Medicine & Science in Sports & Exercise
Issue: Volume 31(8), August 1999, pp 1088-1093

Publication Type: [Clinical Sciences: Clinical Investigations]
ISSN: 0195-9131
Accession: 00005768-199908000-00002
Keywords: STRESS FRACTURE, EXTERNAL LOADS, BONE GEOMETRY, BMD, RUNNING, TIBIA, KINETICS, OVERUSE INJURIES

[Clinical Sciences: Clinical Investigations]

Ground reaction forces, bone characteristics, and tibial stress fracture in male runners

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Submitted for publication August 1998.
Accepted for publication September 1998.
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ABSTRACT

Ground reaction forces, bone characteristics, and tibial stress fracture in male runners. *Med. Sci. Sports Exerc.,* Vol. 31, No. 8, pp. 1088-1093, 1999.

Purpose: Tibial stress fracture is a common overuse running injury resulting from repetitive mechanical loading. This research project aimed to determine whether runners with a history of tibial stress fracture (TSF) differ in tibial bone geometry, tibial bone mass, and ground reaction force (GRF) parameters during running from those who have never sustained a stress fracture (NSF).

Methods: Forty-six male running athletes (23 TSF; 23 NSF) ranging in age from 18 to 42 yr were recruited for this cross-sectional study. A force platform was used to measure selected GRF parameters (peak and time to peak for vertical impact force, vertical active force, and horizontal braking force) during running at 4.0 m[middle dot]s^{-1}. Tibial bone geometry (cross-sectional dimensions and area) was calculated from a computerized tomography (CT) scan at the junction of the middle and distal thirds. Dual energy x-ray absorptiometry (DXA) provided measurements of tibial bone area, bone mineral content (BMC), and bone mineral density (BMD).

Results: The TSF group had significantly smaller tibial cross-sectional area ($P = 0.02$) and DXA tibial bone area ($P = 0.02$), after adjusting for height and weight, than the NSF group. There were no significant differences between groups for GRF, tibial BMC, or tibial BMD.

Conclusion: These findings support the contention that bone geometry plays a role in stress fracture development and that male athletes with smaller bones in relation to body size are at greater risk for this bony injury.

Tibial stress fracture is a serious injury commonly sustained by running athletes that causes considerable interference with training and competition (6,17). It is the consequence 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 strength and geometry of bone and to the magnitude and rate of loading applied.

Runners strike the ground approximately 600 times per kilometer (12,31) and with every heel-strike a peak vertical ground reaction force of 2-4 times the runner's body weight is applied to the leg (2,12). Although joint structures and soft tissues attenuate some of the force, a proportion is transmitted to the skeleton resulting in bone strain or deformation (21). Bone strain may become excessive as a result of increases in load magnitude, rate of loading, or 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. Ground reaction force (GRF) provides an indirect measure of both the magnitude and rate of external load on the lower extremity during running (27).

Evidence that loading, as measured by GRF, may be important in runners with a history of stress fracture was provided by Grimston and colleagues in two cross-sectional studies (15,16). They found significant differences in GRF between the stress fracture and nonstress fracture groups. However, in the initial study, the forces were higher in the stress fracture group whereas in the subsequent study, they were lower. These conflicting results highlight the need for further research investigating the role of GRF in stress fracture prone individuals.

The ability of bone to resist the external loads applied during running depends upon a number of factors including bone geometry and bone material properties (29). The relationship between bone geometry and stress fractures has been examined prospectively in the male military population (3,13,14,23-25). Significantly more stress fractures were sustained by recruits with a smaller mediolateral tibial width, measured using standard radiographs, than by those with a wider tibia (13,14,24,25). A narrower tibia may be associated with a smaller area moment of inertia and hence decreased ability of the tibia to resist bending forces in the anteroposterior direction. These findings were confirmed by a recent prospective study of male recruits where dual energy x-ray absorptiometry (DXA) was used to derive tibial structural geometry (3). These studies provide evidence that smaller bones subjected to intense unaccustomed physical activity in male military recruits may lead to a higher rate of stress fracture. No studies have examined whether bone geometry plays a similar role in athletes.

Theoretically, low BMD could contribute to the development of a stress fracture by decreasing the fatigue resistance of bone to loading (9-11). Results from studies comparing regional BMD in male and female military and athletic groups with and without stress fracture have been inconclusive (3,5,6,13,15). In general, site-specific bone density has not been shown to be related to risk of stress fracture in men (6,13). In female athletes, there is prospective evidence to show that those who sustain a tibial stress fracture have significantly lower tibial BMD than those who do not sustain a stress fracture (6). The discrepancy between results may reflect differences in populations, measurement techniques, and bone regions.

Most of the stress fracture research in men has been conducted in the military environment whereas athletic studies have primarily focused on women. No study has examined the role of external loading during running together with bone characteristics in athletes who have previously sustained a stress fracture. Therefore, the aim of this cross-sectional study was to determine whether GRF, tibial bone geometry, and tibial bone mass differ in male runners with and without a history of tibial stress fracture.

METHODS

Subjects. Approval from the Human Research Ethics Committees of the University of Melbourne, Victoria University of Technology and Monash University was obtained before the commencement of this project and all subjects gave written informed consent. Forty-six male running athletes ranging in age from 18 to 42 (mean = 24.7 +/- 5.54) yr were recruited for this project. Twenty-three subjects with a history of a healed tibial stress fracture (TSF) were compared with a matched group of 23 subjects with no history of stress fracture (NSF). Subjects were excluded if they had: (i) a history of previous leg surgery or major trauma, (ii) current lower limb musculoskeletal injury, or (iii) a forefoot or mid-foot strike running pattern to ensure that the sample had a similar ground reaction force pattern. Stress fracture subjects were obtained via patient records of several sports medicine clinics in Melbourne.

Each control was selected to match a stress fracture subject on age, height, weight, years of running, weekly training volume, competitive distance, and performance. The majority of controls were training partners or competitors of the stress fracture subjects. Details of subject characteristics are included in Table 1. There was no significant difference between the groups for any of these characteristics.

Subject Characteristics	Tibial SF (N = 23)	Non SF (N = 23)
Age (yr)	25.1 (4.9)	24.4 (6.2)
Height (m)	1.79 (0.08)	1.78 (0.07)
Mass (kg)	75.8 (9.4)	71.4 (7.7)
BMI (kg·m^{-2})	23.7 (3.0)	22.5 (1.7)
Training years[a]	9.0 (6.2)	9.2 (4.4)

[a] Number of years training at least twice per week.
BMI, body mass index; tibial SF, tibial stress fracture; non SF, nonstress fracture.

TABLE 1. Mean (SD) for subject characteristics of tibial stress fracture and nonstress fracture groups.

Stress fracture characteristics. Diagnosis of a previous tibial stress fracture was made by a physician and a radiologist from a history of insidious onset of progressive shin pain, exacerbated by exercise and relieved by rest, combined with positive findings on a triple-phase isotope bone scan (7). A total of 36 tibial stress fractures were sustained by the TSF group, with nine subjects sustaining more than one tibial stress fracture. Eleven of the subjects had sustained unilateral stress fractures, and 12 subjects (52%) sustained a stress fracture in both left and right legs. All tibial stress fractures occurred in the posteromedial cortex, with 26% at the junction of middle and lower thirds, 26% in the middle third, 30% in the distal third, and 18% in the proximal third. Stress fractures diagnosed at lower limb sites other than the tibia had occurred in 35% of the 23 TSF subjects. The sites of other stress fractures included the femur, metatarsal, and navicular. The number of years since the most recent stress fracture and the time of the study ranged from 0.2 to 4.6 yr, with a mean of 1.9 (+/- 1.3) yr.

Force platform measurements. Ground reaction force data were collected on all subjects by a force platform (Advanced Mechanical Technology Incorporated, Newton, MA, model LG6-4) interfaced to an IBM compatible computer via an analog to digital converter (Data Translation DT2801, Marlboro, MA). The sampling frequency was 500 Hz. The force platform (1.2 m x 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 software. Subjects were instructed to wear their regular running shoes as human adaptive capabilities can exceed the variability introduced by different shoe types (19,20,22).

All subjects performed practice running trials to ensure consistent landing with each foot on the center of the force platform at a horizontal velocity of 4.0 m[middle dot]s^{-1} +/- 10%. A photoelectric timing device provided feedback to the researcher and subject about each trial speed over the platform. GRF data were collected for a total of 10 successful trials on each leg. Ten trials have been identified in previous studies as an appropriate number to achieve typical characteristics of ground reaction force data (1,2,18). 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 in this project were peak vertical impact force (VIF_{peak}), time to peak vertical impact force (VIF_{time}), peak vertical active force (VAF_{peak}), time to peak vertical active force (VAF_{time}), peak horizontal braking force (HBF_{peak}), and time to peak horizontal braking force (HBF_{time}) and are indicated in Figure 1 (A and B).

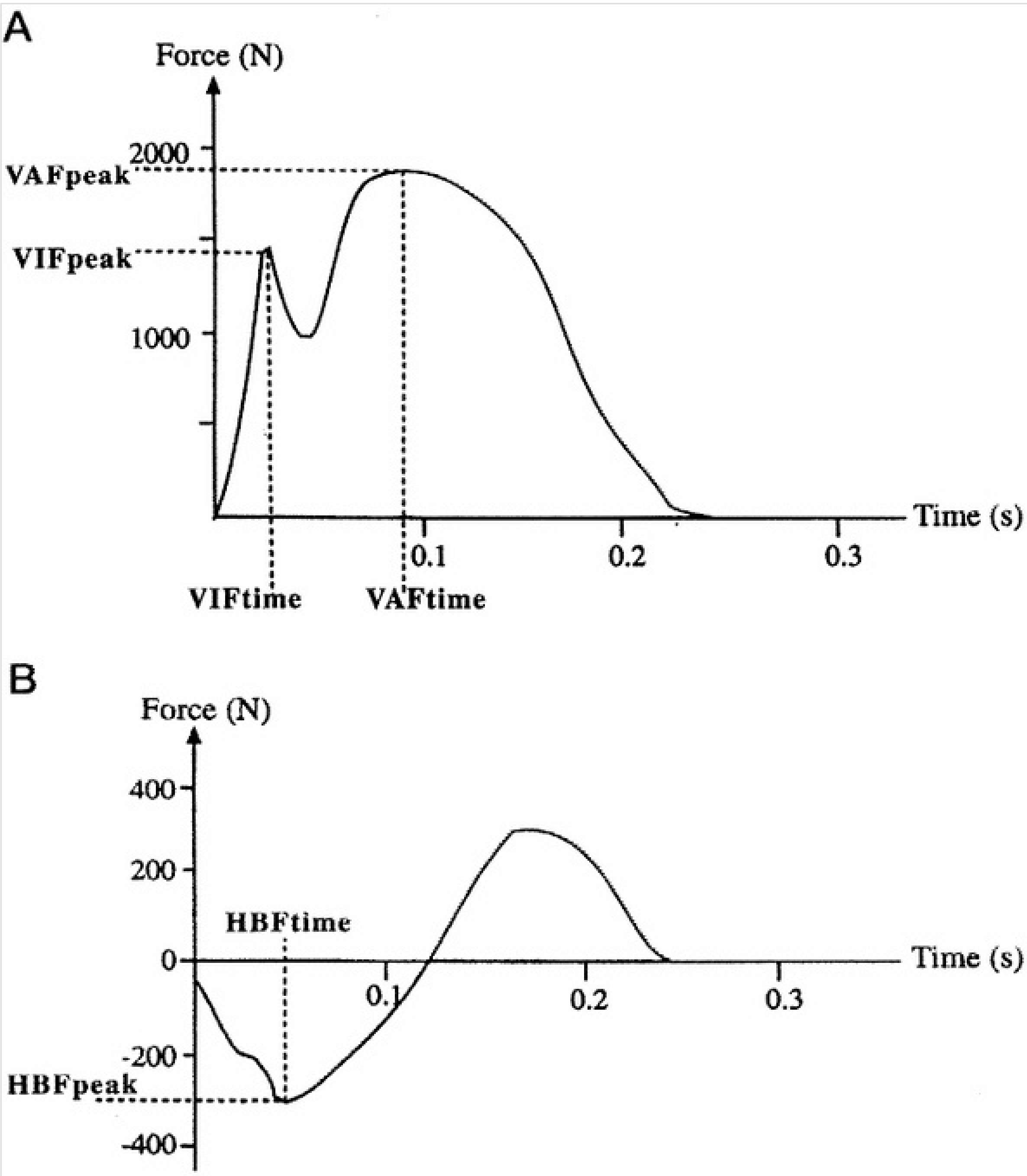

Figure 1-Schematic representation of ground reaction force. A, Vertical ground reaction force. B, Horizontal ground reaction force. VIF_{peak}, peak vertical impact force; VIF_{time}, time to peak vertical impact force; VAF_{time}, time to peak vertical active force; HBF_{peak}, peak horizontal braking force; HBF_{time}, time to peak horizontal braking force.

Ten of the 23 TSF subjects underwent testing on two occasions 1 wk apart to establish test-retest reliability. Results showed good reliability with intraclass correlation coefficients (ICC, model 3, 10) ranging from 0.82 to 0.99 (4). Values for the SE_{meas} were all less than 7% of mean values with most less than 2%.

Dual energy x-ray absorptiometry. Dual energy x-ray absorptiometry (DXA) measurements of tibial bone area, BMC, and BMD were acquired on a Hologic QDR 1000W densitometer (Hologic Inc., Waltham, MA) using pencil mode and the lumbar spine protocol Version 4.47. Both left and right legs were scanned. The subject was positioned in long sitting on the scanning table. 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 anteroposteriorly. The foot was strapped to a positioning device to stabilize the leg. To enable visualization of the level of the middle and lower third of the tibia (as measured from the tip of the medial malleolus to the medial knee joint) on the DXA scan, a detectable marker was placed on the subject's skin. A standardized subregion of the tibia measuring 45 mm wide x 35 mm high and centred at the level of the marked lower third junction was analyzed from each scan. Of the 46 subjects, six (2 TSF and 4 NSF) were unable to attend for bone densitometry testing.

DXA short-term *in vivo* precision was evaluated from triplicate scans in 10 normal, healthy volunteers. Between scans, subjects were removed from the table and repositioned. The coefficient of variation (CV) was 2.1% for bone area, 1.4% for BMC, and 1.8% for BMD.

Computerized tomography. Thirty-nine subjects (20 TSF and 19 NSF) had a single 3-mm computerized tomography (CT) scan (General Electric Prospeed, 9800, Milwaukee, WI) at a point that represented 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). The mean distance from the medial malleolus was 13.8 (+/- 0.6) cm. The acquisition field of view was 25 cm and the display field of view 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. To minimize subject radiation exposure, only the right leg was scanned.

Video images of the hard copy CT scans were captured via a frame grabber (Data Translation Inc., DT 3155) and Jandell Sigma Scan Pro software (SPPS Inc., Chicago, IL). The tibial dimensions were obtained by manual digitisation of the images (Global Lab Images Data Translation Inc, version 3.1). The longest distance in the mediolateral dimension was recorded as mediolateral tibial width and the anteroposterior dimension (AP tibial width) measured as the largest distance using a line perpendicular to the mediolateral dimension (see Fig. 2). The total cross-sectional area (TCSA) was calculated from the CT scans using a thresholding technique to automatically identify bone area.

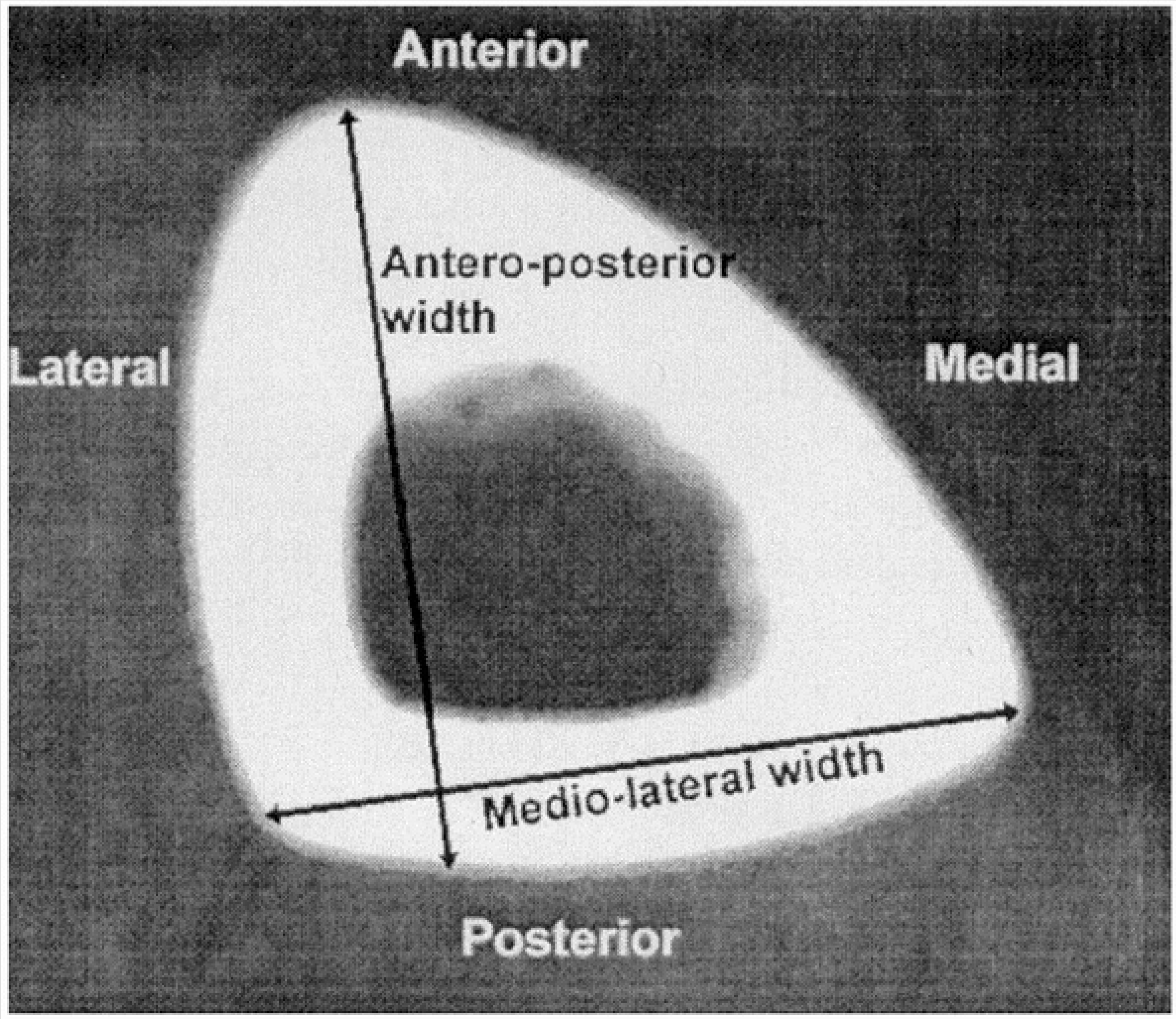

Figure 2-Tibial dimensions obtained via CT scans. Anteroposterior width; mediolateral tibial dimension.

Statistical analysis. All GRF data were normalized by dividing the force by body mass ($N[middle dot]N^{-1}$). For each subject, the GRF and DXA bone data for left and right legs were averaged. This was justified as there was no significant left-right difference noted for any of these variables ($P > 0.05$). Independent *t*-tests with a two-tailed significance level of [alpha] = 0.05 were used to compare the TSF and NSF groups. For DXA bone measurements and bone geometry measurements, body mass and height were included as covariates. In the subset of 11 TSF subjects who had sustained unilateral stress fractures, comparisons between injured and uninjured legs were made using paired *t*-tests.

RESULTS

Ground reaction force. Comparisons of GRF data between TSF and NSF groups are shown in Table 2. There was no significant difference between the TSF and NSF groups for the normalized peak forces or time to peak forces of VIF, VAF, and HBF. In subjects with a history of unilateral stress fracture, there was also no significant difference between the previously injured and noninjured leg for these variables.

Ground Reaction Force	Tibial SF (N = 23)	Non SF (N = 23)
VIF_{peak} ($N \cdot N^{-1}$)	1.890 (0.387)	1.970 (0.337)
VIF_{time} (s)	0.031 (0.005)	0.031 (0.005)
VAF_{peak} ($N \cdot N^{-1}$)	2.843 (0.235)	2.856 (0.189)
VAF_{time} (s)	0.099 (0.009)	0.097 (0.011)
HBF_{peak} ($N \cdot N^{-1}$)	−0.496 (0.056)	−0.492 (0.104)
HBF_{time} (s)	0.050 (0.008)	0.051 (0.013)

VIF_{peak}, peak vertical impact force; VIF_{time}, time to peak vertical impact force; VAF_{time}, time to peak vertical active force; HBF_{peak}, peak horizontal braking force; HBF_{time}, time to peak horizontal braking force; tibial SF, tibial stress fracture; non SF, nonstress fracture.

TABLE 2. Mean (SD) of ground reaction force data comparing tibial stress fracture and non-stress fracture groups.

Dual energy x-ray absorptiometry. The results of the dual energy x-ray absorptiometry data for TSF and NSF groups are shown in Table 3. There was no significant difference between the TSF and NSF groups for the unadjusted tibial area, BMC, or BMD. However, using total body mass and height as covariates the tibial bone area was significantly smaller in the TSF group (P = 0.023). Because the height dimension of the region of interest was equal in all subjects, the smaller bone area in the TSF group implies a narrower tibia. In the subjects with a history of unilateral stress fractures, there was no significant difference between the TSF and NSF groups for any of these measured variables.

DXA	Tibial SF (N = 21)	Non SF (N = 19)
Area (cm^2)	8.333 (0.460)	8.603 (0.858)
BMC (g)	10.061 (0.974)	10.187 (1.252)
BMD ($g \cdot cm^{-2}$)	1.209 (0.089)	1.118 (0.072)

BMC, bone mineral content; BMD, bone mineral density; tibial SF, tibial stress fracture; non SF, nonstress fracture.

TABLE 3. Mean (SD) of unadjusted dual energy x-ray absorptiometry (DXA) tibial data comparing tibial stress fracture and non-stress fracture groups.

Tibial geometry. The results of the tibial geometry data for TSF and NSF groups are shown in Table 4. There was no significant difference between the TSF and NSF groups for unadjusted total cross sectional area, cortical area, medullary area, tibial length, anteroposterior tibial width, or posterior tibial width. However, when body mass and height were used as covariates, the TSF group had a significantly smaller total cross sectional area (P = 0.024) than the NSF group.

Tibial Bone Geometry	Tibial SF (N = 20)	Non SF (N = 19)
TCSA (mm^2)	435.4 (48.7)	463.9 (65.5)
AP width (mm)	26.62 (2.05)	27.26 (2.75)
ML width (mm)	23.31 (1.78)	23.77 (2.58)
Tibial length (m)	0.41 (0.02)	0.42 (0.02)

TCSA, total cross sectional area; AP width, anteroposterior tibial dimension; ML width, mediolateral tibial dimension; tibial SF, tibial stress fracture; non SF, nonstress fracture.

TABLE 4. Mean (SD) of bone geometry data comparing tibial stress fracture and nonstress fracture groups.

DISCUSSION

We investigated the mechanical loads applied on the legs during running together with indices of tibial bone strength in male runners with and without a history of tibial stress fracture. Our results showed that the stress fracture group had a significantly smaller tibial cross-sectional area and DXA tibial bone area (adjusted for height and weight) than the nonstress fracture group. For a long bone, one of the most important geometric properties influencing its ability to resist fracture is the cross-sectional area (29). Thus physically active male athletes with smaller bones appear to be at greater risk for stress fracture than those with larger bones. However, we found no differences in GRF parameters or tibial BMC and BMD between groups.

Our study is the first to examine bone geometry in male athletes with stress fractures. Although bone geometry has been investigated in the military, recruits differ from athletes in that many recruits have low initial levels of fitness before embarking on a short period of unaccustomed, intense physical activity. The presence of smaller and hence weaker bones in such individuals may lead to a higher rate of bone microdamage. Without adequate time for adaptive cortical remodelling to occur, a stress fracture may result. It was not known whether bone geometry would play a similar role in athletes as their bones are loaded gradually over an extended period of time and thus may adapt by developing stronger and larger cortices.

Our findings in male athletes do support those of prospective cohort studies in military populations, suggesting that bone geometry plays a role in stress fracture development (3,13,24). Direct comparisons of absolute values for TCSA between studies cannot be made given differences in methodology. However, the relative magnitude of the difference in TCSA between our TSF and NSF groups was of the order of 8.4%. This is lower than the 10.6% reported by Beck et al. (3) from DXA scans but higher than the 4.4% found by Milgrom et al. (24) from radiographs, although neither method is a direct measure of TCSA. We used computed tomography to obtain tibial TCSA thereby eliminating some of the problems associated with calculating TCSA from radiographs and DXA.

The area moment of inertia about the anteroposterior axis of bending was found to be the most significant predictor of stress fracture risk in military recruits (23,24). These studies based their calculations upon the assumption that the cross-section of the tibia is basically an elliptical shape. However, when we examined our CT scans, the shape of the tibia more closely approximated a triangle and not an ellipse, and even so there was considerable variation in the shapes (see Fig. 2). Because of the nonuniform cortical wall thickness, there was no simple geometrical model that would allow accurate calculation of tibial cross sectional area moment of inertia from our data.

Even if bone geometry plays a role in stress fracture development, the clinical relevance of this risk factor is limited. Large scale screening of tibial geometry via radiograph or DXA techniques is impractical and costly. With further research, it may be possible to develop surrogate indicators of tibial geometry via simple anthropometric measurements. Even if these allow identification of at risk individuals, bone geometry cannot be easily altered. Instead strategies could be implemented to reduce loading of inherently weaker bones, such as manipulation of training regimens, footwear modifications, and muscle strengthening.

Although intuitively, the stress fracture group might have been expected to have a higher GRF magnitude (implying greater mechanical load) and shorter time to peak force (implying greater rate of loading) than the NSF group, our results showed no significant differences in GRF parameters between the two groups.

Our results differ from those reported in studies by Grimston and colleagues (15,16) where significant differences in peak GRF parameters were found between the stress fracture and nonstress fracture groups although in opposing directions. Sample characteristics and testing procedures differed between their two studies and in some aspects were poorly controlled, which may have contributed to the inconsistent findings. We attempted to control for some of the methodological problems present in these studies by using a larger, more homogenous sample, a larger number of running trials, and standardized running speed and testing conditions.

Assessment of tibial bone load is problematic. We chose to use GRF as an indication of the external load applied to the body as a whole during running. However, because bone load results from a combination of both external (GRF) and internal forces (from muscle contraction, joint reaction forces, ligaments, and tendons) (30), similar GRF in the TSF and NSF groups does not preclude actual differences in tibial bone load. Further information could be gained by using GRF in combination with measurements of muscle strength and anthropometry to estimate the load on the tibia at a given site via mathematical models. Even so, mathematical models still rely on assumptions that may not necessarily be valid for each individual. In addition to load magnitude, stress fracture development is also a function of the number of loading cycles. In runners, this translates to training volume. Although we attempted to match the subjects on weekly running distance, this does not preclude the existence of differences as our measurement was based on recall of average kilometers run.

We found no difference in tibial BMC or BMD between TSF and NSF groups. This concurs with the prospective results of Giladi et al. (13) in 289 male Israeli recruits and of Bennell et al. (6) in 49 male track and field athletes. Although Beck et al. (3) reported significantly lower tibial and femoral bone density in 23 male military recruits who developed stress fractures compared with 587 controls, this result may be explained by differences in body weight (stress fracture group was 11% lighter) and the fixed additional load carried by the group during training. Because body weight is a major predictor of bone density, it is important to ensure that the groups are matched on this factor or that this factor is controlled statistically, otherwise the independent relationship of bone density and stress fractures cannot be determined.

Levels of bone density are heterogenous in the population of men with stress fractures, suggesting that bone density is not a good predictor of the risk of this bony injury. Based on current approaches to the assessment of bone density, bone densitometry has no place as a general screening tool in otherwise healthy individuals. This is in contrast to female athletes where low bone density increases the likelihood of stress fracture (6,26). The difference may be related to the effect of female sex hormones on bone as female athletes with stress fractures also have a greater prevalence of menstrual disturbances (6,8). This highlights the importance of assessing risk factors separately in men and women.

We are aware of the limitations of cross-sectional designs, but unlike military populations, which lend themselves well to data collection and permit much larger samples, it is more difficult to conduct a prospective cohort study in athletes. Our subjects were closely matched to avoid differences between TSF and NSF groups on other factors that may influence stress fracture risk. However, as the measurements were conducted after the stress fracture event, we are unable to determine their preinjury status. Nevertheless, bone geometry, BMD, and GRF would be expected to be relatively stable over the time period between the onset of injury and the measurement of these parameters in our cohort (20,22,28). It is unlikely that bone density was lower in the TSF group before injury and then increased afterward as the runners had been training consistently since recovery from injury. If anything, one might expect bone density to be reduced after the injury where a period of detraining has occurred. The nonsignificant results found for GRF and tibial BMC and BMD are not a function of limited power. Our calculations show that our sample size provides us with 95% power to detect a clinically relevant difference of 10% for both GRF and tibial BMD.

In conclusion, our cross-sectional study found that male runners with a history of tibial stress fracture were more likely to have smaller tibiae than runners without a previous stress fracture, supporting the findings in military populations. No differences were found between groups for GRF or tibial BMC and BMD. Further research should focus on detailed analyses of bone geometry from cross-sectional imagery (e.g., CT), taking into account the effect of body size differences on bone size. In addition, simple methods to assess bone geometry should be investigated that may allow screening of physically active individuals in a field or clinical setting. Preventative strategies could then be trialed and evaluated once at-risk athletes have been identified.

The authors would like to thank Associate Professor John Wark, Dr. Z. Steven Kiss, and staff at East Melbourne Radiology, Melanie Foley, Melanie Farlie, Narelle Sibte, Tony Natoli, Patrick McLaughlin, and Sue Kantor for their assistance with this study. We are also gratefully acknowledge the subjects who gave their time so willingly to participate in this study.

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Key Words: STRESS FRACTURE; EXTERNAL LOADS; BONE GEOMETRY; BMD; RUNNING; TIBIA; KINETICS; OVERUSE INJURIES

IMAGE GALLERY

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Subject Characteristics	Tibial SF (*N* = 23)	Non SF (*N* = 23)
Age (yr)	25.1 (4.9)	24.4 (6.2)
Height (m)	1.79 (0.08)	1.78 (0.07)
Mass (kg)	75.8 (9.4)	71.4 (7.7)
BMI (kg·m^{-2})	23.7 (3.0)	22.5 (1.7)
Training years[a]	9.0 (6.2)	9.2 (4.4)

[a] Number of years training at least twice per week.
BMI, body mass index; tibial SF, tibial stress fracture; non SF, nonstress fracture.

Table 1

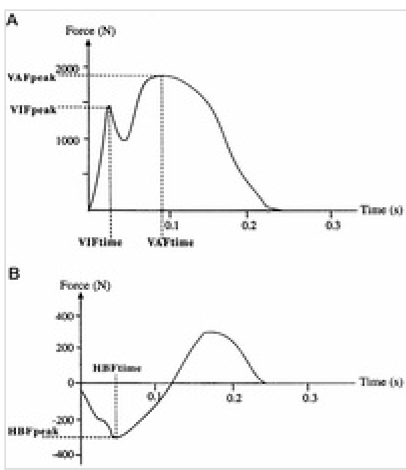

Figure 1-Schematic r...

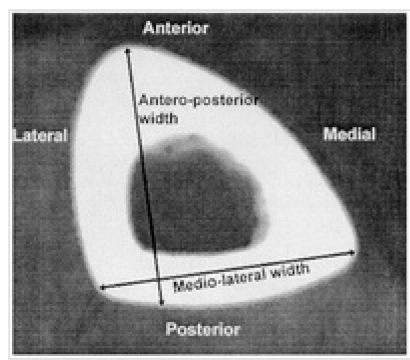

Figure 2-Tibial dime...

Ground Reaction Force	Tibial SF (*N* = 23)	Non SF (*N* = 23)
VIF_{peak} (N·N^{-1})	1.890 (0.387)	1.970 (0.337)
VIF_{time} (s)	0.031 (0.005)	0.031 (0.005)
VAF_{peak} (N·N^{-1})	2.843 (0.235)	2.856 (0.189)
VAF_{time} (s)	0.099 (0.009)	0.097 (0.011)
HBF_{peak} (N·N^{-1})	−0.496 (0.056)	−0.492 (0.104)
HBF_{time} (s)	0.050 (0.008)	0.051 (0.013)

VIF_{peak}, peak vertical impact force; VIF_{time}, time to peak vertical impact force; VAF_{time}, time to peak vertical active force; HBF_{peak}, peak horizontal braking force; HBF_{time}, time to peak horizontal braking force; tibial SF, tibial stress fracture; non SF, nonstress fracture.

Table 2

DXA	Tibial SF (*N* = 21)	Non SF (*N* = 19)
Area (cm^2)	8.333 (0.460)	8.603 (0.858)
BMC (g)	10.061 (0.974)	10.187 (1.252)
BMD (g·cm^{-2})	1.209 (0.089)	1.118 (0.072)

BMC, bone mineral content; BMD, bone mineral density; tibial SF, tibial stress fracture; non SF, nonstress fracture.

Table 3

Tibial Bone Geometry	Tibial SF (*N* = 20)	Non SF (*N* = 19)
TCSA (mm^2)	435.4 (48.7)	463.9 (65.5)
AP width (mm)	26.62 (2.05)	27.26 (2.75)
ML width (mm)	23.31 (1.78)	23.77 (2.58)
Tibial length (m)	0.41 (0.02)	0.42 (0.02)

TCSA, total cross sectional area; AP width, anteroposterior tibial dimension; ML width, mediolateral tibial dimension; tibial SF, tibial stress fracture; non SF, nonstress fracture.

Table 4

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