.2 (0.5)	3.8 (0.6)	4.1 (0.0)	4.0 (0.0)	0.08 (0.04)	1.9%	0.25	−0.01 to 0.2	0.066
SSI tibia (mm³)	2100.5 (329.2)	2140.0 (489.6)	2207.1 (80.3)	2127.1 (75.6)	80.0 (111.6)	3.6%	0.04	−163.1 to 323.1	0.487

Table 15. Baseline and six month adjusted bone variables at measurement sites in tibia for supplemented and placebo group. Adapted from Tibial bone responses to 6-month calcium and vitamin D supplementation in young male jockeys: A randomized control trial. By Silk, Greene, Baker, & Jander, *2015, Bone, 81, 554-561*. 2015 by Elsevier Ltd.

	Unadjusted baseline values		ANCOVA six-month adjusted values						
	S group (n = 8) Mean (SD)	P group (n = 8) Mean (SD)	S group (n = 8) Adj Mean (SE)	P group (n = 8) Adj Mean (SE)	Adjusted Mean diff (SE)	% diff	Partial Eta²	95% CI diff	p-Value
25OH Vit D (nmol/L)	64.6 (19.5)	81.2 (24.4)	81.9 (3.6)	67.1 (3.6)	14.8 (5.2)	18.1%	0.38	3.6 to 26.1	*0.014*
CTx (ng/L)	371.3 (201.0)	380.0 (141.1)	357.5 (21.3)	446.3 (21.3)	−88.8 (30.2)	−24.8%	0.40	−154.0 to −23.6	*0.011*
P1NP (μg/L)	104.2 (46.4)	108.9 (31.6)	107.3 (5.7)	101.9 (5.7)	5.4 (8.0)	5.0%	0.03	−11.9 to 22.7	0.511

Table 16. Baseline and six month blood variables between supplemented and placebo group. Adapted from Tibial bone responses to 6-month calcium and vitamin D supplementation in young male jockeys: A randomized control trial. By Silk, Greene, Baker, & Jander, *2015, Bone, 81, 554-561*. 2015 by Elsevier Ltd.

Results showed a significant increase in vitamin D levels in the supplemented group compared to the placebo group from baseline to 6 months [93]. CTx levels had significantly decreased by almost 25% from baseline to 6 months in the supplemented group compared to the placebo group. P1NP did not show differences between baseline and 6 months. The greater bone density at the proximal tibia found in the supplemented group compared with the placebo group at 6 months indicates a possible strategy to negate the consequences of high bone turnover [93]. These results are summarized in Tables 15 and 16. Silk et al. 2015 suggests the increase in bone density at the proximal tibia may have resulted from supplementation of calcium and vitamin D over the 6 month period and could apply as a strategy for collegiate distance runners to increase their vitamin D levels and decrease bone turnover [93].

Lovell et al. 2008 illuminated the vitamin D and calcium deficiencies and prevalence of SF among an athletic population at a high risk of SF, while Silk et al. 2015 demonstrated the benefits of vitamin D and calcium supplementation on elevating vitamin D levels and improving bone mineral density [64, 93]. An important consideration for vitamin D supplementation in athletes is the dosage. Backx et al. 2016 investigated the prevalence of vitamin D deficiency in 128 highly trained athletes as well as the dose-response relationship between vitamin D_3 and the total 25(OH)D concentration in these athletes [3]. Athletes were classified as deficient (< 50 nm/L), insufficient (50-75 nm/L), or sufficient (> 75 nm/L) based on their baseline 25(OH)D measurements [3]. Athletes classified as having a 25(OH)D deficiency or insufficiency were randomized to take 400, 1100, or 2200 IU of vitamin D_3 per day for one year, while the athletes classified as having sufficient 25(OH)D continued the study without receiving supplements. In addition to having 25(OH)D levels assessed during this study, athletes recorded vitamin D and calcium intake, sun exposure, and general well-being in order for researchers to assess the prevalence of vitamin D deficiency in highly trained athletes. Forty-three athletes had a vitamin D deficiency, 46 had an insufficiency, and 39 had a sufficient baseline concentration [3]. Seventy percent of the athletes in this study had either a deficiency or an insufficiency in 25(OH)D, and based on previous research this could increase an athlete's risk of stress fracture [58].

	March T=*0*	*June* T=*3*	*September* T=*6*	*December* T=*9*	*March* T=*12*
A					
Sufficient group	95±12	100±22	129±32	102±24	96±22
N	13	12	11	11	11
400 IU/day	50±16[a]	80±17[a]	111±31[b]	85±22[c,b]	81±26[c]
N	31	23	22	19	16
1100 IU/day	49±16[a]	79±18[a]	119±27[c,b]	85±25[c,b]	76±29[c,b]
N	29	18	16	12	14
2200 IU/day	50±15[a]	94±19	144±33[c]	120±28[c]	100±27[c]
N	29	19	23	19	20

Table 17. Total 25(OH)D concentrations in athletes for different daily vitamin D_3 dosages. Adapted from The impact of 1-year vitamin D supplementation on vitamin D status in athletes: a dose-response study. By Backx, Tieland, Maase, Kies, Mensink, van Loon, & de Groot, 2016 by Macmillan Publishers Limited.

Table 17 shows that all three dosage groups increased total 25(OH)D concentration, compared to the sufficient group. A sufficient total 25(OH)D concentration (> 75 nm/L) was achieved in 85% of the athletes taking 2200 IU/day within 3 months, whereas a sufficient total concentration was achieved in 50% of the athletes taking 1100 IU/day and 57% taking 400 IU/day within the first 3 months. This result gives evidence that supplementing with 2200 IU/day is sufficient to improve serum 25(OH)D concentrations in athletes who show a concentration lower than 75 nm/L [3]. Backx et al. 2016 also demonstrated that once athletes had reached a sufficient concentration of 25(OH)D, supplementing with 400 IU/day, instead of 2200 IU or 1100 IU, was adequate for maintaining a sufficient concentration [3]. Backx et al. 2016 concluded that it is important to assess athlete's total 25(OH)D concentration based on previous research showing an increase in stress fracture risk associated with levels below 75 nm/L [3, 58]. These results can be implicated for collegiate cross country runners who have deficient or insufficient levels of vitamin D and could improve their vitamin D levels by supplementing with 2200 IU of vitamin D_3 once a sufficient level is reached, then reduce supplementation to 400 IU per day [3].

Greene and Naughton 2011 examined the effects of calcium and vitamin D supplementation on bone structural properties in peripubertal females, similar to Silk et al. 2015 [42]. This study found that a 6-month supplementation of calcium and vitamin D, 800 mg and 400 IU/day, improved bone structural properties compared to the placebo group [42]. The supplemented group demonstrated gains in trabecular density, trabecular area, and strength strain index at the 4% of the distal tibial and radial sites compared to the placebo group. The supplemented group also demonstrated gain in cortical area at the 38% and 66% of the tibia compared to the placebo group. Greene and Naughton 2011 suggest that calcium supplementation along with vitamin D supplementation may improve tibial bone properties [42]. These results are similar to Silk et al.'s 2015 findings, although show improvements in tibial bone properties in a female population [42, 97]. Results from these studies are important considerations for collegiate distance runners who may benefit from supplementation of calcium along with vitamin D to improve tibial bone properties and may protect against SF.

Influence of Oral Contraceptives on Risk of Stress Fracture

The use of oral contraceptives (OC) may have an effect on bone mineral density in female runners [51]. There have been controversial results from studies observing no impact of OC on BMD, small and insignificant impact, and a decrease in BMD in eumenorrheic runners [22].

Cobb et al. 2007 conducted a randomized trial to study the controversial effects of OC use on bone mass and SF rates in competitive female distance runners [22]. The participants for this study included 124 competitive female distance runners from a collegiate team, post-collegiate clubs, and road races. The subjects were randomly assigned to receive OC or no treatment. Questionnaires about menstrual history, previous OC use, SF history, training, diet, eating attitudes and behaviors. Subjects were further categorized into amenorrheic, oligomenorrheic, and eumenorrheic based on the number of menstrual cycles that occurred in the previous 12 months. Subjects reported to the clinical site and were assessed for these categorizations and questionnaires at 1 year and 2 years. DEXA was used to measure BMD, bone mineral content (BMC), and body composition.

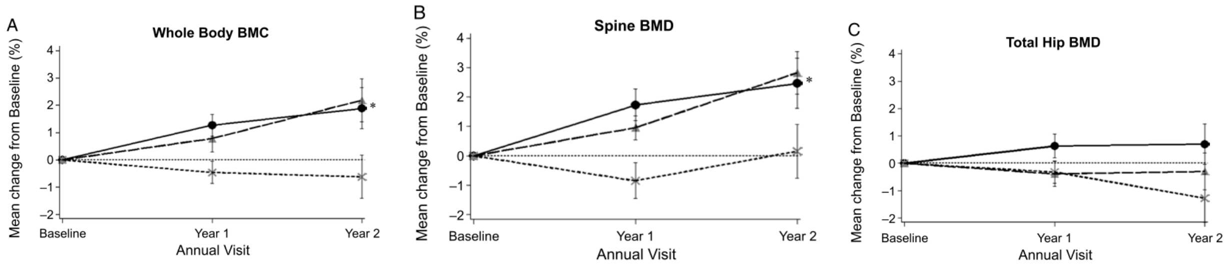

Figure 8. Mean percent change in whole body bone mineral content, spine and hip bone mineral density. Adapted from The Effect of Oral Contraceptives in Bone Mass and Stress Fracture in Female Runners. By Cobb, Bachrach, Sowers, Nieves, Greendale, Kent, Brown, Pettit, Harper, & Kelsey, *2007, Medicine and Science in Sport and Exercise, 39(9), 1464-1473.* 2007 by the American College of Sports Medicine.

Subjects in the OC group and those who spontaneously regained their menstrual cycle increased in whole-body BMC and spinal BMD by about 1% per year, whereas the subjects who remained oligo/amenorrheic had no change in BMD or BMC. These results are summarized in Figure 8. In contrast to previous studies, Cobb et al. 2007 did not find that OC use had a detrimental affect on BMD in eumenorrheic runners [24]. This study illuminated that oral contraceptives may be a practical suggestion for collegiate distance runners experiencing menstrual irregularity to increase their BMD and may decrease the risk of SF. Although Cobb et al., 2007 found that OC may increase BMD by regulating the menstrual cycle, Chen et al. 2013 discusses the contradictory findings of OC on BMD [20, 24]. This is a topic that should be researched further to find more information on the effects of OC on BMD.

Effect of Prior Ball Sport Participation on Risk of Stress Fracture

Prior sport participation is a factor speculated to have an influence on BMD and subsequent SF based on the remodeling of bone following mechanical loading [27,30,99]. Fehling et al. 1995 examined the difference in BMD among female athletes in impact loading (volleyball and gymnastics) and active loading sports (swimming) [32]. Results demonstrated that athletes participating in impact loading had increased BMD compared to the active loading sports [32]. Although this study did not look at distance runners, researcher has suggested that distance runners have lower BMD compared to sports with higher impacts, which presents an important factor when assessing risk for SF among distance runners [42].

Fredericson et al. 2005 hypothesized that participation in ball sports as an adolescent athlete may prevent SF in runners later in life [35]. This study surveyed elite track athletes to find out about running history, age when they sustained SF, and age when they played a ball sport. Basketball and soccer are two sports that have been shown by Milgrom et al. 2000 and Calbet et al. 2001 to induce higher peak strains, but at relatively lower volume compared to running, which may stimulate an increase in BMD [17, 70]. Subjects for this study were 156 female and 118 male track distance runners who competed in the 800 meters or greater.

	No Stress Fracture	Stress Fracture
Men		
n (%)	86 (73)	32 (27)
Even played soccer or basketball (%)	87.2	75.0
Ever played soccer (%)	40.7	28.1
Ever played basketball (%)	73.3	62.5
Years played (ball-sport players only)	7.3 (3.5)	5.5 (3.6)*
Age started playing ball sports (players only)	7.5 (2.7)	10.5 (3.3)†
Started ball sports before 10th birthday (players only, %)	82.9	29.2†
Women		
n (%)	111 (71)	45 (29)
Ever played soccer or basket ball (%)	80.2	62.2†
Ever played soccer (%)	54.0	35.6†
Ever played basketball (%)	55.8	44.4
Years played (ball-sport players only)	5.9 (3.5)	5.4 (3.8)
Age started playing ball sports (players only)	8.9 (3.1)	9.4 (3.1)
Current menstrual irregularity‡	39.6	55.6
Delayed menarche, past the 16th birthday (%)	13.5	11.1
Started running before menarche (%)	83.3	85.7
Started ball sports before menarche (players only, %)	40.5	42.2

Table 18. History of ball sport participation among elite competitive male and female runners and occurrence of stress fracture. Adapted from Effects of Ball Sports on Future Risk of Stress Fracture in Runners. By Fredericson, Ngo, & Cobb, *2005, Clinical Journal of Sports Medicine, 15(3), 136-141.* 2005 by Lippincott Williams & Wilkins.

Eighty-three percent of men and women who never sustained a SF had reported playing soccer or basketball for at least 6 months during childhood compared to 68% who had sustained a SF [36]. Table 18 demonstrates significant results, as depicted by the highlighted portions, for men and women separately. For female runners the questionnaire asked about menstrual regularity and age of menarche. It was seen that a substantial amount of females reported current or past irregular menstrual cycles [36]. Female runners who had sustained a SF had also reported menstrual irregularities more than those who did not sustain a SF [36]. This finding is supported by other studies indicating a link to menstrual irregularity and increased risk of SF [22]. It was found that the protective effect of playing soccer or basketball during adolescence was less pronounced in women experiencing menstrual irregularity [36]. Women experiencing regular menstruation showed an increased protective effect of playing soccer or basketball during adolescence compared to women experiencing menstrual irregularity [36]. The higher percentage of runners who played soccer or basketball during adolescence and did not sustain a SF, compared to those who did not play soccer or basketball and did sustain a SF, suggests there is a protective mechanism [36]. The loading placed on the musculoskeletal system during these sports may stimulate bone mineral acquisition [27]. Frederickson et al. 2005 provide a potential assessment for collegiate distance runners who may be more protected against SF if they participated in ball sports during adolescence compared to those who did not [36].

Influence of Sleep Deprivation on Risk of Stress Fracture

Sleep deprivation is common among college students and research has shown it can have adverse health effects on metabolic and endocrine functions [98]. Spiegel et al. 1999 found that in a cohort of young men sleeping 4 hours a night, cortisol concentrations were raised in the afternoon and early evening compared to a group receiving an adequate amount of sleep [100]. Based on a report by Weinstein et al. 1998 demonstrating that glucocorticoid administration decreases bone formation rate and bone mineral density in mice, there is evidence that suggests a potential decrease in BMD may occur by elevated cortisol levels caused by sleep deprivation [112]. To further investigate this relationship, Specker et al. 2007 conducted a cross-sectional analysis of sleep and bone data on over 1,000 individuals [99]. Nineteen percent of these individuals were classified as sleep deprived. It was found that the women who were sleep deprived had significantly lower cortical volumetric BMD compared to the women who received adequate sleep. Women who were sleep deprived also showed a significantly lower bone area at the proximal hip compared to the women who were not. Men who were sleep deprived had significantly lower polar stress strain index, an estimate of torsional bending strength, compared to men who were not sleep deprived. The results from Specker et al. 2007 suggest there is a relationship between sleep deprivation and certain measurements of BMD and bone strength [99].

These findings indicate an important consideration for collegiate distance runners who may be sleep deprived and jeopardizing their BMD and bone strength and increasing their risk of SF.

Similar to Specker et al. 2007, Ben-Sasson et al. 1994 examined the effect of sleep deprivation on infantry recruits' bone metabolism [6]. This study specifically investigated bone metabolites, calcium and hydroxyproline urine excretions, which indicate increased bone resorption and may have an effect on BMD [6]. Recruits were divided into three groups, those who were sleep deprived for 63 hours, those who slept in a vertical position for 6 hours for three consecutive nights, and those who slept horizontally for 6 hours for three consecutive nights. The sleep deprivation group showed a 170% increase in bone resorption markers, indicating a high bone turn over rate. As previous studies have shown, high bone resorption markers have been associated with a decrease in BMD [65, 89]. The group with inadequate sleep, sleeping in a vertical position for three consecutive nights, demonstrated a 68% increase in bone resorption markers. Compared to the sleep deprived group and the inadequate sleep group, the adequate sleep group, 6 hours of horizontal sleep for three consecutive nights, had no increase in bone resorption markers. Upon further analysis, it was found that 40% of both groups were "responders" with altered bone metabolites in response to inadequate sleep, whereas 60% were "non-responders" with no changes in bone metabolites. A comparison between the responders' and non responders' BMD revealed that the responders had a significantly lower BMD than the nonresponders. These results suggest that sleep deprivation may increase bone resorption markers and may have a negative effect on BMD that could potentially increase the risk of SF.

Swanson et al. 2017 investigated the effect of sleep restriction and circadian disruption on bone turnover markers [101]. Ten healthy men underwent a sleep intervention that began with a period of sleep satiation followed by a period of forced desynchrony in which the sleep-wake cycle is desynchronized from the internal circadian cycle. This period of desynchrony was accompanied by sleep restriction in which subjects were only allowed 5.6 hours of sleep per night over a three week interval. Younger men demonstrated higher bone turnover rates compared to the older men, which is consistent with studies that have observed higher rates of bone remodeling at this age due to peak bone mass consolidation [101]. The results, summarized in Figure 9, revealed that post intervention, P1NP, a bone formation marker, was significantly lower compared to baseline.

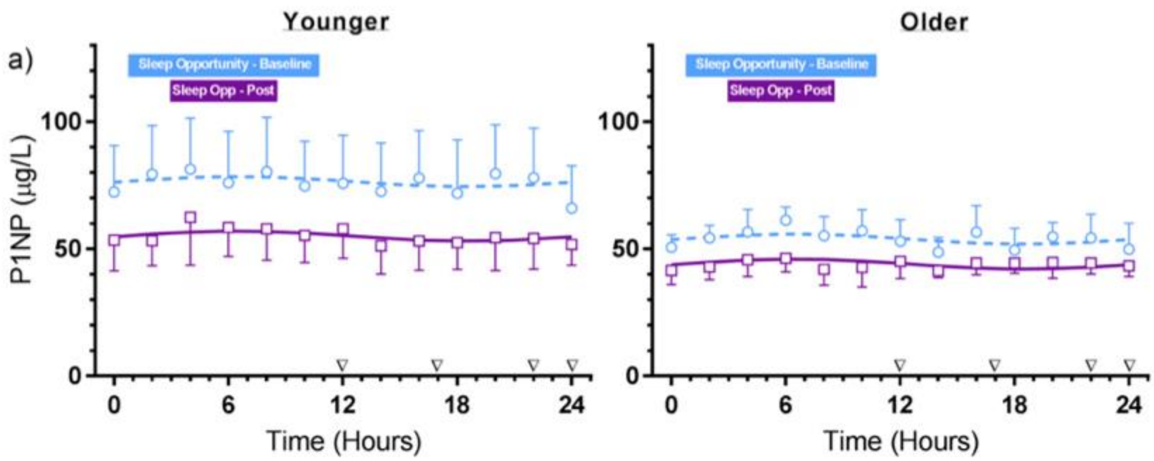

Figure 9. Changes in bone formation marker P1NP at baseline and after sleep restriction and circadian disruption. Adapted from Bone Turnover Markers After Sleep Restriction and Circadian Disruption: A Mechanism for Sleep-Related Bone Loss in Humans, *2017, Journal of Clinical Endocrinology and Metabolism, 102(10), 3722,3730.* 2017 by Endocrine Society.

Swanson et al. 2017 suggest that sleep restriction and circadian disruption may create a window of bone loss due to the decrease in bone formation marker, P1NP [101]. This results is an important consideration for collegiate distance runners who are at the age of peak bone mass consolidation and may not be receiving adequate sleep [100, 101]. Collegiate distance runners may experience a decrease in bone formation marker, P1NP, with sleep deprivation, creating a potential window of bone loss and increasing their risk of SF [100, 101].

Resistance Training May Increase Bone Mineral Density in Distance Runners

Research has shown several factors that may decrease BMD and increase the risk of SF in collegiate distance runners. Research has also shown that physical activity in different forms is an important contribution to the accrual of bone mass [43, 45]. Heinrich et al. 1989 illuminated the differences between the BMD and BMC of different forms of physical activity and demonstrated the form with the highest bone mass accrual [44]. Results from this study demonstrate that while collegiate distance runners engage in physical activity that has been shown to increase BMD and BMC, there are other forms of physical activity that increase BMD and BMC to a greater extent and serve as a protective mechanism against low BMD and BMC [44]. Figure 1 displays the results of Heinrich et al.'s 1989 study examining the BMC of cyclically menstruating female resistance and endurance trained athletes. This figure shows that the body builders, or resistance trained athletes, have the highest BMD at the lumbar spine, suggesting that lifting weights can stimulate greater bone mass accrual compared to athletes who only engage in endurance training, such as collegiate distance runners. These results suggest that resistance training may be an important consideration for collegiate distance runners when assessing training [44].

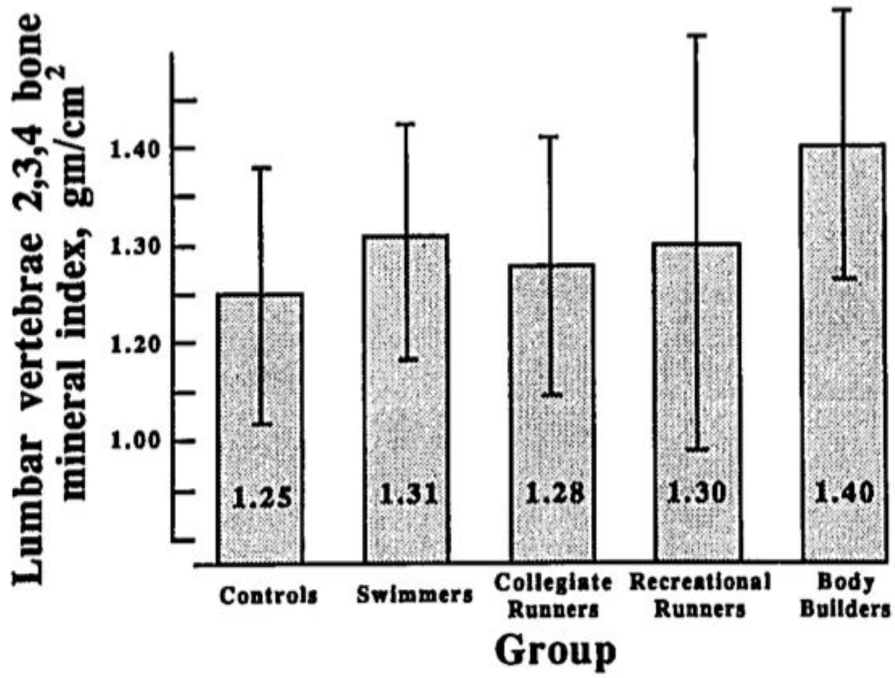

Figure 10. Lumbar vertebrae bone mineral content in athletes and controls. Adapted from Bone mineral content of cyclically menstruating female resistance and endurance trained athletes. By Heinrich, Going, Pamenter, Perry, Boyden, & Lohman, *1989, Medicine and Science in Sports and Exercise, 22(5), 558-563.* 1990 by the American College of Sports Medicine.

Heinrich et al. 1989 demonstrated in Figure 10 that resistance trained athletes have significantly higher BMD compared to their endurance trained counterparts, including collegiate runners [44]. Fehling et al. 1995 demonstrated that athletes participating in high impact sports, such as volleyball and gymnastics, had higher BMD compared to athletes in sports that were considered active loading, such as swimming [33]. The protective effect of these higher impacts in other sports can be seen in the results of Frederickson et al.'s 2005 study showing that runners who had participated in a ball sport during adolescence had a decreased incidence rate of SF [36]. Lanyon et al. 1984 suggest a greater osteogenic effect in activities that elicit high impact forces by demonstrating that higher strains placed on bone result in proportional increases in bone area [60].

Morris et al. 1997 conducted a study examining the effects of a weight-bearing, strength building exercise program on lean mass, strength, and bone mineral response in premenarcheal girls [75]. At completion of the exercise program, the exercise group had gained significantly greater BMD at several sites compared to the control subjects who did not participate in the exercise program. Bone mineral content was also greater at several sites in the exercise group compared to the control group. These results provide important suggestions for collegiate distance runners, and even high school distance runners interested in participating in collegiate distance running [75]. A weight bearing, strength building exercise program may increase the BMD and BMC in collegiate athletes, which may protect them against the risk of SF [75].

Similar to Morris et al. 1997, Mosti et al. 2014 examined the effects of maximal strength training on BMD in young adult women [76]. This study, in addition to observing changes in BMD, also observed changes in bone turn over markers, type 1 collagen amino terminal propeptide (P1NP) and type 1 collagen C breakdown products (CTX) [76]. The maximal strength training (MST) protocol consisted of a progression of a squat exercise, leading up to 4 sets of 3 to 5 repetitions of 85% to 90% of the subject’s 1 repetition max (1RM). Following the 12 weeks MST, the exercise group had significantly increased BMD and BMC at the lumbar spine, intertrochanteric hip, and total hip compared to the control group. The bone formation marker, P1NP, was significantly increased in the exercise group compared to the control group. Mosti et al. 2014 demonstrated an effective intervention to increase BMD and BMC at sites in the spine and hip, as well as an increase in serum levels of the bone formation marker, P1NP [76]. As previous studies have shown, low BMD in runners can increase their risk for SF [78]. These results suggest an important training intervention for collegiate distance runners to minimize the risk of SF and maximize training time.

Influence of Footwear on Risk of Stress Fracture

Footwear may have an influence on risk of stress fractures in distance runners. It is suggested that biomechanical alterations can occur when running in a minimalist shoe compared to running in a neutral shoe [12,14]. Bergstra et al. 2014 associated minimalist footwear with an increase in forefoot plantar pressure and Firminger et al. 2017 associated this footwear with an increase in ankle and metatarsophalangeal joint movements [13, 32]. Bonacci et al. 2013 associated minimalist footwear with a decrease in stride length, which Edwards et al. 2009 showed to have a relationship with an increase in shock attenuation and decrease in loading rates at certain lower extremity sites [15, 30].

Firminger et al. 2017 studied the effect of footwear and stride length on metatarsal strains and risk of SF [32]. Subjects of this study ran overground on a 23-meter runway where a motion capture system recorded markers placed on the foot and ankle. Pedar-X pressure-sensing insole, inserted into the shoe, was used to record plantar pressure. Subjects performed ten trials for each condition. The conditions were traditional shoe at preferred stride length (PSL), traditional shoe at 90% PSL, minimalist shoe at PSL, and minimalist shoe at 90% PSL.

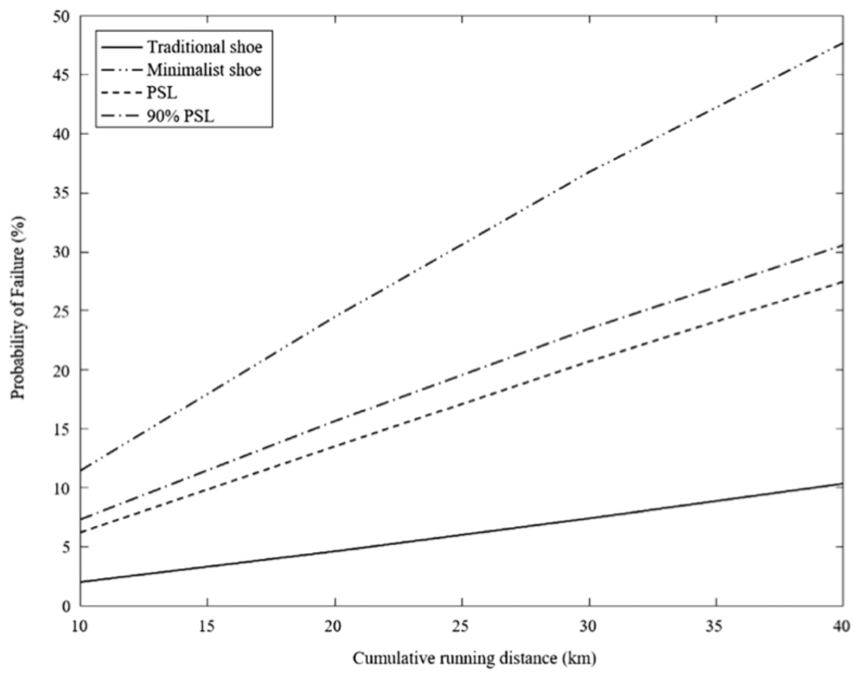

Figure 11. Probability of failure of second metatarsal for traditional shoe, minimalist shoe, preferred stride length, and 90% of preferred stride length over cumulative running distance. Adapted from Effects of footwear and stride length on metatarsal strains and failure in running. By Firminger, Fung, Loundagin, & Edwards, *2017, Clinical Biomechanics, 49, 8-15.* 2017 by Elsevier Ltd.

Figure 11 illustrates an increase in strain in all metatarsals when subjects ran in the minimalist shoes compared to the traditional shoes. The probability of failure (SF) increased among the second, third, and fourth metatarsals. Running at 90% PSL demonstrated a decrease in strain in the fourth metatarsal, yet no change was seen for overall probability of failure. Firminger et al. 2017 suggest that running in a minimalist shoe compared to a traditional shoe may increase the likelihood of a metatarsal SF [32]. Based on incidence rate reports, metatarsal SF is a common site of SF and can be decreased by training in a traditional shoe [10, 35]. Results from this study provide suggestions for collegiate distance runners who may think that running in a minimalist shoe will increase their performance, when it may increase their risk of metatarsal SF.

Practical Recommendations for Collegiate Distance Runners Based on the Literature

Incidence reports have demonstrated that collegiate distance runners sustain stress fractures at a higher rate compared to other collegiate sports[9,31,81]. These high incidence rates indicate an importance to identify and mitigate risk factors associated with SF in order to decrease the risk in collegiate distance runners. The literature has demonstrated the multifaceted nature of SF with risk factors including biomechanical properties, training parameters, biological factors, psychological factors, and environmental influences. Researchers examining the effects of these risk factors on SF suggest that an increase in these risk factors may increase the risk of SF in athletic populations. While this paper has focused on specific recommendations for collegiate distance runners, it is important to note the pathology of a SF is cumulative in nature. This indicates that some of these risk factors may occur during adolescence. For this reason, it is important to assess the risk factors for SF in distance runners prior to the commencement of their collegiate training. Figure 12 summarizes the risk factors that contribute to the risk of SF, based on findings in the literature.

Figure 12. Visual representation of risk factors contributing to stress fracture in collegiate distance runners. Adapted from How to manage patellofemoral pain – Understanding the multifactorial nature and treatment options. By Lack, Neal, De Oliveira Silva, Barton, *2018, Physical Therapy in Sport*, *32, 155-166.* 2018 by Elsevier Ltd.

Recommendations: Biomechanical Risk Factors

- Visual feedback from accelerometer [24]
    - Accelerometer displays line at 50% of tibial shock on a monitor in front of the runner, which runner attempts to keep their tibial shock below the line
- Modest step rate increase (7.5%) [112]
    - Accelerometer displays cadence, runner increases cadence (step rate) by 7.5% and monitors this using the feedback from the accelerometer
- Sound intensity monitoring [102]
    - iPad displays decibel level of impact, runner keeps decibel level below certain threshold by using the visual feedback displayed on iPad

Recommendations: Biological Risk Factors

- Adequate energy availability [105]
    - Energy input meets energy output
    - Maintain regular menstrual cycle
        - Oral contraceptives [24]
            - Controversial topic that needs further investigation [20]
- Maintain sufficient vitamin D level (>75 nmol) [3, 94]
    - 2200 IU/day until 75 nmol reached
    - Maintain sufficient level with 400 IU/day
- Maintain adequate calcium consumption [42, 97]
    - 800 mg of calcium

Recommendations: Environmental Risk Factors

- Increase bone mineral density
    - Adequate sleep to maintain proper bone metabolism [6, 31, 100]
    - Resistance training [74, 75]
        - High strain on bone may have greater osteogenic effect [60]

  - Other sport participation (e.g. soccer, basketball) during adolescence [36, 106]
    - Adolescence important bone mineral accrual period
- Proper footwear [13, 15, 32]
  - Use minimalist shoe in moderation (e.g. intervals, races)
  - Use traditional shoe during training runs

Recommendations: Training Load

- Acute:chronic workload between 0.8 and 1.3 [37, 38, 48, 49]
  - Monitor training volume and training intensity using running logs and RPE scale

Conclusion

The literature has given evidence to suggest collegiate distance runners are at a high risk of SF, which can take significant time away from training and competing. Research has also demonstrated the cumulative and multifaceted nature of these injuries that can affect bone mineral density and loading characteristics. It is important to know each individual distance runner's risk factors through assessment prior to the commencement of training. Following this assessment, it is then important to properly manage each individual's risk factors. Figure 13 describes the practical suggestions for collegiate distance runners and coaches of these athletes to take into consideration when assessing the risk of SF.

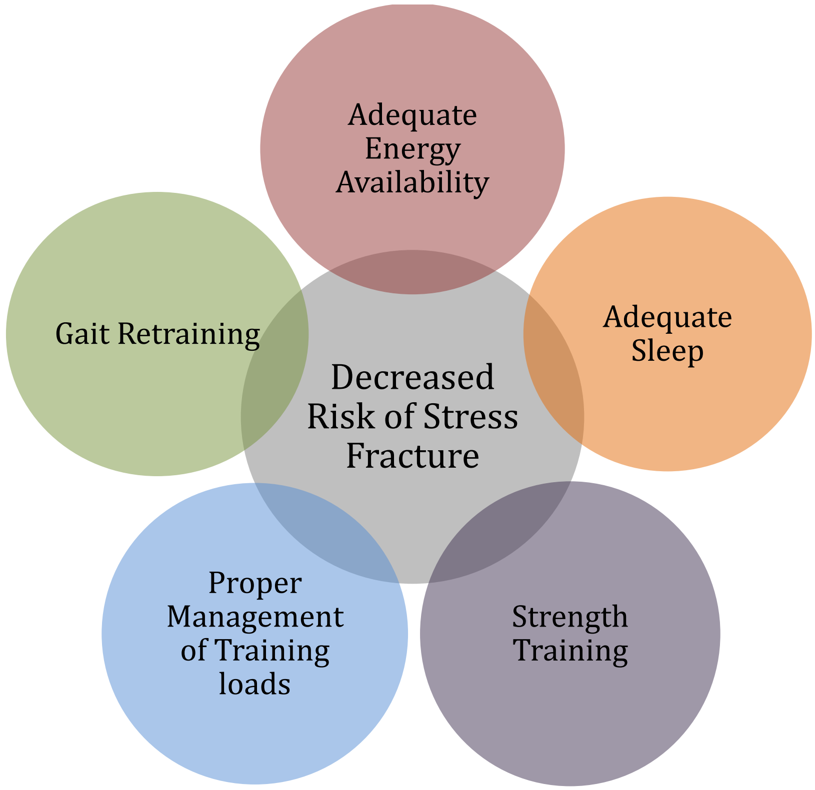

Figure 13. Visual representation of possible interventions and assessments to decrease risk of stress fracture in collegiate distance runners. Adapted from How to manage patellofemoral pain – Understanding the multifactorial nature and treatment options. By Lack, Neal, De Oliveira Silva, Barton, *2018, Physical Therapy in Sport, 32, 155-166.* 2018 by Elsevier Ltd.

References

1. Angeline, M. E., Gee, A. O., Shindle, M., Warren, R. F., & Rodeo, S. A. (2013). The effects of vitamin D deficiency in athletes. *The American Journal of Sports Medicine, 41*(2), 461-464.
2. Arendt, E., Agel, J., Heikes, C., & Griffiths, H. (2003). Stress injuries to bone in college athletes. *The American Journal of Sports Medicine, 31*(6), 959-968.
3. Backx, E. M. P., Tieland, M., Maase, K., Kies, A. K., Mensink, M., van Loon, L. J. C, & de Groot, L. C. P. G. M. (2016). The impact of 1-year vitamin D supplementation on vitamin D status in athletes: A dose-response study. *European Journal of Clinical Nutrition, 70*(9), 1009-1014.
4. Beals, K. A., & Hill, A. K. (2006). The prevalence of disordered eating, menstrual dysfunction, and low bone mineral density among US collegiate athletes. *International Journal of Sport Nutrition and Exercise Metabolism, 16*(1), 1-23.
5. Beck, B. R. (1998). Tibial stress injuries: An aetiological review for the purposes of guiding management. *Sports Medicine, 26*(4), 265-279.
6. Ben-Sasson, S. A., Finestone, A., Moskowitz, M., Maron, R., Weinner, M., Leichter, I., Rubinger, D. (1994). Extended duration of vertical position might impair bone metabolism. *European Journal of Clinical Investigation*, *24*(6), 421-425.
7. Bell, L. M., Ingle, L. (2013). Psycho-physiological markers of overreaching and overtraining in endurance sports: A review of the evidence. *Medicina Sportiva, 17*(2), 81.
8. Bennell, K., Crossley, K., Jayarajan, J., Walton, E., Warden, S., Kiss, Z. S., Wrigley, T. (2004). Ground reaction forces and bone parameters in females with tibial stress fracture. *Medicine and Science in Sports and Exercise, 36*(3), 397-404.
9. Bennell, K. L., Malcolm, S. A., Wark, J. D., Brukner, P. D. (1996). Models for the pathogenesis of stress fractures in athletes. *British Journal of Sports Medicine, 30*(3), 200-204.
10. Bennell, K. L., Malcolm, S. A., Thomas, S. A., Wark, J. D., Brukner, P. D. (1996). The incidence and distribution of stress fractures in competitive track and field athletes. *The American Journal of Sports Medicine, 24*(2), 211-217.
11. Bennell, K., Brukner, P. (2005). Preventing and managing stress fractures in athletes. *Physical Therapy in Sport, 6*(4), 171-180.
12. Bennett, J. E., Reinking, M. F., Rauh, M. J. (2012). The relationship between isotonic plantar flexor endurance, navicular drop, and exercise-related leg pain in a cohort of collegiate cross-country runners. *International Journal of Sports Physical Therapy, 7*(3), 267.
13. Bergstra, S.A. Kluitenberg, B. Dekker, R. Bredeweg, S.W. Postema, K. Van den Heuvel, E.R. Hijmans, J.M. Sobhani, S. (2014). Running with a minimalist shoe increases plantar pressure in the forefoot region of healthy female runners. *Journal of Science and Medicine in Sport*, *18*(4), 463-468.
14. Bobbert, M. F., Schamhardt, H. C., & Nigg, B. M. (1991). Calculation of vertical ground reaction force estimates during running from positional data. *Journal of Biomechanics, 24*(12), 1095-1105.
15. Bonacci, J., Saunders, P.U., Hicks, A., Rantalainen, T., Vicenzino, B.G.T., Spratford, W., (2013). Running in a minimalist and lightweight shoe is not the same as running barefoot: a biomechanical study. Br. J. Sports Med. 387–392.

16. Bonci, C. M., Bonci, L. J., Granger, L. R., Johnson, C. L., Malina, R. M., Milne, L. W., Ryan, R. R., Vanderbunt, E. M. (2008). National athletic trainers' association position statement: Preventing, detecting, and managing disordered eating in athletes. *Journal of Athletic Training, 43*(1), 80-108.
17. Calbet, J. A., Dorado, C., Diaz-Herrera, P., & Rodriguez-Rodriguez, L. P. (2001). High femoral bone mineral content and density in male football (soccer) players. *Medicine and Science in Sport and Exercise, 33*(10).
18. Cavanagh, P. R., Lafortune, M. A. (1980). Ground reaction forces in distance running. *Journal of Biomechanics, 13*(5), 397-406.
19. Chen, T.L. An, W.W. Chan, Z.Y.S. Au, I.P.H. Zhang, Z.H. Cheung, R.T.H. (2016). Immediate effects of modified landing pattern on a probabilistic tibial stress fracture model in runners. *Clinical Biomechanics, 33*, 49-54.
20. Chen, Y., Tenforde, A., & Fredericson, M. (2013). Update on stress fractures in female athletes: Epidemiology, treatment, and prevention. *Current Reviews in Musculoskeletal Medicine*, *6*(2), 173-181.
21. Clansey, A. C., Hanlon, M., Wallace, E. S., Lake, M. J. (2012). Effects of fatigue on running mechanics associated with tibial stress fracture risk. *Medicine and Science in Sports and Exercise*, *44*(10), 1917-1923.
22. Cline, A. D., Jansen, G. R., Melby, C. L. (1998). Stress fractures in female army recruits: Implications of bone density, calcium intake, and exercise. *Journal of the American College of Nutrition, 17*(2), 128.
23. Cobb, K., Bachrach, L., Greendale, G., Marcus, R., Neer, R., Nieves, J., Sowers, M., Brown, B., Gopalakrishnan, G., Luetters, C., Tanner, H., Ward, B., Kelsey, J. (2003). Disordered eating, menstrual irregularity, and bone mineral density in female runners. *Medicine & Science in Sports & Exercise, 35*(5), 711-719.
24. Cobb, K., Bachrach, L., Sowers, M., Nieves, J., Greendale, G., Kent, K., Brown, B., Pettit, K., Harper, D., Kelsey, J. (2007). The effect of oral contraceptives in bone mass and stress fractures in female runners. *Medicine and Science in Sports and Exercise, 39*(9), 1464-1473.
25. Crowell, H., Davis, I. (2010). Gait retraining to reduce lower extremity loading in runners. *Clinical Biomechanics, 26*(1), 78-83.
26. Davis, I; Milner, CE; and Hamill, J, "Does increased loading during running lead to tibial stress fractures? A prospective study" (2004). *Medicine and Science in Sport and Exercie*, 36(5), 359.
27. Duckham, R. L., Peirce, N., Meyer, C., Summers, G. D., Cameron, N., Brooke-Wavell, K. (2012). Risk factors for stress fracture in female endurance athletes: A cross-sectional study. *BMJ Open, 2*(6), 1920.
28. Duncan, C. S., Blimkie, C. J. R., Cowell, C. T., Burke, S. T., Briody, J. N., Howman-Giles, R. (2002). Bone mineral density in adolescent female athletes: Relationship to exercise type and muscle strength. *Medicine and Science in Sports and Exercise, 34*(2), 286-294.
29. Dye, S. F., Stäubli, H. U., Biedert, R. M., Vaupel, G. L. (1999). The mosaic of pathophysiologycausing patellofemoral pain: Therapeutic implications. *Operative Techniques in Sports Medicine, 7*(2), 46-54.
30. Edwards, W.B., Rudolphi, T.D., Gillette, J.C., Derrick, T.R. (2010). Effects of running speed on a probabilistic stress fracture model. *Clinical Biomechanics, 25*(4), 372-377.

31. Edwards, W. B., Taylor, D., Rudolphi, T. J., Gillette, J. C., Derrick, T. R. (2009). Effects of stride length and running mileage on a probabilistic stress fracture model. *Medicine and Science in Sports and Exercise, 41*(12), 2177-2184.
32. Finestone, A., Milgrom, C. (2008). How stress fracture incidence was lowered in the israeli army: A 25-yr struggle. *Medicine and Science in Sports and Exercise,* , 623-629.
33. Firminger, C. R., Fung, A., Loundagin, L. L., Edwards, W. B. (2017). Effects of footwear and stride length on metatarsal strains and failure in running. *Clinical Biomechanics, 49*, 8-15.
34. Fehling, P. C., Alekel, L., Clasey, J., Rector, A., Stillman, R. J. (1995). A comparison of bone mineral densities among female athletes in impact loading and active loading sports. *Bone, 17*(3), 205-210.
35. Fogarty, S., PhD. (2014). Massage treatment and medial tibial stress syndrome; A commentary to provoke thought about the way massage therapy is used in the treatment of MTSS. *Journal of Bodywork & Movement Therapies, 19*(3), 447-452.
36. Fredericson, M., Jennings, F., Beaulieu, C., Matheson, G. O. (2006). Stress fractures in athletes. *Topics in Magnetic Resonance Imaging : TMRI, 17*(5), 309-325.
37. Fredericson, M., Ngo, J., Cobb, K. (2005). Effects of ball sports on future risk of stress fracture in runners. *Clinical Journal of Sport Medicine, 15*(3), 136-141.
38. Gabbett, T. J., Hulin, B. T., Blanch, P., Whiteley, R. (2016). High training workloads alone do not cause sports injuries: How you get there is the real issue.*British Journal of Sports Medicine, 50*(8), 444-445.
39. Gabbett, T. (2015). The training-injury prevention paradox: Should athletes be training smarter and harder?, 1-9.
40. George, W. T., Vashishth, D. (2005). Influence of phase angle between axial and torsional loadings on fatigue fractures of bone. *Journal of Biomechanics, 38*(4), 819-825.
41. Giladi, M., Milgrom, C., Simkin, A., Stein, M., Kashtan, H., Margulies, J., .Rand, N., Chisin, R., Steinberg, R., Aharonson, Z. (1987). Stress fractures and tibial bone width. A risk factor. *The Journal of Bone and Joint Surgery. British Volume, 69*(2), 326-329.
42. Greene, D., & Naughton, G. (2011). Calcium and vitamin-D supplementation on bone structural properties in peripubertal female identical twins: A randomised controlled trial. *Osteoporosis International, 22*(2), 489-498.
43. Halson, S., Bridge, M., Meeusen, R., Busschaert, B., Gleeson, M., Jones, D., Jeukendrup, A. (2002). Time course of performance changes and fatigue markers during intensified training in trained cyclists. *Journal of Applied Physiology, 93*(3), 947-956.
44. Hamill, J., Bates, B. T., Knutzen, K. M., Sawhill, J. A. (1983). Variations in ground reaction force parameters at different running speeds., 45-56.
45. Heinonen, A., Oja, P., Kannus, P., Sievanen, H., Haapasalo, H., Mänttäri, A., Vuori, I. (1995). Bone mineral density in female athletes representing sports with different loading characteristics of the skeleton. *Bone, 17*(3), 197-203.
46. Heinrich, C., Going, S., Pamenter, R., Perry, C., Boyden, T., Lohman, T. (1989). Bone mineral content of cyclically menstruating female resistance and endurance trained athletes. *Medicine and Science in Sports and Exercise, 22*(5), 558-563.
47. Hinton, P., Nigh, P., Thyfault, J. (2015). Effectiveness of resistance training or jumping-exercise to increase bone mineral density in men with low bone mass: A 12-month randomized, clinical trial. *Bone, 79*, 203-212.

48. Hreljac, A. (2004). Impact and overuse injuries in runners. *Medicine and Science in Sports and Exercise, 36*(5), 845-849.
49. Hughes, J. M., Popp, K. L., Yanovich, R., Bouxsein, M. L., Matheny, R. W. (2017). The role of adaptive bone formation in the etiology of stress fracture. *Experimental Biology and Medicine, 242*(9), 897-906.
50. Hulin, B. T., Gabbett, T. J., Caputi, P. (2016). Low chronic workload and the acute:chronic workload ratio are more predictive of injury than between-match recovery time: a two-season prospective cohort study in elite rugby players. *British Journal of Sports Medicine,* 50, 1008-1012.
51. Hulin, B. T., Gabbett, T. J., Caputi, P., Lawson, D. W., Sampson, J. A. (2016). The acute:chronic workload ratio predicts injury: high chronic workload may decrease injury risk in elite rugby league players. *British Journal of Sports Medicine,* 50, 231-236.
52. Iwamoto, J., Takeda, T. (2003). Stress fractures in athletes: Review of 196 cases. *Journal of Orthopaedic Science, 8*(3), 273-278.
53. Jones, B. H., Thacker, S. B., Gilchrist, J., Kimsey, J., C Dexter, Sosin, D. M. (2002). Prevention of lower extremity stress fractures in athletes and soldiers: A systematic review. *Epidemiologic Reviews, 24*(2), 228-247.
54. Joy, E., De Souza, M. J., Nattiv, A., Misra, M., Williams, N. I., Mallinson, R. J., Gibbs, J.C., Olmstead, M., Goolsby, M., Matheson, G., Barrack, M., Burke, L., Drinkwater, B., Lebrun, C., Loucks, A.B., Mountjoy, M., Nichols, J., Borgen, J. S. (2014). 2014 female athlete triad coalition consensus statement on treatment and return to play of the female athlete triad. *Current Sports Medicine Reports, 13*(4), 219-232.
55. Keller, T. S., Weisberger, A. M., Ray, J. L., Hasan, S. S., Shiavi, R. G., Spengler, D. M. (1996). Relationship between vertical ground reaction force and speed during walking, slow jogging, and running. *Clinical Biomechanics, 11*(5), 253-259.
56. Kelsey, J. L., Bachrach, L. K., Procter-Gray, E., Nieves, J., Greendale, G. A., Sowers, M., Brown, B., Matheson, K., Crawford, S., Cobb, K. L. (2007). Risk factors for stress fracture among young female cross-country runners. *Medicine and Science in Sports and Exercise, 39*(9), 1457-1463.
57. Kiernan, D., Hawkins, D. A., Manoukian, M. A. C., McKallip, M., Oelsner, L., Caskey, C. F., Coolbaugh, C. L. (2018). Accelerometer-based prediction of running injury in national collegiate athletic association track athletes. *Journal of Biomechanics, 73*, 201-209.
58. Kim, B. Y., Kraus, E., Fredericson, M., Tenforde, A. S. (2016). Serum Vitamin D Levels Are Inversely Associated with Time Lost to Bone Stress Injury in a Cohort of NCAA Division I Distance Runners. *Clinical Journal of Sports Medicine*, 26(2).
59. Kreher, J. B., Schwartz, J. B. (2012). Overtraining syndrome. *Sports Health, 4*(2), 128-138.
60. Kuhman, D. J., Paquette, M. R., Peel, S. A., Melcher, D. A. (2016). Comparison of ankle kinematics and ground reaction forces between prospectively injured and uninjured collegiate cross country runners. *Human Movement Science, 47*, 9-15.
61. Lack, S., Neal, B., De Oliveira Silva, D., Barton, C. (2018). How to manage patellofemoral pain – understanding the multifactorial nature and treatment options. *Physical Therapy in Sport, 32*, 155-166.

62. Lappe, J., Cullen, D., Recker, R., Ahlf, R., Thompson, K. (2008). Calcium and vitamin D supplementation decreases incidence of stress fractures in female navy recruits. *Journal of Bone and Mineral Research, 23*(4), 741-749.
63. Lanyon, L. E., Rubin, C. T. (1984). Static vs dynamic loads as an influence on bone remodelling. *Journal of Biomechanics, 17*(12), 897-905.
64. Lastella, M., Vincent, G. E., Duffield, R., Roach, G. D., Halson, S. L., Heales, L. J., Sargent, C. (2018). Can sleep be used as an indicator of overreaching and overtraining in athletes? *Frontiers in Physiology, 9*, 436.
65. Lehmann, M., Baumgartl, P., Wiesenack, C., Seidel, A., Baumann, H., Fischer, S., Spori, U., Gendrisch, G., Kaminski, R., Keul, J. (1992). Training-overtraining: Influence of a defined increase in training volume vs training intensity on performance, catecholamines and some metabolic parameters in experienced middle- and long-distance runners. *European Journal of Applied Physiology and Occupational Physiology, 64*(2), 169.
66. Li, S., Zhang, Y., Gu, Y., Ren, J. (2017). Stress distribution of metatarsals during forefoot strike versus rearfoot strike: A finite element study. *Computers in Biology and Medicine, 91*, 38-46.
67. Lim, B., Hinman, R. S., Wrigley, T. V., Bennell, K. L. (2008). Varus malalignment and its association with impairments and functional limitations in medial knee osteoarthritis. *Arthritis and Rheumatism, 59*(7), 935-942.
68. Lovell, G. (2008). Vitamin D status of females in an elite gymnastics program. *Clinical Journal of Sport Medicine, 18*(2), 159-161.
69. Malone, S., Owen, A., Mendes, B., Hughes, B., Collins, K., Gabbett, T. (2017). High-speed running and sprinting as an injury risk factor in soccer: Can well-developed physical qualities reduce the risk? *Journal of Science and Medicine in Sport, 21*(3), 257-262.
70. Mandell, J. C., Khurana, B., & Smith, S. E. (2017). Stress fractures of the foot and ankle, part 1: Biomechanics of bone and principles of imaging and treatment. *Skeletal Radiology, 46*(8), 1021-1029.
71. Meardon, S., Derrick, T. (2014). Effect of step width manipulation on tibial stress during running. *Journal of Biomechanics, 47*(11), 2738-2744. doi:10.1016/j.jbiomech.2014.04.047
72. Meardon, S., Willson, J., Gries, S., Kernozek, T., Derrick, T. (2015). Bone stress in runners with tibial stress fracture. *Clinical Biomechanics, 30*(9), 895-902.
73. Milgrom, C., Simkin, A., Eldad, A., Nyska, M., & Finestone, A. (2000). Using bone's adaptation ability to lower the incidence of stress fractures. *The American Journal of Sports Medicine, 28*(2), 245-251.
74. Miller, T. L., Best, T. M. (2016). Taking a holistic approach to managing difficult stress fractures. *Journal of Orthopaedic Surgery and Research, 11*(1), 98.
75. Milner, C., Hamill, J., Davis, I. (2007). Are knee mechanics during early stance related to tibial stress fracture in runners? *Clinical Biomechanics, 22*(6), 697-703.
76. Milner, C. E., Ferber, R., Pollard, C. D., Hamill, J., Davis, I. S. (2006). Biomechanical factors associated with tibial stress fracture in female runners. *Medicine and Science in Sports and Exercise, 38*(2), 323-328.

77. Milner, C. E., Hamill, J., Davis, I. S. (2010). Distinct hip and rearfoot kinematics in female runners with a history of tibial stress fracture. *The Journal of Orthopaedic and Sports Physical Therapy, 40*(2), 59-66.
78. Morris, F., Naughton, G., Gibbs, J., Carlson, J., Wark, J. (1997). Prospective ten-month exercise intervention in premenarcheal girls: Positive effects on bone and lean mass. *Journal of Bone and Mineral Research, 12*(9), 1453-1462.
79. Mosti, M., Carlsen, T., Aas, E., Hoff, J., Stunes, A., Syversen, U. (2014). Maximal strength training improves bone mineral density and neuromuscular performance in young adult women. *Journal of Strength and Conditioning Research, 28*(10), 2935-2945.
80. Mountjoy, M., Sundgot-Borgen, J., Burke, L., Carter, S., Constantini, N., Lebrun, C., Meyer, N., Shermann, R., Steffen, K., Budgett, R., Ljungqvist, A. (2014). The IOC consensus statement: Beyond the female athlete Triad—Relative energy deficiency in sport (RED-S). *British Journal of Sports Medicine, 48*(7), 491-497.
81. Murray, S. R., Reeder, M. T., Udermann, B. E., Pettitt, R. W. (2006). High-risk stress fractures: Pathogenesis, evaluation, and treatment. *Comprehensive Therapy, 32*(1), 20-25.
82. Myburgh, K., Hutchins, J., Fataar, A., Hough, S., Noakes, T. (1990). Low bone density is an etiologic factor for stress fractures in athletes. *Annals of Internal Medicine, 113*(10), 754-759.
83. Nattiv, A. (2000). Stress fractures and bone health in track and field athletes. *Journal of Science and Medicine in Sport, 3*(3), 268-279.
84. Nattiv, A., Kennedy, G., Barrack, M. T., Abdelkerim, A., Goolsby, M. A., Arends, J. C., Seeger, L. L. (2013). Correlation of MRI grading of bone stress injuries with clinical risk factors and return to play. *The American Journal of Sports Medicine, 41*(8), 1930-1941.
85. Nielsen, R. Ø, Parner, E. T., Nohr, E. A., Sørensen, H., Lind, M., Rasmussen, S. (2014). Excessive progression in weekly running distance and risk of running-related injuries: An association which varies according to type of injury. *The Journal of Orthopaedic and Sports Physical Therapy, 44*(10), 739-747.
86. Newman, P., Waddington, G., Adams, R. (2016). Shockwave treatment for medial tibial stress syndrome; a randomized double blind sham-controlled pilot trial. *Journal of Science and Medicine in Sport, 20*(3), 220-224.
87. Pohl, Mi., Mullineaux, D., Milner, C., Hamill, J., Davis, I. (2008). Biomechanical predictors of retrospective tibial stress fractures in runners. *Journal of Biomechanics, 41*(6), 1160-1165.
88. Popp, K., McDermott, W., Hughes, J., Baxter, S., Stovitz, S., Petit, Moira A. (2016). Bone strength estimates relative to vertical ground reaction force discriminates women runners with stress fracture history. *Bone, 94*, 22-28.
89. Rathleff, M.S. Samani, A. Olesen, C.G. Kersting, U.G. Madeleine, P. (2011). Inverse relationship between the complexity of midfoot kinematics and muscle activation in patients with medial tibial stress syndrome. *Journal of Electromyography and Kinesiology, 21*(4), 638-644.
90. Rauh, M. J. (2014). Summer training factors and risk of musculoskeletal injury among high school cross-country runners. *The Journal of Orthopaedic and Sports Physical Therapy, 44*(10), 793-804.
91. Rauh, M. J., Barrack, M., Nichols, J. F. (2014). Associations between the female athlete triad and injury among high school runners. *International Journal of Sports Physical Therapy, 9*(7), 948.

92. Ristolainen, L., Heinonen, A., Turunen, H., Mannström, H., Waller, B., Kettunen, J. A., Kujala, U. M. (2010). Type of sport is related to injury profile: A study on cross country skiers, swimmers, long-distance runners and soccer players. A retrospective 12-month study. *Scandinavian Journal of Medicine & Science in Sports, 20*(3), 384.

93. Rizzone, K. H., Ackerman, K. E., Roos, K. G., Dompier, T. P., Kerr, Z. Y. (2017). The epidemiology of stress fractures in collegiate student-athletes, 2004-2005 through 2013-2014 academic years. *Journal of Athletic Training*, *52*(10), 966-975.

94. Rutherford, D., Cheryl. J. (2008). Explaining the hip adduction moment variability during gait: Implications for hip abductor strengthening. *Clinical Biomechanics*, *24*(3), 267-273.

95. Queen, R., Abbey, A., Chuckpaiwong, B., Nunley, J. (2009). Plantar loading comparisons between women with a history of second metatarsal stress fractures and normal controls. *The American Journal of Sports Medicine*, *37*(2), 390-395.

96. Rooney, B., Derrick, T. (2013). Joint contact loading in forefoot and rearfoot strike patterns during running. *Journal of Biomechanics*, *46*(13), 2201-2206.

97. Roos, K. G., Marshall, S. W., Kerr, Z. Y., Golightly, Y. M., Kucera, K. L., Myers, J. B., Rosamund, W.D., Comstock, R. D. (2015). Epidemiology of overuse injuries in collegiate and high school athletics in the united states. *The American Journal of Sports Medicine*, *43*(7), 1790-1797.

98. Saxena, A., Fullem, B., Gerdesmeyer, L. (2017). Treatment of medial tibial stress syndrome with radial soundwave therapy in elite athletes: Current evidence, report on two cases, and Proposed treatment regimen. *The Journal of Foot and Ankle Surgery : Official Publication of the American College of Foot and Ankle Surgeons, 56*(5), 985.

99. Silk, L., Greene, D., Baker, M., Jander, C. (2015). Tibial bone responses to 6-month calcium and vitamin D supplementation in young male jockeys: A randomised controlled trial. *Bone, 81*, 554-561.

100. Snead, D., Weltman, A., Weltman, J., Evans, W., Veldhuis, J., Varma, M., Teates, D., Dowling, E., Rogol, A. (1992). Reproductive hormones and bone mineral density in women runners. *Journal of Applied Physiology, 72*(6), 2149-2156.

101. Snyder, K., Earl, J., O'Connor, K., Ebersole, K. (2008). Resistance training is accompanied by increases in hip strength and changes in lower extremity biomechanics during running. *Clinical Biomechanics*, *24*(1), 26-34.

102. Soligard, T., Schwellnus, M., Alonso, J., Bahr, R., Clarsen, B., Dijkstra, H. P., Gabbett, T., Gleeson, M., Hagglund, M., Hutchinson, M., Janse van Rensburg, C., Khan, K., Meeusen, R., Orchard, J., Pluim, B., Raftery, M., Budgett, R., Engebretsen, L. (2016). How much is too much? (part 1) international olympic committee consensus statement on load in sport and risk of injury. *British Journal of Sports Medicine*, *50*(17), 1030-1041.

103. Specker, B., Binkley, T., Vukovich, M., Beare, T. (2007). Volumetric bone mineral density and bone size in sleep-deprived individuals. *Osteoporosis International, 18*(1), 93-99.

104. Spiegel, K., Leproult, R., Van Cauter, E. (1999). Impact of sleep debt on metabolic and endocrine function. *The Lancet, 354*, 1435-1439.

105. Swanson, C., Shea, S., Wolfe, P., Cain, S., Munch, M., Vujovic, N., Czeisler, C., Buxton, O., Orwoll, E. (2017). Bone turnover markers after sleep restriction and circadian disruption: A mechanism for sleep-related bone loss in humans. *Journal of Clinical Endocrinology and Metabolism, 102*(10), 3722-3730.

106. Taafe, D., Robinson, T., Snow, C., Marcus, R. (1997). High-impact exercise promotes bone gain in well-trained female athletes. *Journal of Bone and Mineral Research, 12*(2), 255-260.
107. Tate, J. J., Milner, C. E. (2017). Sound-intensity feedback during running reduces loading rates and impact peak. *The Journal of Orthopaedic and Sports Physical Therapy, 47*(8), 565-569.
108. Tenforde, A., Kraus, E., Fredericson, M. (2016). Bone stress injuries in runners. *Physical Medicine and Rehabilitation Clinics of North America, 27*(1), 139-149.
109. Tenforde, A., Sayres, L., Sainani, K., Fredericson, M. (2010). Evaluating the relationship of calcium and vitamin D in the prevention of stress fracture injuries in the young athlete: A review of the literature. *Pm&r, 2*(10), 945-949.
110. Tenforde, A. S., Carlson, J. L., Chang, A., Sainani, K. L., Shultz, R., Kim, J. H., Cutti, P., Golden, N., Fredericson, M. (2017). Association of the female athlete triad risk assessment stratification to the development of bone stress injuries in collegiate athletes. *The American Journal of Sports Medicine, 45*(2), 302-310.
111. Tenforde, A., Sainani, K., Sayres, Lauren., Milgrom, C., Fredericson, M. (2015). Participation in ball sports may represent a prehabilitation strategy to prevent future stress fractures and promote bone health in young athletes. *Physical Medicine and Rehabilitation, 7*(2), 222-225.
112. Tenforde, A. S., Fredericson, M., Sayres, L. C., Cutti, P., Sainani, K. L. (2015). Identifying sex-specific risk factors for low bone mineral density in adolescent runners. *The American Journal of Sports Medicine, 43*(6), 1494-1504
113. Thomas, A. C., McLean, S. G., Palmieri-Smith, R. M. (2010). Quadriceps and hamstrings fatigue alters hip and knee mechanics.*Journal of Applied Biomechanics, 26*(2), 159-170.
114. Torstveit, M. K., Sundgot-Borgen, J. (2005). The female athlete triad: Are elite athletes at increased risk? *Medicine and Science in Sports and Exercise, 37*(2), 184-193.
115. Warden, S. J., Davis, I. S., Fredericson, M. (2014). Management and prevention of bone stress injuries in long-distance runners. *The Journal of Orthopaedic and Sports Physical Therapy, 44*(10), 749-765.
116. Weinstein, R., Jilka, R., Parfitt, A., Manolagas, S. (1998). Inhibition of osteoblastogenesis and promotion of apoptosis of osteoblasts and osteocytes by glucocorticoids. potential mechanisms of their deleterious effects on bone. *The Journal of Clinical Investigation, 102*(2), 274-282.
117. Willy, R. W., Buchenic, L., Rogacki, K., Ackerman, J., Schmidt, A., Willson, J. D. (2016). In-field gait retraining and mobile monitoring to address running biomechanics associated with tibial stress fracture. *Scandinavian Journal of Medicine & Science in Sports, 26*(2), 197-205.
118. Witzke, K. A., Snow, C. M. (2000). Effects of plyometric jump training on bone mass in adolescent girls. *Medicine and Science in Sports and Exercise, 32*(6), 1051-1057.
119. Zadpoor, A., Nikooyan, A. (2010). The relationship between lower-extremity stress fractures and the ground reaction force: A systematic review. *Clinical Biomechanics, 26*(1), 23-28.