THE IMPORTANCE OF THE TOES IN WALKING

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The importance of well-functioning toes has long been recognised but has not previously been assessed in biomechanical studies. We have examined the weight-bearing function of the foot in 160 normal subjects by use of the pedobarograph. The function of the toes was assessed by reference to the time they were in contact with the ground and the peak pressures they exerted individually in comparison with other parts of the foot.

The toes were in contact for about three-quarters of the stance phase of gait and exerted peak pressures similar to those of the metatarsal region. When the foot was bearing the second peak of total force, the area in contact with the ground (the metatarsal heads and toes) was decreasing.

In 1932 Lambrinudi described the main functions of the toes as being prehensile or ambulatory. Since modern man rarely uses his toes for gripping surfaces or objects, their main function is to enlarge the weight-bearing area so that when the heel is raised full body-weight is not taken on the metatarsal heads alone. Lambrinudi stated that this mechanism was only effective if the toes were maintained flat on the ground with the intrinsic muscles contracting synergistically with the long flexors, and he predicted a reduction in the function of the toes where deformities were present. His views were based on clinical observation and could not be substantiated by objective measurements.

Measurement is now possible but has not so far been focused on the importance of the toes. In gait analysis the whole foot rather than its component parts are assessed. Foot pressure has tended to be measured under the metatarsal heads and where toe pressures are examined they are often grouped together for analysis. Stokes et al (1979), using a force plate made of 12 beams, reported that about 40% of body-weight is imposed on the toes in the final stages of forefoot contact and that most of this is on the great toe. Hutton and Dhanendran (1979) using the Dynapod, a force plate with 128 load cells, recorded that the load carried by the great toe is more than twice that of the other toes combined and that the lateral toes play a minor part in walking. Ctercteko et al (1981), using the same equipment, found that 70% of normal toe loading is taken through the great toe. The results from the Dynapod have been repeated in a comparative study (Hughes, Kriss and Klenerman 1987) where the modified force plates were shown to have relatively poor resolution, which is perhaps why the findings do not accord with Lambrinudi's theory. Good resolution is necessary to pick out the small areas under the toes and this is possible with the dynamic pedobarograph we have used.

The anatomy and walking function of the toes have been described by Bojsen-Møller (1979) and by Mann and Hagy (1979). To demonstrate the importance of the toes during walking we have analysed the peak pressure and contact time (as a proportion of stance phase) for each toe in a large group of people without foot problems.

SUBJECTS AND METHODS

Equipment. The dynamic pedobarograph is a simple optical system to which has been added the Sheffield system of computerised analysis (Duckworth et al 1982). It consists of a thick glass plate, with force transducers under each corner, supported over a mirror fixed at an angle of 45° to the glass. Fluorescent tubes along two edges of the glass plate illuminate its interior by total internal reflection. When pressure is applied to a plastic sheet (foil) on the surface of the glass the conditions necessary for total internal reflection are locally destroyed and light is allowed to escape. This can be observed and recorded by a black and white video camera directed at the mirror. The amount of light that escapes is proportional to the pressure applied.

The pedobarograph is available in several forms.

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The simple version displays the pressure as a colour contour map on a video monitor. It is useful mainly for static measurement and is difficult to calibrate accurately. The most advanced version comes with a computerised system of analysis which calibrates each frame and thus enables dynamic measurements to be accurately recorded. The foil in use at Northwick Park Hospital is thought to react a little slowly and may not record the highest peaks. In practice the pattern of pressure is of more use clinically than the absolute value, and the distribution of the pressure under individual areas of the foot can easily be calculated.

Subjects and tests. In all 160 volunteer subjects, aged five to 78 years, with no foot problems needing treatment were investigated. There were 10 male and 10 female subjects in each of the age groups; five to 10, 11 to 15, 16 to 20, 21 to 30 years, and in decades thereafter. Inevitably some of the older subjects had abnormalities common in this age group, such as hallux valgus. Tests included walking over the pedobarograph, to record each foot three times, and two standing measurements. The valgus index (Rose 1982) and the range of movement of all the joints of the lower limb were recorded. Only the results related to the function of the toes will be presented here.

Table I. Frequency of use of individual toes in walking

	Right foot		
Left foot	**All toes**	**Not all toes**	**Total**
All toes	147	5	152
Not all toes	5	3	8
Total	152	8	160

Table II. Summary of regressions for peak pressure with age, weight and valgus angle for toes and metatarsal heads showing percentage variation R^2 for peak pressures in the left foot

	Age	**Weight**	**Valgus angle**
(a) All subjects*			
Toe			
Great	8.9†	13.5†	5.5†
Second	3.2	12.0	4.5
Third	9.0	10.1	8.1
Fourth	5.2	6.1	5.2
Fifth	3.4	8.0	4.3
Metatarsal head			
First	21.9	21.4	9.8
Second	20.6	33.3	13.2
Third	18.4	35.5	8.4
Fourth	15.6	39.0	4.6
Fifth	6.8	18.4	2.9
Left feet: R^2 for peak pressure			
(b) Adults only‡			
Toe			
Great	0.6	2.9	1.8
Second	1.0	2.6	0.1
Third	0.4	0.3	1.3
Fourth	0.0	0.0	0.6
Fifth	0.3	0.4	0.2
Metatarsal head			
First	2.5	0.0	3.3
Second	2.8	4.1	7.5§
Third	1.6	4.5	2.9
Fourth	0.0	10.2	0.0
Fifth	0.0	4.5	0.3

* critical values for significance: $P<0.05$, $R^2>2,4$; $P<0.01$, $R^2>4.1$
† for right feet – weaker relationship
‡ critical values for significance: $P<0.05$, $R^2>3.9$; $P<0.01$, $R^2>6.6$
§ for right feet – no significant relationship

Table III. Regression equation for peak pressure in KPa versus weight in kg for great toes

	Left feet	**Right feet**
All subjects		
Peak pressure	183 + 1.37 × weight	221 + 0.822 × weight
R^2	*14%*	*5%*
P	<0.001	0.006
Residual mean square	3723	4213
Adults only		
Peak pressure	206 + 1.07 × weight	274 + 0.053 × weight
R^2	*3%*	*0%*
P	0.09	0.94
Residual mean square	4474	4594

Table IV. Peak pressure under toes

	Left feet		**Right feet**	
	Peak pressure (KPa)	***Per cent***	**Peak pressure (KPa)**	***Per cent***
Great toe	256.6	*30.5*	263.2	*29.9*
Second toe	197.8	*23.5*	212.5	*24.2*
Third toe	173.3	*20.6*	183.1	*20.8*
Fourth toe	137.3	*16.3*	137.3	*15.6*
Fifth toe	76.8	*9.1*	83.4	*9.5*
Sum	841.8	*100.0*	879.5	*100.0*

Table V. Number and percentage of use of 155 individual toes during standing

Toe	**Left**		**Right**		**Both feet**		**One foot**		**Neither foot**	
Great	147	*95*	147	*95*	143	*92*	151	*97*	4	*3*
Second	133	*86*	136	*88*	123	*79*	146	*94*	9	*6*
Third	138	*89*	145	*94*	135	*87*	148	*96*	7	*5*
Fourth	121	*78*	138	*89*	117	*75*	142	*92*	13	*8*
Fifth	74	*48*	84	*54*	57	*37*	101	*65*	54	*35*
No toes	3	*2*	4	*3*	2	*1*	5	*3*	150	*97*
All toes	31	*20*	17	*11*	47	*30*	95	*61*	60	*39*

The computerised analysis system allows study of up to 16 areas of interest for each step. In this study 12 areas were examined on each recording. These areas varied in size (for example the heel area was greater than that for each toe) but were identical in size and position on each foot analysed, whatever the size of the foot. They corresponded to the heel, the five metatarsal heads, the five toes, and the base of the fifth metatarsal. Figure 1 shows the positions and size of these areas in relation to the recording for a five-year-old child and for an adult man. The peak pressure and force measured within each of these areas at every frame recorded during the stance

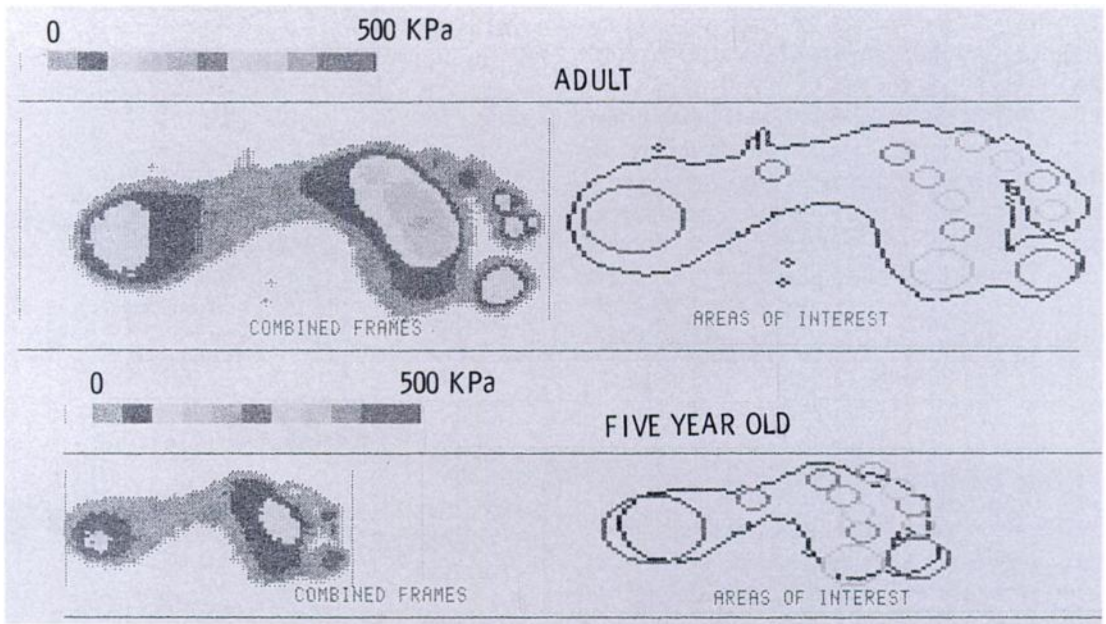

Fig. 1

Twelve areas of interest in an adult and in a five-year-old subject.

Table VI. Peak force under toes during walking

	Left		Right	
Toe	Peak force	*Per cent*	Peak force	*Per cent*
Great	10.63	*60.2*	10.88	*59.1*
Second	2.42	*13.7*	2.61	*14.2*
Third	2.04	*11.6*	2.17	*11.8*
Fourth	1.58	*8.9*	1.66	*9.0*
Fifth	0.99	*5.6*	1.09	*5.9*
Sum	17.66	*100.00*	18.41	*100.0*

Table VII. Digital index for left and right feet of all subjects

	Right great toe			
Left great toe	Shorter	Equal	Longer	Total
Shorter	4	1	3	8
Equal	2	5	7	14
Longer	3	7	127	137
Total	9	13	137	159

Table VIII. Deformity of hallux in left and right feet of all subjects

	Right great toe			
Left great toe	None	Hallux valgus	Hallux rigidus	Total
None	115	2	1	118
Hallux valgus	4	30	0	34
Hallux rigidus	1	0	7	8
Total	120	32	8	160

Table IX. Regression equation for valgus angle of great toe in degrees versus age in years

	Left feet	Right feet
All subjects		
Valgus angle	7.71 + 0.122 × age	7.40 + 0.114 × age
R^2	*23%*	*25%*
P	< 0.001	< 0.001
Residual mean square	20.10	16.17
Adults only		
Valgus angle	10.7 + 0.064 × age	10.4 + 0.057 × age
R^2	*3%*	*4%*
P	0.08	0.07
Residual mean square	25.69	19.58

phase were transferred directly to other computers for analysis. From this information the overall peak pressure and force reached under each area, and the time for which each area is in contact with the ground as a proportion of the duration of stance phase (contact time) were calculated.

Statistical analysis. The median and 5th and 95th centiles were used to show empirical 90% data intervals for peak pressure and contact time, since these variables generally did not have a normal distribution. Linear regression was used when relating two continuous variables, for example peak pressure and age, or contact time and weight. Chi square tests with Yates' correction where appropriate were used to compare two categorical variables, for example digital index and sex. Analysis of variance was used to relate continuous and categorical variables, such as peak pressure and great-toe deformity. The distribution of peak pressure, contact time and residuals from regression and analysis of variance were all checked for normality with the Shapiro Wilks W'test (Royston 1983). Homogeneity of variance for the analysis of variance was assessed with the Schweder test (Schweder 1981).

RESULTS

The results have been calculated from the mean values for the three recorded walks for each foot of each subject, and the mean of two measurements with the subject standing still for the static peak pressure.

Contact time. The contact time of each area, expressed as a proportion of stance phase, is a useful measure of the function of that area. This was calculated for each foot, and Figure 2a shows the median value together with the 5th and 95th centiles for all subjects, for all areas examined. As expected the toes were not in contact with the ground for as long as the metatarsal heads but were down for longer than the heel and the base of the fifth metatarsal. There was a decrease in median contact time between the great and the fifth toes with a plateau in the middle. In 92% of subjects, contact was made with the ground with all toes of both feet (Table I). The remaining 8% made no contact with the ground with one or more toes (usually the fifth) on one or both feet. Contact time did not vary with age or weight.

Peak pressure. Figure 2b shows the median peak pressure with 5th and 95th centiles for all 12 areas for the 100 adult subjects aged 21 and over. The great toe reached the highest peak pressure recorded under the whole foot and the central toes took more pressure than the lateral metatarsal heads. The median peak pressures under the toes showed a regular decrease from the great toe to the fifth toe.

There was a weakly positive linear relationship between peak pressure and age and weight for all the toes. When the 60 subjects under the age of 21 were removed from the analysis these relationships were no longer significant, indicating that the variations could be the result of growth. Table II shows the percentage variation (R^2) explained by each variable in the regressions. Table III and Figure 3 show this in more detail for one area – the great toe, for one variable – weight, for all subjects and for adults only. Because of the variation due to growth, only the results for adults are shown in Figure 2b; when all subjects are included, the pattern formed by the medians is much the same but with slightly reduced pressure.

The mean peak pressure under each toe as a percentage of the sum of mean peak pressures under all the toes gives a measure of relative loading. Table IV shows the mean peak pressure and the percentage of pressure on each toe for both feet. The great toe bears the greatest peak pressure, followed by the second, third, fourth and fifth toes.

Figure 4 shows the median peak pressures with the 5th and 95th centiles for all areas recorded statically in adults only, and demonstrates the lack of toe use during

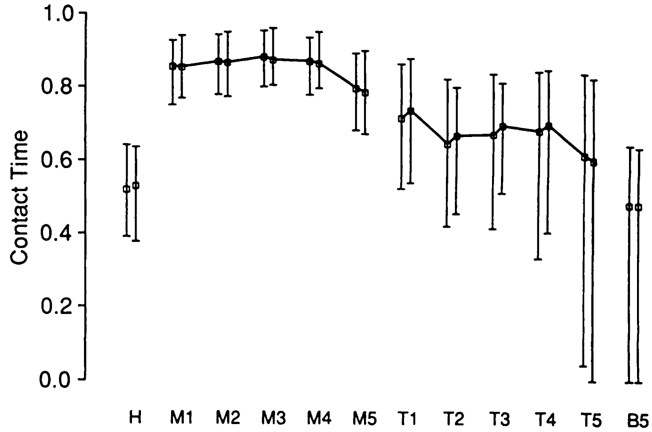

Fig. 2a

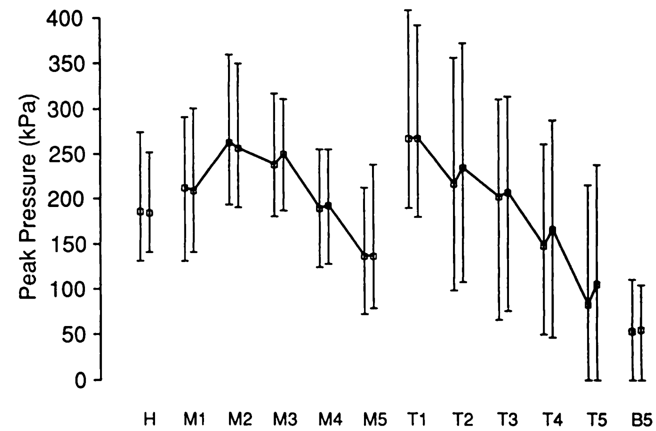

Fig. 2b

The median (–) and 90% data interval (vertical bars) for contact time as a proportion of stance phase for left and right feet (left and right pairs of points) for all subjects for all areas examined and (b) for dynamic peak pressure for left and right feet (left and right pairs of points) for adults only for all areas examined (H – heel; M1 to 5, metatarsal heads; T1 to 5, great to fifth toe; B5 – base of fifth metatarsal).

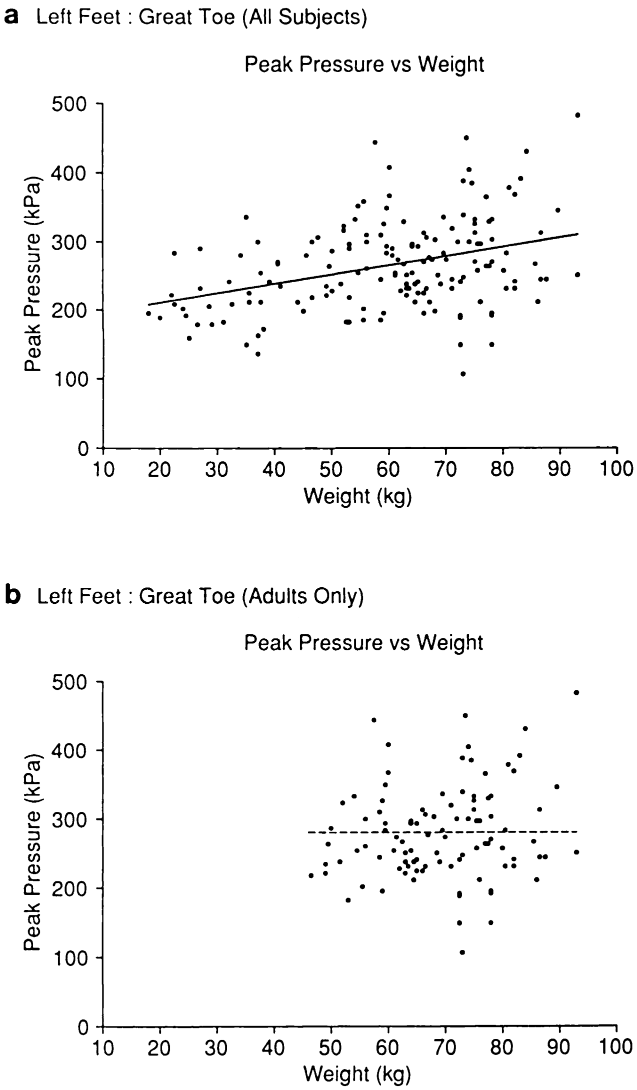

Fig. 3

Regression analysis of peak pressure against weight for the left great toe: (a) all subjects; (b) adults.

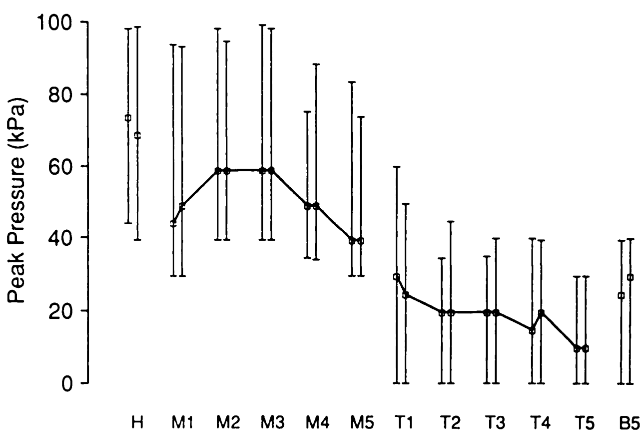

Fig. 4

Median (–) and 90% data interval (vertical bars) for static peak pressure for left and right feet (left and right pairs of points) for adults for all areas examined.

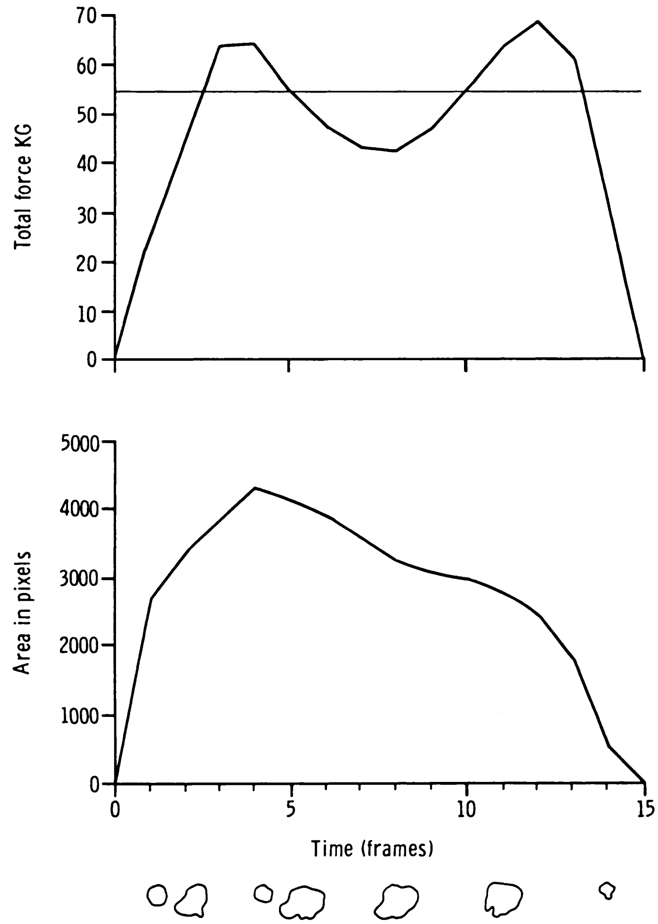

Fig. 5

Total force (above) and area of foot in contact with the ground (below) for a single step plotted against time.

standing compared with that when walking (Fig. 2b); lower pressures are to be expected since the weight is divided between the two feet while standing. Only about a third of the group showed contact with all toes of both feet (Table V). The great toe showed contact in all but four subjects (97% of the group), but about a third did not use the fifth toe at all in standing.

Force. Table VI shows the mean force under each toe as a percentage of the sum of mean peak forces under all the toes from the dynamic measurements. The great toe takes over half the force under the toes, followed by the second, third, fourth and fifth toes.

Area. The area in contact with the ground was measured with an image analysis system. Prints of each frame of the recordings of one right footstep of 20 subjects (randomly selected) were scanned by a television camera connected to the system. The area of the contact region of each frame was automatically detected and measured. The top graph in Figure 5 shows the total force for each frame recorded during stance phase and the characteristic double hump found with this measurement. The lower graph demonstrates the area (the number of pixels) over time. The key at the bottom shows the area visually. Thus, although the force increases for the second peak, the area that takes the load decreases.

Clinical examination. The relation of the length of the great toe to the other toes (the digital index) was measured (Table VII). In 80% of the group the great toes were longer than the second toes on both feet; in 3% the great and second toes were equal in length on both feet; and in 2.5% both the great toes were shorter. Twenty-three (14%) subjects showed an asymmetric digital index. There was no relation between these results and the age or sex of the subject, the degree of great-toe deformity, or the peak pressure or contact time under the toes or metatarsal heads.

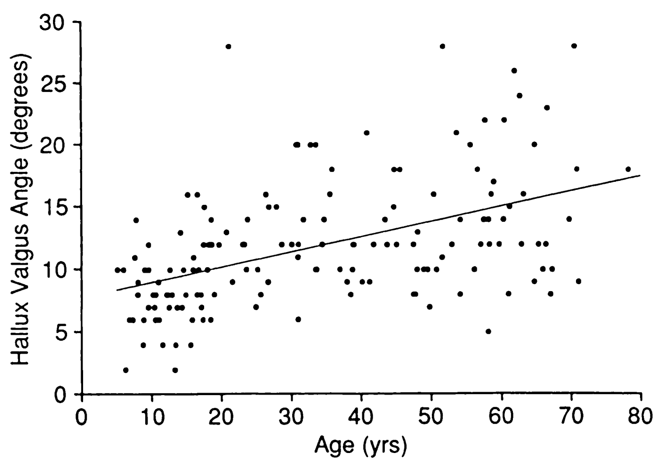

Fig. 6

Regression analysis of valgus angle of the left great toe against age for all subjects.

Table X. Frequency of lesser toe deformities in all subjects

	Left foot				Right foot			
	2	3	4	5	2	3	4	5
Normal	143	140	86	33	139	139	85	35
Hammer	9	3	2	1	10	4	3	1
Curly	7	16	71	125	10	16	71	123
No record	1	1	1	1	1	1	1	1

Table VIII shows the results of clinical examination of the great toe: 72% of subjects had no great-toe deformity on either foot, while 21% had hallux valgus and 5.6% had hallux rigidus of one or both feet. Neither peak pressure nor contact time for any of the other toes, were related to the presence of great-toe deformity.

The mean hallux valgus angle for all subjects was 11.8° (range 2° to 28°) on the left and 11.2° (range 2° to 25°) on the right. The contact time was not related to the valgus angle of the great toe for any area, but the valgus angle was related to age. Figure 6 shows a scatter plot for the left feet of all subjects, together with the best fitting line (regression equation in Table IX). It can be seen that the relation is not truly linear, the increase is faster in young people and becomes slower and more variable with age. The relation of peak pressure with valgus angle is complex. As has already been noted, peak pressure is related to age and weight and these factors must be considered when assessing relations with the valgus angle. Table II shows the percentage variation explained by all the relevant regressions for the left feet for all subjects (a) and adults only (b). Peak pressure under the toes was related to age and weight and valgus angle but the relation was closest for weight (Table IIa). For adults only these relations were not significant (Table IIb). Similar relations for the metatarsal heads between peak pressure, age, weight and the valgus angle of the great toe were also seen (Table IIa). These tend to be stronger for the metatarsal heads than for the toes when all subjects are considered, and do not all disappear in adults.

Table XI. Frequency of plantar callosities in all subjects

	Left foot					Right foot				
	1	2	3	4	5	1	2	3	4	5
No	103	101	117	127	116	100	103	112	130	118
Yes	31	33	17	7	18	34	31	22	4	16
No record	26	26	26	26	26	26	26	26	26	26

Table X shows the numbers of lesser toe deformities observed in the sample. Curly lesser toes were commonly seen. Hammer toes were less frequent and usually involved the second toe.

Table XI shows the distribution of plantar callosities. About half the sample showed a plantar callosity under one or more areas of one or both feet, but initial examination showed no evidence that these areas were subject to peak pressures above the 95th centile. Many factors determine the formation of callosities, only some of which can be measured with the pedobarograph.

DISCUSSION

One possible reason why early workers did not recognise the importance of toe function is that many recordings were taken statically: toes do not have such an important role in the standing position.

There is an apparent discrepancy with respect to the percentage loading of the great toe. Other workers (Hutton and Dhanendran 1979; Stokes et al 1979; Ctercteko et al 1981) used modified force plates to measure the peak or total force under areas of the foot and recorded high values for percentage load under the great toe compared with the other toes. The percentage peak force taken by the great toe in our study (Table IV) was similar (60%) to that which we reported previously (70%) (Hughes et al 1987). The peak pressure under the great toe was also slightly higher than that for the second toe which was higher that that for the third, and so on; the percentage peak pressure followed the same pattern. These values differ because the great toe presents about double the area of any of the lesser toes. Peak pressure is in some respects more important than peak force, for example, when sensation is reduced.

The only clinical finding that correlated with the pressure measurements was the angle of valgus of the great toe. The relationship was weak and implied greater central metatarsal loading with increasing valgus angle. The relation between metatarsalgia and hallux valgus is well recognised (Rogers and Joplin 1947; Bonney and Macnab 1952; Raymakers and Waugh 1971) and it is noteworthy that a link between central loading and valgus angle could be found even in our 'normal' sample, none of whom actually had had metatarsalgia. The absence of foot problems needing treatment was our criterion for selection; this should perhaps have been the absence of foot deformity, but this would not have produced a representative sample of the symptom-free population.

Lambrinudi's theory about the increased area provided by the toes was further supported by image analysis of the area in contact with the ground. When the total force increases for the second time, the area which takes the load decreases, which perhaps accounts for the prevalence of foot problems in the forefoot rather than the hindfoot, since full body-weight is being taken on a decreasing area for part of the second half of the stance phase. If the contact time of the toes is reduced for any reason, such as deformity or amputation, the area taking load is further decreased and there is more pressure under the metatarsal heads.

Conclusions. The toes are in contact for about three-quarters of the walking cycle and exert pressures similar to those from the metatarsal heads. The implication for clinical practice is that the toes play an important part in increasing the weight-bearing area during walking; every effort should be made to preserve their function.

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