*J. Anat.* (1979), **129**, 3, pp. 579–590
*With 9 figures*
*Printed in Great Britain*



# Forces acting on the metatarsals during normal walking

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(*Accepted* 25 *October* 1978)

## INTRODUCTION

During normal walking there is a single support phase when only one foot is in contact with the ground. During the 'push off' phase the heel leaves the ground, and the loading on the forefoot exceeds body weight by about 20 %. This high loading can produce pain in many foot disorders, and may be implicated in the development of painful conditions, deformities and march fractures. Treatment is often directed towards altering the load distribution on the forefoot. Special shoes and shoe insoles aim to do this, and surgical procedures may also have this effect.

The functional anatomy and biomechanics of the forefoot are not well understood. Firstly, the relative proportion of the forefoot load taken by the toes and metatarsal heads, and load distribution between the five metatarsal rays, are not well defined. Secondly, the structures and mechanisms within the foot which support the applied loads have not been fully investigated. Forces applied to the sole of the foot are supported by tensions in muscles and ligaments, forces in the joints and stress in the bones. The magnitudes of these various forces depend upon the geometry and anatomy of the forefoot and the degree of active control of the muscles.

In this study the distribution of vertical load on the foot sole of healthy subjects was measured while they walked. Measurements of the geometry of the forefoot (from radiographs) and its angle with the ground (from cine film) were used to deduce the resulting loads on the metatarsophalangeal joints and the metatarsal bones, and the tensions in some of the muscles and ligaments. The relationship between these various forces can be used to predict the mechanical effects of disease and of treatments which alter any of the forces acting on the forefoot.

## MATERIALS AND METHODS

Six normal subjects were studied and measurements were made on both feet. Data concerning these subjects are shown in Table 1. The variables shown in Figure 1 were either measured directly or calculated from the measured values. The forces acting from the floor were measured, as were the lines of action of these forces relative to the foot skeleton. The remaining dimensions were measured either from the individual subjects or from cadaver feet. The method used to calculate joint forces and forces in the metatarsal bones is similar to that used by Preuschoft (1969) in a study of the comparative anatomy of primate hands and feet, which was based on hypothesised loadings.

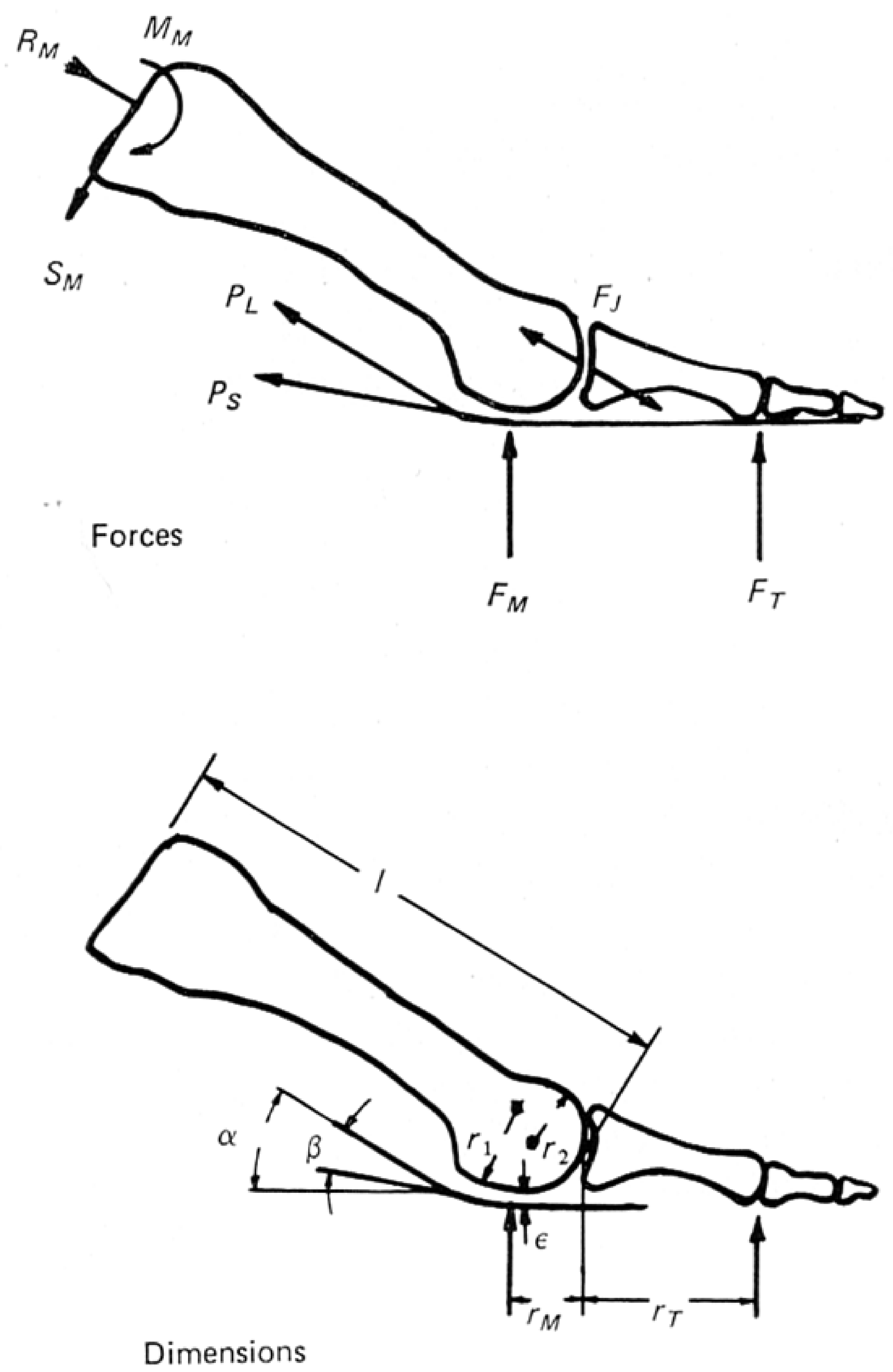


Fig. 1. The variables used in the model of each metatarsal ray of the forefoot. The ground reaction forces were recorded during walking and the dimensions and angles were also measured. From these, the forces acting on the bones and joints of the forefoot were calculated.

*Measurements of forces on the forefoot*

The walkway was fitted with a force platform divided into twelve bands each 144 mm long and 12 mm wide (Stokes, Stott & Hutton, 1974). Strain gauges on each band transduced the vertical load applied to each band as the subject walked on the force platform. Thus, the vertical load on 12 mm wide bands of the foot sole were recorded. The force platform could be turned through 90° so that in successive walks the bands were either longitudinal or transverse to the direction of walking (see Fig. 2).

A computer programme was used to calculate the vertical loads on 144 squares each 12 mm by 12 mm from these recordings (Stokes, 1975). Calculations were made at every 40 msec interval of the recordings. Correct registration between the longitudinal and transverse recordings was achieved by means of an inked impression of the foot made as the subject stepped on the force platform. This foot impression also indicated squares of the matrix which received no load. In this way the loads on about 80 squares had to be calculated from 24 recordings of loads on bands of the forefoot. This calculation was approximate, but experiments with known distributions of load indicated that the procedure gave the load under 'functional areas' of the forefoot with an accuracy of about $\pm 30\%$.

The 'functional areas' of the forefoot were the five toes and the five metatarsal heads. Loads on individual squares were assigned to these areas by reference to an

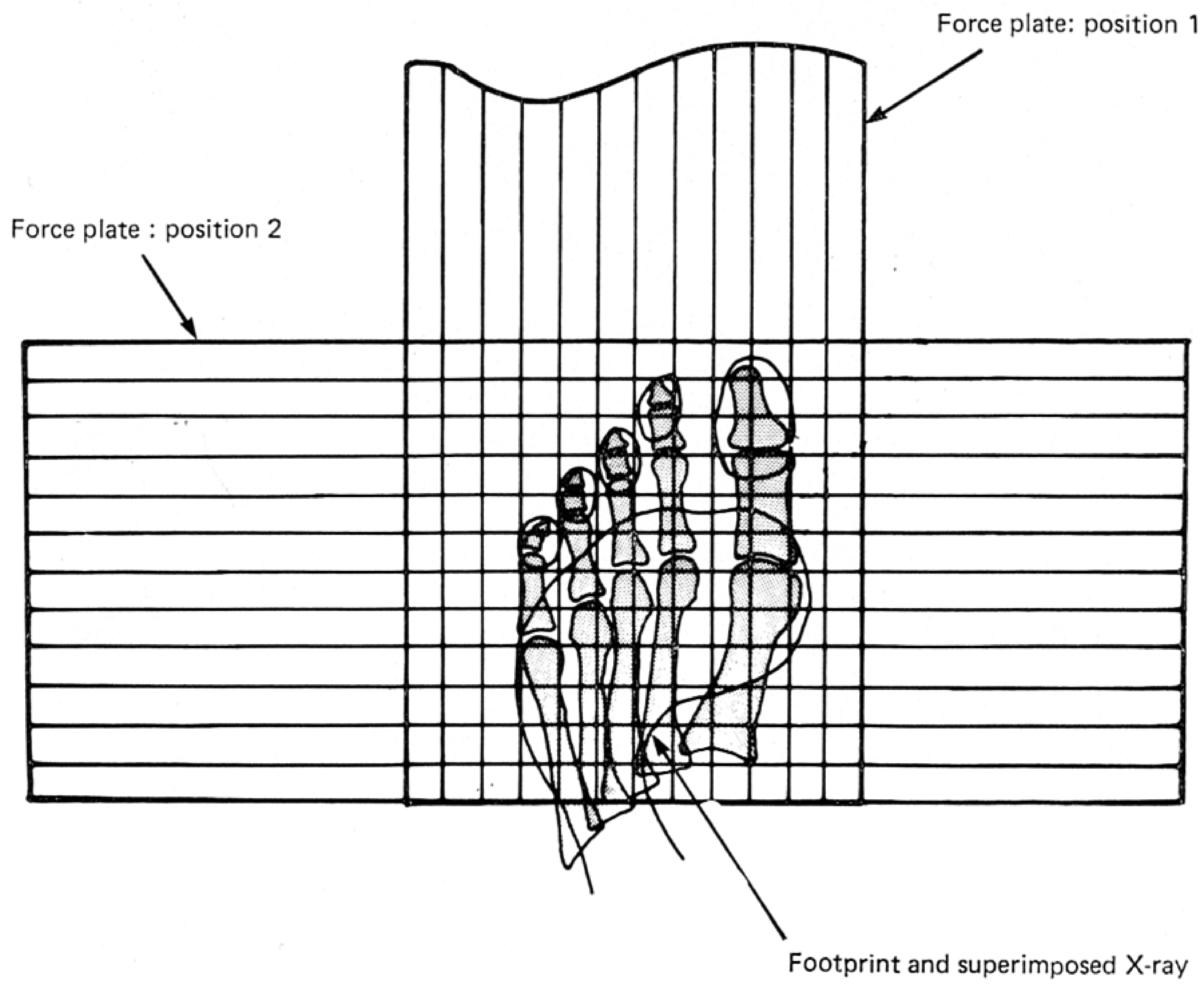


Fig. 2. A force plate divided into twelve bands was used to record loads on bands of the forefoot. Two successive recordings with the force plate rotated through 90° were combined to estimate forces on squares under the foot. A footprint made during each walk gave the correct registration. The X-ray of the foot was positioned over these footprints to assign each square to a bone of the forefoot.

anteroposterior radiograph of the foot which was superimposed over the corresponding footprint from the walkway (see Fig. 2). These loads, at 40 msec intervals, were finally expressed as the total load on each toe, the moment of this force about the metatarsophalangeal (m.t.p.) joint, the total force on each metatarsal head, and its moment about the corresponding m.t.p. joint.

*Measurements of shape and movements of the forefoot*

Three sets of measurements were made:

(1) the profile of the articular surface of the metatarsal heads;

(2) the length of each metatarsal and its angle with the horizontal in stance;

(3) the angle of the forefoot with the ground during walking.

Metatarsal head profiles are important in establishing the line of action of the forces in the m.t.p. joints. On the assumption that the joints are frictionless, forces should act normal to the articular surface. It was difficult to measure these profiles accurately from lateral radiographs, so measurements were made from lateral photographs of metatarsals from amputated feet. These were of similar age to our subjects, and without history of foot pathology. The four parameters used to describe each metatarsal head profile are shown in Figure 3, and measured values for these are listed in Table 2. The radii of the profile were multiplied by a scaling factor for each subject (Table 1). This factor was derived from the width of each metatarsal head measured from the radiograph, divided by the width of the corresponding

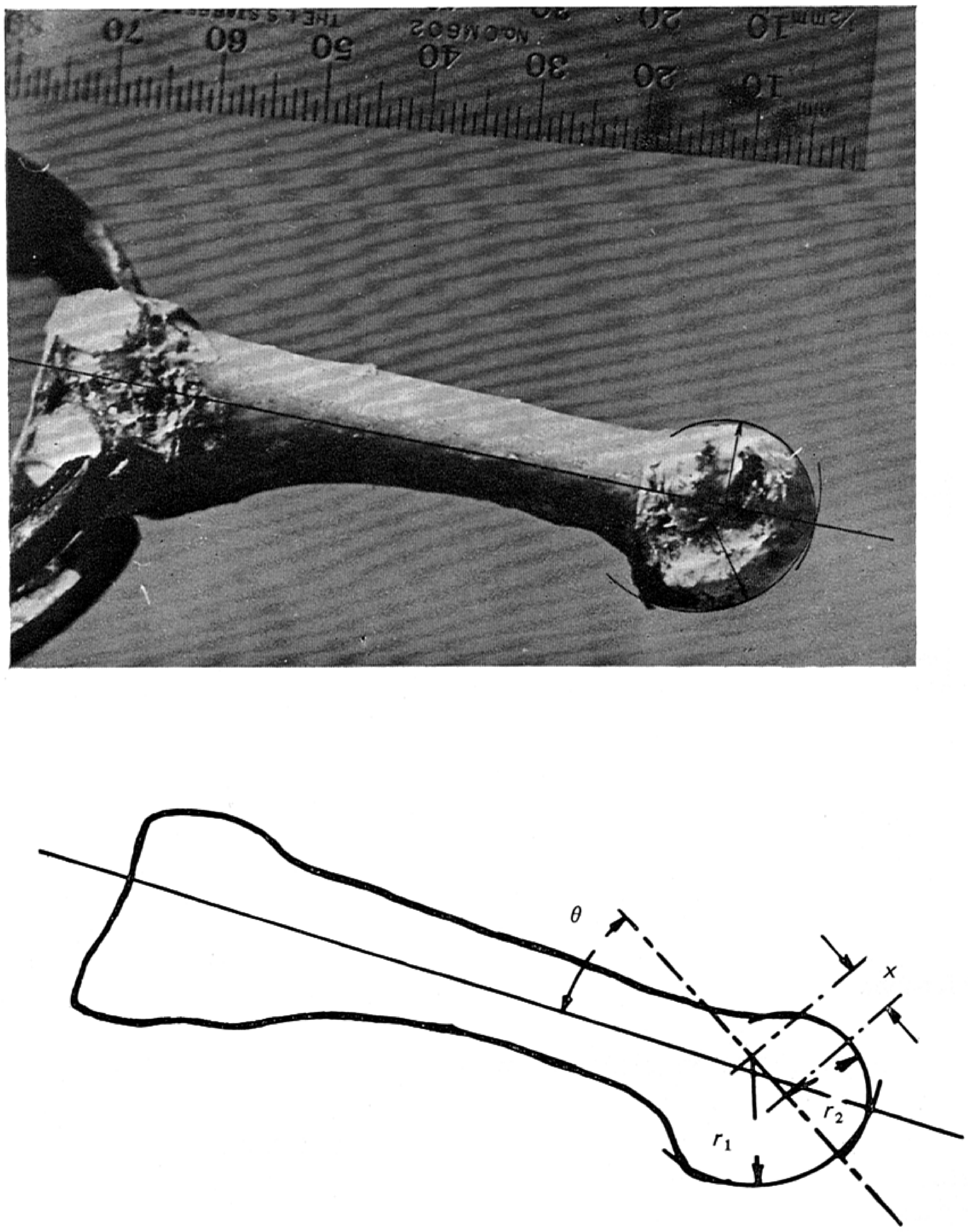


Fig. 3. The profile of a metatarsal head described by two circular arcs. The four variables used to define this profile for each of the five metatarsal heads were measured from cadaver metatarsals (Table 2).

metatarsal head from amputed specimens. These values were averaged over the five metatarsals of each foot to give the scaling factor used.

The angle made by each metatarsal with the floor in stance was measured from lateral radiographs, if these were available. Otherwise, these angles were estimated from lateral photographs of the feet with skin markers over the heads and bases of the first and fifth metatarsals. The length of each metatarsal was measured from anteroposterior radiographs, corrected by the cosine of its angle to the horizontal film plane.

The angle of the forefoot with the ground in walking was measured from a lateral view cine film of the foot with the skin markers described above. Synchronisation with the force recordings was by means of timing pulses delivered by the cine camera to the force platform recorder. The cine recordings of foot angle on the medial and lateral sides were found to be similar within the accuracy of this measurement ($\pm 4°$).

Table 1. *Details of the six subjects studied*

| Subject no. | Sex | Age (years) | Body mass kg | Height m | Metatarsal scaling factor |
|---|---|---|---|---|---|
| 1 | Male | 24 | 67 | 1·78 | 1·07 |
| 2 | Male | 27 | 80 | 1·71 | 1·07 |
| 3 | Male | 35 | 70 | 1·70 | 1·02 |
| 4 | Male | 28 | 76 | 1·88 | 1·13 |
| 5 | Female | 20 | 48 | 1·62 | 0·98 |
| 6 | Female | 28 | 56 | 1·68 | 0·98 |

Table 2. *The parameters used to describe the profiles of the five metatarsal heads (see Fig. 3). These were measured from cadaver bones, and scaled by the factor given in Table 1 to suit each subject's foot size*

| Metatarsal no. | $r_1$ (mm) | $r_2$ (mm) | $x$ (mm) | $\theta$ (degrees) |
|---|---|---|---|---|
| 1 | 11 | 10 | −2 | 104 |
| 2 | 13 | 9 | 4 | 36 |
| 3 | 10 | 8 | 2 | 15 |
| 4 | 12 | 8 | 4 | 36 |
| 5 | 10 | 7 | 3 | 40 |

*Calculation of the forces in the joint*

Forces in the m.t.p. joints were calculated according to the model in Figure 4 for each 40 msec interval for which force platform data were available. Subsequently, the equilibrium of the metatarsals was considered in order to calculate the three components of loading in these bones (compressive or strut load, bending load, and shear load).

The following simplifying assumptions were made in these calculations:

(1) The m.t.p. joints are frictionless. The lateral profile of the metatarsal heads can be defined by two circular arcs as shown in Figure 3.

(2) Forces due to the accelerations of the components are negligible.

(3) No extensor muscles act on the toes during the stance phase of walking (which is partially justified by the E.M.G. recordings of Carlsöö (1972)). The short toe flexor muscle and the plantar aponeurosis act horizontally when the foot is flat on the ground. The long toe flexor acts in a direction which is parallel to the long axis of the metatarsal. Forces resulting from both act in a vertical plane through the long axis of the metatarsal. Forces in the ligaments across the m.t.p. joints are negligible.

(4) The five rays of the foot act independently.

(5) Only vertical forces from the floor need to be considered.

(6) The tension in the long toe flexor tendons is equal to, or exceeds, the total tension in the short flexor tendon and that exerted on the tendon sheath by the plantar aponeurosis.

In Figure 4 the net floor reaction on the toe ($F_T$) and its distance from the m.t.p. joint ($r_T$) was calculated. The parameters $r_1$, $r_2$, $x$ and $\theta$ were measured from the metatarsal head profiles. The angle $\alpha$ was the sum of the stance angle of the bone ($\beta$) and the angle of the foot measured from the cine film. The distance of the tendons from the metatarsal head ($\epsilon$) was estimated (from dissected feet) as 4 mm for the first

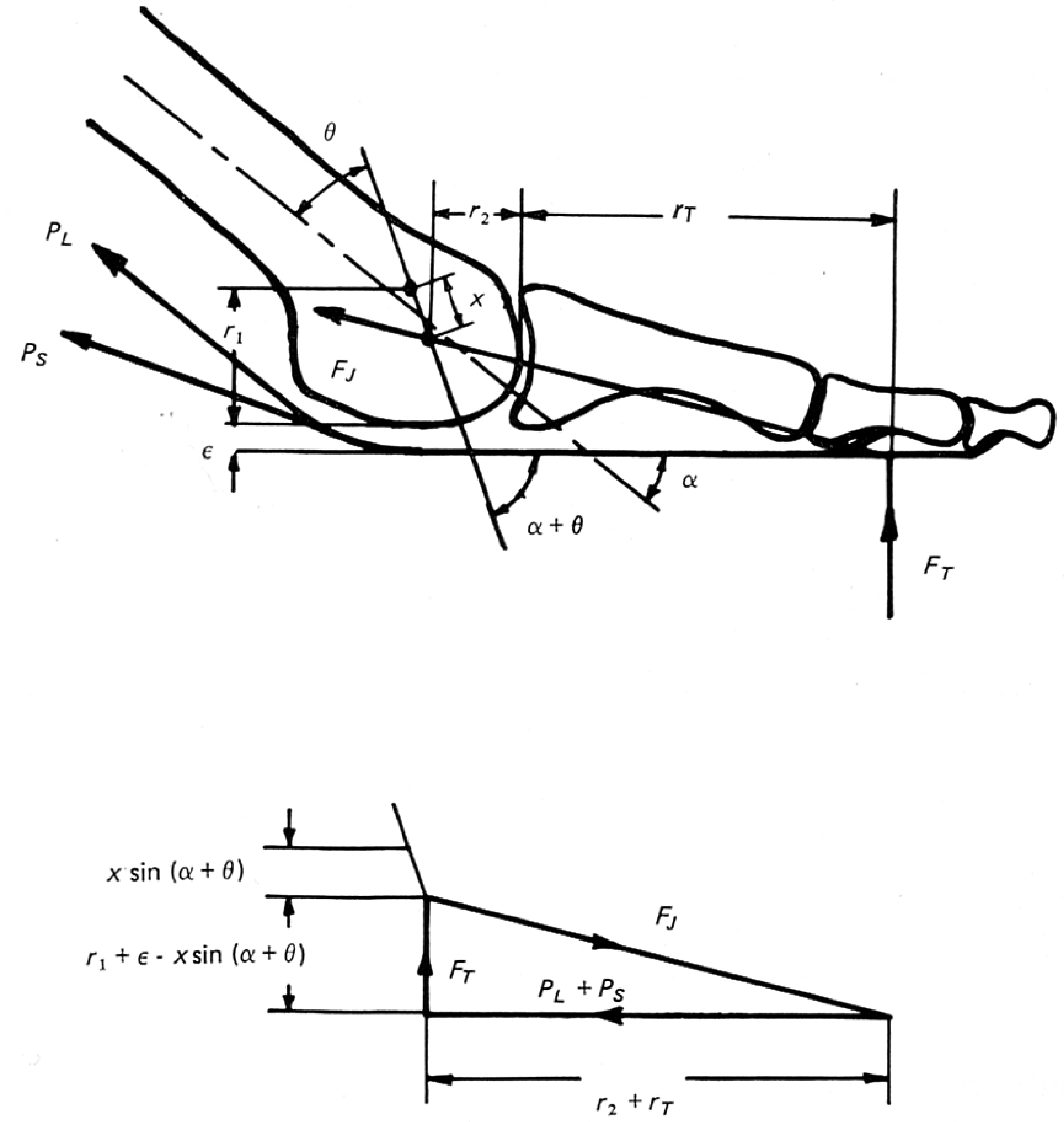


Fig. 4. The forces acting on the toe during walking and the triangle of forces used to calculate the forces in the metatarsophalangeal joint and toe flexor tendons.

metatarsal and 2 mm for the lesser bones. This left the tendon tensions $P_L$ and $P_S$ (in the long flexor tendon, and the short tendon and tendon sheath respectively) and the joint force $F_J$ as unknowns.

The triangle of forces (Fig. 4) was used to find the unknown forces as follows:

$$\frac{P_L+P_S}{F_T} = \frac{r_T+r_2}{r_1+\epsilon-x\sin(\theta+\alpha)} \tag{1}$$

$$F_J^2 = (P_L+P_S)^2 + F_T^2. \tag{2}$$

These equations were solved for the total tendon force $(P_L+P_S)$ and the joint force $(F_J)$.

*Calculation of the forces on the metatarsal*

The metatarsal was considered to be under the influence of the forces shown in Figure 5. By resolving forces parallel to, and perpendicular to the axis of the metatarsal, and by taking moments about the metatarsal base, three equilibrium equations were derived:

Axial (strut) load in the bone:

$$R_M = (F_T+F_M)\sin\alpha + P_L + P_S\cos\beta \tag{3}$$

(by summing forces along the axis).

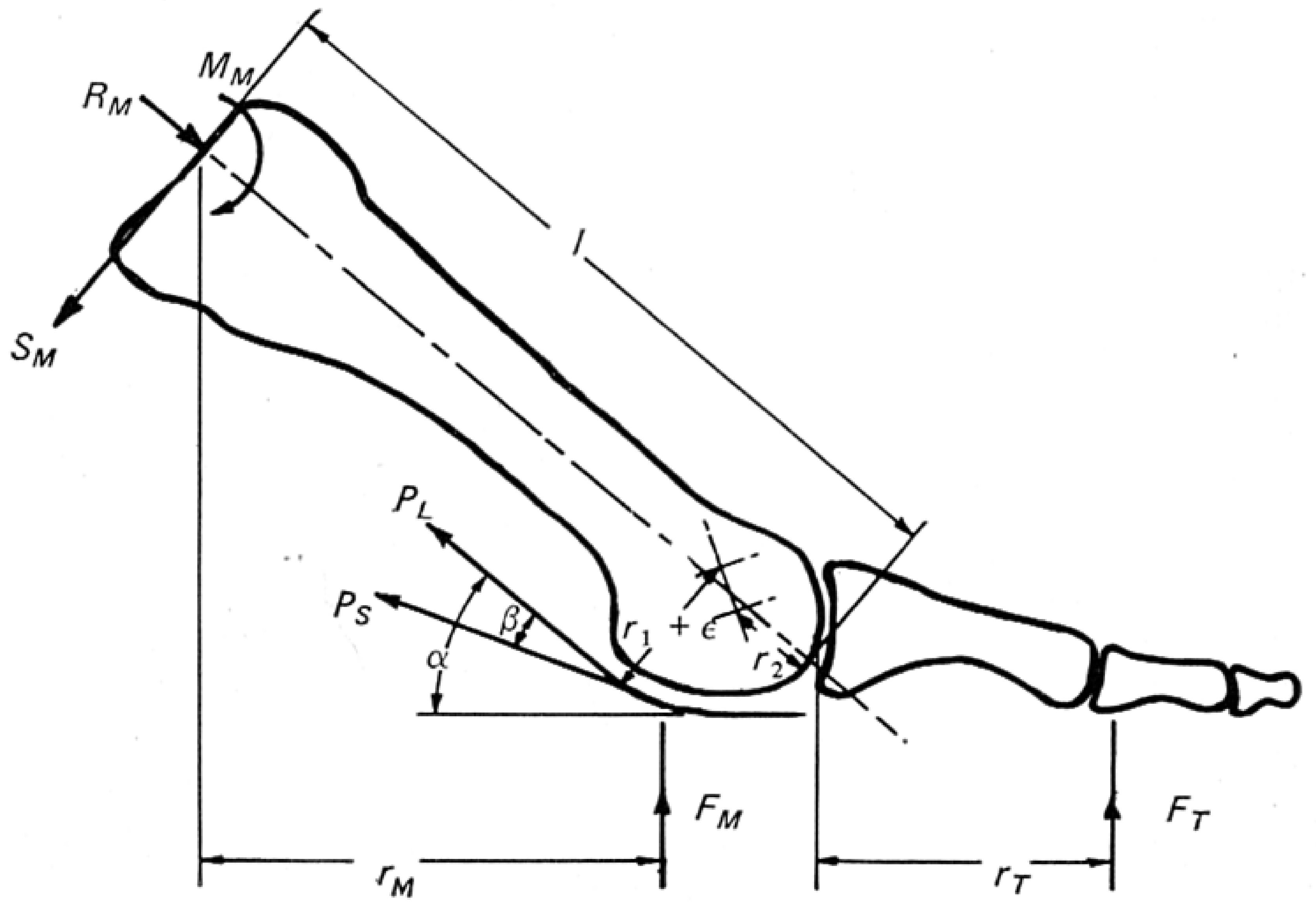


Fig. 5. The forces acting on a metatarsal during walking. Upper and lower bounds of the axial force, bending moment and shear force were calculated.

Shear force in the bone:

$$S_M = (F_T + F_M)\cos\alpha - P_S \sin\beta \tag{4}$$

(by summing forces perpendicular to the axis).

Bending moment at the metatarsal base:

$$M_M = F_M r_M + F_T(r_T + l\cos\alpha) - P_L(r_1+\epsilon) - P_S[r_1+\epsilon+(l-r_2)\sin\beta] \tag{5}$$

(by making the approximation that the axis of the metatarsal passes through the centres of both arcs of the joint profile).

Rearranging equation (1):

$$P_S + P_L = \frac{(r_T + r_2)F_T}{r_1 + \epsilon - x\sin(\theta+\alpha)} \tag{6}$$

There are five unknowns in the four equations (3), (4), (5) and (6), namely $R_M$, $S_M$, $M_M$, $P_L$ and $P_S$. Solutions to the equations were obtained by making an assumption about the relative values of the tensions in the long and short flexor tendons ($P_L$ and $P_S$). Upper and lower bounds for the unknown forces were obtained by assuming that the tension in the short flexor tendon and sheath ($P_S$) was between zero and half of the total tendon tension. In other words the tension in the short flexor could not exceed the tension in the long flexor.

## RESULTS

The model of the forefoot and the experimental data gave values for the m.t.p. joint force ($F_J$) and upper and lower bounds for the three components of load in the metatarsal bones ($R_M$, $S_M$ and $M_M$). Typical values of the lower bound values (from subject 3, right foot) are shown in Figures 6, 7, 8 and 9. All the feet gave graphs of similar form, with a quite distinct maximum in the late stage of forefoot contact. These maximum values are given in Table 3. There is considerable variability in the sample, reflecting the variability of the distribution of load between the five

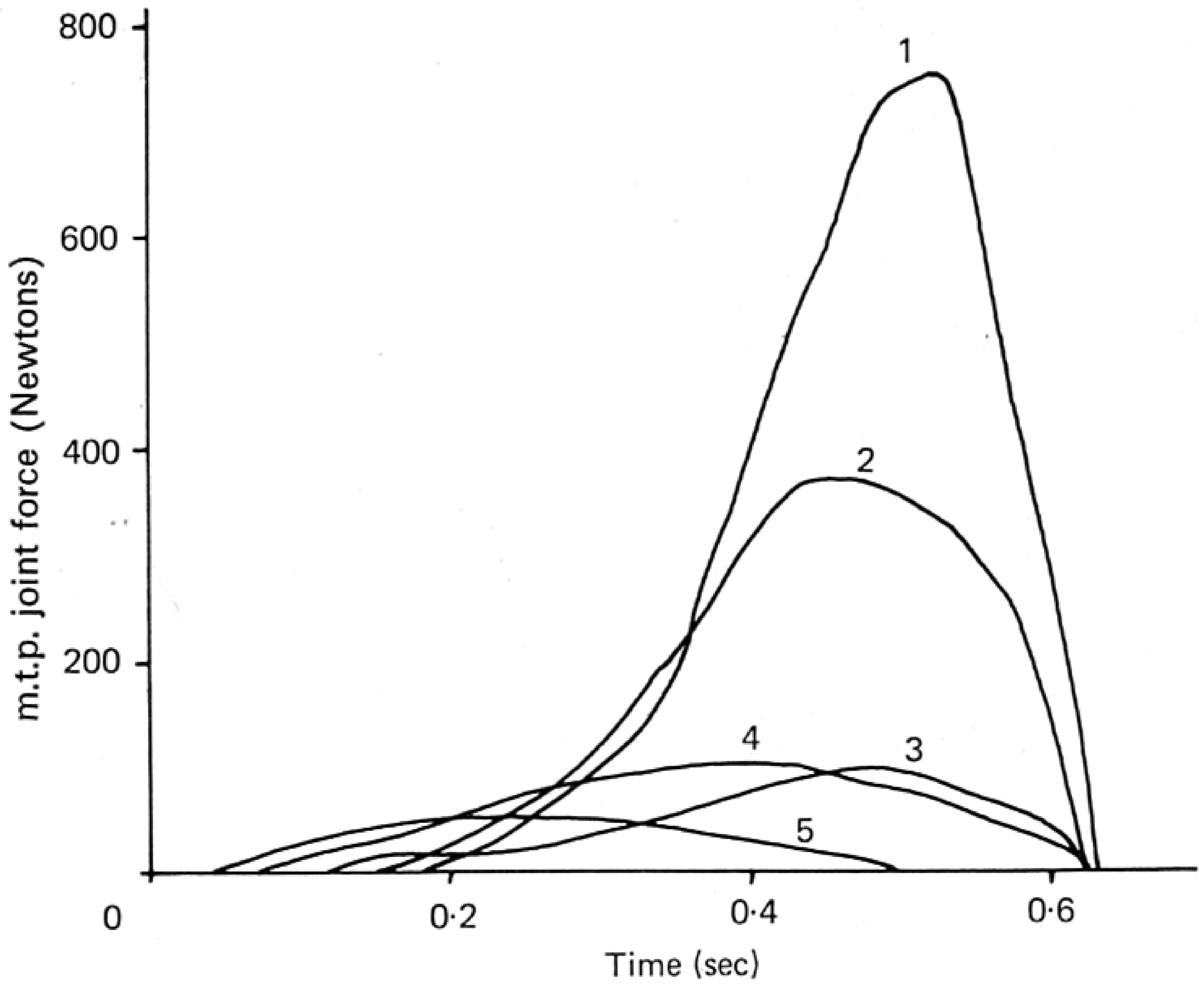


Fig. 6. The calculated forces acting on the metatarsophalangeal joints ($F_J$) of subject 3, right foot, during walking.

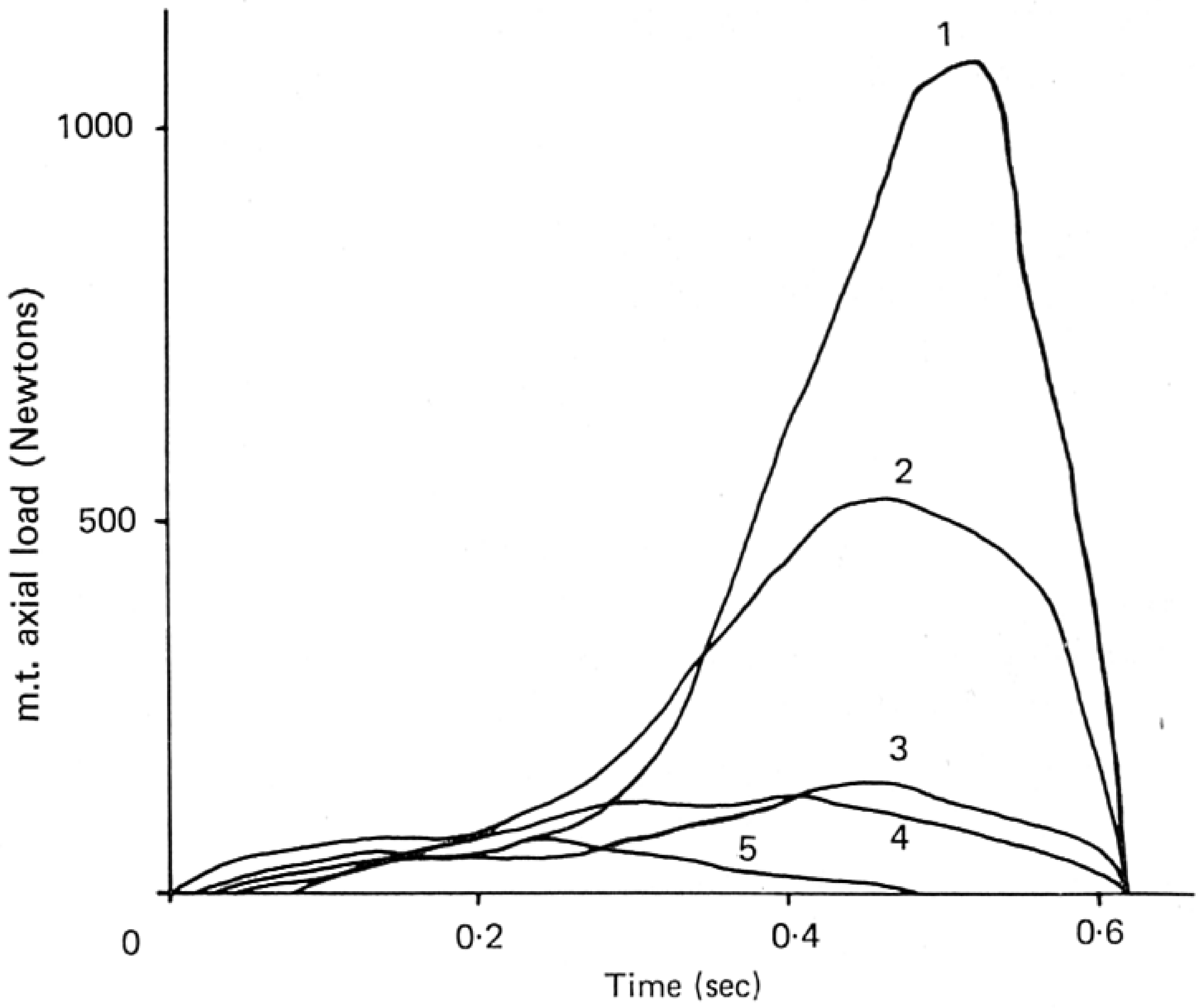


Fig. 7. The calculated forces ($R_M$, lower bound) in the metatarsals of subject 3, right foot.

metatarsal rays among these feet, and to some extent the various body weights of the subjects (Table 1).

The accuracy of these results depends upon the accuracy of the measurements, and of the assumptions in the mechanical model. The major source of error in the measurements is in the distribution of force under the foot ($\pm 30\%$). The overall accuracy of the calculated results is estimated to be about $\pm 50\%$.

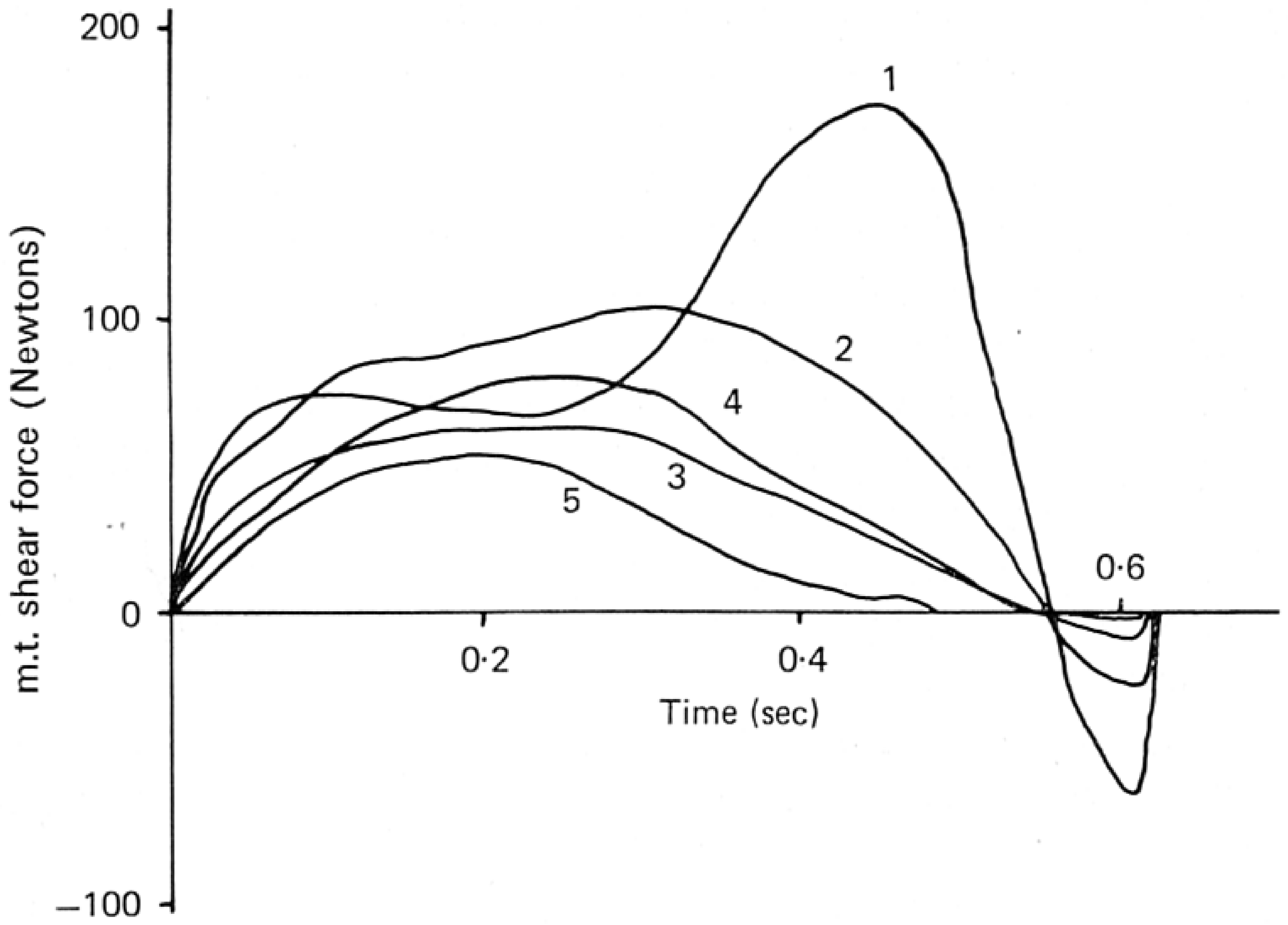


Fig. 8. The calculated shear forces ($S_M$, lower bound) in the metatarsals of subject 3, right foot.

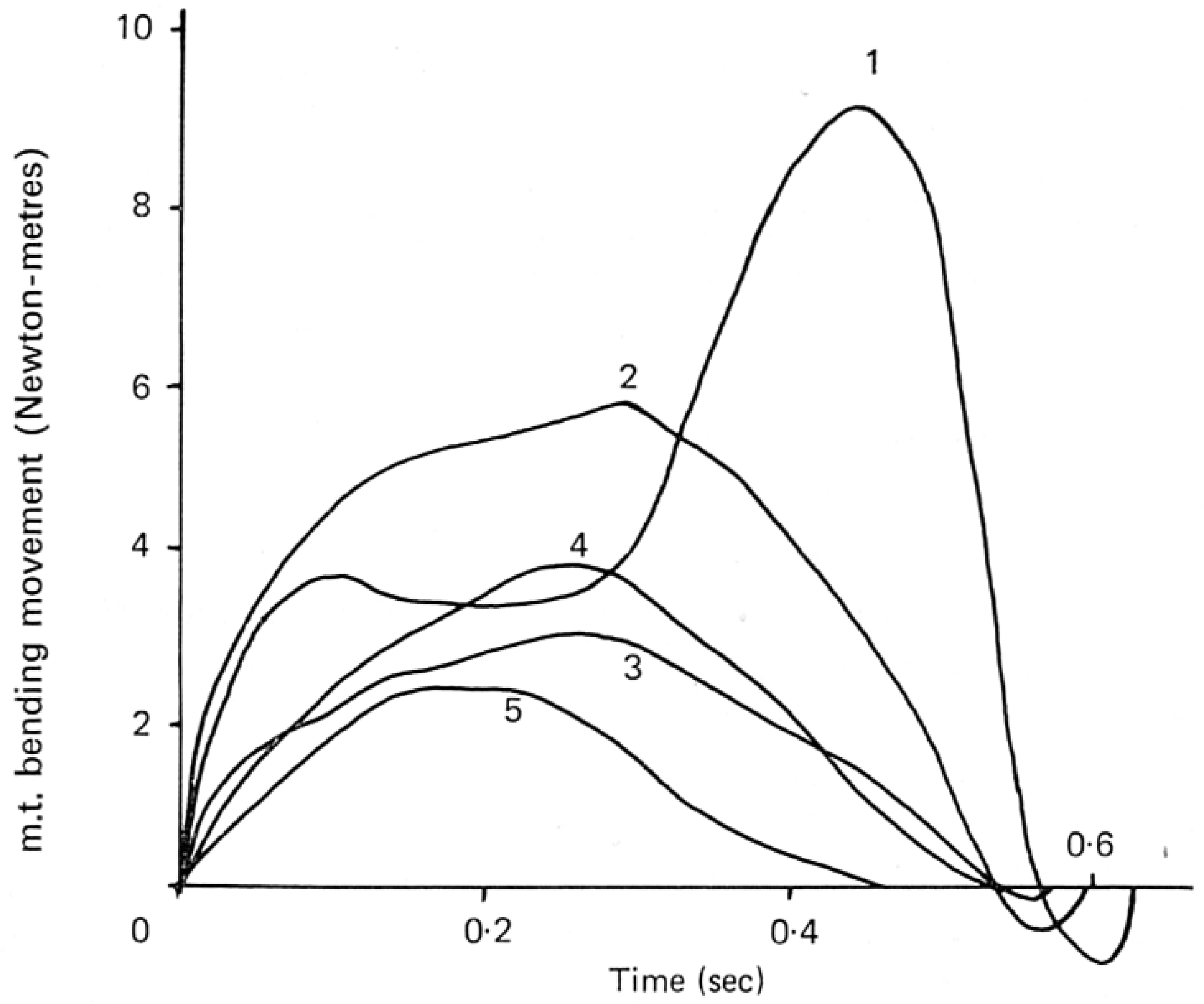


Fig. 9. The calculated bending moments ($M_M$, lower bound) at the bases of metatarsals of subject 3, right foot.

## DISCUSSION

The forces found to act through the m.t.p. joints have implications in our understanding of pain and degeneration at these joints. In the final stage of forefoot contact during walking there was a peak force of around 30 % of body weight on the toe, around 10 % of body weight on the second toe, and smaller forces on the lesser toes. These forces combine with activity in the toe musculature and tension in the plantar aponeurosis to produce forces in the m.t.p. joints which are sometimes comparable with body weight. The greatest loads in walking were in the first m.t.p.

joint, which is physically the largest. The sesamoid bones increase the distance of the flexor tendons from the first joint. This is helpful in minimising the joint force.

The relative contributions of the long and short toe flexors and the plantar aponeurosis had to be estimated in the calculations. The bulk of the muscles suggests that the long flexor should produce the greatest pull, but the contribution of the plantar aponeurosis has been stressed by Hicks (1955). He worked with cadaver feet and deduced that this structure imposed a force of 100 N on each toe in stance, and that its tension would be increased by a 'windlass' effect with dorsiflexion of the toes in walking. However, he also found a rupture tension of about 1000 N which placed an upper limit on its possible effect.

The toe flexor muscles and the aponeurosis which produce high loadings in the m.t.p. joints also give some support to the longitudinal arch of the foot against the effect of the floor reaction on the forefoot, and against loads on the calcaneum from the floor or Achilles tendon. However, the results of this study show that the metatarsals are still subjected to an upward shear force and bending moment during most of the period of forefoot contact with the ground. These forces are counteracted by tensions in the short plantar ligaments which secure the metatarsals to the tarsus. Thus, excessive bending moments in the metatarsals can result from inactivity of the toe flexor musculature. Such forces may be responsible for 'march' or 'fatigue' fractures of the metatarsals, for metatarsalgia and for flattening of the longitudinal arch of the foot by stretching the plantar ligaments.

The calculated forces were found to be highest for the first metatarsal and lowest for the fifth. The first metatarsal is mechanically strong, has a large metatarsal joint surface, sesamoid bones to give the flexor tendons a good mechanical advantage to minimise joint forces, and a large inclination to the horizontal to minimise its shear and bending forces. The lesser metatarsals, especially the second and third, may therefore be loaded out of proportion to their sizes. This suggests why these bones are prone to metatarsalgia and 'march' fractures (Devas, 1975).

Previous studies with this apparatus (Stokes, Hutton & Evans, 1975; Stokes, Faris & Hutton, 1975) have shown that feet with hallux valgus or diabetic neuropathy function abnormally in that they carry less than normal loads on the toes, and also impose smaller than normal loads on the first metatarsal ray as compared with the lesser metatarsals. While these abnormalities would reduce the forces in the metatarsophalangeal *joints*, they would however increase the bending forces in the metatarsal *bones*, especially the lesser ones.

The model of the forefoot used here made it possible to investigate the effects of reduced toe load quantitatively. The forces in the forefoot were recalculated, neglecting loads on the toes but increasing the loads on each metatarsal by the amount of load which had been recorded on the corresponding toe. The result was an increase of about 10% in the metatarsal bending moments, but a reduction to about one third in the axial forces in the metatarsals. Hicks (1955) found that if the 'arch supporting' structures were divided in cadaver feet about three times body weight could be supported by the forefoot without damage to the metatarsal bone attachments. Thus, it should be possible to walk without the 'arch supporting' structures, though more energetic activities would damage the arch of the foot.

Table 3. *Calculated values of the metatarsophalangeal joint forces and the three components of force in the metatarsal bones.*

(Values are given in absolute units and as proportions of body weight. The mean for the group of six subjects (12 feet) is given in each case and the numbers in parentheses are the standard deviations in the group. Variability between subjects was much greater than that between footsteps of individual subjects. Differences between the two feet of each subject were almost as great as those between subjects. Calculations of forces in the metatarsal bones depended on assumptions about relative muscle activity, so an upper bound (UB) and a lower bound (LB) of these forces is given.)

| | | Metatarsal | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| *m.t.p. joint force* | Newtons | 604 (318) | 373 (184) | 192 (110) | 131 (51) | 86 (48) |
| | % body wt. | 79·9 (46·0) | 58·3 (30·3) | 29·5 (14·2) | 20·9 (9·1) | 13·9 (10·2) |
| *Axial metatarsal force* ($R_M$) | Newtons | | | | | |
| | UB | 852 (410) | 545 (214) | 281 (140) | 176 (66) | 102 (62) |
| | LB | 820 (392) | 526 (206) | 274 (137) | 173 (65) | 102 (62) |
| | % body wt. | | | | | |
| | UB | 134 (70) | 84·3 (32·8) | 43·1 (17·3) | 27·9 (12.4) | 16·7 (13·5) |
| | LB | 129 (67) | 81·2 (31·6) | 41·7 (17·1) | 27·5 (12·2) | 16·6 (13·4) |
| *Bending moment in metatarsal* ($M_M$) | Newton-metres | | | | | |
| | UB | 13·0 (4·4) | 9·4 (3·1) | 6·7 (2·8) | 5·3 (2·6) | 3·6 (3·3) |
| | LB | 8·0 (2·6) | 6·5 (3·0) | 5·4 (2·6) | 4·6 (2·6) | 3·4 (3·1) |
| | % body wt. × metres | | | | | |
| | UB | 2·0 (0·7) | 1·4 (0·4) | 1·0 (0·4) | 0·8 (0·4) | 0·6 (0·5) |
| | LB | 1·2 (0·4) | 1·0 (0·4) | 0·8 (0·3) | 0·7 (0·4) | 0·5 (0·5) |
| *Shear force in metatarsal* ($S_M$) | Newtons | | | | | |
| | UB | 245 (75) | 169 (43) | 117 (36) | 105 (37) | 71 (49) |
| | LB | 150 (35) | 116 (48) | 97 (31) | 93 (33) | 66 (46) |
| | % body wt. | | | | | |
| | UB | 36·8 (12·2) | 25·1 (6·6) | 17·4 (4·7) | 15·8 (6·4) | 10·8 (8·1) |
| | LB | 22·1 (7·3) | 17·0 (7·2) | 14·5 (4·3) | 14·0 (5·8) | 10·2 (7·6) |

## CONCLUSIONS

(1) Around 40% of body weight is imposed on the toes in the final stages of forefoot contact. Most of this is imposed on the great toe. Toe loads are counteracted by tension in the toe flexor tendons and tendon sheaths. These forces react against the m.t.p. joints to produce a joint force around 600 N in the first joint, and around 100 N in the fifth. There was considerable variability in the distribution of load on the forefoot between individuals, resulting in a spread of these calculated forces.

(2) The metatarsals carry a load which is due primarily to the ground reaction during the first half of forefoot contact time, and due primarily to the m.t.p. joint force in the second half of this contact time. The ground reaction force is near to vertical (only the vertical component was considered here) but the joint force has a large horizontal component. These forces together produce a large axial force in the metatarsals in walking, but also sufficient non-axial load to give a bending moment in the dorsiflexion direction. This moment has to be resisted by the short plantar ligaments which tie the metatarsal to the tarsus.

(3) In most of the normal feet studied, the forces in the the rays of the forefoot were ranked in sequence so that the first ray carried the highest loads and the fifth carried the smallest loads.

(4) The foot can be considered partly as an arch structure (loaded through the talus, the heel and Achilles tendon, and through the forefoot) and partly as a beam or lever. There are 'arch supporting' structures (toe flexor tendons and the plantar aponeurosis) which reduce the bending moment in the arch by about 10% compared with what it would be in the absence of the function. These also increase the axial loads in the metatarsals and the joint reactions. The remaining bending moment at the base of the metatarsal is resisted by closely applied ligaments.

(5) Disorders of the foot which reduce the load-bearing function of the toes result in less load in the m.t.p. joints. However, they also give greater bending moments in the metatarsal bones, and produce greater stresses at the attachments of the metatarsals to the tarsus. This may be a common reason for pain and march fractures in the metatarsals, and for progressive changes and deformities in the midfoot joints.

This work was carried out at the Polytechnic of Central London, with financial support from the Inner London Education Authority and the Medical Research Council. Mr R. Emerson constructed the special apparatus used and helped with the experimental work. I.A.F.S is now at the Oxford Orthopaedic Engineering Centre, with financial support from the Department of Health and Social Security.

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