Clin. Biomech. 1994; **9**: 111–116

Toward early detection of the tendency to stress fractures

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Summary

Certain characteristics of the foot structure represented by the contact pressure display method provide a clear indication of the tendency to experience stress fractures. The main results of the research project are (i) the static foot–ground pressure diagram may supply basic information about the foot structure, needed to understand its behaviour, (ii) a new concept of stress intensity parameters was introduced and appeared to be basic for the foot structure evaluation, (iii) a set of criteria was established to classify the foot structure and its tendency to stress fractures, (iv) a simple computerized screening technique can calculate and classify the values of above parameters and relate them to the established criteria. The results may enable a scientific and practical approach in characterizing foot orthopaedic problems and might help to rate the stress fracture risk.

Relevance

Foot structures and their tendency to develop stress fractures can be screened and classified (for sports and other activities involving marching exercises) according to characteristic parameters of the foot–ground pressure diagrams; special protecting shoes or insoles may then be recommended.

Key words: Stress intensity parameters, longitudinal arch, foot–ground pressure distribution, stress fracture, fatigue fracture

Introduction

Stress fractures are injuries that occur in different bones in the skeletal system[1] developed during an overwork period of time without being the result of a trauma. The site of such phenomena depends upon the activity that produces them; however, their development in the lower limbs is significantly higher. Thus stress fractures, especially those located in the lower limbs, are fairly common occurrences in heavy sport or military activity and they cause limitations in training schedules and types of exercise[2–4].

It is believed that stress fractures, most of a fatigue type, result from repetitive prolonged muscular action on a bone which is not accustomed to that action[5]. Therefore attempts have been made to understand the influence of activities like walking and running on the human body in general and on the lower limbs in particular.

During locomotion, the body is subjected to forces which develop as a reaction between foot and ground and which can be measured. By using a force plate and accelerometer systems, the repetitive impact loads related to the heel strike can be assessed[6–7]. Lately it has been claimed that such events may be a source of damaging effects to the human body[8].

Most parts of the musculoskeletal system act as natural shock absorbers which attenuate the impulsive wave[9]. However, Smeathers[10], who used accelerometers to analyse the transient velocity of the impulsive shock wave during heel strike, found that shock absorption occurs mainly in the legs. Since stress fractures are a result of repetitive loading, efforts have been made to understand the role of different parts of the lower limbs in the attenuation process. The foot structure, comprising bones, muscles, and ligaments, exhibits special features such as arch geometry, heel sharpness, and alternation of soft and hard tissues, and offers a significant contribution to wave attenuation. Attempts have been made to obtain information related to foot structure and its behaviour by using

Received: 30 December 1992
Accepted: 22 June 1993
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0268–0033/94/020111–06

static and dynamic experiments[11] or by developing theoretical models[12]. Also the heel pad plays an important role as a shock absorber in attenuating the impulsive wave[13] since it is the first contact location between body and ground during gait.

Considering the incidence of stress fractures, it is assumed that some basic correlation could be found between such phenomena and the foot structure characteristics, like the deformability of the half dome foot shape or of the longitudinal arch shape. Moreover these characteristics appear to be well enough represented by the static foot–ground pressure pattern (FGP) in order to use it for evaluating the functional response of the foot during gait[14].

The aim of this paper is to introduce a non-invasive *in-vivo* evaluation and screening method to be used in defining some new geometrical–mechanical parameters characterizing the foot structure by analysing the static pressure pattern and relating the resulting data to the incidence of stress fractures.

Methods

Experimental technique

The selected method for measurements was the contact pressure display (CPD) system, which provides a quantitative pattern, in the present case the foot–ground pressure pattern. The CPD method[15–16] makes use of a birefringent integrated optical sandwich in order to analyse the contact pressure. Through this method (Figure 1) the total transferred load is discretized into local contact points by a matrix of pins with spherical tips (16 × 12 mm apart). Concentric isochromatic circles appear under every local contact and their maximal diameter is a function of the local contact load.

The CPD method, which may be applied not only to foot–ground static contact patterns but also to gait analysis[17–18] and sitting posture assessment[19], proved able to give significant information related to the human body by using non-invasive techniques.

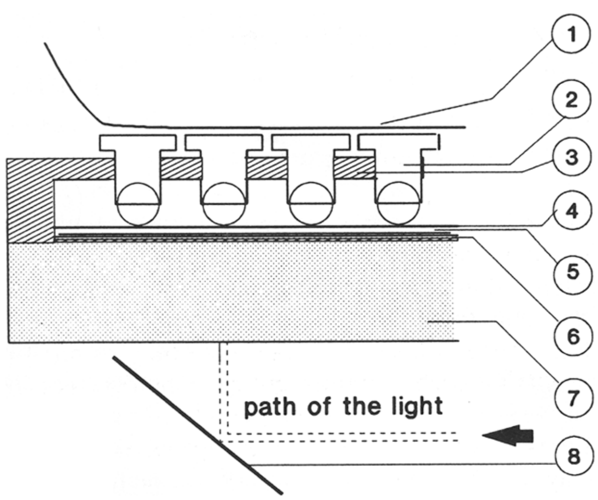
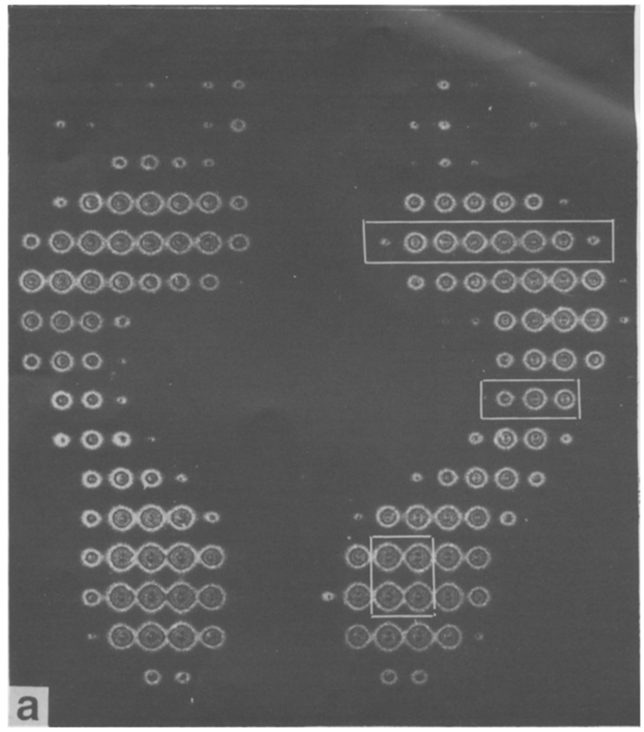


Figure 1. Schematic diagram of the contact pressure display (CPD) method and instrument. 1, Human body (e.g. foot); 2, pins (spherical tip); 3, metal plate; 4, reflective layer; 5, photoelastic sheet; 6, circular polarizer; 7, plate of glass; 8, mirror.



b

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
16						0	1						0	1						
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14				1	1	0	0							0	0					
13		0	1	4	3	2	2	1					1	1	3	3	2			
12	1	1	3	5	4	2	2	1					1	2	6	8	9	7		(1)
11	1	3	4	4	2	2	1						1	2	2	5	7	8	2	
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9	0	2	3	2	1											1	2	3	1	
8		1	2	2	1											1	2	2		(2)
7		1	2	2	1											1	2	3		
6			2	2	2	1									1	2	2	1		
5			1	2	3	3	1						2	2	3	3	1			
4			1	2	6	7	9					5	12	13	7	4				(3)
3			1	3	11	14	12					8	13	15	12	6				
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Figure 2. **a** Characteristic foot ground pressure (FGP) pattern, and **b** related numerical contact loads in Newtons: highest loaded areas (1), (3) for metatarsal heads and for heel and lowest loaded area (2) for midfoot, as marked.

Image processing

The obtained pattern was analyzed automatically using an image-processing system and program. A videocamera (JE-7242X, Javelin, CA, USA), facing the mirror which reflected the contact pattern, was connected to a frame-grabber (PC-Vision, Imaging Technology, MA, USA) and a video monitor interfaced to a PC/AT IBM compatible computer. The program[20] (and Rosenberg, personal communication) scanned the contact pattern which was simultaneously observed on the monitor. The outer radius of the first fringe was measured for each contact point, and was translated into a discrete local load ($p_{i,j}$) by using a non-linear calibration curve. The accuracy for load estimation in the interval 0.5–30 N (the regular load variation per contact point) was ±1.5%. Hence a quantitative FGP pattern (Figure 2a) resulted in a matrix of contact loads (Figure 2b), easy to translate into contact stresses.

Data acquisition

Forty-two male subjects, mean age 19.4 (SD 0.36) years, who underwent the same heavy physical activities (very long marches) participated in this research. Orthopaedic examination by bone scan found out that 48% of them (20 subjects) had suffered stress fractures. Among the injured subjects, 81% of the fractures occurred in the tibia, 11% occurred in the femur, and 8% in the foot.

The height and weight of each subject were recorded and then all subjects were requested to stand barefoot in an upright relaxed position on the CPD platform and to split the load as much as possible symmetrically on the two feet (with the distance between heels around 4 cm) while data acquisition was performed.

The data obtained from the FGP diagrams were classified into two groups: non-injured and injured, with the last group not being divided according to fracture site, due to the small number of tested subjects. Finally, Student t test, Pearson correlation test, and Chi-square test were used for the statistical analysis; significance was set at the 5% level.

Biomechanical considerations

Foot structure is usually characterized by its longitudinal arch. The FGP patterns of a standing subject provide data characterizing the foot behaviour as an arch. Evaluation of contact loads transferred by the foot may show that the arch rise, at the midfoot, might still be partially supported through the tissues underneath by small loads, while two high-contact loads are obtained under the heel and metatarsal heads.

Two approaches were considered in the evaluation of such an arch structure. The first considers a traditional simplified approach which divides the foot into three segments[21,22]. The second is a refined approach which emphasizes the characteristics of the foot structure as an arch.

Results

Body characteristics

The mean height and weight of the non-injured subjects were 178 (SD 16) cm and 770 (SD 68) N respectively, while for the injured ones measurements resulted in 173 (SD 19) cm height and 730 (SD 85) N weight. These results showed no significant differences between the two tested groups.

Segment loading approach

Traditionally the ratio of loads or areas related to foot segments is often used to describe a foot[21,22].

The quantitative processing of the FGP permitted calculation of the contact load over an area S, as the sum of all discrete contact loads $p_{i,j}$:

$$P_s = \sum_{i=k}^{l} \sum_{j=p}^{q} p_{i,j} \qquad (1)$$

where k, l (columns) and p, q (rows) represent the matrix borders of the segment area S.

Observation of the FGP diagrams and the software used for processing allowed not only separation of the contact loads of the right and left feet but also division of the contact area into three traditional basic segments: heel, midfoot, and forefoot. The division was related to the FGP pattern, which combines local load distribution and foot contact shape of each suject, and was performed by defining the location of the borders between foot segments as transverse lines. These lines separated heel, midfoot, and forefoot, using some arbitrary geometrical considerations; this conventional division was used just as a first mechanical approach in order to mention the traditional foot segment load distribution and its relationships with the stress fracture phenomena. The authors believe that their refined approach subsequently presented (the stress intensity parameters) characterizes the foot arch behaviour, without inducing any arbitrary considerations.

Data processing according to the above-mentioned areas resulted into a set of load values for each subject:

P_r, P_l	total contact load transmitted by each foot (right and left)
P_r^h, P_l^h	segment load transmitted by the heel
P_r^m, P_l^m	segment load transmitted by the midfoot
P_r^f, P_l^f	segment load transmitted by the forefoot.

The relative segment loading for each subject was calculated as the ratio between the contact load transmitted by a segment and by the total contact load of the same foot.

The mean values of load distribution on foot segments for each examined group, in percentages, are presented in Table 1. These results show that the differences between the two groups of subjects are mainly in the heel and midfoot segments loading, rather than in the forefoot. In both groups the relative loading carried by the forefoot was similar. The statistical Student t test for the two groups on each of these ratios showed that the relative midfoot loading is significantly different ($P < 0.05$) while the heel zone

Table 1. Load distribution on foot segments (%)

Parameter	Mean load ratios (SD)		P
	Non-injured	Injured	
Heel	36 (12)	43 (11)	NS
Midfoot	24 (12)	17 (8)	<0.05
Forefoot	40 (9)	40 (8)	NS

NS, not significant.

loading does not present significant differences between the non-injured and injured subjects.

Stress intensity approach

Based on the above knowledge, a set of contact pressure parameters could be subsequently calculated using specific software provisions (Figure 2):

σ_{avg} average foot ground pressure calculated as the real load transmitted separately by the left and by the right foot (P_l, P_r) divided by the respective contact area;

σ^m_{min} average pressure on a minimally loaded transverse strip characterizing the arch rise of midfoot (area 2 in Figure 2);

σ^h_{sharp} average pressure on a square of 4 adjacent maximally loaded contact points, characterizing the heel of each foot (area 3 in Figure 2);

σ^f_{max} average pressure on a maximally loaded transverse strip characterizing the metatarsal heads area of each foot (area 1 in Figure 2).

In addition, stress intensity parameters (SIP) were defined as ratios between the above contact pressure parameters in order to characterize the foot structure:

for the midfoot (the arch rise):

$$\alpha = \frac{\sigma^m_{min}}{\sigma_{avg}} \qquad (2)$$

for the heel sharpness:

$$\kappa = \frac{\sigma^h_{sharp}}{\sigma_{avg}} \qquad (3)$$

for the forefoot:

$$\beta = \frac{\sigma^f_{max}}{\sigma_{avg}} \qquad (4)$$

These parameters were calculated for the left and right foot and each subject was characterized by the extreme values $\min[\alpha_l, \alpha_r]$, $\max[\kappa_l, \kappa_r]$, $\max[\beta_l, \beta_r]$.

Average values of SIP (α, β, and κ) for each group of subjects are given in Table 2. The results show that the α parameter presents significantly smaller values for the injured group than for the non-injured one ($P < 0.02$). The κ parameter, which characterizes heel sharpness, presents significantly higher values for the injured group ($P < 0.02$). In addition it was found that these two characteristic parameters, κ and α, are significantly correlated ($R = -0.53$, $P < 0.001$). However, the parameter β, which is related to the forefoot, is not significantly different for the two groups ($P < 0.5$).

Discussion

This preliminary study included a small size group of 42 subjects with 20 of them experiencing stress fractures in their lower extremities, most of them (81%) in the tibia. No significant difference in body characteristics was found between these groups. However, by using a non-invasive screening technique, the contact pressure display method, which yielded foot-ground pressure patterns (FGP) and newly developed stress intensity parameters (SIP), showed that the injured subjects were characterized by high arch and heel sharpness compared to the non-injured ones.

As already pointed out, the segment loading approach was considered only because it is traditional to divide the foot into three basic segments. Some arbitrary considerations were related to this approach and yielded less significant statistical characteristics.

A refined approach, the definition of SIPs, based on contact stress data, appears to be able to detect the foot structure characteristics and its tendency to develop stress fractures. Hence, selecting parameters related to minimum pressure transferred by the midfoot and to maximum pressure developed under metatarsal heads or under heel zones one may obtain a better, non-arbitrary characterization of the foot structure as an arch.

Introducing SIPs as ratios between the above extreme pressures and the average contact pressure developed by the foot, allowed to characterize foot structure; the α parameter is related to the arch rise while the κ and β are related to load concentration developed by the heel and metatarsal heads.

Applying the SIP concept to the two groups of subjects led to the conclusion that the injured group was characterized by smaller values of α and higher values of κ compared to the non-injured group (Table 2).

Table 2. Stress intensity parameters

Parameter	Mean values (SD)		P
	Non-injured	Injured	
α	0.51 (0.20)	0.34 (0.24)	<0.02
κ	2.81 (0.94)	3.58 (0.92)	<0.02
β	1.79 (0.88)	1.76 (0.08)	NS

NS, not significant.

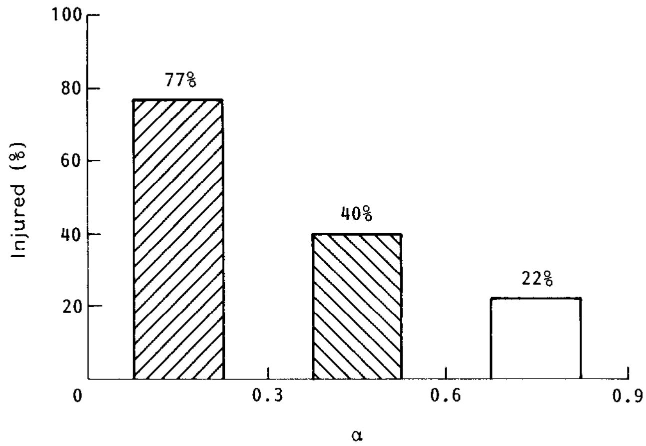

Figure 3. Frequency of injured cases for the three basic intervals of the α stress intensity parameter. ▨ high risk; ▧ medium risk; □ low risk.

The following numerical criteria allowed classification of foot structures into three groups (function of the α or κ values):

(a) for the arch rise

high arch foot $0 < \alpha < 0.3$
normal arch foot $0.3 \leqslant \alpha \leqslant 0.6$
flat foot $0.6 < \alpha$

or similarly

(b) for the heel sharpness

high sharpness $4.5 < \kappa$
normal sharpness $2.5 \leqslant \kappa \leqslant 4.5$
low sharpness $0.5 < \kappa < 2.5$

The relevance of these criteria of foot structure classification as related to the stress fracture phenomena could be checked by a step by step statistical evaluation: the parameter values for each subject allowed some preliminary classifications, with the percentage of injured subjects in each interval calculated. Final classification was done after applying

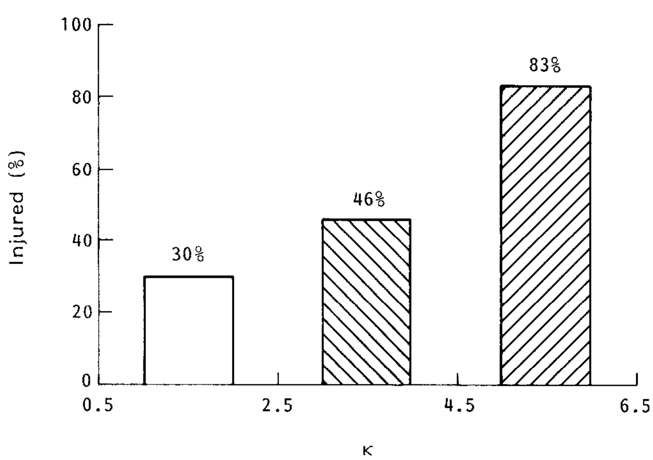

Figure 4. Frequency of injured cases for the three basic intervals of the κ stress intensity parameter. ▨ high risk; ▧ medium risk; □ low risk

the Chi-square test. Such results for the α parameter e.g. (Figure 3) show that the frequency of injured subjects in the three intervals is significantly different ($P < 0.025$); among the 42 tested, from the subjects who presented high arch foot ($0 < \alpha < 0.3$), 77% were injured, while from the subjects with lower arch ($\alpha > 0.3$), a much lower percentage suffered the same phenomena. Similarly, from the subjects who presented heel sharpness (high values of κ), 83% were injured, while among the subjects with normal and low sharpness, a lower percentage suffered such phenomena (Figure 4).

It can be concluded that the main SIP characteristics are the α and κ values. Subjects who are characterized by high arch foot structure (small values of α) are prone to experience stress fractures more than those who are characterized by higher α values. This conclusion is also supported by other studies[23,24]. Similarly, subjects characterized by high stress concentration due to heel sharpness are also prone to such phenomena; significant correlation between the high arch and heel sharpness, showed that the lower the pressure on the arch rise, the higher the tip pressure under the heel, while no significant difference in β values concerning the metatarsal region appears.

Looking now for the probability that the developed criteria can be applied to separate the injured and the non-injured subjects from a group, each of the significant parameters, α and κ, can be used. If we apply the α criterion:

10 of the 13 subjects with $\alpha < 0.3$ were injured and
19 of the 29 subjects with $\alpha > 0.3$ were not injured,

then we might suspect that the probability of obtaining either of the subjects is 29/42 (69%).

If we apply the κ criterion:

5 of the 6 subjects with $\kappa > 4.5$ were injured and
21 of the 36 subjects with $\kappa < 4.5$ were not injured.

The probability related to this criterion is 26/42 (62%).

The above high probabilities emphasize the ability of the present approach to classify the subjects according to the newly developed criteria. Moreover, considering the tendency to stress fractures, as resulting from this study, sports or military people, who are going to experience highly stressing physical activities should be examined according to their foot structure, and those who are characterized by high arch foot and high heel sharpness should be equipped with correctly designed insoles or shoes in order to attenuate the impact shock waves[25,26].

In addition the above newly defined parameters may be a useful scientific approach in characterizing other foot and orthopaedic problems.

Conclusions

The static foot–ground pressure diagram supplies information about the foot structure as needed to understand its behaviour.

A new concept of stress intensity parameters (SIP) was introduced and appeared to be basic for the foot structure evaluation, which may be adopted to different foot problems.

A set of criteria was established to classify the foot structure and its tendency to stress fracture.

A simple computerized screening technique can calculate and classify the values of the SIPs and relate them to the established criteria.

The results may enable a scientific and practical approach in characterizing some important foot orthopaedic problems and might help to establish the stress fracture risk.

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