FOOT PRESSURE PATTERNS DURING GAIT

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ABSTRACT

Peak pressure and temporal parameters of foot function were determined in 21 men and 11 women; few differences between men and women in any of the parameters were observed, either when walking barefoot or when wearing shoes. However, significant differences were observed when barefoot and shod walking were compared. The main influence of shoes appears to be in modifying the behaviour of the forefoot, by changing the pressure distribution across the metatarsal heads and increasing the contact times for the toes. The implications of such changes are discussed. Intersubject variability in the pattern and magnitude of the peak pressure distributions under the foot, which appear to be consistent in both the short and long term, may prove to be of importance in the clinical environment, by providing an individual baseline from which change can be measured. A new measure, the pressure-time integral, could be a more valuable single measure than either the peak pressure or the temporal parameters.

Keywords: Mosculoskeletal system, gait analysis, feet, pressure patterns

INTRODUCTION

The human foot is a complex structure which gives support during standing and provides the required restraint and propulsion during gait; between 'heel strike' and 'toe off' it has to adapt to a changing pattern of loading and must be relatively compliant yet still maintain its functional integrity.

Several investigators have devised methods for recording and analysing foot function[1-8], among which are techniques for characterizing the vertical force distribution under the foot; but many collect data from only one gait cycle per walk. There is an obvious advantage in techniques which enable consecutive step recordings to be made and analysed. From the majority of these latter methods the measure of most interest appears to be the maximum vertical force generated under the foot, which although of clinical interest[9-12] does not contain information about functional behaviour. For example, the time for which each part of the foot is in contact with the ground, combined with peak force data, will give valuable information on the way in which the foot is being used, particularly under pathological conditions.

There is some disagreement concerning the behaviour of the foot during the stance phase of gait, an early report byMorton[13] suggesting that the heel bears the highest pressures, followed by the first metatarsal head and then the remaining metatarsal heads. Similar findings were later reported by Stott *et al.*[14], who found that there was an even load distribution across the static forefoot, and also that the peak pressure under the heel occurs at heel strike and is medial to the midline. In contract, Grundy *et al.*[15] reported that the maximal heel pressures are reached only when the lateral border of the heel and metatarsal heads have made contact with the ground, being well forward of the ball of the heel. These pressures are of the order of 650 kPa [16] but can be as high as 1000 kPa [17] when wearing shoes, in which case the peak pressure occurs under the rear lateral border of the heel[17]. The hindfoot is weight-bearing for approximately 43% of the stance period[18]. It is generally agreed that the midfoot plays little part in transferring weight from the hindfoot to the forefoot[6,14] and that when the load is transferred to the forefoot there is an increase in ground reaction forces as the heel leaves the ground and the toes make contact[6]; Stott *et al.*[14] have reported an additional peak just prior to the heel leaving the ground. Measured peak pressures under the forefoot range from 650 kPa [16] to 860 kPa [17], the highest pressure being under the second and third metatarsal heads[1,14,19], when wearing shoes. With the load on the forefoot, the centre of foot pressure (CFP) remains in the region of the metatarsal heads, even after full toe contact has been made[6], although the toes do give support for a relatively long time[18]. According to Grundy *et al.*[15] the small forces contributed by the toes come mainly from the first and second toes, but Stokes *et al.*[20] have reported that healthy persons impose 36% of body weight on the toes during the final stages of foot contact. Moreover, pressures of 600 kPa have been recorded under the first and second toes when wearing shoes[17]. Grundy *et al.*[15] conclude that the load-bearing function of the forefoot is three times that of the hindfoot.

There is a consensus that the influence of wearing shoes is to spread the load over a wider area of the foot and for foot contact times to be increased[6,17,21]. Grundy *et al.*[15] observed that the rigidity of the soles of the shoes can influence peak pressures and contact times, for example, increasing the rigidity leads to the metatarsal heads being in contact with the ground for a longer period, and consequently the CFP moves forwards towards the forefoot more rapidly. Pollard *et al.*[22] present data on the horizontal shear forces, as well as the vertical forces, at various sites beneath the foot, both when wearing shoes, and when walking barefoot. They agree that peak vertical forces are decreased when wearing shoes, but show also that both the longitudinal and transverse horizontal shear forces tend to decrease when wearing shoes.

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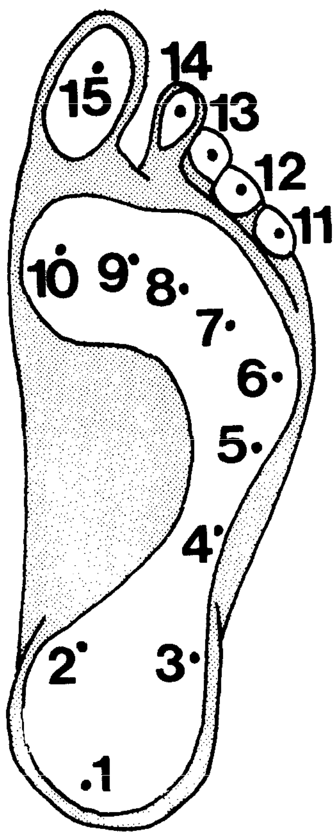

Figure 1 The sites of transducer attachment

There appears to be little relation between peak pressure and body build[21]; however, Stott *et al.*[14] note that heavier subjects tend to put more weight on the lateral side of the foot. A slight increase in peak pressures has been observed from childhood to adulthood, but the range is reported to be very small, the ratios of heel to forefoot peak pressures being approximately unity[23].

METHOD

Plantar pedal pressures were recorded from 21 men and 11 women, who had no known history of foot problems and no apparent disorders of gait. Measurements were taken from the left foot only, both with the subject walking barefoot and when wearing their normal shoes, each recording consisted of six to eight consecutive steps. From these, peak pressure, transducer contact time as a percentage of total foot contact, time to peak pressure as a percentage of transducer contact time, and the pressure-time integral were determined for each subject for both the barefoot and shod conditions. In order to assess the accuracy of transducer placement and the intrasubject variability of the measurements, photographs of the feet with the transducers attached and recordings of pedal pressures were taken from six subjects (three men, three women) on at least two occasions, either on the same day or within a period of six months.

Pedal pressures were recorded using small semiconductor strain gauge transducers, the output of each of which was connected to a PDP 11 computer, digitized at 200 Hz and stored on magnetic tape for analysis. The transducers were placed on the posterior, medial and lateral heel (1–3), the midfoot region (4,5), the fifth to first metatarsal head (6–10) and the fifth to first toe (11–15) with the long axis of the cantilever in line with the long axis of the foot (*Figure 1*). A full description of the transducers and recording system can be found in Soames *et al.*[8].

RESULTS

The age and weight characteristics of the subjects are given in *Table 1*. The women were both significantly younger and lighter than the men; the male and female data were analysed separately. Variances for this and all other measurements were calculated from not less than six steps for each subject on every occasion; the level of significance is $P > 0.01$ throughout.

Transducer placement

For each subject, photographs of the feet were superimposed and tracings made of transducer positions. The most variable positions in transducer placement were found to be on the medial and lateral heel and along the lateral border of the foot, however, even in these positions the transducer cantilever, 5 × 3 mm, was contained within an area of 8 × 5 mm, the centre of the cantilever, and hence the middle of the strain gauge, being contained within an area 3 × 2 mm. The accuracy of placement of the transducers under the metatarsal heads and toes was well within these limits.

Intrasubject variability

Data recorded, while walking barefoot, from one subject (FS) within a single day and another subject (MH) within a six month period are presented in *Figure 2*. For each subject there was no difference, at the 1% level of significance, in pressures at the various sites between one recording session and another, either on the same day or within the six month period. However, as can be seen from *Figure 2*, the pattern of pedal pressure distribution for these two subjects is different. For the heel, the highest peak pressure is similar in both subjects, 790–830 kPa, but the site at which this maximum occurs differs, being under the posterior heel in subject FS and under the medial heel in subject MH. In addition, pressures under the lateral four metatarsal heads tend to be greater in subject MH

Table 1 The means and standard deviations of the age and weight of the subjects

	Age (years) $\bar{x}$ (s.d.)	Weight (kg) $\bar{x}$ (s.d.)
Men	23.3(4.1)	69.4(10.4)
Women	20.6(3.3)	50.1(7.6)
Combined	22.4(4.0)	65.2(11.1)

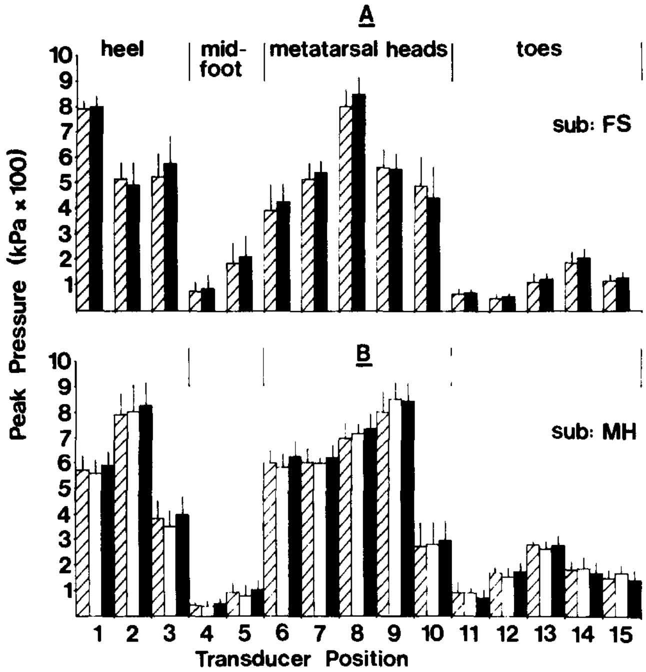

Figure 2 The mean peak pressure (kPa × 100) distribution, and its standard deviation, when walking barefoot. Recorded on two separate occasions within the same day (A), and on three separate occasions within a six-month period (B)

than in subject FS, while pressure under the first metatarsal head is significantly lower in MH than in FS. There is also some difference in the magnitude and pattern of peak pressures seen under the toes. From *Figure 2,* it would appear that each individual has an invariant pattern of pedal pressure distribution; such a 'footprint' could serve as a base line from which to measure variations due, for example, to trauma.

Relation of peak pressure to body weight

The correlations between body weight and peak pressure, measured at each transducer site, are presented in *Table 2.* It can be seen that for both men and women there is a suggestion that pressures on the lateral side of the foot increase with increasing weight; under the fifth metatarsal head in the men, and under the midfoot in the women. In addition there is, for the men, a significant positive correlation between body weight and posterior heel pressure. When the male and

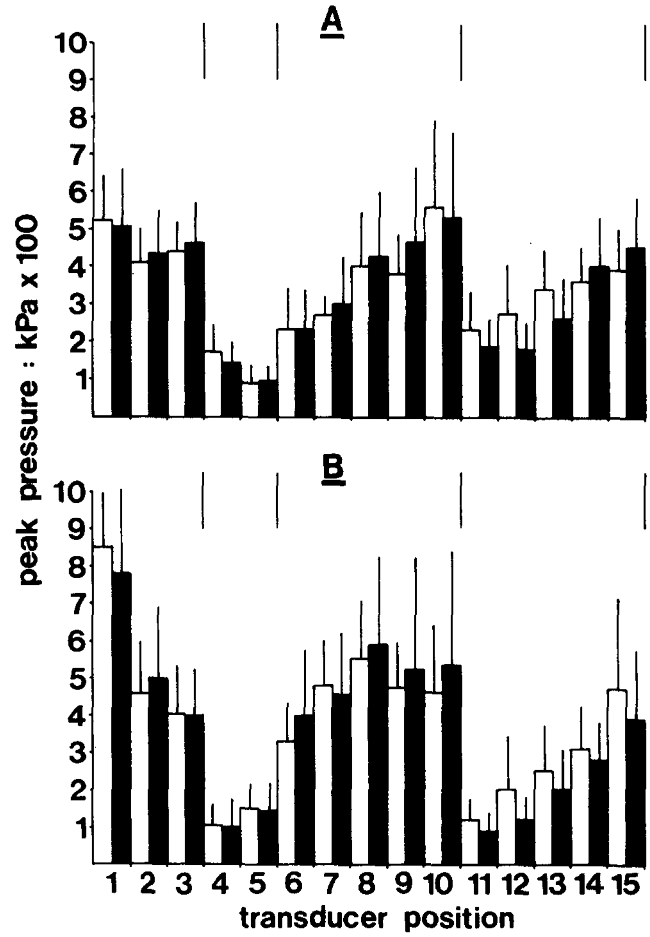

Figure 3 Mean peak pressure (kPa × 100) distribution and its standard deviations in men [■] and women [□] when walking in shoes (A) and barefoot (B)

female data are combined, the correlations are low, although there is still a significant relationship between body weight and fifth metatarsal head pressure. It should be noted that although some of the latter correlations are significant, in no case can more than 50% of the variance be accounted for.

Peak pressures

Patterns of pedal pressures under the foot are similar for both men and women, walking barefoot or wearing shoes; there are however differences between the barefoot and shod conditions (*Figure 3*). Apart from significantly lower pressures in men

Table 2 Correlation between peak pressure (kPa), when walking barefoot, and body weight (Kg) at each transducer location for men, women and combined group data

	Transducer location														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Men (n = 21)	0.64*	0.46	0.29	0.34	0.33	0.65*	0.33	0.20	0.05	0.44	0.33	0.16	0.13	0.13	0.06
Women (n = 11)	0.02	0.20	0.02	0.69*	0.05	0.19	0.58	0.42	0.22	0.11	0.14	0.17	0.04	0.31	0.21
Combined (n = 32)	0.22	0.35	0.15	0.28	0.14	0.48*	0.33	0.24	0.05	0.35	0.40	0.39	0.14	0.10	0.26

*Significant at 1%

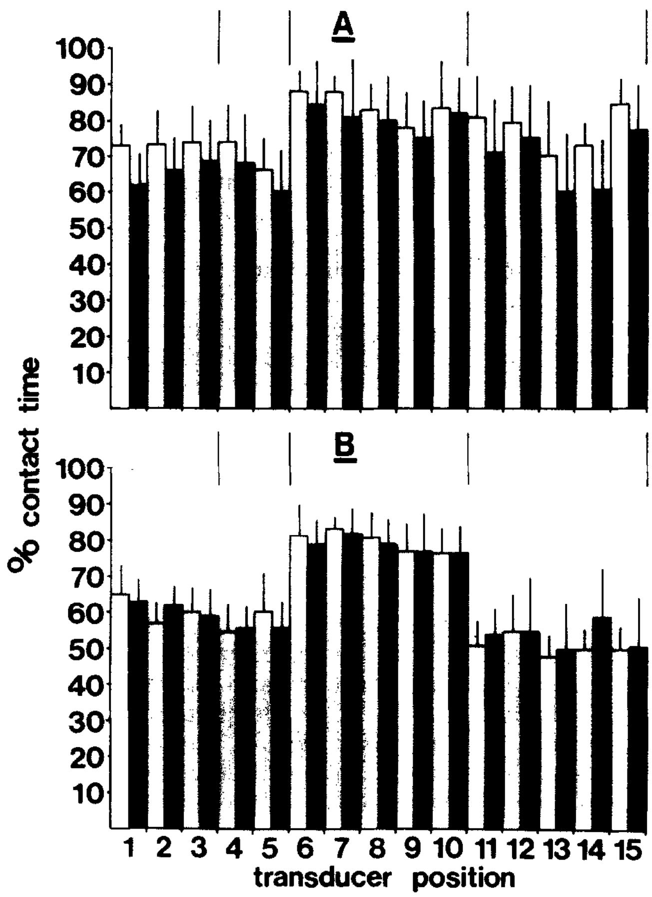

Figure 4 Percentage contact time and standard deviations, for men [■] and women [□] when walking in shoes (A) and barefoot (B)

under the fourth toe (barefoot) and third and fourth toes (shod), there were no differences in the magnitudes of pedal pressure between the sexes. Both the male and female groups show similar changes in pressure patterns between shod and barefoot walking, with the majority of changes being associated with the lateral side of the foot. The effect of wearing shoes is to lower significantly pressures under the posterior heel from 780 and 850 kPa to 500 and 530 kPa in men and women respectively, and to increase significantly pressure under the lateral heel from 400 to 480 kPa in men, there are also some lateral midfoot changes. However, the metatarsal head and toe pressures show the greatest changes with a significantly reduced pressure under the lateral three metatarsal heads in both men and women; there is no change under the medial two metatarsal heads. As can be seen from *Figure 3* the basic pattern of pressures beneath the metatarsal heads is different when wearing shoes compared with barefoot walking. When walking barefoot the highest mean pressure (550–590 kPa) is found under the third metatarsal head, decreasing both medially and laterally, with the first and second metatarsal head pressures being greater than those under the fourth and fifth. Wearing shoes changes this pattern dramatically, there being a gradual increase from lateral (230 kPa) to medial (530–560 kPa) across the metatarsal heads. For the toes there is a significant reduction in pressure under the fifth toe in both sexes; in addition there is a significant reduction under the fourth and second toes for men.

Temporal parameters

Contact time. The contact times at each transducer location, as a percentage of total foot contact time, are shown in *Figure 4.* Percentage contact times are similar for both men and women walking barefoot, there are no significant differences for any part of the foot. The heel and midfoot region are in contact with the ground for approximately 60% of the stance period of gait, while the metatarsal heads are in contact with the ground for some 80% of the time and the toes for 50–55% of the time. These contact times generally increase when wearing shoes, particularly under the heel, midfoot and toes (*Figure 4*). Apart from a significantly reduced duration of contact under the posterior heel in men compared with women, no other significant differences were observed when wearing shoes, although contact times for men tend to be slightly shorter than for women. When wearing shoes the heel and midfoot are in contact with the ground for about 70% of the stance period, the metatarsal heads for 80–85% of the time and the toes between 60 and 85% of the time.

The major differences in contact times are seen between barefoot and shod walking conditions, there being some differences between men and women. With the exception of the second toe in men there are significant increases in contact times across all toes for both men and women; changes in contact times under the metatarsal heads show a marked sex difference. Only the first metatarsal head for the men shows a significant increase in contact time when wearing shoes, whereas the two lateral metatarsal heads both show significant increases in the duration of ground contact for the women. Contact times under all of the heel and posterior lateral midfoot region in women also show significant increases when wearing shoes, but only the lateral heel and posterior lateral midfoot show increased contact times in the men.

Rise time to peak pressure. The time taken, 'rise time', to reach the peak pressure at each transducer location, calculated as a percentage of the contact time for that transducer, is shown in *Figure 5.* These times are similar for both men and women within each condition, i.e. barefoot walking and wearing shoes, although there are some differences for each sex between the two conditions. Walking barefoot, rise times for the anterior lateral midfoot and fifth toe are significantly shorter for the men than for the women, while the rise time under the second toe is significantly longer for the men. Peak pressure under the heel is achieved some 35% of the time after contact for that site, the midfoot region is more variable with peak pressures being attained 45–60% of the time after initial contact. The metatarsal heads have been in contact with the ground much longer (on average 70% of the time) before the peak pressure is reached, although there is a marked shortening of this time for the first metatarsal head. Rise times for the toes show the greatest variability, particularly for men, ranging from 40 to 70% of the time after contact. Peak

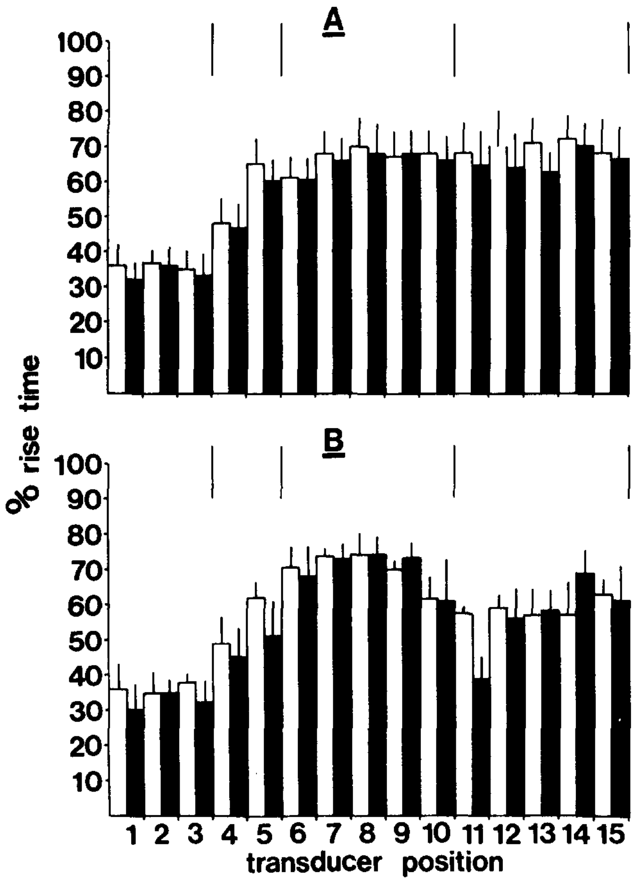

Figure 5 Percentage rise times to peak pressure and their standard deviations in men [■] and women [□] when walking in shoes (A) and barefoot (B)

pressures under the toes for women occur 55–60% of the time after contact of the toe with the ground.

Wearing shoes changes the pattern of peak pressure attainment, particularly under the metatarsal heads and toes (*Figure 5*). In general there is a reduction in rise times under the metatarsal heads and an increase in these times under the toes, such that the mean rise times for both the metatarsal heads and toes is about 65% of the time after initial ground contact. The only difference in rise times between the sexes is seen under the third metatarsal head which is significantly shorter for men. However, differences in rise times between barefoot walking and wearing shoes are not the same for both sexes. In women there are significant increases in the time to peak pressure under the lateral four toes, and a significant reduction in the time under the fifth metatarsal head. For men only the fifth toe showed a significant increase in time to peak pressure, while the second, fourth and fifth metatarsal heads showed significantly reduced rise times when wearing shoes. In addition, again for men, the anterior lateral midfoot also showed a significant increase in rise time when wearing shoes.

Pressure-time integral

Although the peak pressure and temporal parameters are both capable of showing differences in foot function between men and women and between barefoot walking and wearing shoes, they are nevertheless discrete variables conveying limited information. The pressure–time integral combines information regarding both the pressure distribution and the time of foot contact, and may be a better indicator of foot function than either parameter individually.

The calculated pressure–time integrals for each region of the foot are shown in *Figure 6*. The pattern of these values, both when wearing shoes and when walking barefoot, are similar to the corresponding patterns of peak pressure distribution described earlier (*Figure 3*). It would appear, however, that the pressure–time integral accentuates the importance of the first metatarsal and its phalanges, i.e. the first metatarsal and great toe.

When walking barefoot there are few differences between men and women in the magnitude of the integrals. Where there are significant differences (anterior lateral midfoot, third and fourth toes) the male values are always larger; the greatest integral being under the posterior heel and associated with heel strike. The pattern under the metatarsal heads shows that the highest value is associated with the

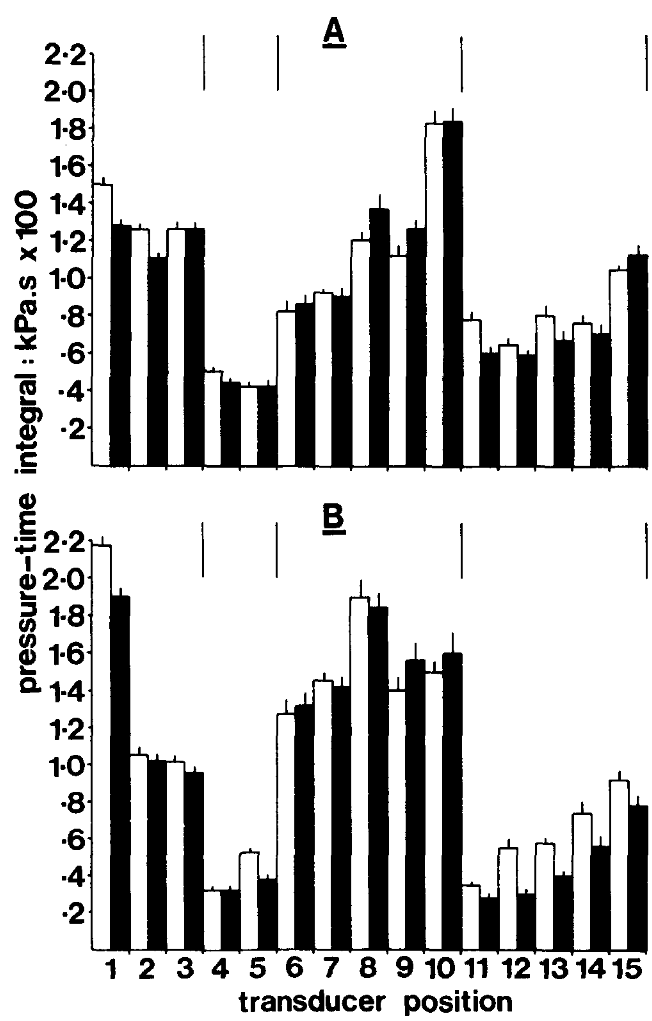

Figure 6 The pressure–time integrals (kPa.s × 100) and their standard deviations in men [■] and women [□] when walking in shoes (A) and barefoot (B)

third metatarsal head (compare peak pressure data) – it decreases both medially and laterally. With respect to the toes there is a gradual increase in the integral magnitude from lateral to medial positions.

There were no differences in the pressure–time integrals between men and women wearing shoes, however, the pattern of these values in this condition is different from barefoot walking. The values under the heel are more uniform; those under the metatarsal heads are generally lower and tend to increase from lateral to medial, while those under the toes are greater and again tend to increase from lateral to medial. Men and women show different responses to wearing shoes. In the women there is a significant reduction in integral values under the posterior heel and under the lateral three metatarsal heads, with a significant increase under the posterior lateral midfoot, the first metatarsal head and the fifth toe. Men also show significant reductions under the posterior heel and the lateral three metatarsal heads, but in addition show significant increases under all but the second toe and the lateral heel region.

DISCUSSION

The pattern and magnitude of the pedal pressures are similar to those reported by other investigators; however, in addition two temporal parameters have been presented together with a new and potentially more useful measure – the pressure–time integral. This latter appears to identify those regions of the foot which are subject to high loading, and may be preferable as an indicator of foot function than either the pressure or temporal parameters individually. Comparison of *Figures 3* and *6* shows the distribution of each is similar in shape, but that differences in the magnitude of the integral measures associated with different regions of the sole of the foot are greater. It is not surprising that this should be the case since both the peak pressure attained, and its duration, determine the behaviour of that part of the foot, particularly if the threshold of pain is exceeded. In this respect it is not the magnitude of the peak pressure which is important, but the rate at which the pressure is applied.

One of the criticisms levelled at measurement systems employing individual transducer attachment is the repeatability of their placement, and thus the confidence that can be placed in any data derived from them, particularly if recordings are taken on several occasions. Although the attachment of the transducers is relatively time-consuming, they can be positioned accurately and consistently over the sites of interest, e.g. metatarsal heads, if sufficient care is taken in the palpation of bony landmarks. Positioning of the transducers in the forefoot presents few problems because of the ease of palpating bony landmarks. The hindfoot and midfoot show a slightly greater variability, nevertheless the centre of the measuring strain gauge is still contained within an area of 6 mm^2. Problems may arise, not only with respect to the repeatability of placement, but also in the spatial relationship between the individual transducers on feet which are undergoing structural change, either through pathology or surgical intervention; in such circumstances the interpretation of the data would need to be carefully considered.

There is little correlation between the magnitude of the observed peak pressures and body weight, the few significant correlations observed being associated with peak pressure under the hind and midfoot regions. In agreement with Stott *et al.*[14], it is the lateral side of the foot which tends to show these relationships in both the men and women, although at different sites along this border. The lack of a relationship between peak pressure and body weight is probably due to the nature of the recording system. Using individual transducers placed on the sole of the foot gives the pressure distribution pattern at discrete positions on the sole; it is obvious that other areas of the sole will be in contact with the ground and thus be weight-bearing. In general, larger and heavier individuals will have larger feet, and consequently a larger surface area in contact with the ground. Although the force transmitted to the ground is greater in a heavier person, there need be no increase in the pressure between the sole and the ground. However, the increase in lateral foot pressures, with increasing weight, are probably due to the additional problems involved in controlling the lateral stability of an increased body weight during gait.

There are relatively few differences between men and women in any of the measures. The major differences are between barefoot and shod walking conditions. It is apparent that shoes influence the way we walk. It may be argued that walking barefoot is to the majority of individuals unnatural; nevertheless, with the wide variety and type of footwear worn during the study, important differences in foot function were still observed when wearing shoes. All parameters of foot behaviour show some change when walking in shoes; peak pressures under the hell become more more uniform, and the heel is for a greater proportion of its time in contact with the ground. The pattern of peak pressures under the metatarsal heads changes, such that there is a gradual increase in peak pressure from fifth to first metatarsal head when wearing shoes. Shoes tend to load the medial side of the foot, whereas when walking barefoot the magnitude of peak pressures aross the metatarsal heads is more evently distributed, the maximum pressure being under the third metatarsal head. Contact times under the metatarsal heads are similar in both conditions. The pressure-time integrals for the metatarsal heads show marked differences between the two conditions (*Figure 6*) and although there is a slight increase in peak pressures under the toes, the major influence of shoes on the function of the toes is to increase the time for which they are in contact with the ground (*Figure 4*).

Alteration in pressure distribution under the metatarsal heads, together with the increased time of contact for the toes, suggests that the forefoot is being subjected to an 'unnatural' pattern of stresses when wearing shoes compared with walking barefoot. Presumably such changes, for any one individual, will be different for each type of shoe: soft-soled, low-heeled, high-heeled etc. Soames and Clark[24] have shown that as heel height increases pressures under the medial metatarsal heads increase, while that under the lateral metatarsal heads decreases, these authors have also discussed the implications of those changes with regard to the loading of the metatarsals. Few individuals wear one type of shoe exclusively; most will wear several different types of shoe in their working and social lives, consequently there is no consistent modification of loading patterns under the forefoot. Some individuals, because of either working environment or trauma, e.g. rheumatoid arthritis, may wear one type of shoe almost exclusively, in such cases there will be a more or less consistent change to the normal loading of the forefoot. It is possible that these changed loading conditions may exacerbate the existing problems of the individual. Orthopaedic footwear may be just as guilty of initiating secondary pathological change as any other type of footwear, indeed, the habitual wearing of shoes may be the catalyst for the disease condition to manifest itself. A great deal of attention is given to the fit and support of the shoes for sports professional, possibly because of the high financial returns for the sponsor of a successful competitor; there appears to be a lack of such commitment to the pathologic foot. Obtaining a good cosmetic fit to a deformed foot is not sufficient, a good shoe must give support where required, as well as reduce areas of high loading.

Intersubject variability in the pattern and magnitude of peak pressure distribution, highlights the individuality of foot function during gait. This, together with the consistency of these patterns in both the short and long term, is of considerable importance, particularly in a clinical situation, for it provides a baseline from which change can be measured.

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