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Risk Factors for Stress Fractures in Track and Field Athletes

A Twelve-Month Prospective Study*

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ABSTRACT

The aim of this 12-month prospective study was to investigate risk factors for stress fractures in a cohort of 53 female and 58 male track and field athletes, aged 17 to 26 years. Total bone mineral content, regional bone density, and soft tissue composition were measured using dual-energy x-ray absorptiometry and anthropometric techniques. Menstrual characteristics, current dietary intake, and training were assessed using questionnaires. A clinical biomechanical assessment was performed by a physical therapist. The incidence of stress fractures during the study was 21.1%, with most injuries located in the tibia. Of the risk factors evaluated, none was able to predict the occurrence of stress fractures in men. However, in female athletes, significant risk factors included lower bone density, a history of menstrual disturbance, less lean mass in the lower limb, a discrepancy in leg length, and a lower fat diet. Multiple logistic regression revealed that age of menarche and calf girth were the best independent predictors of stress fractures in women. This bivariate model correctly assigned 80% of the female athletes into their respective stress fracture or nonstress fracture groups. These results suggest that it may be possible to identify female athletes most at risk for this overuse bone injury.

Stress fractures are common overuse injuries sustained by athletes and cause considerable interference with training and competition. Stress fracture development occurs along a continuum, with repetitive mechanical loading, bone remodeling, and microdamage accumulation playing roles.[25] Numerous factors have been proposed as potential risk factors for stress fractures. These include low bone density, soft tissue composition, menstrual disturbances, dietary insufficiency, biomechanical variants, and excessive training.[6] Although several of these factors have been comprehensively assessed in large cross-sectional and prospective studies in male military recruits, results from military personnel cannot be generalized to sports populations because of differences in training, footwear, and initial fitness level.[14,15,32]

Most studies of female athletes have been cross-sectional designs with measurements obtained after injury. Although there has been one prospective study investigating risk factors for stress fractures, only preliminary results are available.[53] No studies focus specifically on the male athletic population. Once risk factors have been identified, it may be possible to implement measures to prevent this overuse bone injury. In the sports environment, prevention is far more attractive than even the most effective treatment. Therefore, the aims of this 12-month prospective study were to 1) assess the differences in bone mass, soft tissue composition, menstrual characteristics, diet, biomechanical features, and training between male

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and female athletes who subsequently develop stress fractures and those who do not, and 2) investigate the ability of risk factors to predict the likelihood of a stress fracture.

MATERIALS AND METHODS

Subjects

The cohort consisted of 53 female and 58 male track and field athletes registered with an Athletics Victoria club. Athletes ranged in age from 17 to 26 years (20.4 ± 2.1, mean ± 1 SD). Athletes were competing at club, state, or Australian national levels in a variety of events, except throwing and walking. Subjects were excluded from participation if they reported past (>12 months) or present use of anabolic steroids or human growth hormone, a history of disease with the potential to influence bone density, or if they were currently taking medication likely to influence bone density (with the exception of the oral contraceptive pill). In the year preceding the study, 21 (39.6%) women and 27 (46.6%) men were ranked within the top 50 Australian athletes and 13 (24.5%) women and 12 (20.7%) men were ranked within the top 20.[2] Subject recruitment and cohort demographics have been described in further detail in a previous study.[4]

Procedures

This research project was undertaken after approval from the Human Experimentation Ethics Committees of La Trobe University and The Royal Melbourne Hospital. All measurements except diet and training were assessed at the commencement of the 12-month study.

Dual-energy x-ray absorptiometry, employing a Hologic QDR 1000 W densitometer (Hologic Inc., Waltham, Massachusetts), was used to measure total-body bone mineral content, regional-areal bone mineral density, and soft tissue composition. Dual-energy x-ray absorptiometry acquisition and analyses were performed using the standard whole-body protocol version 5.47. Regional bone mineral density measurements included left and right upper limb, thoracic spine (T-1 to T-12), lumbar spine (L-1 to L-4), and left and right lower limbs. The lower limb was further subdivided into three regions: femur (proximal femoral neck to the knee joint); tibia and fibula (knee joint to the ankle joint); and foot (below the level of the ankle joint). The athletes' left and right sides were averaged to give the overall values for peripheral skeletal sites. We evaluated short-term in vivo precision of dual-energy x-ray absorptiometry from triplicate scans in 15 noninjured, healthy subjects. The coefficient of variation varied from 0.6% to 1.9% for bone mass measurements and from 0.4% to 1.2% for soft tissue composition measurements.

Anthropometric techniques were used to obtain height, weight, skinfold thickness, and limb girths based on procedures outlined by Ross and Marfell-Jones.[42] To provide a better indication of lean mass, corrected thigh and calf girths were calculated by subtracting the appropriate skinfold thickness measurement from the girth measurement.

Details regarding current and past menstrual status of female subjects were obtained via a questionnaire. Subjects were questioned regarding age of menarche; use of the combined oral contraceptive pill; duration of amenorrhea, defined as ≤3 menses per year; duration of oligomenorrhea, defined as 4 to 8 menses per year; duration of eumenorrhea, defined as ≥9 menses per year; previous pregnancies; commencement of athletic training in relation to menarche; and the number of menses in the year preceding the study. The number of years of amenorrhea, oligomenorrhea, and eumenorrhea were used to calculate a menstrual index for each subject. The menstrual index, adapted from the index devised by Grimston et al.,[16] quantifies the average number of menstrual cycles per year since menarche. The menstrual index ranged from 1.5 to 10.5 with a number less than 10.5 indicating ≤9 menses each year since menarche.

Current daily dietary intake was calculated from two 4-day food records that were completed during the summer and winter months of the study and from a food frequency questionnaire administered by the same researcher (KLB) at the conclusion of the study. The questionnaire pertained only to the athlete's usual calcium, caffeine, and alcohol intake during the 12-month study. Data from the food records and the questionnaire were analyzed by a registered dietitian (SJR) using the "Diet/1" software package, version 3.22 (Xyris Software, Brisbane, Australia), which uses the Nuttab Australia (1990) database (Commonwealth Department of Health and Community Services, Canberra, Australia). Other baseline dietary information was obtained via questionnaire, including past and current calcium supplementation use and lifetime alcohol consumption.[52] Eating attitudes and dietary behaviors were assessed using the EAT-40, a test designed and validated by Garner and Garfinkel.[13] The test is useful for identifying those persons with emotional disturbances characteristic of anorexia nervosa and with abnormal concerns about weight and food.

Athletes were interviewed by a researcher (KLB) at the conclusion of the study to obtain specific information about their track and field training during the preceding 12 months. Questions were divided into sections based on mode of training and included running, interval, hill, plyometric, skill, stretching, and cross-training. Details included amount, duration, and intensity of training, as well as footwear and surface.

The same physical therapist (KLB) performed a baseline clinical lower-limb biomechanical assessment on all athletes. The measurements chosen were those commonly used in a clinical setting that are simple to perform, time-efficient, and require minimal equipment. The measurements included sit-and-reach to assess hamstring muscle and lumbar spine flexibility,[44] passive range of hip external and internal rotation in the positions of hip flexion and extension using a gravity goniometer,[19,41] structural leg length,[21] dorsiflexion lunge to assess the range of ankle dorsiflexion in a weightbearing position,[32] and calf flexibility. The alignment of the lower limb in a nonweightbearing position was defined as relative varus, straight, or valgus.[32] The subject's foot type, assessed visually when the subject was bearing weight, was classified as either cavus, planus, or neutral.[10] Test-retest reliability of each measurement was evaluated in 14 young, healthy subjects, tested on 2 occasions 1 week apart. Intraclass correlation coefficients[47] or kappa coefficients[24] ranged from 0.74 to 1.0 and were taken to indicate acceptable reliability.

Stress Fracture Diagnosis

Athletes were closely monitored for signs and symptoms of a stress fracture over the 12 months.[17,28] Stress fractures were diagnosed by positive findings on clinical examination, triple-phase isotope bone scan, and CT scan. The diagnosis of stress fracture on radiographic investigations was made using a blinded protocol. A radiologist and a sports medicine physician independently interpreted the scans. Bone scans were considered diagnostic of a stress fracture if there was focal increased uptake, which was ovoid in shape, at the site of pain.[1,43,48] The CT scans were considered diagnostic of a stress fracture if they showed signs of a linear cortical defect, focal cortical lucency, periosteal new bone, cortical bridging, or focal sclerosis.[23,33,48]

Statistical Analysis

All statistics were performed with the Statistical Package for the Social Sciences (SPSS Inc., Chicago, Illinois). Risk factor variables were compared between the stress fracture and nonstress fracture groups during the 12-month study using univariate t-tests, Mann-Whitney U-tests, or chi-square tests at a two-tailed significance level of $P < 0.05$. Data from the men and women athletes were analyzed separately. Risk factors that were identified as being important in univariate analyses were entered into a forward, stepwise multiple logistic regression. The aim was to build a suitable multivariate model with a minimal number of independent or predictive variables.[20]

RESULTS

Over the course of the study, six subjects withdrew because of work commitments, nine retired from athletics or did not train during the year, and one relocated overseas. Among the remaining 46 female and 49 male athletes, 10 men and 10 women sustained at least 1 stress fracture during the 12 months and were therefore classified as belonging to the stress fracture groups. The other 36 female and 39 male athletes composed the nonstress fracture groups. Among the 26 stress fractures sustained, tibial fractures were the most common, composing 45% of the total. Further details regarding stress fracture incidence and distribution in this cohort have been previously reported.[4]

Table 1 shows the means (±SD) for total-body bone mineral content and regional bone mineral density, comparing athletes with and without stress fractures. Women who developed stress fractures had significantly lower values for total-body bone mineral content, and lumbar spine and foot bone mineral density. There were no significant differences between male athletes who developed stress fractures and those who did not for any bone mass variable. However, there appeared to be a trend toward lower bone mass in the male stress fracture group with deficits of 6.8% for total-body bone mineral content and 4.0% for tibial and fibular bone mineral density. Figure 1 shows deficits (±SE) in the bone mass of athletes with stress fractures as a percentage of those without them.

In the subgroup of athletes who sustained tibial stress fractures, tibial and fibular bone mineral density on the injured side was compared with the average tibial and fibular bone mineral density in athletes in the nonstress fracture group. The female tibial stress fracture group had 8.1% less tibial and fibular bone mineral density than the athletes in the nonstress fracture group ($P < 0.01$). In the men, the tibial stress fracture group had 4.0% less tibial and fibular bone mineral density than the nonstress fracture group, although this finding was not significant ($P = 0.17$).

When the bone mass values for the female athletes with stress fractures were compared with those of an age-matched group of female nonathletes ($N = 28$), the athletes with the bone injuries had significantly higher lower-limb bone mineral density ($P < 0.05$) and similar total-body bone mineral content and lumbar spine bone mineral density.

There was no difference between female or male stress

TABLE 1
Mean (±SD) of Baseline Total Body Bone Mineral Content (BMC) (in grams) and Regional Bone Mineral Density (BMD) (in grams per square centimeters) for Stress Fractures (SF) and Nonstress Fracture (NSF) Groups

Variable	Women		Men	
	SF (N = 10)	NSF (N = 36)	SF (N = 10)	NSF (N = 39)
Total body BMC	2000.4 (244.8)	2200.5 (253.8)[a]	2481.6 (210.9)	2662.3 (346.3)
Upper limb BMD	0.773 (0.06)	0.799 (0.041)	0.874 (0.045)	0.904 (0.054)
Thoracic spine BMD	0.852 (0.109)	0.913 (0.096)	0.837 (0.064)	0.873 (0.114)
Lumbar spine BMD	0.996 (0.165)	1.131 (0.124)[b]	1.145 (0.092)	1.154 (0.125)
Lower limb BMD	1.108 (0.080)	1.146 (0.080)	1.250 (0.080)	1.287 (0.089)
Femur BMD	1.181 (0.107)	1.207 (0.101)	1.318 (0.099)	1.357 (0.115)
Tibia/fibula BMD	1.075 (0.082)	1.122 (0.072)	1.190 (0.078)	1.240 (0.093)
Foot BMD	0.980 (0.069)	1.049 (0.097)[a]	1.219 (0.118)	1.223 (0.097)

[a] $P < 0.05$, t-test.
[b] $P < 0.01$, t-test.

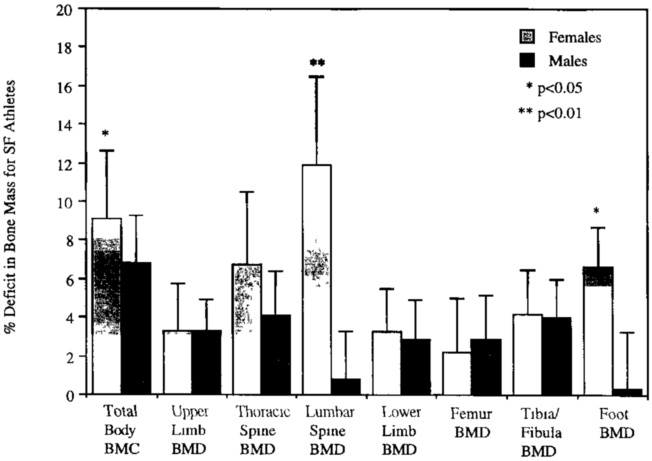

Figure 1. Percentage (±SE) deficits in total body bone mineral content (BMC) and regional bone mineral density (BMD) of the stress fracture group compared with the nonstress fracture group

fracture and nonstress fracture groups for age, height, weight, total lean mass, sum of eight skinfolds, corrected thigh girth, or total body-fat mass. However, women with stress fractures had significantly less lean mass in the lower limb, as measured using dual-energy x-ray absorptiometry, and a smaller corrected calf girth compared with the women in the nonstress fracture group.

Table 2 shows menstrual characteristics for athletes with and without stress fractures. Female athletes who sustained a stress fracture had a significantly later age of menarche, fewer menses in the year preceding the study, and a lower menstrual index indicating fewer menses per year since menarche. Although a greater percentage of women who developed a stress fracture reported a history of amenorrhea, this finding was not significant. There were no differences between female groups for years since menarche, participation in premenarcheal training, and past or current use of the oral contraceptive pill.

Table 3 shows a comparison of daily macro- and micronutrient intake for stress and nonstress fracture groups of both sexes. There was no difference between male groups for any of the dietary variables. Women who sustained a stress fracture had a significantly lower fat intake per kilogram of body weight and a higher calcium intake in relation to total energy intake when compared with the female nonstress fracture group. However, daily calcium intake, assessed by either the food records or the food frequency questionnaire, did not differ between female groups. Using 800 mg as the recommended daily intake for calcium,[9] stress fracture and nonstress fracture female groups consumed 134% and 123% of the recommended daily intake, respectively. Similar results were obtained when assessing calcium intake derived from the questionnaire. For men, the daily calcium intake was 166% of the recommended daily intake in the stress fracture group and 157% in the nonstress fracture group. There was no difference in calcium intake as a proportion of total-body bone mineral content or as a proportion of other nutrients comparing stress fracture and nonstress fracture groups in either sex. There was no difference between the stress fracture and nonstress fracture groups for prevalence or total duration of calcium supplementation use. Current daily energy intake and intake of protein, carbohydrate, alcohol, caffeine, fiber, sodium, or phosphorus did not differ between the groups. Scores on the EAT-40 test were also similar in both groups with scores indicating that few athletes had eating behaviors or attitudes characteristic of anorexia nervosa.

TABLE 2
Menstrual Characteristics for Female Athletes With and Without Stress Fractures

Characteristic[a]	Stress Fracture	Nonstress Fracture
Age of menarche (years)	15.6 (2.2)	13.9 (1.3)[b]
Premenarcheal training *N* (%)	7 (70%)	22 (61%)
Menstrual index (1.5–10.5)	6.5 (3.5)	8.8 (1.6)[c]
Number of menses in previous year	8.6 (4.5)	11.3 (2.5)[c]
Currently oligo- or amenorrheic *N* (%)	3 (30%)	4 (11%)
History of oligomenorrhea *N* (%)	3 (33%)	13 (36%)
History of amenorrhea *N* (%)	5 (50%)	10 (28%)
Ever used OCP *N* (%)	6 (60%)	21 (58%)
Taken OCP in past 12 months *N* (%)	4 (40%)	13 (36%)

[a] OCP, oral contraceptive pill. Mean (±SD) or frequency (%).
[b] $P < 0.01$, *t*-test or Mann-Whitney *U* test.
[c] $P < 0.05$, *t*-test or Mann-Whitney *U* test.

The results of the clinical biomechanical assessment comparing athletes in the stress fracture and nonstress fracture groups showed no difference between groups for sit-and-reach, range of hip internal and external rotation, calf flexibility, and range of ankle joint dorsiflexion. Differences between left and right sides and between hip internal and external rotation were also similar in both groups. The percentage of athletes with neutral, planus, or cavus foot types and with straight, varus, or valgus lower-limb alignment did not differ between groups. However, a significantly greater number of women in the stress fracture group (70%) displayed a difference in leg length than did their counterparts in the nonstress fracture group (36%) ($P < 0.05$). Although stress fractures occurred with equal frequency in the longer and shorter limb, 71% of the injuries occurred in the dominant lower limb.

There was great variation in the weekly training characteristics of athletes (when not injured) in the year of the study because of the combination of different track and field event groups. Athletes in the stress fracture and nonstress fracture groups commenced athletic training at a similar age, approximately 11 years, with more than 78 (70%) athletes involved in the sport for more than 5 years. There were no significant differences between athletes who did and did not develop a stress fracture for any of the measured training variables, including weekly training hours, running distance, training mode, footwear, and surface.

In female athletes, the results of the logistic regression model showed that corrected calf girth (β, −1.38; SE, 0.52) and age of menarche (β, 1.40; SE, 0.66) were significant, independent predictors of the probability of stress frac-

TABLE 3
Comparison of Mean (±SD) Daily Macro- and Micronutrient Intake for Stress Fracture (SF) and Nonstress Fracture (NSF) Groups

Nutrient[a]	Women		Men	
	SF	NSF	SF	NSF
Energy (kj)	7258.3 (1783.9)	8525.8 (2371.9)	13340.9 (2399.8)	13257.0 (2573.4)
Protein (g)	82.9 (19.1)	89.1 (35.0)	116.9 (13.4)	124.3 (27.0)
CHO (g)	252.2 (87.3)	269.8 (74.4)	424.8 (84.0)	419.7 (92.5)
Fat (g)	43.4 (17.9)	66.3 (31.1)	114.9 (29.4)	110.6 (30.8)
Caffeine FFQ (mg)	174.6 (356.1)	121.1 (228.6)	66.0 (60.9)	117.3 (155.1)
Fiber (g)	30.9 (17.4)	28.1 (9.1)	33.5 (12.1)	36.2 (12.5)
Calcium (mg)	1075.2 (426.7)	985.1 (297.0)	1325.5 (373.5)	1252.8 (423.8)
Calcium FFQ (mg)	1277.1 (841.1)	981.5 (721.5)	1213.3 (534.1)	1416.4 (619.8)
Sodium (mg)	2295.0 (660.6)	2308.1 (782.6)	3555.1 (1212.3)	3726.8 (919.9)
Phosphorus (mg)	1381.5 (387.9)	1431.8 (443.2)	1835.3 (325.3)	1951.6 (488.9)

[a] CHO, carbohydrate; FFQ, food frequency questionnaire.

ture. Odds ratios revealed that for every additional year of age at menarche, the risk of stress fracture increased by a factor of 4.1. For every 1-cm decrease in calf girth, the risk of sustaining a stress fracture increased fourfold. The probability of a stress fracture at different ages of menarche was calculated as a function of small, average, and large corrected calf girths and plotted in Figure 2. The results show that one's corrected calf girth exerts a greater influence on the risk of stress fracture than does one's age of menarche.

The two predictive variables in this logistic regression model were tested in relation to their influence on stress fracture incidence. Each variable was divided into two subgroups using the median value. The trend of stress fracture morbidity was assessed by assigning a quantitative value to each subgroup (0, no risk; 1, risk). Age of menarche more than 14 years and a corrected calf girth less than 32.2 cm were each assigned a score of 1. The percentage of women with stress fractures was lowest (0%) when neither of the risk factors were present (risk score, 0), intermediate (15%) when one risk factor was present (risk score, 1), and highest (50%) when two risk factors were present (risk score, 2) ($P < 0.01$).

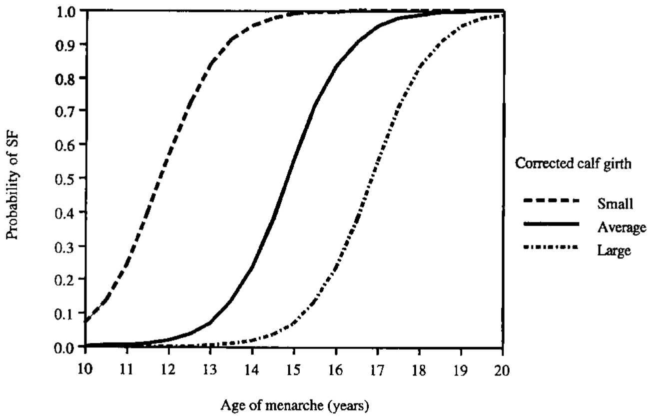

Figure 2. Plot of the probability of stress fracture at different ages of menarche for different corrected calf girths in female athletes. The plot for small corrected calf girth was calculated using the minimum value measured in the sample. The average girth was calculated using the mean value, and the large girth was calculated using the maximum value.

The logistic regression model, containing the variables corrected calf girth and age of menarche, was able to correctly classify 89 (80.4%) athletes into the appropriate stress fracture or nonstress fracture groups ($P < 0.05$). The model correctly predicted 33 (91.7%) of the women would be in the nonstress fracture group and 4 (40.0%) of the women would be in the stress fracture group, indicating a greater proportion of false-negatives than false-positives. Because the sample size was relatively small, the effect of adding a third variable to this logistic regression model was evaluated. The results showed that although none of the third variables was significant when included into the model, the variables of bone mineral density of the foot and leg-length difference significantly improved the model's predictive ability. Therefore, if the aim is to improve the prediction of stress fracture occurrence, a three-variable model, including either bone mineral density of the foot or leg-length difference, may be suitable.

DISCUSSION

The aim of this study was to conduct a comprehensive analysis of risk factors for stress fractures in track and field athletes using a prospective cohort design. Results differed between men and women, highlighting a sex effect. Female athletes who developed stress fractures had significantly less total-body bone mineral content, lower lumbar spine and foot bone density, less lean mass in the lower limb, a later age of menarche, fewer menses per year since menarche, a lower fat diet, and a leg-length discrepancy compared with their nonstress fracture counterparts. Contrary to expectations, dietary calcium intake, restrictive dietary patterns, use of the oral contraceptive pill, training parameters, height, weight, and total body-fat mass did not differ between those who did and did not sustain stress fractures.

For men, there were no significant differences between the stress fracture and nonstress fracture groups for any bone mass, body composition, dietary, biomechanical, or training variable. Thus, none of the measured variables could be used to identify the male athletes most likely to develop a stress fracture. The null findings could be because of a lack of statistical power, given the size of the stress fracture group, or because of the relative unimportance of the selected variables. Other factors not assessed in this study may play a greater role in conferring risk of stress fracture in men. It is also possible that risk factors are specific to the stress fracture sites and to event groups within track and field. Because of the limited sample size, risk factors could not be analyzed in this manner. This may have resulted in a failure to identify potential relationships for some factors. Although no comparable data exist for male athletes, the nonsignificant findings tend to agree with those of prospective military studies in which much larger cohorts were involved and few risk factors were identified from an extensive number of subjects measured.[14,15]

This is the first prospective study to address whether low bone density predisposes athletes to stress fractures. Women who developed stress fractures had lower bone densities with significant deficits in both the axial and appendicular skeletons. Cross-sectional studies have found similar results at the lumbar spine.[7,34] The magnitude of the reported deficits, 4.0% and 8.5%, are less than the 11.9% shown presently. This may partly relate to the use of the less-precise dual-energy x-ray absorptiometry in one study,[7] and to the inclusion of men in another.[34]

Because stress fractures did not occur in the lumbar spine, the finding of lower bone density at this site does not support a causal relationship. Instead, lower axial bone density may be an indicator of other factors associated with stress fracture risk, such as ovarian dysfunction or inadequate dietary intake. The higher prevalence of menstrual disturbances reported by the athletes with stress fractures may well have contributed to both spinal osteopenia and stress fracture development. However, support for a possible cause-and-effect relationship between low bone density and stress fracture is provided by our findings of significantly lower foot bone density in the stress fracture group and lower tibial and fibular bone density in the subgroup of women who sustained tibial stress fractures. Although bone density is lower in athletes with stress fractures, it nevertheless remains significantly higher at the lower limb and similar at the lumbar spine than that of less active nonathletes. This suggests that the level of bone density required by athletes for short-term bone health is greater than that required by the general population.

Conversely, bone density values did not predict stress fracture occurrence in the men. This may be because of higher regional bone density in the men compared with the women. However, the possibility that lower bone density is a risk factor in male athletes cannot be entirely excluded.[40] Deficits in bone density were noted at most regional anatomic sites in the men who developed stress fractures, and the deficits were similar in magnitude to those seen in the women, except at the lumbar spine and foot. The sex difference at the lumbar spine could highlight the role played by estrogen in the maintenance of axial bone density in women.

Both anthropometric and dual-energy x-ray absorptiometric measurements evaluating lower limb muscularity revealed that female athletes who sustained stress fractures were less muscular compared with female athletes in the nonstress fracture groups. This deficit appeared to be a regional, rather than a generalized phenomenon, because total body lean mass and thigh girth values did not differ between the two groups. Our results confirm those reported by Milgrom,[30] who used the same measurement technique to obtain calf circumference in male military recruits. However, it is unclear why our finding was only apparent in the female and not the male athletes.

The association between muscle mass and stress fracture occurrence might be explained by lower regional bone density because both corrected calf girth and dual-energy x-ray absorptiometric lower limb lean mass were positively correlated with tibial and fibular bone density (r, 0.37 to 0.41). A second possible explanation relates to the theory that the shock-absorbing ability of muscle plays a major role in reducing forces on bone.[39] In vivo animal models have shown that muscle contraction enhances bone strength and protects against fracture.[36–38] Using a biomechanical model, Scott and Winter[46] calculated that during running, the region of the tibia where most stress fractures occur is subjected to a large forward-bending moment as a result of ground-reaction force. The calf muscles oppose this large bending moment by applying a backward moment as the muscles contract to control the rotation of the tibia and the lowering of the foot to the ground. The total effect is a smaller bending moment. Extrapolating from this, a stress fracture could result if the calf muscles are unable to produce adequate force to counteract the loading at ground contact and decrease excessive bone strain.

Women who developed stress fractures had fewer menses in the preceding year than their nonstress-fracture counterparts, and they were more likely to have a history of menstrual disturbance. This supports the findings of numerous cross-sectional studies.[7,8,22,26,27,34,35,51] Therefore, factors associated with menstrual disturbances are acting to confer an increased risk for stress fracture in these athletes. Conversely, the results of the present study do not support the contention that use of the oral contraceptive pill protects against stress fracture.[3,34] However, a randomized controlled trial is necessary to clarify this issue because reasons for use or nonuse of the oral contraceptive pill may confound the relationship.

Women with an older menarcheal age had a greater likelihood of developing a stress fracture, which is consistent with the finding of some cross-sectional studies.[7,50,51] Age of menarche is associated with several other factors capable of influencing stress fracture development. We noted an inverse relationship with lumbar spine bone density ($r = -0.31$) but not with bone density at stress fracture sites. Women with a later age of menarche were also more likely to report a history of menstrual disturbance. However, other factors cited in association with later menarcheal age, such as intensive physical activity during puberty,[12,49] low levels of body fat or weight,[31] and low energy intake,[31] did not differ between our stress fracture and nonstress fracture groups.

Risk of stress fracture was not associated with current calcium intake, current intake of nutrients known to influence calcium bioavailability and bone mass, or use of calcium supplementation. Because two different dietary intake measurement tools essentially yielded the same results, the findings are strengthened. Furthermore, when expressed in terms of energy intake, female athletes in the stress fracture group were consuming significantly more calcium than those in the nonstress fracture group. It has been previously demonstrated that dietary calcium intakes more than 800 mg/day may be protective against stress fracture in athletes.[34] Because the majority of athletes in our study were consuming more than this amount, the results suggest that the relative risk of stress fracture is not influenced by daily intakes above this level. This concurs with findings of a large randomized calcium intervention trial in the military.[45] It also supports the concept of calcium as a threshold nutrient, whereby effects on the skeleton are only apparent up to a certain level.[29] The results do not exclude calcium deficiency as a risk factor for stress fracture given the high level of calcium consumed by our athletes. In addition, historical calcium intake may play an important role, but this factor was not assessed given the limitations associated with recall over such a time frame.[34]

A difference in leg length more than 0.5 cm was more common in the women who developed stress fractures than in those who did not. This has been previously noted in male military recruits using radiographic techniques to assess leg length[11] and in male and female runners via self-reports.[5] Friberg[11] found that tibial, metatarsal, and femoral stress fractures were more likely to occur in longer limbs, and fibular fractures were more likely to occur in shorter limbs. We found that stress fractures occurred with equal frequency in the shorter and longer limbs, which may be because of the combination of all stress fracture sites. However, stress fractures were more likely to occur in the dominant limb. This could be because of greater usage of this limb, especially in events such as long jump and hurdles where loading is likely to be asymmetrical.

No other measurements included in the clinical biomechanical assessment were useful predictors of stress fracture occurrence. There are several feasible explanations for this result. First, it is possible that the relative importance of biomechanical risk factors will differ according to skeletal site. Second, given the small stress fracture sample in this study, the moderate precision of measurement and the degree of variability in the data, large differences between groups would have been required to achieve statistical significance. Although more complex techniques with greater precision are available, it was considered important to use techniques in common clinical usage to facilitate the clinical relevance of the results. Third, the level of certain variables may exhibit temporal fluctuation. This means that baseline measurements might not adequately reflect the status of the variable in the weeks preceding a stress fracture. Fourth, static measurements may not necessarily correlate with the dynamic situation.[18] Finally, it is possible that other biomechanical factors not measured in this study, such as malleolar torsion and range of subtalar joint motion, are more important in the prediction of stress fractures.

Because a stress fracture is an overuse injury resulting from repetitive loading, training must play a part in affecting the likelihood of this injury by influencing the characteristics of the mechanical strain environment. Although there was no difference between athletes who did and did not sustain stress fractures for training amount, mode, surface, or footwear, the retrospective nature of data collection must be considered. Limitations arise from difficulties in accurate recall and the inability to quantify training in the weeks preceding a stress fracture. In addition, there was great variability in training regimes reflecting the inclusion of numerous event groups. Ideally, the effect of training on stress fracture development should be assessed separately in each group.

Among the significant risk factors identified, the best predictive model for stress fractures in women comprised age of menarche and corrected calf girth. The inclusion of either bone density of the foot or leg-length difference increased the sensitivity of this model. From a practical perspective, age of menarche, corrected calf girth, and leg length could be easily assessed by health professionals or coaches at minimal cost and effort. The assessment of bone density of the foot is less practical because it requires attendance at an appropriate facility, exposure to radiation, albeit minimal, and is relatively costly. Because leg-length discrepancy and bone density of the foot were equally effective in improving the predictive ability of the model and no further benefits were achieved by including both variables, leg length would be the more practical risk factor to measure. Once athletes had been screened and identified as being at high risk for stress fracture, these athletes could be given modified training programs designed to reduce repetitive mechanical loading, and they could be monitored closely for signs and symptoms of excessive bone strain. Educating athletes about the nature of overuse bone pain and encouraging them to advise the coach or seek medical attention immediately after the onset of any symptoms, however minor, would allow early intervention. A brief rest or reduced training at an early stage may facilitate repair and prevent the progression of bone microdamage. This approach might reduce the time missed from training and the associated morbidity. Although it is possible that altering the risk factors themselves could reduce the incidence of stress fractures, a causal relationship cannot be established from this study.

CONCLUSIONS

This is the first study to assess risk factors for stress fractures specifically in male athletes and the first to evaluate the role of bone density as a risk factor for stress fractures in male and female athletes using a prospective research design. The results indicate a sex difference in the predictability of stress fracture occurrence in this cohort of track and field athletes. In women, several factors were associated with the development of stress fractures. A predictive model was established incorporating the variables of age of menarche and calf girth. This model may be useful in a clinical setting to assist in the identification of female athletes at risk for stress fracture who warrant specialized attention from coaches and medical personnel.

In contrast, none of the measured variables contributed to stress fracture risk in the male athletes. This result may imply that other contributory factors not included in this study are more important in men. Further research should be directed at identifying predictors in male athletes, at confirming the present results in an independent cohort, and at assessing the efficacy of preventive strategies in an attempt to reduce the incidence of this overuse bone injury.

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REFERENCES

1. Ammann W, Matheson GO: Radionuclide bone imaging in the detection of stress fractures. *Clin J Sports Med 1:* 115–122, 1991
2. Athletics Australia: *Handbook of Records and Results 1991–92.* Melbourne, Victoria, 1992
3. Barrow GW, Saha S: Menstrual irregularity and stress fractures in collegiate female distance runners. *Am J Sports Med 16:* 209–216, 1988
4. Bennell KL, Malcolm SA, Thomas SA, et al: The incidence and distribution of stress fractures in competitive track and field athletes: A twelve-month prospective study. *Am J Sports Med 24:* 211–217, 1996
5. Brunet ME, Cook SD, Brinker MR, et al: A survey of running injuries in 1505 competitive and recreational runners. *J Sports Med Phys Fitness 30:* 307–315, 1990
6. Cameron KR, Wark JD, Telford RD: Stress fractures and bone loss—the skeletal cost of intense athleticism. *Excel 8:* 39–55, 1992
7. Carbon R, Sambrook PN, Deakin V, et al: Bone density of elite female athletes with stress fractures. *Med J Aust 153:* 373–376, 1990
8. Clark N, Nelson M, Evans W: Nutrition education for elite female runners. *Physician Sportsmed 16(2):* 124–136, 1988
9. Commonwealth Department of Health: Recommended Dietary Intakes for Use in Australia. Canberra: Australian Government Publishing Service, 1987
10. Dahle LK, Mueller M, Delitto A, et al: Visual assessment of foot type and relationship of foot type to lower extremity injury. *J Orthop Sports Phys Ther 14:* 70–74, 1991
11. Friberg O: Leg length asymmetry in stress fractures. A clinical and radiological study. *J Sports Med Phys Fitness 22:* 485–488, 1982
12. Frisch RE, Gotz-Welbergen AV, McArthur JW, et al: Delayed menarche and amenorrhea of college athletes in relation to age of onset of training. *JAMA 246:* 1559–1563, 1981
13. Garner DM, Garfinkel PE: The Eating Attitudes Test: An index of the symptoms of anorexia nervosa. *Psychol Med 9:* 273–279, 1979
14. Giladi M, Milgrom C, Simkin A, et al: Stress fractures: Identifiable risk factors. *Am J Sports Med 19:* 647–652, 1991
15. Giladi M, Milgrom C, Stein M, et al: External rotation of the hip. A predictor of risk for stress fractures. *Clin Orthop 216:* 131–134, 1987
16. Grimston SK, Sanborn CF, Miller PD, et al: The application of historical data for evaluation of osteopenia in female runners: The menstrual index. *Clin Sports Med 2:* 108–118, 1990
17. Ha KI, Hahn SH, Chung M, et al: A clinical study of stress fractures in sports activities. *Orthopaedics 14:* 1089–1095, 1991
18. Hamill J, Bates BT, Knutzen KM, et al: Relationship between selected static and dynamic lower extremity measures. *Clin Biomech 4:* 217–225, 1989
19. Hoppenfeld S: *Physical Examination of the Spine and Extremities.* Norwalk, CT, Appleton-Century-Crofts, 1976, pp 158–159
20. Hosmer DW, Lemeshow S: *Applied Logistic Regression. Volume 1240.* New York, John Wiley & Sons Inc, 1989
21. Hoyle DA, Latour M, Bohannon RW: Intraexaminer, interexaminer, and interdevice comparability of leg length measurements obtained with measuring tape and metrecom. *J Orthop Sports Phys Ther 14:* 263–268, 1991
22. Kadel NJ, Teitz CC, Kronmal RA: Stress fractures in ballet dancers. *Am J Sports Med 20:* 445–449, 1992
23. Kiss ZS, Khan KM, Fuller PJ: Stress fractures of the tarsal navicular bone: CT findings in 55 cases. *AJR 160:* 111–115, 1993
24. Landis JR, Koch GG: The measurement of observer agreement for categorical data. *Biometrics 33:* 159–174, 1977
25. Li G, Zhang S, Chen G, et al: Radiographic and histologic analyses of stress fracture in rabbit tibias. *Am J Sports Med 13:* 285–294, 1985
26. Lloyd T, Triantafyllou SJ, Baker ER, et al: Women athletes with menstrual irregularity have increased musculoskeletal injuries. *Med Sci Sports Exerc 18:* 374–379, 1986
27. Marcus R, Cann C, Madvig P, et al: Menstrual function and bone mass in elite women distance runners: Endocrine and metabolic features. *Ann Intern Med 102:* 158–163, 1985
28. Matheson GO, Clement DB, McKenzie DC, et al: Stress fractures in athletes. A study of 320 cases. *Am J Sports Med 15:* 46–58, 1987
29. Matkovic V, Heaney RP: Calcium balance during human growth: Evidence for threshold behaviour. *Am J Clin Nutr 55:* 992–996, 1992
30. Milgrom C: The Israeli elite infantry recruit: A model for understanding the biomechanics of stress fractures. *J R Coll Surg Edinb 34:* S18–S22, 1989
31. Moisan J, Meyer F, Gingras S: A nested case-control study of the correlates of early menarche. *Am J Epidemiol 132:* 953–961, 1990
32. Montgomery LC, Nelson FRT, Norton JP, et al: Orthopedic history and examination in the etiology of overuse injuries. *Med Sci Sports Exerc 21:* 237–243, 1989
33. Murcia M, Brennan RE, Edeiken J: Computed tomography of stress fracture. *Skeletal Radiol 8:* 193–195, 1982
34. Myburgh KH, Hutchins J, Fataar AB, et al: Low bone density is an etiologic factor for stress fractures in athletes. *Ann Intern Med 113:* 754–759, 1990
35. Nelson ME, Clark N, Otradovec C, et al: Elite women runners: Association between menstrual status, weight history and stress fractures. *Med Sci Sports Exerc 19:* S13, 1987
36. Nordsletten L, Ekeland A: Muscle contraction increases the structural capacity of the lower leg: An in vivo study in the rat. *J Orthop Res 11:* 299–304, 1993
37. Nordsletten L, Ekeland A: Muscle contribution to tibial fracture strength in rats. *Acta Orthop Scand 64:* 157–160, 1993
38. Nordsletten L, Kaastad TS, Obrant KJ, et al: Muscle contraction increases the in vivo structural strength to the same degree in osteopenic and normal rat tibiae. *J Bone Miner Res 9:* 679–685, 1994
39. Paul IL, Munro MB, Abernethy PJ, et al: Musculo-skeletal shock absorption: Relative contribution of bone and soft tissues at various frequencies. *J Biomech 11:* 237–239, 1978
40. Pouilles JM, Bernard J, Tremollieres F, et al: Femoral bone density in young male adults with stress fractures. *Bone 10:* 105–108, 1989
41. Reid DC, Burnham RS, Saboe LA, et al: Lower extremity flexibility patterns in classical ballet dancers and their correlation to lateral hip and knee injuries. *Am J Sports Med 15:* 347–352, 1987
42. Ross WD, Marfell-Jones MJ: Kinanthropometry, in MacDougall JD, Wenger HA, Green HJ (eds): *Physiological Testing of the High-Performance Athlete.* Second edition. Champaign, IL, Human Kinetics Books, 1991, pp 223–308
43. Roub LW, Gumerman LW, Hanley EN, et al: Bone stress: A radionuclide imaging perspective. *Radiology 132:* 431–438, 1979
44. Safrit MJ: *Introduction to Measurement in Physical Education and Exercise Science.* St. Louis, Times Mirror/Mosby, 1986, pp 241–244
45. Schwellnus MP, Jordaan G: Does calcium supplementation prevent bone stress injuries? A clinical trial. *Int J Sport Nutr 2:* 165–174, 1992
46. Scott SH, Winter DA: Internal forces at chronic running injury sites. *Med Sci Sports Exerc 22:* 357–369, 1990
47. Shrout PE, Fleiss JL: Intraclass correlations: Uses in assessing rater reliability. *Psychol Bull 86:* 420–428, 1979
48. Somer K, Meurman KO: Computed tomography of stress fractures. *J Comput Assist Tomogr 6:* 109–115, 1982
49. Warren MP: The effects of exercise on pubertal progression and reproductive function in girls. *J Clin Endocrinol Metab 51:* 1150–1157, 1980

50. Warren MP, Brooks-Gunn J, Fox RP, et al: Lack of bone accretion and amenorrhea: Evidence for a relative osteopenia in weight bearing bones. *J Clin Endocrinol Metab 72:* 847–853, 1991
51. Warren MP, Brooks-Gunn J, Hamilton LH, et al: Scoliosis and fractures in young ballet dancers: Relation to delayed menarche and secondary amenorrhea. *N Engl J Med 314:* 1348–1353, 1986
52. Young D, Hopper JL, Nowson CA, et al: Determinants of bone mass in 10- to 26-year-old females: A twin study. *J Bone Miner Res 10:* 558–567, 1995
53. Zernicke R, McNitt-Gray J, Otis C, et al: Stress fracture risk assessment among elite collegiate women runners. *Proceedings of the International Society of Biomechanics XIVth Congress.* Paris, 1506–1507, 1993