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FOOT & ANKLE

Combined Effect of Foot Arch Structure and an Orthotic Device on Stress Fractures

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ABSTRACT

In a prospective study, quantitative measures of the structure of the longitudinal arch of the foot were established and related to the incidence of stress fractures in the bones of the lower limbs of military recruits. In addition, the role of a semirigid orthotic device (Langer military stress orthotic) in preventing stress fractures was evaluated as a function of the structure of the longitudinal arch. Femoral and tibial stress fractures were found to be more prevalent in the presence of feet with high arches, whereas the incidence of metatarsal fractures was higher in feet with low arches. The use of an orthotic device reduced the incidence of femoral stress fractures only in the presence of feet with high arches and the incidence of metatarsal fractures only among feet with low arches. The findings suggest that the normal foot with a low arch acts as a better shock absorber than the normal foot with a high arch, and that an orthotic device may improve the shock absorbing capacity of the arch.

During intensive physical training, such as that experienced by military recruits, loads of high magnitude are exerted on the lower limbs. The repetitive stressing of the bones by these loads is considered the main factor in the formation of stress fractures. These fractures are a major problem among military trainees.[11]

The fact that, under similar training activities performed in the same environment, stress fractures develop in only a certain percentage of the trainees indicates that intrinsic factors are affecting the prevalence of these fractures. Several such factors were identified in previous studies.[3, 4 10, 13] The forces causing the fractures are generated primarily during the interaction between the ground and the foot; therefore, in several studies, the relation between foot arch type and the occurance of stress fractures has been investigated. However, in these studies[2, 5, 6, 8] subjective criteria were used to assess the foot type. In three of the studies, the populations investigated included only subjects who had already sustained stress fractures. This article is a prospective study in which a quantitative measure for the structure of the longitudinal arch of the foot was established. The influence of this measure on the incidence of stress fractures in the bones of the lower limb was investigated in subjects with normal feet.

The effect of an orthotic device intended to partially absorb the impact on the lower limb has been already described.[9] It was found that the incidence of femoral stress fracture was reduced in a group using this device. In the present study, the role of this orthotic device in preventing stress fractures was evaluated as a function of the structure of the longitudinal arch.

PATIENTS AND METHODS

A group of 295 male military recruits assigned to combat units participated in this study. Prior to their basic training each of the recruits underwent an orthopaedic examination through which those with pes planus or pes cavus were excluded.

Of the 295 recruits, 143 were randomly chosen and given military stress orthotics (Langer Biomechanics Group Inc, Deer Park, NY; Fig. 1) before the beginning of a vigorous 14-week training period. The prefabricated orthotic device was allocated according to the shoe size of the recruit. Its shell was a semirigid 3.5-mm polyolefin plastic module that extended from the heel to the metatarsal heads and was designed for an average arch height. A 45-durometer styrene butadene rubber hindfoot post at 3° varus was added to the shell. A 0.312-cm (1⁄8-in) PPT (open cell urethane foam) was applied beneath the heel post and on top of the shell. The top PPT layer was laminated with a moisture-

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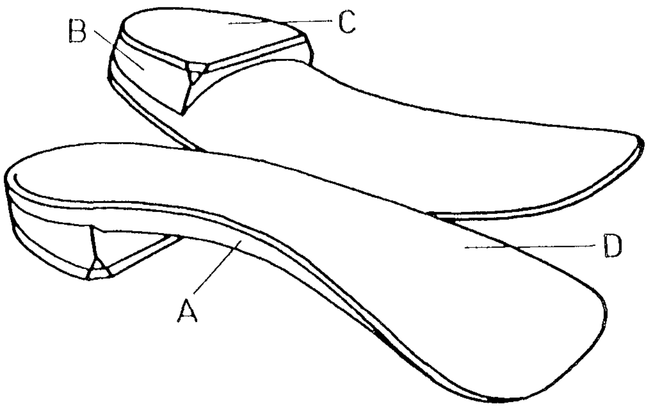

Fig. 1. Orthotic device. *A,* Prefabricated semi-rigid shell made of 3.5-mm polyolefin. *B,* A 45-durometer styrene butadene rubber hindfoot post angled at 3° varus. *C,* 0.312-cm (1/8-in) PPT pad beneath the heel post. *D,* 0.312-cm PPT top cover laminated with a moisture-resistant expanded vinyl.

resistant expanded vinyl. The use of the device was discontinued by 30 soldiers during the first 2 weeks of training because of difficulties in accommodating them. Thus, 113 recruits with orthotic devices and 152 without such devices took part in the study.

Before the training period, lateral x-ray films of both feet in a weightbearing, barefoot, standing position were taken for each subject. The positioning procedure was the one described by Clark[1] in which the patient stands on a wood platform with a shallow gap in its midline (Fig. 2). Two film packs, separated by a protective lead sheet, were placed vertically between the feet that are brought together in close contact with them. The weight of the subject is equally supported by both feet, while stability is gained by the hand resting on a vertical support. The center of the x-ray field is directed horizontally toward the cuboid. The tube-film distance in this study was 90 cm and the exposure 8 mA at 80 KV(p).

From the lateral x-ray film, three parameters were defined to describe the structure of the longitudinal arch of the foot (Fig. 3): (1) calcaneal angle (CA)—the angle formed between the tangent to the inferior surface of the calcaneus and the horizon; (2) forefoot angle (FOR)—the angle formed between the horizon and the tangent to both the inferior surface of the medial sesamoid bone and the inferior surface of the talar head; (3) Height to length ratio (H/L)—the ratio between the height and length of the arch. The height was defined as the distance from the inferior surface of the talar head to the platform on which the foot was resting. The length of the arch was defined as the distance from the posterior surface of the calcaneus to the anterior surface of the first metatarsal head.

It should be noted that the parameters described above are either angles or ratios between lengths, so that errors resulting from different magnifications of x-ray films are eliminated. All measurements were taken on both the right and left x-ray films. Radiograms of sufficient quality for the calculation of these parameters were obtained only for 256 soldiers, 111 with the orthotic devices and 145 without them.

During the training course the recruits were observed by a medical staff in the field and a hospital-based orthopaedist. All recruits were encouraged to report symptoms compatible with stress fractures. In addition, they had mandatory check-ups every 3 weeks throughout training. In case of a complaint, AP and lateral x-ray films of the involved limb segments were taken and late phase Tc-99m methylene diphosphonate (MDP) whole body scintigraphy was performed, plus spot views of the feet, tibias, knees, and femurs. Stress fractures were diagnosed on the basis of a positive x-

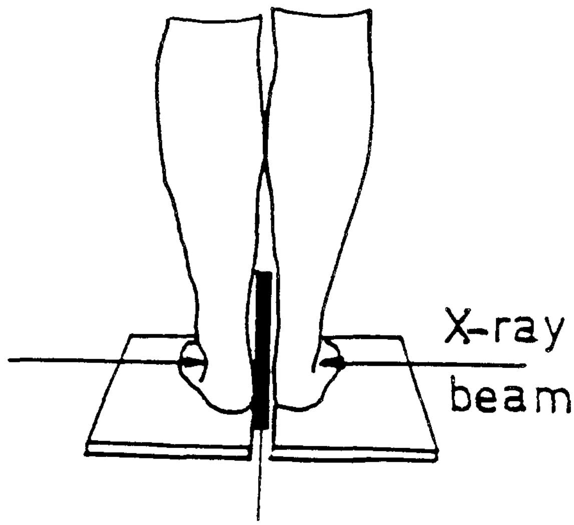

Fig. 2. The standing weightbearing position and the x-ray technique used to obtain a lateral radiograph of the foot.

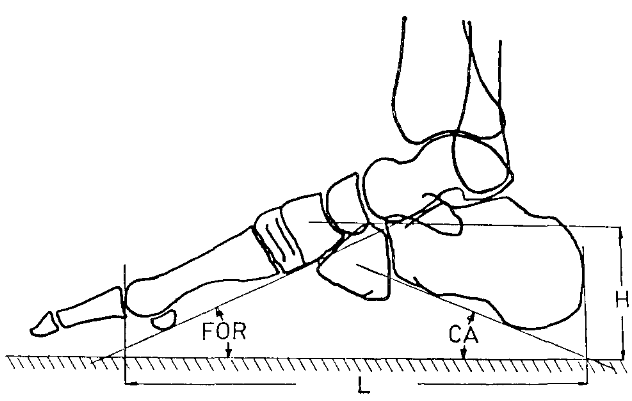

Fig. 3. The parameters defining the longitudinal arch of the foot, measured on a lateral x-ray film, taken in a standing position. Abbreviations: CA, calcaneal angle; FOR, forefoot angle; H, arch height; L, arch length.

ray film and/or positive scintigram. A scintigram was considered diagnostic of a stress fracture when a sharply marginated area of increased activity, compared with the contralateral side, was identified, in the absence of other bone pathology.[12]

STATISTICAL METHODS

The incidence of stress fractures in the lower limb was analyzed per foot rather than per soldier, because a paired *t* test had shown that the difference between the calcaneal angle in the right and left foot was highly significant ($P < .001$). Moreover, 75% of the femoral fractures, 59% of the tibial fractures, and 73% of the metatarsal fractures were unilateral.

The effect of the interaction between arch structure and the presence of an orthotic device on the incidence of stress fractures was evaluated by preparing contingency tables and evaluating them with the χ^2 test. If the expected value in one or more cells of the contingency table was less than 5, the Fisher exact probability test was performed.

RESULTS

In Table 1, the mean value, standard deviation, and range of each of the three parameters of the longitudinal arch are presented. Before we analyzed the relation of these parameters to the incidence of fracture we evaluated the intercorrelations among them. The correlation coefficients were: CA and FOR, 0.593; CA and H/L, 0.625; FOR and H/L, 0.822 ($P < .001$ for all three). These figures demonstrate that the three parameters were not highly correlated and none of them could be predicted by the other two. Therefore each parameter was evaluated separately.

In an attempt to relate the structure of the longitudinal arch to fracture incidence, eliminating the effect of the orthotic device, we first performed the analysis on the 145 soldiers who were training without orthotic devices. The use of a *t* test showed no significant difference in the mean values of any arch parameter between the soldiers with and without a fracture. This result was obtained separately for the femoral, tibial, and metatarsal fractures.

To determine whether the arch parameters among nonusers of the orthotic device can be categorized into two groups (of high and low values) that differ significantly in their proportion of stress fractures, the χ^2 test was used. The point dividing the values into high and low categories was determined using the Kolmogorov-Smirnov two-sample test. In this test, the point dividing the population into two groups with the highest difference in fracture incidence is defined. The cutpoint was determined separately for femoral, tibial, and metatarsal fractures. Feet having exactly the cutpoint value were allocated to the low group.

The first arch parameter to be examined was the calcaneal angle. The cutpoint values for this parameter with relation to femoral, tibial, and metatarsal fractures were 17, 16, and 17 degrees, respectively. The frequencies of each fracture in the groups of low and high calcaneal angle are presented in contingency Tables 2. The femoral fracture incidence in the low group was 2.6% and in the high group, 15.5%. The χ^2 test showed that the difference between the femoral fracture incidences in the two groups was statistically significant ($P < .006$). The tibial fracture incidences were 9.8% in the low group and 17.3% in the high group, but the χ^2 test showed that the difference between the groups was not significant ($P < .219$). The metatarsal fracture incidence showed an opposite trend than either the femoral or tibial fractures: the fracture incidence in the low group was 6.3%, larger than that of the high group—1.9%. However, the difference between the groups was not significant ($P < .07$, Fisher exact probability test).

Similar analysis of fracture incidences among nonusers of orthotic devices, using the forefoot angle or the

TABLE 1
Mean Value, Standard Deviation, and Range of the Longitudinal Arch Parameters of the Soldiers in This Study (512 Feet)

Parameter	Mean	S.D.	Range
Calcaneal angle (°)	20.60	5.22	6.0–41.0
Forefoot angle (°)	21.71	2.53	15.0–30.0
Height to length ratio	0.254	0.028	0.170–0.349

TABLE 2
Number of Femoral, Tibial, and Metatarsal Stress Fractures in the High and Low Calcaneal Angle (CA) Groups[a]

Type of fracture (°)	No. without orthotic device	No. (%) with orthotic device	No. in both groups
Femoral[b]			
CA <17°	76	2 (2.6)	78
CA >17°	175	32 (15.5)	207
Total	251	34 (11.9)	285
Tibial[c]			
CA <16°	55	6 (9.8)	61
CA >16°	186	39 (17.3)	225
Total	241	45 (15.7)	286
Metatarsal[d]			
CA <17°	74	5 (6.3)	79
CA >17°	203	4 (1.9)	207
Total	277	9 (3.2)	286

[a] Numbers in parentheses are the total number of feet presented is less than 290 (145 soldiers) because in several cases the presence of fracture was not clear; these cases were omitted from the analysis.
[b] $P < .006$, χ^2 test.
[c] $P < .219$, χ^2 test.
[d] $p < .07$, Fisher exact probability test.

H/L ratio to define the arch structure, failed to show significant differences in fracture incidence between low and high values of the parameters, except for the incidence of metatarsal fractures in relation to H/L ratio. In Table 3, the results of this analysis is presented when the cutpoint used for the H/L ratio was 0.247. The metatarsal fracture incidence in the group of low H/L ratio was 6.0%, whereas that in the high ratio group was 1.2%, and this difference was statistically significant ($P < 0.03$, Fisher exact probability test).

The next step was to evaluate the effect of the orthotic device on the fracture incidence as a function of arch structure. The high and low groups according to the calcaneal angle and the H/L ratio were examined separately. The same cutpoints found earlier were used for both parameters. In contingency Table 4, the number of femoral fractures among users and nonusers of the orthotic device is seen. Among the soldiers with the high values (Table 4), the femoral fracture incidence was 5.1% among those who used orthotic devices, whereas in those who did not use them this incidence was 15.5%. This difference was found to be statistically significant ($P < .003$, χ^2 test). An opposite trend was found among soldiers with low arches (Table 4). The femoral fracture incidence in users of the orthotic devices was 7.9%, whereas in the nonusers it was 2.6%. This difference, however, was not significant ($P < .29$, χ^2 test). The use of the orthotic devices did not significantly affect the incidence of either the tibial or metatarsal fractures in either group, high or low calcaneal angle.

When the H/L ratio was used as a measure of arch structure (Table 5), it was found that in the group with low H/L ratio the use of the orthotic device significantly reduced the metatarsal fracture incidence to 0% compared with 6% in nonusers of the device ($P < .02$, Fisher exact probability test). In the group with high H/L ratio, the use of the orthotic device had no significant effect on the incidence of metatarsal fractures.

TABLE 3
Number of Metatarsal Fractures in the High and Low Height to Length (H:L) Ratio Groups[a]

Metatarsal fractures[b]	No. without orthotic device	No. (%) with orthotic device	No. in both groups
H:L ≤0.247	110	7 (6.0)	117
H:L >0.247	167	2 (1.2)	169
Total	277	9 (3.2)	286

[a] Numbers in parentheses are incidences given as percentages. The total number of feet presented is less than 290 (145 soldiers) because in several cases the presence of fracture was not clear; these cases were omitted from the analysis.
[b] $P < .03$, Fisher exact probability test.

TABLE 4
Number of Femoral Fractures Among Soldiers With "High" and "Low" Calcaneal Angle (CA) Who Were Users and Nonusers of Orthotic Device[a]

Femoral fractures	No. without	No. (%) with	No. in both groups total
CA >17°[b]			
Nonusers of device	175	32 (15.5)	207
Users of device	150	8 (5.1)	158
Total	325	40 (11.0)	365*
CA ≤17°[c]			
Nonusers	76	2 (2.6)	78
Users	58	5 (7.9)	63
Total	134	7 (5.0)	141

[a] Numbers in parentheses are incidences given in percentages. The total number of feet presented is less than 512, because in several cases the presence of fracture was not clear; these cases were omitted from the analysis.
[b] $p < .003$, χ^2 test.
[c] $p < .29$, χ^2 test.

TABLE 5
Number of Metatarsal Fractures Among Soldiers With "Low" and "High" Height to Length (H/L) Ratio Who Were Users and Nonusers of Orthotic Devices[a]

Metatarsal fractures	No. without	No. (%) with	No. in both groups
H/L ≤0.247[b]			
Nonusers	110	7 (6.0)	117
Users	90	0 (0.0)	90
Total	200	7 (3.4)	207*
H/L >0.247[c]			
Nonusers	167	2 (1.2)	169
Users	131	1 (0.8)	132
Total	298	3 (1.0)	301

[a] The numbers in parentheses are fracture incidences given in percentages. The total number of feet presented is less than 512, because in several cases the presence of fracture was not clear; these cases were omitted from the analysis.
[b] $P < .02$, Fisher exact probability test.
[c] Not significant.

DISCUSSION

In this study, it was shown that the structure of the longitudinal arch of the foot affects the incidence of femoral, tibial, and metatarsal stress fractures in training recruits. However, although femoral and tibial stress fractures were more prevalent in subjects with high calcaneal angle, metatarsal fractures were more prevalent in feet with low angles. The opposite effect of the calcaneal angle on the incidence of femoral compared with metatarsal stress fractures may be explained by considering the foot as a shock-absorbing device.[7] The energy absorbed by the foot is transferred primarily to its elasic soft tissues; however, the part absorbed repeatedly by its bones may cause stress fractures. Feet with relatively low calcaneal angles seem to absorb more energy during the stance phase of locomotion than feet with high angles; there is, therefore, less energy transferred to the bones of the shank and thigh. Thus, in feet with low calcaneal angles, the incidence of metatarsal stress fractures was comparatively large, whereas that of the femoral and tibial stress fractures was smaller. In feet with a high calcaneal angle the energy absorbing mechanism is less effective and increases the prevalence of the femoral and tibial fractures but reduces the fracture incidence in the metatarsal bones.

The relation between shock-absorbing capacity and the calcaneal angle was reinforced by our examination of the 13 cases in which fractures developed in both the tibia and femur. In all of these cases the calcaneal angle was greater than 19° (average 23.4°). Similarly, in the 9 cases in which two fractures developed in one bone, either the tibia or the femur, the calcaneal angle was greater than 20° (average 26.8°). Thus, all of the cases with multiple fractures in the bones above the foot developed in subjects with a high calcaneal angle whose arches have a low energy-absorbing capacity.

When the feet were classified as high arched or low arched, according to the calcaneal angle and H/L ratio, it was found that the effect of the orthotic device on the prevalence of the fractures was different in the two groups. In feet with a high arch, the presence of the orthotic device significantly reduced ($P < .003$) the prevalence of the femoral fractures but did not significantly reduce the prevalence of metatarsal fractures. In feet with a low arch, the presence of the orthotic device significantly reduced ($P < .02$) the incidence of metatarsal fractures and increased the incidence of femoral fractures, although not significantly. The prevalence of tibial fractures was not affected by the use of the orthotic device either in high-arched or in low-arched feet.

The orthotic device used in this study was designed as an additional shock-absorbing mechanism, working in concert with the foot. Our results indicate that the insufficient absorbing capacity of the high-arched foot seems to be augmented by adding the orthotic devices, thus reducing the incidence of femoral fractures. In the low-arched foot, the orthotic device relieves the energy load carried by the foot, thus reducing the incidence of metatarsal fractures.

The insignificant increase in the incidence of femoral stress fractures in feet with low arches provided with an orthotic device that was not custom made may indicate the unsuitability of this device for feet with low arches. Moreover, a different design may be needed for extremely high or low arches, which was not included in the present study, because the recruits were screened for pes planus and pes cavus during enrollment to the combat units.

Although in the present study a significant relationship was shown between the structure of the longitudinal arch of the foot and the occurance of stress fractures, it should be realized that the etiology of these fractures is multifactorial. Other known risk factors for these fractions are tibial width,[3] the area moment of inertia of the tibial cross section,[10] the external rotation at the hip joint,[4] and body physique[13]. However, these risk factors cannot be readily modified, whereas, as shown in this study, the effect of the longitudinal arch can be controlled by a suitable orthotic device.

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