PLANTAR PRESSURES AND TROPHIC ULCERATION
An Evaluation of Footwear

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Trophic ulceration is a most serious hazard to the man with anaesthetic feet who leads an active life. The only way to heal an ulcer is to rest it. If the patient walks on the ulcer it deepens and osteomyelitis ensues; the scarring and distortion make further ulceration inevitable until walking finally becomes impossible.

The entire history of a plantar trophic ulcer is dominated by mechanical factors. It starts from trauma or excessive local pressure and is maintained by repeated minor injuries; it heals readily without special treatment if rested completely, and its recurrence can be prevented by careful regulation of stresses on the scar. There are, of course, changes in denervated tissues which alter their response to injury and modify their mechanism of repair. These intrinsic changes are imperfectly understood and difficult to change, but they are insufficient to cause or maintain a plantar ulcer in the absence of external mechanical factors.

In many parts of the world today thousands of leprosy patients are having trophic ulcers of the feet treated for months and years by various forms of local applications and dressings at a high cost in time and money. To obtain this treatment patients have to walk to and from their homes on bandaged feet, continuing the mechanical stresses which are largely responsible for the ulceration.

At the trophic ulcer clinics of the Christian Medical College and Hospital, Vellore, limitation of ward space has made it necessary to treat hundreds of patients by methods which allow ambulation. The results were poor indeed until immobilisation in plaster (Khan 1939) became the standard treatment. The regularity and speed with which these trophic ulcers heal in a walking plaster is most impressive and support the concept that the ulceration is related mainly to mechanical factors. From the practical point of view it suggests firstly that ulceration can be prevented, and secondly that recurrence of ulceration can be avoided by the wearing of shoes which provide conditions similar to those in a plaster.

These possibilities prompted our study of pressures on feet during walking in plasters and in various types of footwear. To appreciate the relationship between pressure and plantar ulceration it is necessary first to analyse the forces acting on the sole of the foot. For this it is helpful to divide any such force into two components—one parallel and the other perpendicular to the surface of the skin.

FACTORs RELATED TO THE PERPENDICULAR COMPONENT OF PRESSURE
Continuous pressure—It requires only slight pressure to deprive tissues of blood supply; if maintained for a long time, ischaemic necrosis occurs. Animal experiments (Kosiak 1961, Lindan 1961) suggest that this pressure need be only of the order of 0.8 kilogram per square centimetre.* Even if we assume that total ischaemia is produced only by external pressures greater than systolic blood pressure, 0.2 kilogram per square centimetre should be sufficient to produce necrosis. Thus a normal person would develop gangrene of the sole of the foot if

* 1 kg./cm.² = 14.2 lb./in.² = 736 mm. Hg.
he stood completely still for a sufficiently long time. Ischaemic necrosis is not a common cause of plantar ulceration in an active person because with each step all pressure is removed. Tight shoes, of course, may cause pressure necrosis, but usually on the dorsum of the foot.

**Thrust**—The pressures which occur during walking or running are intermittent and are related to two factors. The first is the static factor—the weight of the body. The second is the dynamic factor—deceleration at heel-strike and acceleration at push-off. For simplicity we will group these intermittent pressures under the term "thrust."

Such pressures of short duration probably cause tissue necrosis only if strong enough to crush cells or rupture capillaries. Because skin is more resistant to trauma than the subcutaneous tissues, a deep focus of necrosis or a haematoma is produced. At this stage the damage is not apparent, and if the foot is rested the affected tissues are repaired or replaced by scar. If, however, high pressures are repeated, further damage occurs and an accumulation of necrotic tissue may point superficially and rupture to form an ulcer. This process has been well described by Price (1959b).

**Penetration**—This is a special case of thrust in which the area through which the pressure is applied is so small that the skin itself is penetrated. It commonly occurs from thorns or sharp stones, but with shoes it usually occurs from a small stone inside the shoe or because nails have been used in making the shoes—a crime when the feet are anaesthetic.

**FACTORS RELATED TO THE PARALLEL COMPONENT**

**Sliding friction**—When the skin of the foot rubs on the shoe or ground, friction is produced. A blister forms which may become an ulcer.

**Shear**—When increased perpendicular force accompanies the force parallel to the skin, friction is increased to the point that the skin no longer moves or slides over the ground. Movement then takes place between skin and bone through soft tissues. When tissues are in good condition their elasticity permits such movement. Once tissues have been scarred by previous ulceration, however, elasticity is lost and shear may tear tissues rather than stretch them.

It is common experience that when the feet are anaesthetic a long walk is more likely to produce ulceration than a number of short walks under similar conditions. It seems likely that when the sole of the foot is subjected to a long succession of mildly traumatic steps there may be a cumulative effect in the tissues, possibly oedema, which makes them more susceptible to serious damage from subsequent steps.

Several of the above factors combine to make the tissues under the metatarsal heads the most frequent site of ulceration. The foot bends while bearing weight in the forefoot phase of Barnett (1956), for which we use the descriptive term "push-off." For this reason, concentrated in this area, there is an interplay of forces associated with the rotation of the weight-bearing metatarsal heads over the skin, which is immobilised by the ground (Price 1959a). These damaging forces have been grouped under the term "flexion" by Ross (1962), but since simple bending of the forefoot is not injurious the term is misleading. The damaging stresses at this phase of gait are probably a combination of shear and thrust.

These factors must be considered in the design and construction of shoes for active people with anaesthetic feet. Continuous pressure and penetration may be eliminated by elementary care. The injurious effects of sliding friction can be minimised by taking certain precautions such as the gradual breaking in of new shoes and the frequent inspection of the feet for early signs of damage. Friction between the sock and the foot also can be reduced by wearing a second pair of socks so that friction takes place between the socks.

In spite of these precautions patients still get ulcers. Therefore it appears that thrust and shear are the main damaging factors in the patient who wears shoes. Numerous special shoes have been designed to reduce these factors, but only clinical impressions and theoretical
applications of physical principles have been used to evaluate them. For a completely objective evaluation actual measurements of intermittent pressure and shear during walking are needed.

Shear, however, is difficult to measure; it is of most significance in the foot with advanced scarring and distortion. Nevertheless, measurements of the perpendicular pressures alone are useful in evaluating the potentially damaging forces acting on the foot, firstly because the parallel component of a force applied at a given angle cannot increase without a corresponding increase in the perpendicular component, and secondly because a parallel force will produce not shear but only sliding friction in the absence of sufficient perpendicular force.

We have previously described a method for measuring pressure at selected points on the sole in a person walking barefoot or wearing shoes (Bauman and Brand 1963). This present paper presents the results obtained with this method. It is divided into two parts: 1) a comparison of plantar pressures during barefoot walking in normal, in anaesthetic, and in deformed feet; and 2) an evaluation of the effect of modifications in footwear on the plantar pressures in anaesthetic and deformed feet.

GENERAL METHODS

The technique of pressure measurement has already been described in detail (Bauman and Brand 1963). Pressures on the sole of the foot were measured with the aid of transducers (capacitors which respond to increased pressure with increased capacity) which were 1 millimetre thick and had a pressure sensitive area of 1 square centimetre.* Pressures at five selected points were recorded simultaneously by a photographic recorder.

Before applying the transducers to the foot a pressure-indicating footprint was obtained (Bauman and Brand 1963). The transducers after calibration were then attached to the foot with adhesive tape and a second footprint was obtained to record their position. A thin cotton sock was worn over the transducers during the experiment to protect them, and indeed was worn for all "barefoot" walking. Pressures were measured while the subject walked in a straight line on a polished concrete floor to the beat of a metronome. Small changes from the usual rate of 100 steps per minute were permitted for individual subjects, but the same rate was maintained during each experiment.

ANALYSIS OF BAREFOOT WALKING

Normal feet—Twenty-two experiments with twelve normal male hospital employees were carried out; in two subjects only one foot was studied. To make comparison with leprosy patients valid, an effort was made to select subjects with a similar social background.

Anaesthetic feet—Thirteen male leprosy patients served as subjects for twenty-three experiments. Plantar sensation, judged by the ability to perceive pinprick, was absent in twelve patients (twenty-one experiments). One patient (two experiments) was able to feel but not to localise pinprick.

Although originally it was planned to study anaesthetic feet completely free of ulcers, it was found that most feet with complete plantar anaesthesia had at least one scar from previous ulceration. Therefore patients were included who had small well-healed scars. Fourteen feet had such scars, but in seven there was no contact between transducer and scar. None of the feet was deformed, that is to say, no foot had deep ulcer scars or absent, much shortened or clawed toes.

Drop feet—Fourteen experiments were carried out in twelve male leprosy patients with drop foot due to lateral popliteal nerve paralysis. Three patients had normal peroneal muscles

* Developed by the Franklin Institute, Philadelphia, Pennsylvania.
and in all cases the muscles supplied by the medial popliteal nerve were normal. Ten patients had plantar anaesthesia, complete in eight. A transducer was in contact with an ulcer scar in one experiment. No foot had deep ulcer scars or absent, much shortened, or clawed toes.

**FIG. 1**
Two shortened feet shown with a normal foot. (Figure 4, top, and Figure 11 show pressure recordings made by the foot on the right.)

**Shortened, deformed feet**—Most patients who have had a succession of trophic ulcers under the metatarsal heads develop destructive and absorptive changes in this area. The result (Fig. 1) is a shortened foot either without toes or with flail joints between the foot and any remaining toes. Eleven experiments with ten male leprosy patients comprise this series. All these feet were markedly shortened, and significant toe function as noted on the footprint was present in only one man (Fig. 4). Areas of complete plantar anaesthesia were present in nine feet.

**Transducer placement**—For all except patients with shortened, deformed feet five transducers were placed in standard positions (Fig. 2)—just distal to the interphalangeal joint of the great toe, directly under the first, second and fifth metatarsal heads, and in the middle of the weight-bearing area of the heel.

In the group of patients with shortened feet the three transducers for the forefoot were placed under the areas of highest pressure as indicated by the footprint, all well anterior, and named medial, central and lateral. The fifth transducer was placed under the arch.

Sample records made by a normal subject, a patient with drop foot, and two patients with shortened feet are shown in Figures 3 and 4.

**Results**—In the evaluation of results, a step was excluded from consideration when the total time the foot was
bearing weight varied more than 0.05 second from the average. The maximum pressure recorded by each transducer was determined and the average peak pressure for each area of the foot was calculated (Figs. 5 and 6).

**EVALUATION OF FOOTWEAR**

**Insole material**—We have made no systematic study of the effects of various insole materials upon plantar pressures. It is probable, however, that a soft and resilient insole lowers peak pressures by distributing them in space and time: in space, by applying pressure to areas of the foot which take little pressure on a flat, hard surface: in time, by lengthening the period of acceleration (push-off) and deceleration (heel-strike).

Clinical experience suggests that foam rubber is too soft; it is completely flattened by thrust and it is not durable. Cork and commercial microcellular rubber are durable but too firm. We have used extensively a special grade of microcellular rubber (approximately 15 degrees shore) for insole material. It is soft, resilient and durable. Figure 7 shows a comparison of steps made by a man walking without shoes on polished concrete, on leather and on microcellular rubber.

**Basic shoe design**—This aspect of the study is concerned primarily with the influence of the weight-bearing parts of the shoe on plantar pressures.
We have noted that plantar ulcers heal while walking is allowed in a below-knee plaster moulded to the sole, even when padding around the calf prevents weight from being carried anywhere except on the sole of the foot. It seems probable, therefore, that a plaster is superior to the ordinary shoe, either because it holds the foot rigid, or because the plaster is moulded to the contour of the foot.

Shoes were selected for trial so that the individual contributions of rigidity and moulding could be analysed. Secondly, an attempt was made to choose shoes suitable for rural areas of India, where a full shoe is worn only if necessary and inexpensive.

The shoes were specially fitted to the feet of each patient. Shoes of the same type were worn on both feet and were tested in random sequence, except that the Oxford (shoe B) in the first series and the sandal (shoe H) in the second series were tested at the beginning and end of each experiment.
Average peak pressures for barefoot walking. Each symbol represents the average peak pressure of all acceptable steps with one foot. Because of transducer failure no heel pressures were recorded for two anaesthetic, non-deformed feet. The differences between means for normal and anaesthetic feet were not significant ($P > 0.05$) at any area. For drop feet, the mean pressures under the great toe, second metatarsal head, and heel were less than for normal feet ($P < 0.05$) and anaesthetic feet ($P < 0.01$). By contrast, the mean pressures for drop feet were significantly higher than for normal feet under the fifth metatarsal head ($P < 0.05$). There was no significant difference ($P > 0.05$) in mean pressures under the fifth metatarsal head between drop feet and anaesthetic feet. There was also no significant difference in the mean pressures under the first metatarsal head between any of the three types of feet.
PLANTAR PRESSURES AND TROPHIC ULCERATION

Fig. 6
Average peak pressures during barefoot walking for shortened feet. Whereas the sensitive areas bore average pressures, all the high as well as all the low pressures were under anaesthetic areas.

Fig. 7
Record of man with anaesthetic foot walking barefoot. Successive steps were taken on polished concrete, 1.5-centimetre leather pad, 1.5-centimetre microcellular rubber pad, and polished concrete. Note that the greatest benefit from the microcellular rubber occurred at points of highest thrust, and that the most striking feature of the step on rubber was that all areas tended to receive equal thrust. There is evidence that the transducer response is less for the same applied pressure when pressed against a soft surface than when pressed against a hard surface. This error, however, is not sufficiently great to account for the differences observed in this record.
ANALYSIS OF SHOES IN PATIENTS WITH ANAESTHETIC NON-DEFORMED FEET

It was the purpose of this series to study the effects of modifications of the shoe on plantar pressures in feet normal except for plantar anaesthesia. Lack of sensation enhances objective shoe analysis because the patient does not change his gait to avoid high pressures which would normally cause discomfort.

Subjects and methods—Twenty-one experiments were made with twelve patients. The patients were the same ones in whom barefoot walking was studied. The five transducers were placed in the same standard positions. (Two experiments were eliminated—one because not all shoes were studied, another because pressures in more than half of the shoes were too high to measure accurately.)

<table>
<thead>
<tr>
<th>Shoe</th>
<th>Pattern</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>South Indian sandal with no heel strap or heel counter. This shoe was simply a flat piece of leather with a heel 0·3 centimetre thick and two leather straps across the dorsum of the foot</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>Oxford shoe which had been made on a last and had a full leather upper. The leather heel was 0·6 centimetre thicker than the sole</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>Oxford shoe similar to B, with metatarsal bar of leather. The anterior edge was placed just behind the metatarsal heads and was 0·3 centimetre high in front and 0·6 centimetre high at the back. It measured 4 centimetres from front to back</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td>Lancashire clog which had a leather upper and a wooden sole and heel 2 centimetres high. The sole curved from the front edge of the heel to form a concave surface for the foot. When placed on a level floor the portion of the curved sole beneath the metatarsal heads touched the floor</td>
</tr>
<tr>
<td>E</td>
<td></td>
<td>Sandal with flat wooden undersole and wooden rocker centred under the metatarsal heads. This rocker was held in position by screws and could easily be moved. Both heel and rocker extended 2·5 centimetres below the under-surface of the wooden sole</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td>Same shoe as E with arch support of microcellular rubber. The arch supports were fitted for each patient</td>
</tr>
<tr>
<td>G</td>
<td></td>
<td>Same shoe as E with rocker moved 1·7 centimetres behind the metatarsal heads</td>
</tr>
</tbody>
</table>

The shoes studied in this series of experiments are described in Table I. Shoes D, E, F and G had an upper of the same type pictured in Figure 13. Because the purpose of this study was to evaluate shoe design and not insole material, and because transducer calibration may be affected by the properties of materials touching it, the sole of each shoe was constructed so that the foot was in contact with 0·6 centimetre of leather. This was accomplished with a removable leather insole in shoes D to G. Special care was taken that none of the transducers touched the rubber arch support in shoe F.

Results—As in the barefoot series, a step was excluded if the total time the foot was in contact with the floor varied more than 0·05 second from the average. For each experiment the average peak pressure for each transducer for all steps taken with each of the seven shoes was calculated

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(thirty-five values per experiment). The range and mean of these average peak pressures from all experiments are shown in Tables II to IV. The variation in actual pressure between individual experiments was great.

**TABLE II**

**AVERAGE PEAK PRESSURES, STANDARDISED VALUES, AND SIGNIFICANCE LEVELS OF PRESSURES UNDER THE GREAT TOES OF ANAESTHETIC NON-DEFORMED FEET**

Results of Twenty-one Experiments (Twenty for Shoe G)

<table>
<thead>
<tr>
<th>SHOE</th>
<th>AVERAGE PEAK PRESSURE (KG/CM²)</th>
<th>STANDARDIZED VALUE</th>
<th>LEVEL OF SIGNIFICANCE *</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>3-6.2 1.5</td>
<td>78</td>
<td>6.5</td>
</tr>
<tr>
<td>G</td>
<td>4-5.8 1.6</td>
<td>89</td>
<td>5.2</td>
</tr>
<tr>
<td>F</td>
<td>3-4.4 1.6</td>
<td>90</td>
<td>4.3</td>
</tr>
<tr>
<td>B</td>
<td>7-4.1 1.7</td>
<td>101</td>
<td>5.3</td>
</tr>
<tr>
<td>C</td>
<td>6-5.3 1.8</td>
<td>107</td>
<td>6.1</td>
</tr>
<tr>
<td>D</td>
<td>6-4.7 1.8</td>
<td>114</td>
<td>5.8</td>
</tr>
<tr>
<td>A</td>
<td>3-6.8 2.1</td>
<td>122</td>
<td>6.7</td>
</tr>
</tbody>
</table>

* NS indicates P > 0.05.

**TABLE III**

**AVERAGE PEAK PRESSURES, STANDARDISED VALUES, AND SIGNIFICANCE LEVELS OF PRESSURES UNDER THE SECOND METATARSAL HEAD OF ANAESTHETIC NON-DEFORMED FEET**

Results of Twenty-one Experiments (Twenty for Shoe G)

To make statistical comparisons between shoes, a method was devised to standardise the results. For clarity, the procedure followed will be considered first for one transducer area, the heel. The average peak heel pressures for each of the seven shoes in an experiment
TABLE IV
Average Peak Pressures, Standardised Values, and Significance Levels of Pressures Under the Heel of Anaesthetic Non-deformed Feet
Results of Nineteen Experiments

<table>
<thead>
<tr>
<th>SHOE</th>
<th>AVERAGE PEAK PRESSURE (KG./CM²)</th>
<th>STANDARDIZED VALUE</th>
<th>LEVEL OF SIGNIFICANCE*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RANGE</td>
<td>MEAN</td>
<td>STD. ERROR</td>
</tr>
<tr>
<td>C</td>
<td>1.1-2.6</td>
<td>1.9</td>
<td>69</td>
</tr>
<tr>
<td>B</td>
<td>1.3-3.2</td>
<td>2.1</td>
<td>78</td>
</tr>
<tr>
<td>D</td>
<td>1.5-4.8</td>
<td>2.9</td>
<td>106</td>
</tr>
<tr>
<td>F</td>
<td>1.7-4.9</td>
<td>2.9</td>
<td>106</td>
</tr>
<tr>
<td>G</td>
<td>1.6-4.4</td>
<td>3.1</td>
<td>113</td>
</tr>
<tr>
<td>E</td>
<td>1.8-4.6</td>
<td>3.1</td>
<td>114</td>
</tr>
<tr>
<td>A</td>
<td>1.8-5.3</td>
<td>3.1</td>
<td>114</td>
</tr>
</tbody>
</table>

*NS indicates P>0.05.

FIG. 8
Mean and standard error of standardised values for second metatarsal head of anaesthetic, non-deformed feet for twenty-one experiments (twenty for shoe G).
were averaged to find the mean peak heel pressure for the entire experiment. This average was assigned arbitrarily the value of 100, and the individual shoe averages were given a proportionate standardised value. Thus, in any experiment a shoe which received a standardised value greater than 100 had given an average heel pressure greater than the average for all seven shoes tested in that experiment. On the basis of this standardised value the mean and standard error for each of the shoes for the entire series of experiments were obtained, and a test of significance was made.

The mean, standard error, and significance level of the standardised values obtained for the heel, great toe, and individual metatarsal head areas for each of the shoes are shown in Tables II to IV. Figure 8 demonstrates graphically the results for the area under the second metatarsal head.

TABLE V
SHOES TESTED WITH SHORTENED, DEFORMED FEET

<table>
<thead>
<tr>
<th>Shoe</th>
<th>Pattern</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td><img src="image" alt="Sandal" /></td>
<td>Sandal with a flat leather sole and 0.8 centimetre thick heel</td>
</tr>
<tr>
<td>I</td>
<td><img src="image" alt="Sandal" /></td>
<td>Sandal similar to H with metatarsal bar constructed as described for shoe C except that it was 0.8 centimetre high in front and 0.8 centimetre high at the back</td>
</tr>
<tr>
<td>J</td>
<td><img src="image" alt="Sandal" /></td>
<td>Same shoe as I but with arch support of microcellular rubber</td>
</tr>
<tr>
<td>K</td>
<td><img src="image" alt="Sandal" /></td>
<td>Sandal with flat wooden undersole and wooden rocker placed anterior to the front of the foot</td>
</tr>
<tr>
<td>L</td>
<td><img src="image" alt="Sandal" /></td>
<td>Same shoe as K but with rocker under the forefoot</td>
</tr>
<tr>
<td>M</td>
<td><img src="image" alt="Sandal" /></td>
<td>Same shoe as K but with rocker under the anterior half of the medial longitudinal arch of the foot</td>
</tr>
<tr>
<td>N</td>
<td><img src="image" alt="Sandal" /></td>
<td>Same shoe as M but with arch support of microcellular rubber</td>
</tr>
</tbody>
</table>

ANALYSIS OF SHOES IN PATIENTS WITH DEFORMED FEET

It was the purpose of this series to study the effect of modifications of the shoe on pressures under deformed feet without functioning toes.

Subjects and methods—Eleven experiments with ten patients were carried out. The patients were the same ones in whom barefoot walking was studied. The transducers were placed as previously described.

The shoes studied in this series are described in Table V. All shoes had an upper of the type pictured in Figure 13. To protect the patients' feet during the experiments all of the
shoes accommodated a removable insole of microcellular rubber 1.5 centimetres thick. For each patient two pairs of insoles were made from the same sheet of rubber—one pair plain and the other with an arch support.

![Graph showing pressures during walking in different shoes by patient with a shortened, deformed foot.](image)

**Fig. 9**

Pressures during walking in different shoes by patient with a shortened, deformed foot. Top—sandal (shoe H); middle—rigid-soled shoe with rocker under metatarsal heads (shoe L); bottom—same rigid-soled shoe with rocker moved posteriorly (shoe M). All shoes had the same microcellular rubber insole. Dotted line indicates position of rocker. In deformed feet without functioning toes, rigid-soled shoes showed marked superiority over flexible shoes, and the centrally placed rocker over one under the forefoot.

**Results**—The results for each transducer area were processed in the manner already described. Figure 9 shows three pressure tracings from one experiment. The actual pressures, standardised values, and levels of significance are given in Tables VI to VIII. Figure 10 presents the findings graphically for the central forefoot.
TABLE VI
AVERAGE PEAK PRESSURES, STANDARDISED VALUES, AND SIGNIFICANCE LEVELS OF PRESSURES UNDER THE MEDIAL FOREFOOT OF SHORTENED FEET
Results of Ten Experiments

<table>
<thead>
<tr>
<th>SHOE</th>
<th>AVERAGE PEAK PRESSURE (KG/CM²)</th>
<th>STANDARDIZED VALUE</th>
<th>LEVEL OF SIGNIFICANCE*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RANGE</td>
<td>MEAN</td>
<td>STD. ERROR</td>
</tr>
<tr>
<td>N</td>
<td>2-2.9</td>
<td>1.0</td>
<td>59</td>
</tr>
<tr>
<td>M</td>
<td>2-2.9</td>
<td>1.1</td>
<td>70</td>
</tr>
<tr>
<td>J</td>
<td>2-3.3</td>
<td>1.3</td>
<td>78</td>
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<tr>
<td>I</td>
<td>6-3.9</td>
<td>1.6</td>
<td>101</td>
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<tr>
<td>L</td>
<td>5-4.0</td>
<td>1.8</td>
<td>114</td>
</tr>
<tr>
<td>H</td>
<td>8-4.3</td>
<td>2.0</td>
<td>131</td>
</tr>
<tr>
<td>K</td>
<td>8-5.2</td>
<td>2.3</td>
<td>148</td>
</tr>
</tbody>
</table>

* NS indicates $P > 0.05$.

Although the difference between means was not significant, the average peak pressure in shoe N was lower than that in shoe J in nine of the ten experiments. The possibility of this happening by chance alone is approximately 1 in 100.

TABLE VII
AVERAGE PEAK PRESSURES, STANDARDISED VALUES, AND SIGNIFICANCE LEVELS OF PRESSURES UNDER THE CENTRAL FOREFOOT OF SHORTENED FEET
Results of Eleven Experiments

<table>
<thead>
<tr>
<th>SHOE</th>
<th>AVERAGE PEAK PRESSURE (KG/CM²)</th>
<th>STANDARDIZED VALUE</th>
<th>LEVEL OF SIGNIFICANCE*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RANGE</td>
<td>MEAN</td>
<td>STD. ERROR</td>
</tr>
<tr>
<td>N</td>
<td>3-1.2</td>
<td>0.7</td>
<td>66</td>
</tr>
<tr>
<td>M</td>
<td>3-1.3</td>
<td>0.8</td>
<td>77</td>
</tr>
<tr>
<td>J</td>
<td>4-2.0</td>
<td>0.9</td>
<td>88</td>
</tr>
<tr>
<td>I</td>
<td>5-1.8</td>
<td>1.0</td>
<td>99</td>
</tr>
<tr>
<td>L</td>
<td>4-2.0</td>
<td>1.1</td>
<td>105</td>
</tr>
<tr>
<td>K</td>
<td>4-2.9</td>
<td>1.4</td>
<td>130</td>
</tr>
<tr>
<td>H</td>
<td>5-3.3</td>
<td>1.5</td>
<td>133</td>
</tr>
</tbody>
</table>

* NS indicates $P > 0.05$.

Although the differences between means were not significant, the pressure in shoe N was lower than that in shoe M in ten of the eleven experiments and the pressure in shoe J was lower than that in shoe I ten of eleven times. The possibility of either of these happening by chance alone is less than 1 in 100.
TABLE VIII
AVERAGE PEAK PRESSURES, STANDARDISED VALUES, AND SIGNIFICANCE LEVELS OF PRESSURES UNDER THE LATERAL FOREFOOT OF SHORTENED FEET.
Results of Ten Experiments

<table>
<thead>
<tr>
<th>SHOE</th>
<th>AVERAGE PEAK PRESSURE (KG/CM²)</th>
<th>STANDARDIZED VALUE</th>
<th>LEVEL OF SIGNIFICANCE*</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>.4-1.8</td>
<td>.6</td>
<td>85 5.7</td>
</tr>
<tr>
<td>M</td>
<td>.3-1.5</td>
<td>.6</td>
<td>89 6.5</td>
</tr>
<tr>
<td>J</td>
<td>.4-3.9</td>
<td>.8</td>
<td>95 5.8</td>
</tr>
<tr>
<td>L</td>
<td>.4-1.2</td>
<td>.7</td>
<td>100 7.1</td>
</tr>
<tr>
<td>H</td>
<td>.4-3.8</td>
<td>.9</td>
<td>108 5.5</td>
</tr>
<tr>
<td>K</td>
<td>.4-4.1</td>
<td>1.0</td>
<td>109 5.2</td>
</tr>
<tr>
<td>I</td>
<td>.4-4.8</td>
<td>1.0</td>
<td>115 7.3</td>
</tr>
</tbody>
</table>

* NS indicates P>0.05.

ANALYSIS OF PLANTAR PRESSURES INSIDE A PLASTER

It is of interest to compare the plantar pressures in plaster with the pressures in shoes designed to provide rigidity and moulding. Also, an analysis of the factors which contribute to the usefulness of a plaster might suggest modifications in the uppers of shoes. These experiments are incomplete and only tentative conclusions can be drawn.

Subjects and methods—In this preliminary work no rigid protocol was followed. Nine experiments were performed, four with anaesthetic, non-deformed feet and five with shortened feet. For each foot the transducers were placed as previously described. Pressures of walking were recorded in the following sequence: 1) In rigid-soled and other footwear; 2) after the upper of the rigid-soled shoe had been removed and the foot bound to the insole and sole with elastic, adhesive bandage; 3) after more bandage had been applied to support the ankle; 4) after the ankle support had been removed and the remaining assembly incorporated in a plaster shoe which left the ankle free; 5) after the plaster had been extended to form an unpadded below-knee case.

Results—The below-knee plaster consistently reduced pressures under the metatarsal heads to low levels. The reduction in heel pressure was not always so striking. For patients with shortened feet rigid-soled shoes with an arch support and rocker under the arch gave approximately the same pressures as any plaster shoe or elastic-bandage shoe or boot. As demonstrated in Figure 11, rigid-soled shoes at times gave pressures nearly as low as those inside the below-knee case.

DISCUSSION

Barefoot walking—We had assumed that anaesthetic feet would strike the ground more forcefully than feet with normal sensation. These results show, however, that in the absence of deformity or muscle paralysis the plantar pressures are of the same order. It is possible that the selection of feet with absent or minimal ulceration biased the study; these might have been patients with a habit of careful walking. Because the average pressures under anaesthetic...
Mean and standard error of standardised values for central forefoot area of shortened, deformed feet for eleven experiments.
feet actually were higher at all points, it is possible that in a larger series the differences would be significant, but almost certainly not of an order to account for trophic ulceration. For these experiments the subjects walked on a level floor at an even pace, and mis-steps were

![Diagram](image1.png)

**Fig. 11**

A comparison between shoes and a plaster made in a patient with a shortened, deformed foot. *Top*—sandal; *middle*—rigid-soled shoe with rocker under arch; *bottom*—same rigid-soled shoe (upper removed) incorporated in a below-knee plaster. The same leather insole with a microcellular rubber arch support was in contact with the foot each time. The dotted line indicates the position of the rocker. The sandal allowed high pressure peaks under the medial forefoot at push-off. This peak was completely eliminated in the rigid-soled shoe with a central rocker. When the sole of this latter shoe was enclosed in plaster, all the pressures were approximately equalised.

excluded. These experiments will be repeated on an irregular surface and it may be found that anaesthetic feet are less able to perceive and compensate for localised excessive pressures.

The finding that patients with drop foot showed a significant increase in pressure under the lateral forefoot with a corresponding decrease under other areas of the foot suggests that
muscle imbalance—in this case the unopposed action of the tibialis posterior—plays a more important role than anaesthesia alone in producing abnormal pressure distribution.

Still more striking were the pressure changes found with feet that had been deformed. The loss or paralysis of toes caused a sharpening and intensification of pressures under the forefoot. This was probably related to loss of the final toe thrust which normally spares the metatarsal heads during push-off. In cases where previous ulceration had produced a distorted foot with unevenly projecting metatarsals, most of the thrust was transmitted through one small area of the foot.

Because one or two areas in these deformed feet carried nearly all the forefoot pressure, the mean pressures for each area given in Figure 6 combine both high and low pressures and are deceivingly low. A better indication of the high pressure at at least one area of each of these feet is given by the single highest average peak pressure recorded by any of the three forefoot transducers during each experiment. This highest average peak forefoot pressure exceeded 3 kilograms per square centimetre in 5 per cent of normal feet, in 17 per cent of anaesthetic, non-deformed feet, in 14 per cent of drop feet and in 73 per cent of shortened, deformed feet. The mean of these pressures for all experiments was 2 kilograms per square centimetre for normal, 2.5 for anaesthetic non-deformed, 2.4 for drop and 4 for shortened deformed feet. It must be recognised that the method of transducer placement favoured finding areas of highest pressure in the deformed feet, but analysis of footprints from the other experiments indicated that areas of high pressure were more diffuse and had not been missed by placing transducers in standard positions.

These results are in agreement with clinical studies of the late consequences of sciatic nerve injury. Clawson and Seddon (1960) came to the conclusion that fixed deformity is a far more important cause of ulceration than complete anaesthesia of the foot.

The damaging nature of the high pressures found associated with deformity is emphasised by our experience with several patients. At the time of development of the pressure recording method it was necessary to determine the magnitude of pressure to be encountered. A man whose badly deformed and once chronically ulcerated feet had been kept free from ulceration for several years with rigid-soled, rocker footwear was asked to stand barefoot and to raise his heel while the pressure underneath his forefoot was measured. Although he did this only five or six times, he developed at the site of maximum pressure a haematoma which later ulcerated. Another patient, ulcer-free for more than a year with rigid-soled, rocker shoes, developed bleeding from his high pressure area after only two steps on the hard smooth surface of the footprint board.

Footwear—The purpose of moulding the sole of the shoe to the curvature of the foot is to distribute pressure over more of the plantar surface of the foot. Accurate moulding to all contours of the foot is not advisable, however, because the foot always moves inside the shoe. An arch support provides a simple and generally applicable approach to moulding. With non-deformed feet, shoe F, which was the same as E except that it contained an arch support, showed significantly lower pressures than shoe E at all three metatarsal head areas. The arch support did not lower pressures under the great toe.

For shortened feet an arch support was of value in lowering both forefoot and heel pressures. Although trophic ulceration in the arch can be produced by an arch support, the pressures recorded in the arch never reached high levels in these experiments. It should be emphasised, however, that the arch supports were specially fitted for each foot and were made of soft material.

Another practical approach to better pressure distribution is provided by a metatarsal bar. Compared with the Oxford shoe without metatarsal bar, the Oxford with metatarsal bar showed a significant reduction in pressure under the second metatarsal head and heel in non-deformed feet. In shortened feet, the sandal with metatarsal bar was significantly superior to the plain sandal at both medial and central forefoot areas. The marked difference in results between the heel pressures of non-deformed feet and of shortened feet in shoes with metatarsal
Fig. 12
A demonstration of the necessity for a rocker of adequate height. The pressure tracing on the left shows the high peak pressures (both lateral and medial forefoot sustained peaks of approximately 3-5 kilograms square centimetre) produced in a rigid-soled shoe with a rocker under the arch (shoe M) when the tip of the shoe struck the floor during push-off (lower drawing). The high pressures were due to the sudden transfer of the fulcrum from the centre to the front of the shoe. The top drawing shows that a higher rocker allows the same tilt of the shoe, but prevents the tip of the shoe from touching.

Fig. 13
A photograph of an inexpensive rigid-soled shoe designed for patients with shortened feet.
bars is unexplained. The position of the bar is important; it can lead to undesirable pressures if placed too far forward or under an area of risk beneath the metatarsal shafts.

The striking difference in pressures under the heel between the Oxfords (with and without metatarsal bars) and the rest of the shoes tested in non-deformed feet was probably related to the moulding inherent in the construction of the two Oxfords. In these shoes the bottom edge of the leather upper was secured between two layers of the sole leather. Because this extra leather was only around the edge it produced a concavity in the sole which approximated to the natural curvature of the heel. In the wooden-soled shoes the leather of the upper was simply tacked to the side of the wooden sole. The Oxfords also provided more lateral support to the heel and this may have prevented some flattening of the heel during weight bearing. This explanation was supported in several experiments with specially constructed rigid-soled shoes with a heel construction similar to that of the Oxfords. The thick rubber insole made these construction differences less significant in shoes made for shortened feet.

The extremely flexible leather sandal showed high pressures under the second and fifth metatarsal heads, and particularly under the great toe. It is probable that this high great toe pressure was necessary to keep the foot from slipping off the sandal during push-off. This concentration of pressure under the great toe was accompanied by a significant decrease in pressure under the first metatarsal head.

In non-deformed feet with functioning toes the value of a flat, rigid-soled shoe was most apparent in reducing pressure under the great toe. There is just a suggestion that rigidity also lowered the pressures under the metatarsal heads. As will be pointed out, it is probable that shoes for feet of normal length do not permit optimal placement of the rocker for reduction of the forefoot pressure.

It has been our experience that the progressive destruction of an anaesthetic foot by trophic ulceration becomes increasingly rapid as the foot becomes shorter. A foot without toes is urgently in need of protection, and it is with this type of foot that rigid-soled shoes produce consistent and significant reduction of forefoot pressures. However, rigidity alone is not enough; it must be combined with some provision for preventing concentration of force under the forefoot during push-off. In a plaster the ankle is held rigid and the thrust of plantar-flexion is eliminated. This thrust is also eliminated if a fulcrum, the rocker, is placed under the rigid sole in a position which ensures that plantar-flexing thrust simply tilts the shoe. Thus, whereas a plaster makes plantar-flexion impossible, a well-placed rocker makes it harmless by removing all resistance.

Placement of the rocker under the metatarsal heads (shoe L) did not satisfy this requirement. Placement of a support in front of the foot (shoe K) was supposed to lower forefoot pressures by causing the patient to shuffle rather than lift his heel while walking (Ross 1961), but under the conditions of these experiments this did not occur and the shoe produced very high forefoot pressures.

The height of the rocker must be increased as the rocker is moved posteriorly in order to prevent the front of the shoe from touching the ground at push-off. Figure 12 demonstrates this mechanism and shows the high pressure peaks that can result when the front of the shoe strikes the ground. Because of this, for feet of normal length it is difficult, even with a high rocker, to place the rocker sufficiently far back to reduce forefoot pressures significantly. Even for shortened feet it is difficult to make an attractive shoe with a rocker of adequate height. One attempt is shown in Figure 13.

The wooden clog is also rigid, has a much more acceptable appearance, and has been commended in practice (Price 1960, Ross 1962), but it made a poor showing in these experiments. This may have been due to faulty design, but probably relates to the bending which the foot

* The clogs were copied from a model kindly supplied by Mr E. W. Price but differed from his published description (1960) in that the sole thickness of our clogs was the same throughout. This resulted in slightly more curvature of the inner surface of the sole.
must undergo to conform to the curved sole, and to the fact that the point of contact between shoe and ground moves anteriorly as the foot rolls forward as with an anterior rocker at push-off.

![Figure 14](image)

To show the pressures during walking in different shoes by a patient with a shortened, deformed foot. **Top**—sandal (shoe H); **middle**—sandal with metatarsal bar (shoe I); **bottom**—rigid-soled shoe with a rocker in the posterior position (shoe M). All the shoes had the same microcellular rubber insole. The area of high pressure in this man’s foot was farther back than usual. Note that the pressures under this area of risk were increased by both the metatarsal bar and the rigid-soled shoe.

It is probable that a rigid-soled shoe with the heel moved anteriorly would reduce heel pressures by the same mechanism that the posteriorly placed rocker has reduced forefoot pressures. This remains to be proved.

It is important to fit each shoe to the patient with a pressure-indicating footprint for guidance. Figure 14 shows pressure tracings obtained from an atypical deformed foot with a
high pressure area under the first metatarsal shaft. As might be expected in this patient, the sandal with metatarsal bar and arch support (shoe J) produced the highest pressures under this area, and the plain sandal (shoe H) was the best of the shoes tested.

It is also important that any shoe with arch support or metatarsal bar should have a full heel counter to ensure that the relationship of the foot to these appliances remains constant.

**SUMMARY AND CONCLUSIONS**

1. With the object of perfecting the design of footwear for feet anaesthetic from leprosy, pressures on the soles of feet during walking were measured with transducers sufficiently thin to be worn inside ordinary shoes.
2. It was found that anaesthetic feet without deformity or muscle imbalance did not produce significantly higher pressures than normal feet during barefoot walking on a flat surface. The pressure distribution under drop feet with active posterior tibial muscles differed from normal, with increased pressure under the lateral forefoot and decreased pressures elsewhere.
3. Loss of toes or function of the toes results in high, sharp pressure peaks under the anterior end of the foot during push-off. In deformed feet these pressures are usually concentrated at one or two small areas.
4. In anaesthetic feet the prevention of trophic ulceration largely depends on the even distribution of pressure over the sole of the foot.
5. Moulding by carefully placed arch supports or metatarsal bars effectively redistributes plantar pressure.
6. A shoe with a rigid sole pivoting on a rocker near the centre of the foot most effectively reduces pressures under the forefoot of shortened, deformed feet.
7. We recommend the use of insoles made of microcellular rubber (approximately 15 degrees shore).
8. The importance of studying each deformed foot for areas of high pressure before fitting shoes is stressed; a pressure-indicating footprint is satisfactory for this purpose.

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**REFERENCES**


