# An Analysis of the Biomechanical Mechanism of Tibial Stress Fractures Among Israeli Infantry Recruits

## A Prospective Study

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**The biomechanical mechanism of tibial diaphyseal stress fractures was studied prospectively in a group of 286 Israeli recruits. Before training each recruit had roentgenograms taken of his tibiae. Measurements of total tibial and cortical widths in the anteroposterior (AP) and mediolateral planes were made on these roentgenograms at two levels: at the point of the narrowest tibial width on AP roentgenograms (Level 1) and at the point of the narrowest width on lateral roentgenograms (Level 2). The tibial cross section was idealized as an eccentric ellipse within an ellipse, and on the basis of measurements taken from the roentgenograms, the cross-sectional area (compression strength), area moments of inertia about AP and mediolateral axes of bending (bending strength), and the area polar moment of inertia (torsional strength) were calculated for each cross section. During the course of 14 weeks of training, 20% of the recruits sustained tibial diaphyseal stress fractures, all of which were along the medial cortex. Using stepwise logistic regression analysis the tibia's bending strength along an AP axis of bending at Level 2 was found to be the most significant factor determining whether or not a recruit would develop a tibial stress fracture.**

The tibial stress fracture is the most common stress fracture seen in the Israeli Army[4,11] and in the civilian running population.[1] In some units of the Israeli Army, incidences of tibial stress fractures approaching 20% have been found.[11]

Many of the attempts made to lessen the incidence of stress fractures have centered on the foot–ground interface. Orthotics designed for shock absorption and worn within army boots were not found to have a statistically significant effect on the incidence of tibial stress fractures in an Israeli study.[10] In a report from the American Army a lowering of stress fracture incidence was partially attributed to an avoidance of running on hard surfaces.[13] Other studies have accentuated the superior biomechanical characteristics of running shoes.[6]

Preliminary to the development of a new army boot as a possible means to reduce the incidence of stress fractures in the Israeli Army, the authors undertook to identify the forces that cause stress fractures. The results of a prospective study to analyze the biomechanical mechanism of tibial stress fractures among a group of Israeli infantry recruits are reported here.

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FIG. 1. Scintigram showing a focal area of increased uptake of the right tibia indicating a stress fracture.

## MATERIALS AND METHODS

### PATIENT POPULATION

A group of 295 new male infantry recruits between the ages of 18 and 20 years were evaluated during 14 weeks of basic training in a prospective study of stress fractures. All of the participants in the study signed an informed consent.

Each of the recruits had a detailed pretraining screening. The screening included the following: (1) measurement of weight and height; (2) anteroposterior (AP) roentgenograms of the tibiae with the feet positioned at 15° internal rotation; and (3) standard lateral roentgenograms of the tibiae. The tube to film distance was 90 cm. Measurement of total tibial and cortical widths in the AP and mediolateral planes were made on these roentgenograms at two levels: at the point of the narrowest tibial width on AP roentgenograms (Level 1) and at the point of the narrowest tibial width on lateral roentgenograms (Level 2). All measurements were taken by one person using a magnification ruler.

During the course of 14 weeks of basic training, recruits had mandatory examinations every three weeks by a team of army doctors in the field. They were questioned about symptoms compatible with stress fractures, and those recruits with complaints had physical examinations. The recruits had free access to the medical staff on a daily basis and were encouraged to report symptoms. Recruits with symptoms compatible with stress fractures were given three days rest and, if still symptomatic on return to activity, were sent to the hospital orthopedist.

The sites at which the recruits reported pain were recorded and measured from anatomic landmarks. Appropriate roentgenograms were taken and late phase Tc 99 MDP scintigraphy was routinely performed. A diagnosis of a stress fracture was made on the basis of positive roentgenograms and/or a positive scintigram, using the criteria of Prather *et al.*[12] Scintigraphy was considered to be diagnostic of a stress fracture when a focal area of increased uptake was found in the absence of other bony pathology (Fig. 1).

### CALCULATIONS OF TIBIAL RESISTANCE TO COMPRESSION, BENDING, AND TORSIONAL LOADS

For the purpose of these calculations, the tibial cross section was idealized as an elliptical ring with an eccentric hole (Fig. 2). Two cross sections were examined, corresponding to Level 1 (narrowest tibial width on AP roentgenograms) and Level 2 (narrowest tibial width on lateral roentgenograms). For each cross section, the following dimensions were measured on the roentgenograms: A = the tibial width in the mediolateral direction; B = the tibial width in the AP direction; $C_m$ = the medial cortical width; $C_l$ = the lateral cortical width; $C_a$ = the anterior cortical width; and $C_p$ = the posterior cortical width. From these dimensions, the following cross-sectional (CS) parameters were calculated. The formula for each parameter is derived in the appendix.

1. The CS area is a measure of the resistance of the tibial to axial compression load (Fig. 3A).
2. The area moment of inertia about a mediolateral axis through the section's center (IML) is a measure of the resistance of the tibia to bending moments in the saggital plane (Fig. 3B).
3. The area moment of inertia about an AP axis through the section's center (IAP) is a measure of the resistance of the tibia to bending moments in the frontal plane (Fig. 3C).
4. The area polar moment of inertia about a vertical axis through the section's center (IP) is a measure of the resistance of the tibia to torsional moments (Fig. 3D).

### Statistical Analysis

A standard evaluation form for data collection was designed before the study began. Statistics were calculated with the Statistical Package for the Social Sciences (SPSS) and the Statistical Analysis System (SAS).

The distributions of all the CS parameters were found to be asymmetric; therefore, nonparametric statistical tests were used in the analysis. Associations between the variables and tibial stress fractures were examined using the ranks of variables instead of the original values with stepwise logistic regression tests. The Wilcoxon rank sum test was used to examine differences in each variable between recruits with and without tibial stress fractures.

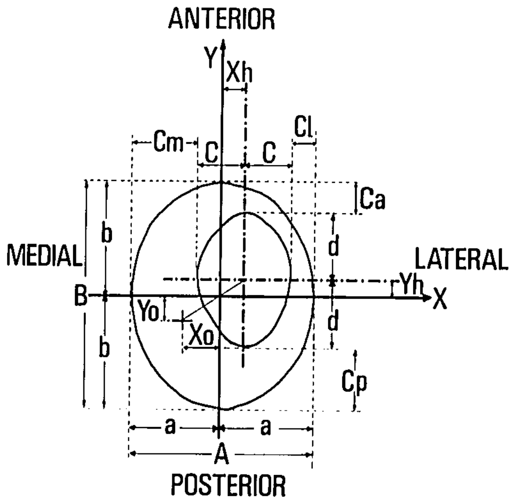



FIG. 2. The method used to determine the center of gravity, CS area, area moment of inertia, and the area polar moment of inertia for each cross section based on roentgenograms.

## RESULTS

Tibial bone widths were measured bilaterally in 288 recruits. The derived calculations of CS area, IAP, and IP were calculated in 286 of these recruits. The mean values of the right and left tibiae were used in all calculations.

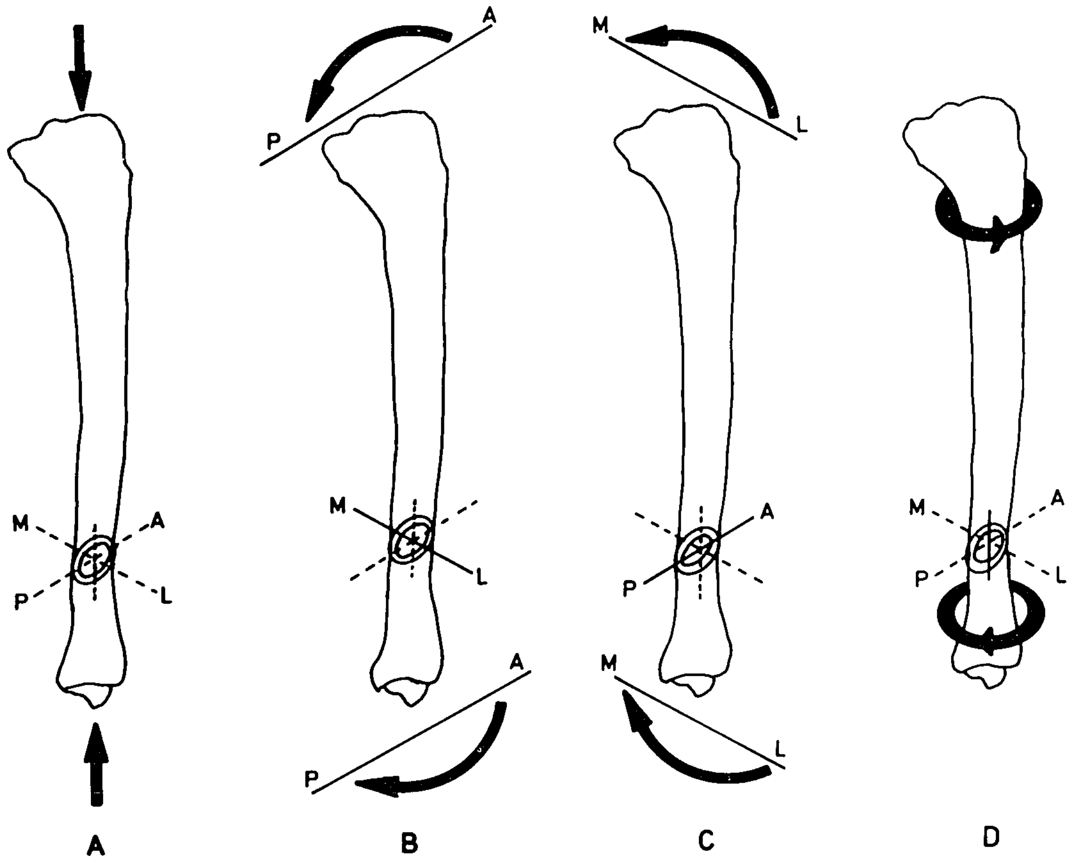
Fifty-eight of the 286 recruits (20%) sustained a total of 81 tibial diaphyseal stress fractures on the basis of scintigrams. These were all located along the medial cortex, with 88% in the middle one-third, 10% in the distal one-third, and 2% in the proximal one-third of the tibia. Eight percent of these stress fractures were asymptomatic at the time of diagnosis.

Table 1 compares the mean values for each of the CS parameters measured between recruits with and without tibial stress fractures at two CS levels. The differences between the means of all of the variables at Level 2 (except for the lateral tibial width), and the AP width and IAP at Level 1, were statistically significant when analyzed separately in univariant analysis. However, when stepwise logistic regression analysis was performed, the area moment of inertia about the AP axis of bending (IAP) at Level 2 was found to be the most significant variable for tibial stress fractures. The contribution of the other variables to the multivariant analysis was insignificant. Height and weight had no statistically significant relationship to the incidence of tibial stress fractures.

## DISCUSSION

The tibia is subjected during training to repetitive compression, tension, torsion, and bending forces.[7] These forces originate primarily from the foot–ground interface[7] as well as from muscle traction forces on bone.[2] Depending on the training situation these forces can act singly or in combination to cause tibial stress fractures.

The ability of the tibia to resist each type of force can be calculated for any given tibial cross section studied. Because the geometry of the tibia is complex and changes continually along the length of the tibia, calculations require an idealization of its shape. In this study the shape was idealized as an elliptical ring with an eccentric hole. The two CS levels used in this study (the narrowest AP [Level 1] and lateral widths [Level 2]) were chosen because they were anatomic points on the tibia easily distinguished for each recruit on the basis of roentgenograms. At




FIGS. 3A–3D. The four loading modes of the tibia and their respective relevant CS properties. (A) Axial loading (compression or tension): cross-sectional area ($mm^2$). (B) Bending in the AP plane: CS moment of inertia with respect to the mediolateral axis ($mm^4$). (C) Bending in the mediolateral plane: CS moment of inertia with respect to the AP axis ($mm^4$). (D) Torsion around the long axis of the tibia: CS polar moment of inertia ($mm^4$).

Level 2 the cross section approached that of a hollow cylinder.[8]

The resistance of the tibia to compression is proportional to its CS area. Resistance to bending is proportional to the area moment of inertia of the bone about the axis of bending studied for the cross section. The area moment of inertia measures the distribution of the area of the bone in relationship to an axis of bending.[3] The farther the material is distributed away from the axis of bending, the greater is the ability of the bone to resist bending forces. In this study area moments of inertia were calculated about two axes of bending, the AP and the mediolateral. These two axes were used because data were obtained from AP and lateral roentgenograms. The resistance of the tibia to torsional forces is proportional to the polar moment of inertia of the bone for the cross section studied. It is a measure of the distribution of the area of the materal similar to the area moment of inertia. The polar moment of inertia, however, does this with respect to the centroid of the cross section and not an axis.[3]

The authors previously reported that the bone–mineral content of the tibia did not contribute to the incidence of stress frac-

TABLE 1. The Mean Measurements of Tibial Biomechanical Strengths in Recruits with and without Tibial Stress Fractures

| | *Tibial Stress Fractures* | | |
|---|---|---|---|
| | *With (n = 58)* | *Without (n = 228)* | *p Value** |
| Level 1 | | | |
| AP Tibial Width (mm) | 23.1 ± 2.1 | 24.4 ± 1.9 | 0.013 |
| Lateral Tibial Width (mm) | 28.1 ± 2.7 | 28.3 ± 2.6 | 0.450 |
| CS area ($mm^2$) | 386 ± 65 | 395 ± 60 | 0.168 |
| Area moment of IML ($mm^4$) | 24,684 ± 8738 | 25,646 ± 8211 | 0.320 |
| Area moment of IAP ($mm^4$) | 17,467 ± 5690 | 18,730 ± 5054 | 0.030 |
| Polar moment of I ($mm^4$) | 42,150 ± 1366 | 44,376 ± 1261 | 0.136 |
| Level 2 | | | |
| AP tibial width (mm) | 25.6 ± 2.1 | 26.3 ± 2.0 | 0.014 |
| Lateral tibial width (mm) | 25.4 ± 2.0 | 25.9 ± 2.0 | 0.093 |
| CS area ($mm^2$) | 284 ± 42 | 297 ± 39 | 0.014 |
| Area moment of IML ($mm^4$) | 16,780 ± 4592 | 18,253 ± 5038 | 0.037 |
| Area moment of IAP ($mm^4$) | 16,830 ± 4638 | 18,470 ± 4619 | 0.007 |
| Polar moment of I ($mm^4$) | 33,611 ± 8890 | 36,723 ± 9330 | 0.013 |

* Wilcoxon rank sum test.

tures.[9] They found, however, that the width of the tibia in the mediolateral direction was related to the incidence of stress fractures.[5] Recruits with wider tibiae had a lower incidence of stress fractures than recruits with narrow tibiae. The authors hypothesized that tibial bone width was a risk factor for stress fractures possibly on the basis of its relationship to the area moment of inertia.[5] Because tibial bone width is a factor used in calculating the polar moment of inertia and the CS area as well, this hypothesis could logically be questioned.

From the present study the following conclusions may be reached. (1) The most significant tibial biomechanical factor identified that determines whether or not a recruit will develop a tibial stress fracture is the tibia's bending strength about the AP axis of bending, with movements occurring in a mediolateral direction. This motion coincides with the location of all the recruits' tibial diaphyseal stress fractures along the medial cortex. (2) The area moment of inertia at CS Level 2 has the most statistically significant relationship to the incidence of tibial stress fractures. This probably is because at this level the idealized model approached the actual tibia's geometry. (3) From these data no statement can be made about the relative importance of tibial compression and torsional strengths in resisting development of tibial diaphyseal stress fractures. It can only be said that they were not as important as the bending strength. (4) The importance of bending forces should be considered when designing orthotics or shoe modifications as possible means to limit the incidence of tibial stress fractures.

## APPENDIX

Referring to Figure 1, the cross section parameters were calculated as follows:

The semidiameter of the external ellipse in the mediolateral direction:

$$a = A/2.$$

The semidiameter of the external ellipse in the AP direction:

$$b = B/2.$$

The semidiameter of the internal ellipse in the mediolateral direction:

$$c = a - \frac{C_m + C_l}{2}.$$

The semidiameter of the internal ellipse in the AP direction:

$$d = b - \frac{C_a + C_p}{2}.$$

The CS area is given by:

$$CS = \P(ab - cd).$$

A coordinate system is set, with the x-axis along the mediolateral direction, the y-axis along the AP direction and the origin at the center of the external ellipse.

The coordinates of the center of the internal ellipse are:

$$X_h = a - (C_l + c),$$

$$Y_h = b - (C_a + d),$$

and the coordinates of the cross section centroid are:

$$X_o = -X_h \frac{\P cd}{\P(ab - cd)},$$

$$Y_o = -Y_h \frac{\P cd}{\P(ab - cd)}.$$

The area moment of inertia about a mediolateral axis (IML) through ($X_o$, $Y_o$) is given by:

$$IML = \P ab\left(\frac{b^2}{4} + Y_o^2\right) - \P cd\left[\frac{d^2}{4} + (Y_h - Y_o)^2\right].$$

The area moment of inertia about an AP axis (IAP) through ($X_o$, $Y_o$) is given by:

$$IAP = \P ab\left(\frac{a^2}{4} + X_o^2\right) - \P cd\left[\frac{c^2}{4} + (X_h - X_o)^2\right].$$

The polar moment of inertia (IP) about a vertical axis through ($X_o$, $Y_o$) is given by:

$$IP = IML + IAP.$$

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