Ground Reaction Forces and Bone Parameters in Females with Tibial Stress Fracture

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ABSTRACT

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Purpose: Tibial stress fracture is a common overuse running injury that results from the interplay of repetitive mechanical loading and bone strength. This research project aimed to determine whether female runners with a history of tibial stress fracture (TSF) differ in ground reaction force (GRF) parameters during running, regional bone density, and tibial bone geometry from those who have never sustained a stress fracture (NSF). **Methods:** Thirty-six female running athletes (13 TSF; 23 NSF) ranging in age from 18 to 44 yr were recruited for this cross-sectional study. The groups were well matched for demographic, training, and menstrual parameters. A force platform measured selected GRF parameters (peak and time to peak for vertical impact and active forces, and horizontal braking and propulsive forces) during overground running at 4.0 $m \cdot s^{-1}$. Lumbar spine, proximal femur, and distal tibial bone mineral density were assessed by dual energy x-ray absorptiometry. Tibial bone geometry (cross-sectional dimensions and areas, and second moments of area) was calculated from a computerized tomography scan at the junction of the middle and distal thirds. **Results:** There were no significant differences between the groups for any of the GRF, bone density, or tibial bone geometric parameters ($P > 0.05$). Both TSF and NSF subjects had bone density levels that were average or above average compared with a young adult reference range. Factor analysis followed by discriminant function analysis did not find any combinations of variables that differentiated between TSF and NSF groups. **Conclusion:** These findings do not support a role for GRF, bone density, or tibial bone geometry in the development of tibial stress fractures, suggesting that other risk factors were more important in this cohort of female runners. **Key Words:** EXTERNAL LOADS, BONE GEOMETRY , BONE MINERAL DENSITY, RUNNING, KINETICS , OVERUSE INJURIES

Running athletes commonly sustain tibial stress fractures causing considerable interference to training and competition. These skeletal overuse injuries are the result of the failure of bone to successfully adapt to the repetitive loads encountered during running. The number of loading cycles required to initiate stress fracture development is related to the magnitude and rate of loading applied, and to the ability of bone to resist loading (bone strength) (7).

During running, a ground reaction force (GRF) is generated with each foot strike that is equivalent to 2–4 times body weight in the vertical direction (28). Although this is partly attenuated by joint structures and soft tissues, considerable force is transmitted to the bones of the lower limb. This results in bone deformation (strain) and internal forces acting upon units of area of bone (stress). Bone strain may become excessive as a result of increases in load magnitude, the rate of loading, or the number of loading cycles. In humans, direct measurement of bone strain through the surgical attachment of a bone strain gauge has both ethical and methodological constraints. GRF provides an indirect measure of both the magnitude and rate of external load on the lower extremity during weight-bearing activity (1).

It is unclear whether differences in GRF are evident in athletes with and without stress fractures. In two cross-sectional studies, Grimston and colleagues (16,17) found significant differences in GRF between those with and without a history of stress fracture at various sites. However, in the initial study, the forces were higher in the stress fracture group whereas in the subsequent study they were lower. Conversely, we were unable to find a link between GRF and tibial stress fractures in male runners (10). These conflicting results highlight the need for further research investigating the role of GRF in stress fracture-prone individuals.

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The ability of bone to resist deformation during running depends on a number of factors including bone mass and bone geometry. Theoretically, low bone mineral density (BMD) could contribute to the development of a stress fracture by decreasing the resistance of bone to repeated loading. However, comparisons of regional BMD in individuals with and without stress fracture have been inconclusive (7). The discrepancy between results may reflect differences in populations, gender, measurement techniques, and bone regions.

The relationship between bone geometry, bone strength, and stress fractures has been examined in male (2,14,22,25) and female (3,15) military recruits, and in male runners (10). More stress fractures were sustained by male recruits with a smaller medio-lateral tibial width than by those with a wider tibia as measured using standard radiographs (13,14,22,25). These findings were confirmed in another prospective study of male recruits where dual energy x-ray absorptiometry (DXA) was used to derive tibial structural geometry (2) and in our cross-sectional study of male runners using computerized tomography (CT) (10). Results in female populations are less consistent and confined to military recruits (3,15). Thus, although there is some evidence that geometric differences consistent with a weaker bone may increase the risk of stress fracture in individuals undertaking intense physical activity, this has not been verified in female athletic populations.

As no study has examined the role of external loading during running together with bone strength indices in female runners who have previously sustained a stress fracture, we aimed to investigate GRF, bone density, and tibial bone geometry parameters in female runners with and without a history of tibial stress fracture. In a cross-sectional study design, we hypothesized that female runners with a history of tibial stress fracture would have higher GRF, lower regional bone density, and smaller tibial bone geometric parameters than those without a history of stress fracture.

METHODS

Subjects. Thirty-six female running athletes ranging in age from 18 to 44 yr were recruited via patient records of sports medicine clinics in Melbourne and via advertisements in running magazines and sporting venues. Thirteen subjects with a history of a healed tibial stress fracture (TSF) within the past 4 yr were compared with 23 subjects with no history of stress fracture (NSF). Subjects were included if they were currently running two or more sessions weekly with a total of ≥20 km·wk^{-1}. Subjects were excluded if they: (i) had a history of previous leg surgery or major trauma, (ii) had a current lower-limb musculoskeletal injury or medical condition interfering with training, (iii) were pregnant, (iv) had a body mass index < 17 (to exclude individuals with possible eating disorders), or (v) were long-term users of medications likely to influence bone density (excluding the oral contraceptive pill). Approvals from the Human Research Ethics Committees of the University of Melbourne and Victoria University of Technology were obtained before commencing the project and all subjects gave written informed consent.

TABLE 1. Tibial stress fracture (TSF) and nonstress fracture (NSF) group characteristics.

Characteristic	TSF ($N = 13$)[a]	NSF ($N = 23$)[a]	P
Age (yr)	29.4 (8.4)	30.6 (6.9)	0.63
Height (cm)	169.1 (5.8)	165.1 (6.0)	0.06
Weight (kg)	63.6 (6.4)	60.4 (8.6)	0.25
BMI (kg·m^{-2})[c]	22.2 (1.5)	22.1 (2.8)	0.91
Current km·wk^{-1}[c]	54.2 (32.3)	48.8 (34.7)	0.39
Years run > 20 km·wk^{-1}[c]	8.2 (3.6)	6.7 (6.6)	0.13
Age of menarche (yr)[c]	13.8 (1.5)	14.3 (1.4)	0.35
Menses in last 12 months (N)[c]	10.2 (2.7)	10.3 (3.4)	0.65
Total years amenorrheic[c]	1.1 (2.4)	0.3 (0.6)	0.47
Total years oligomenorrheic[c]	1.1 (1.2)	1.1 (2.3)	0.25
Total years eumenorrheic[c]	13.4 (10.7)	14.9 (8.8)	0.58
Menstrual index[b,c]	8.7 (2.9)	9.7 (1.5)	0.23
Previous OCP use (N)	11 (84.6%)	17 (73.9%)	0.46
Duration OCP use (yr)[c]	6.2 (7.2)	6.4 (5.7)	0.95

[a] Values are mean (SD), except in the case of previous OCP use whose values are number (%).

[b] Menstrual index quantifies the average number of menses per year since menarche; a number less than 10.5 is indicative of a history of menstrual disturbance.

[c] Nonparametric tests used.

Controls for the NSF group were selected to match the stress fracture subjects on age, height, weight, years of running, current weekly training volume, and menstrual status. Details of subject characteristics are included in Table 1. There were no significant differences between the groups, indicating that they were well matched for these characteristics.

Stress fracture characteristics. Diagnosis of a tibial stress fracture was made by a physician and radiologist from the clinical history and examination (insidious onset of progressive shin pain, exacerbated by exercise and relieved by rest, and localized bony tenderness on palpation) combined with radiological confirmation. The latter required positive findings on a triple phase isotope bone scan (focal area of increased uptake on the third phase) or a visible crack on x-ray, CT, or magnetic resonance scan (7).

The TSF group had sustained a total of 20 tibial stress fractures, with the majority located on the dominant leg (65% dominant, 35% nondominant). The number of years since the most recent TSF ranged from 0.3 to 3.4, with a mean (SD) of 1.6 (±1.0) yr. Weekly training volume in the 3 months preceding the most recent TSF ranged widely from 28 to 145 km with a mean (SD) of 79.4 (± 33.9) km·wk^{-1}.

Almost half ($N = 6$, 46%) of the TSF subjects had sustained stress fractures ($N = 14$) at other sites. These included the femur, fibula, navicular, and metatarsals, with dominant and nondominant sides equally represented. Tibial stress fractures comprised 57% of all lower-limb stress fractures sustained by this group. Six individuals reported a previous episode of multiple stress fractures (two or more fractures occurring simultaneously).

Ground reaction force measurements. GRF data were collected on 35 subjects (13 TSF, 22 NSF) by a force platform (Model LG6–4; Advanced Mechanical Technology Inc., Newton, MA) interfaced to an IBM compatible computer via an analog to digital converter (DT2801 Series; Data Translation, Malboro, MA). The sample period was

1.0 s and the sampling frequency 500 Hz. The force platform (1.2 m × 0.6 m) was set into a 30-m indoor running surface with the longest dimension in the line of running. The measurements were calculated using BEDAS-2 data acquisition and analysis software. Subjects wore their regular running shoes.

Subjects completed a 10-min warm-up of stationary cycling and lower leg stretches before practice running trials to ensure consistent landing with each foot on the center of the force platform at a horizontal velocity of $4.0 \pm 0.4\ \text{m}\cdot\text{s}^{-1}$. A photoelectric timing device provided feedback to the researcher and subject about each trial speed over the platform. GRF data were collected for 10 successful trials on each leg. A successful trial was defined as one where the foot landed on the force platform with no visible alteration of the subject's running stride. The GRF variables analyzed were peak and time to peak for vertical impact force, vertical active force, horizontal braking force, and horizontal propulsive force (Fig. 1).

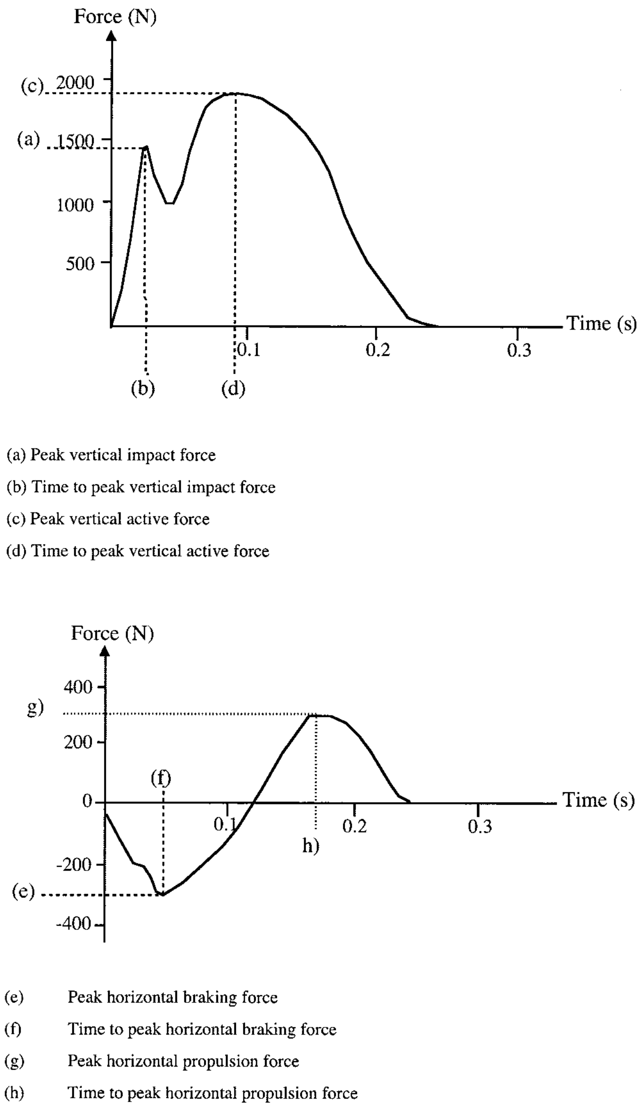

FIGURE 1—Schematic representation of (A) vertical ground reaction force and (B) horizontal anterior-posterior ground reaction force.

We have previously reported the reliability of this test protocol (4). Ten TSF subjects underwent testing on two occasions 1 wk apart. Results showed good reliability with intraclass correlation coefficients ranging from 0.82 to 0.99.

Bone density measurements. Dual energy x-ray absorptiometry (DXA) measurements of areal BMD ($\text{g}\cdot\text{cm}^{-2}$) at the lumbar spine (L1–L4), both proximal femurs and both distal tibias were acquired on a Hologic QDR-4500W Elite-Acclaim Series Densitometer (Hologic Inc., Bedford, MA), using fast array mode. The same technician performed all scans using software version V8.26f :5 (lumbar spine and proximal femur) and V9.1 (tibia). Lumbar spine and femoral T-scores were obtained from the Hologic QDR-4500W reference database. T-scores represent standard deviations from the mean BMD of healthy young, sex-matched adults.

Standardized positioning protocols were used for the proximal femur and lumbar spine scans (Hologic QRD-4500 Users Guide, Waltham, MA). For the tibial scans, the subject was positioned in long sitting with each leg secured in a positioning device. The lower leg was rotated about the long axis so that the medial and lateral malleoli were at the same horizontal level. This position allowed a clear distinction between the tibia and fibula when viewed anterior-posteriorly. A marker that was detectable on the scanned image was placed on the subject's skin at the junction of the distal third and proximal two thirds of the tibia (as measured from the tip of the medial malleolus to the medial knee joint). Two tibial subregions were analyzed on each scan: one measuring 45 pixels wide × 35 pixels high and centered at the level of the marker (region 1, R1), and one incorporating the entire distal third of the tibia (region 2, R2) (10). The distal tibia was selected as it is the most common clinical site of stress fractures (7) and to allow us to compare the results with our previous study in males (10).

DXA short-term *in vivo* precision in our laboratory with subject repositioning between repeat scans, expressed as the coefficient of variation (CV), was 0.7% for total hip, 1.3% for lumbar spine, and 1.8% for the tibia.

Tibial bone geometry and strength measurements. Thirty-five subjects (13 TSF, 22 NSF) had a single 3-mm CT scan taken at the junction of the distal and middle thirds of the tibia of both legs, using one of two scanners (General Electric Prospeed 9800; GE Medical Systems, Milwaukee, WI, or Picker PQ 2000S; Marconi Medical Systems, Cleveland, OH). The acquisition fields of view for the two scanners were 25 cm and 24 cm, respectively, and the display field of view for both was 10 cm. Reconstruction mode was performed with enhancement (number 2) and a large focus. Exposure was set at 120 kV, 1.5 s at 130 mA on the first scanner and 120 kV, 1.0 s at 200 mA on the second scanner.

To assess bone geometry, each CT film was scanned and the images imported into NIH Image 1.62 for the Macintosh (National Institutes of Health, Bethesda, MD). Anterior-posterior width (AP.Wi; cm), medial-lateral width (ML.Wi; cm^2), and total cross-sectional area (Tt.Ar; cm^2) were calculated using standard macros. Measures of cortical area (Ct.Ar; cm^2) and the maximum (I_{MAX}; cm^4), minimum

(I_{MIN}; cm^4), and polar (I_P; cm^4) second moments of area were calculated using customized macros. The second moment of area (I) reflects a structure's resistance to bending and is calculated by dividing the section into small areas (pixels) and multiplying each area (dA) by its squared distance (y) from the neutral plane. This procedure is integrated over the entire cross-section such that:

$$I = \int y^2 dA$$

The macro used calculates I about all possible neutral planes and reports the largest value as I_{MAX} and the smallest value as I_{MIN}, which are perpendicular to one another. The polar second moment of area (I_P) reflects a long bones resistance to torsion and equals the sum of the maximum and minimum moments of area ($I_P = I_{MAX} + I_{MIN}$).

Short-term precision of the measurement procedure was evaluated from duplicate analysis of 10 randomly selected scans by the same investigator, with an interval of 1 d between analyses. Results showed intraclass correlation coefficients all $\geq$ 0.99, indicating excellent precision. However, it was not possible to assess error in the collection of the CT scans due to ethical constraints in relation to radiation exposure.

Statistical analysis. For each GRF and bone parameter, the "affected" leg of the TSF group was compared with the "comparison" leg of the NSF group. The affected leg was defined as the leg of the most recent TSF. Two subjects had bilateral TSF and for these individuals a leg was randomly chosen. It was not possible to compare unaffected and affected legs within the TSF group as only five subjects had not sustained a stress fracture on the other leg.

All GRF data were normalized by dividing the force by body mass (N·N^{-1}). For NSF subjects, the comparison leg was taken as the average of the left and right legs as there were no significant left-right differences noted for any GRF variables ($P > 0.05$). For the bone variables, significant differences existed between the dominant and nondominant legs of subjects. Therefore, in the NSF group, the leg chosen for comparison for all bone data variables was based on the following method: as four (31%) of the affected legs in the TSF group were nondominant and nine (69%) were dominant, a corresponding proportion of leg dominance was randomly chosen in the NSF group (7 (30%) nondominant legs and 16 (70%) dominant legs).

Independent *t*-tests were used to compare the TSF and NSF groups. The bone density data were logarithmically transformed before analysis to achieve a normal distribution. For both DXA- and CT-derived bone measurements, body mass and height were included as covariates as body mass is a major predictor of bone density and structural properties of long bones are mostly dependent on body size.

Because stress fractures are likely to have a multifactorial etiology, factor analysis was also used to identify clusters of variables that might be predictive of stress fractures. These factors were then included in a discriminant function analysis to determine whether these could distinguish between the TSF and NSF groups. All statistical tests were two-tailed with a level of significance of 0.05.

RESULTS

Ground reaction force. Comparisons of GRF data between TSF and NSF groups are shown in Table 2. Many of the GRF variables were higher in the TSF group although, statistically, none of the variables differed between the groups.

Bone density. DXA-acquired BMD measurements for the TSF and NSF groups are shown in Table 3. Mean values of all parameters were up to 5.7% higher in the TSF group. However, *t*-tests controlling for height and weight did not show any significant BMD differences between groups at any of the measured regions.

The mean T-scores for the TSF and NSF groups are shown in Figure 2. Total hip T-scores for both groups were well above zero (average), ranging from 0.8 to 2.8. T-scores were slightly higher, albeit nonsignificantly, in the TSF group compared with the NSF group ($P = 0.67$ lumbar spine, $P = 0.24$ Hip). At the lumbar spine, T-scores of both groups were close to zero with the TSF group mean slightly below average. None of the TSF or NSF subjects were deemed osteoporotic at the lumbar spine or hip (T-score below −2.5). Hip T-scores of all subjects were in the normal range (T-score above −1). At the lumbar spine, one TSF subject (8%) and four NSF subjects (17%) were considered osteopenic (T-scores between −1 and −2.5) with all others in the normal range. There were no differences between TSF and NSF groups.

Tibial geometry. Comparison of CT-derived tibial geometric parameters in the two groups are given in Table 4.

TABLE 2. Ground reaction force (GRF) data in the tibial stress fracture (TSF) and nonstress fracture (NSF) groups.

GRF Parameter	TSF (N = 13)[a]	NSF (n = 22)[a]	% Diff (TSF vs NSF)	P
Peak vertical impact force (N·N^{-1})	1.944 (0.295)	2.080 (0.381)	−6.5	0.32
Time to peak vertical impact force (s)	0.136 (0.016)	0.132 (0.023)	3.0	0.65
Peak vertical active force (N·N^{-1})	2.747 (0.216)	2.786 (0.247)	−1.4	0.47
Time to peak vertical active force (s)	0.452 (0.028)	0.451 (0.047)	0.2	0.94
Average vertical force (N·N^{-1})	1.654 (0.138)	1.696 (0.130)	−2.5	0.37
Peak propulsive force (N·N^{-1})	0.369 (0.064)	0.380 (0.039)	−2.9	0.55
Time to peak propulsive force (s)	0.751 (0.016)	0.757 (0.016)	−0.8	0.35
Average propulsive force (N·N^{-1})	0.213 (0.033)	0.220 (0.021)	−3.1	0.42
Peak braking force (N·N^{-1})	−0.497 (0.080)	−0.515 (0.088)	−3.5	0.54
Time to peak braking force (s)	0.211 (0.063)	0.207 (0.053)	1.9	0.54
Average braking force (N·N^{-1})	−0.232 (0.031)	−0.249 (0.033)	−6.8	0.13

[a] Values are mean (SD).

TABLE 3. Regional bone mineral density (BMD) in the tibial stress fracture (TSF) and nonstress fracture (NSF) groups.

Regional BMD (g·cm^{-2})	TSF (N = 13)[a]	NSF (N = 23)[a]	% Diff (TSF vs NSF)	P
Lumbar spine (L1–L4)	1.053 (0.085)	1.039 (0.102)	1.4	0.54
Hip (total)[b]	1.144 (0.127)	1.098 (0.083)	4.2	0.81
Femoral neck	0.938 (0.147)	0.922 (0.071)	1.7	0.77
Trochanter	0.825 (0.116)	0.801 (0.083)	3.0	0.65
Tibia (region R1)[b]	1.216 (0.255)	1.152 (0.097)	5.6	0.57
Tibia (region R2)[b]	0.929 (0.201)	0.879 (0.056)	5.7	0.57

[a] Values are mean (SD).

[b] Data log transformed prior to analysis as not normally distributed.

t-Tests correcting for weight and height showed no significant differences between the TSF and NSF groups for any of the parameters. As an unequal proportion of TSF and NSF subjects (1 TSF, 5 NSF) were scanned on a second machine, means from the two scanners were compared. No significant difference was evident between the two scanners for any of the measured parameters.

Multivariate analysis. Factor analysis was performed including bone density, GRF, and bone geometry variables together with demographic, training, and menstrual variables. This identified 10 factors with an eigenvalue of more than 1.0 with 69% of the variance explained by the first six factors. Variables with weightings > 0.6 were included in these factors with no variable repeated between factors. A subsequent discriminant function analysis including these six factors was unable to differentiate between the TSF and NSF groups ($P > 0.05$).

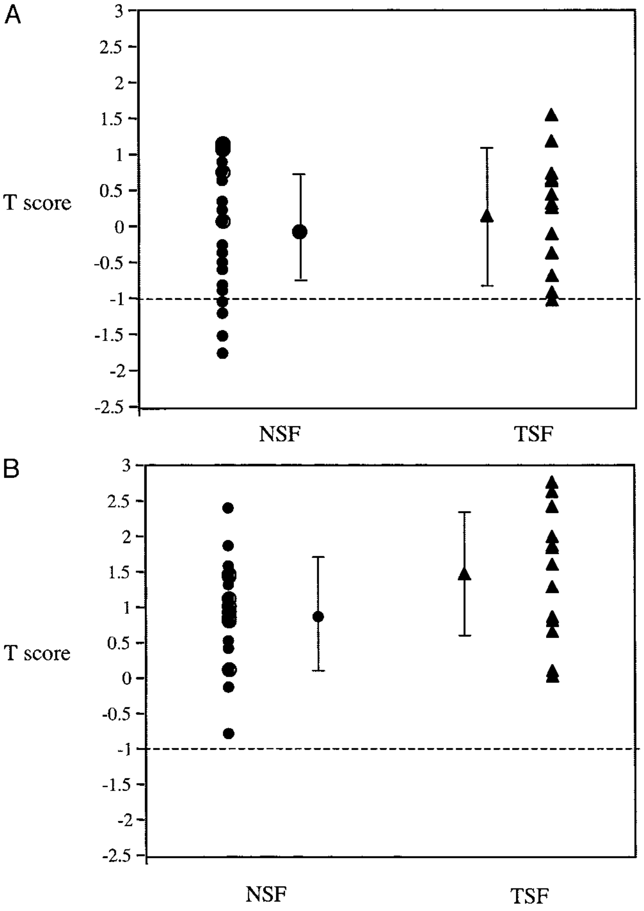

FIGURE 2—T-scores for DXA-acquired BMD at the (a) lumbar spine and (b) total hip given as individual values and mean (SD) for NSF and TSF groups. The *dashed line* represents the upper limit of the World Health Organization diagnostic criteria for osteopenia.

TABLE 4. CT derived tibial bone geometry and strength parameters in the tibial stress fracture (TSF) and nonstress fracture (NSF) groups.

Measurement	TSF (N = 13)[a]	NSF (N = 22)[a]	% Diff (TSF vs NSF)	P
AP.Wi	2.32 (0.16)	2.32 (0.13)	0	0.91
ML.Wi	2.21 (0.15)	2.17 (0.15)	1.8	0.42
Tt.Ar (cm^2)	3.63 (0.27)	3.51 (0.33)	3.4	0.28
Ct.Ar (cm^2)	3.07 (0.30)	2.94 (0.28)	4.4	0.19
I_{MAX} (cm^4)	1.64 (0.31)	1.55 (0.32)	5.8	0.43
I_{MIN} (cm^4)	0.82 (0.11)	0.77 (0.16)	6.5	0.31
I_P (cm^4)	2.46 (0.39)	2.32 (0.44)	6.0	0.35

[a] Values are mean (SD).

AP.Wi, anterior-posterior width; ML.Wi, medio-lateral width; Tt.Ar, total cross-sectional area; Ct.Ar, cortical area; I_{MAX}, maximum second moment of area; I_{MIN}, minimum second moment of area; I_P, polar second moment of area.

DISCUSSION

We investigated the mechanical loads applied to the lower limbs during running together with indices of tibial bone strength in female runners with and without a history of tibial stress fracture. There were no differences between groups for any of the GRF, regional bone density, or tibial bone geometric parameters. Even though stress fractures are likely to have a multifactorial etiology, there were no combinations of variables that could distinguish between the TSF and NSF groups. This implies that in the cohort tested, other factors were more important in influencing the risk of tibial stress fracture.

This is the first study to examine the association between bone geometry and stress fractures in female athletes. Unlike studies in other populations that have relied on measurements from two-dimensional projections (radiographs or DXA images), we used CT to directly image the cross-sectional plane. This provides all relevant dimensions and allows greater accuracy. Our nonsignificant findings do not exclude bone geometry as a risk factor as measurements were taken at one region and not necessarily at the site of the tibial fracture. Differences between groups may have been evident at other regions given that tibial geometry is highly variable along its length and between individuals. Our results also do not exclude the possibility that bone geometry influences stress fracture development at other lower-limb or pelvic bone sites. Beck and colleagues (3) found that tibial bone geometry predicted risk of tibial and femoral stress fractures but not pelvic fractures.

Despite similar methodology, our findings contrast with our previous research in 46 male runners. In this study, males with a history of tibial stress fracture had smaller CT-derived tibial cross-sectional area and smaller DXA tibial bone area (adjusted for height and weight) than the NSF group. These findings concur with those of large prospective cohort studies in male military populations where tibial cross-sectional areas were 10.6% (2) and 4.4% (25) lower in those who developed stress fractures compared with controls. The area moment of inertia about the anterior-posterior axis of bending was also found to be the most significant predictor of stress fracture risk in male military recruits (24).

Our present results in female runners are similar to those of Girrbach and colleagues (15), who measured tibial flexural wave propagation velocity in female recruits. This measurement is related to the area moment of inertia, density, elastic modulus, and cross-sectional area of the tibia. Because no differences were found between those without and without a history of tibial stress fracture, the researchers concluded that local stresses on bone rather than whole bone stiffness may be more important in stress fracture development. In a large prospective study of 693 recruits using DXA-derived measures, Beck et al. (3) found that differences in geometric properties between stress fracture and nonstress fracture recruits were influenced by gender. Although both males and females with stress fractures had smaller section moduli and bone strength indices than those without stress fractures, the female fracture cases had smaller cortical thickness but similar diameter bones to controls, whereas male fracture cases had narrower bones but similar cortical thickness to their control counterparts (2,3).

All evidence to date agrees that physically active males with smaller bones and less resistance to bending moments are at greater risk of stress fracture than those with larger bones and greater resistance. However, this relationship appears to be less consistent in females and may indicate that other risk factors for stress fractures are more important in women.

Bone mass is a major determinant of bone strength, and DXA measurements are used clinically to predict the risk of osteoporotic fracture. However, in our study, athletes with a history of TSF did not have lower regional bone density, even at the tibia, compared with those without. This failure to support the experimental hypothesis is not a product of limited statistical power as our sample size was adequate to detect a clinically relevant bone density difference between groups of one standard deviation (around 10%). Furthermore, there was a trend for higher bone density, up to 6% greater at the tibial sites, in the stress fracture group.

Reports in the literature about the role of bone density in stress fracture development in females are equivocal and difficult to interpret. Most studies have measured the lumbar spine despite the fact that stress fractures do not occur at this site. Although significant spinal BMD deficits, ranging from 4.0% to 11.9%, have been found (6,27), these have often been associated with a greater prevalence of menstrual disturbances. Because the lumbar spine is highly sensitive to reductions in gonadal hormone levels, this may explain why BMD deficits were found in these studies but not in ours where groups were well matched on current and past menstrual status.

Investigations of lower-limb sites have also yielded conflicting results with lower (3,6,20,27), higher (16), and similar (9,15) bone density reported in the female stress fracture group compared with controls. It is feasible that bone density may play a variable role depending on the site of fracture. A recent study found that 89% of women with stress fractures at cancellous sites (pubic rami, sacrum, calcaneus, and medial femoral neck) had osteopenia at the lumbar spine or femoral neck compared with only 27% of those who sustained a cortical stress fracture (metatarsal, tibia, and femoral shaft) (21). Bone density may be an inconsistent risk factor for stress fractures, depending on the region and the presence of menstrual disturbances.

The majority of our subjects had positive DXA T-scores at the lumbar spine and proximal femur, indicating higher bone density than the average young adult. This supports the large body of evidence showing that weight-bearing activity such as running and jumping is associated with increases in bone density (5). T-scores at the proximal femur were higher than those at the lumbar spine. This may reflect the pattern of mechanical loading induced through running or the greater adverse effects of menstrual disturbances at trabecular sites. It is interesting to note that although both groups reported a history of menstrual disturbance that affected, on average 20% of their years since menarche, none of the subjects were considered osteoporotic at the lumbar spine or proximal femur based on diagnostic criteria of a T-score less than -2.5. This supports the contention by Khan et al. (19) that frank osteoporosis is uncommon in female athletes, even those with menstrual disturbances. These authors therefore suggest that osteopenia (T-score between -1 and -2.5) rather than osteoporosis should be included among the interrelated conditions that comprise the female athlete triad.

Although it was hypothesized that the TSF group would have higher GRF magnitude (implying greater mechanical load) and shorter time to peak force (implying greater rate of loading) than the NSF group, GRF was similar in the two groups. Our sample size was powerful enough to detect a 10% difference in peak vertical active force and peak braking force between groups if they existed, but in fact many GRF variables actually showed lower forces in the TSF group.

Our GRF findings in females are similar to our previous findings in males using an identical protocol (10) but contrast with two studies by Grimston and colleagues (16,17). These two studies found significant differences in peak GRF parameters; however, in one study, they were higher in the stress fracture group, and in the other they were lower. This inconsistency may relate to differences in sample characteristics and testing procedures between their two studies as well as variable testing conditions. We attempted to control for some of these methodological issues by using a larger, more homogenous sample, a larger number of running trials and standardized running speed.

It is possible that actual differences in tibial bone strain might still be a factor in stress fracture development but were not detected by our measurement procedure. Bone strain is a function of both the GRF and the internal attenuation of these forces by ligament, tendon, and muscle units to dampen or modulate load. The latter cannot be easily measured but may have differed between TSF and NSF groups. Subjects performed running trials in a nonfatigued state. Muscle contraction can act to minimize the total strain experienced by bone. During running, the tibia is exposed to a large forward bending moment. Contraction of the calf muscles provides an opposing force that acts to decrease force experienced by the tibia (29). Studies in animals and humans using bone strain gauges have shown that muscular fatigue can lead to increases in both strain magnitude (30) and strain rate (12) as well as alterations in strain distribution (30). Similar increases with fatigue have been reported in other indirect measures of bone load including GRF (8) and tibial impact acceleration (26). Furthermore, GRF increased to a greater extent toward the late stages of a 45-min run in athletes with a history of tibial stress fracture than in noninjured athletes (17). Thus, stress fractures may be more likely to develop in those individuals whose muscles fatigue at a greater rate or where there is an imbalance in individual muscle fatigue rates (26). Therefore, GRF did not differ between our groups in a nonfatigued state, a difference that may have become apparent after a period of fatiguing exercise.

In addition to the load magnitude, stress fracture development depends upon the number of loading cycles, loading rates, and distribution of load. Our groups were matched for self-reported years and current weekly kilometers run, but it is possible that other training factors such as surface and speed of running differed. For example, running along a curved track causes greater torsional moments to act on the tibiae (18). Furthermore, laboratory conditions do not adequately represent training conditions, which can influence tibial bone strain and may have differed between groups. We controlled running speed as faster speeds result in larger GRF values. It is possible that the test speed differed from the runner's usual training pace, and thus the GRF values recorded might not reflect those typically experienced by the athlete. Although running volume was similar between groups, it was not possible to accurately quantify running pace to determine whether this differed between TSF and NSF groups, thus influencing the risk for TSF. Other factors such as footwear and shoe orthoses can affect tibial strain *in vivo* (11,23) and may have influenced the risk of stress fracture development in this cohort.

We are aware of the limitations of cross-sectional designs, but unlike military populations that lend themselves well to data collection and permit much larger samples, it is more difficult to conduct a prospective cohort study in athletes, particularly confined to tibial stress fractures. Our groups were closely matched on other factors that may influence stress fracture risk, in particular menstrual status. However, as the measurements were conducted after the stress fracture event, we are unable to determine their preinjury status. Bone geometry is unlikely to have changed substantially after TSF in this age group as the process of bone modeling, which predominantly determines adult bone geometry, mostly occurs during the growing years. Bone density values are more likely to be influenced by changes in exercise levels. However, because bone density was generally higher in the TSF group, it is unlikely that bone density was lower in this group before the injury and then increased afterward. If anything, one might expect bone density to be reduced after the injury where a period of detraining has occurred.

In conclusion, our cross-sectional study found that female runners with a history of tibial stress fracture did not differ from their nonstress fracture injured counterparts in GRF, regional bone density, and tibial bone geometry. This suggests that other intrinsic and extrinsic factors not measured in this study such as lower-limb alignment or soft tissue dampening of imposed load may be more important in influencing risk of tibial stress fracture in this female group.

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