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Graphic analysis of forces acting upon a simplified model of the foot

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Abstract

Application of a graphical technique to analyse internal forces on a simplified model of the foot in various external loading patterns. The method is applied when the external load is acting purely upon the forefoot, the hindfoot and on both locations. The pes planus situation and the effect of the "rocker" and inlay sole are studied.

Introduction

It is often of interest for people taking care of patients with foot diseases to know how the load is distributed on the internal structure of a normal and a pathological foot; how variation of the external load changes the internal load distribution pattern and how a pathological structural change can be followed by a deviation from the normal loading pattern.

The answer to this problem can aid the orthopaedic surgeon in deciding what can be achieved by changing the structure of a foot through surgery. The foot orthotist can make use of the answer by constructing the orthopaedic footwear in such a way that the external load will be satisfactorily accommodated by the internal load distribution. (By external loads is meant the reaction forces from the floor acting upon the foot, while internal loads mean any force acting inside the body.)

The foot with its active and passive structures (muscles, bones, aponeuroses and ligaments) represents a complex three dimensional system. In addition it is not only purely a mechanical system, as an engineer would prefer, but a biological one controlled by the central nervous system. Even emotional conditions make a difference in how the foot acts in certain situations.

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A method that is easy to use in daily practice is presented which analyses the relationship between the internal and external loads. This is extended to forecast how variations of the external load and structure of the foot, whether deliberate or not, influence its internal loading.

For the purpose of the analyses the foot is considered to be a segmented solid coplanar body, placed in the sagittal plane of the foot and articulating with the crus in the talocrural joint. We will further simplify the structure of the foot by substituting the whole plantar passive apparatus with an idealized plantar ligament, taking into consideration just a few of the main muscles. All analyses are limited to static equilibrium situations in the above mentioned sagittal plane. All forces are given in Newtons.

The externally loaded forefoot

Figure 1 shows the forefoot bearing the total bodyweight assumed to be about 800N. This corresponds to the situation which is found when standing on one foot, for example on a stair.

For simplicity, let us start with a foot consisting only of one segment which articulates with the crus through the talocrural joint. The foot as a free body is acted upon by three forces; the ground reaction force R, the load TC on the trochlea tali through the axis of the talocrural (tc) joint and the force TS in the muscle triceps surae.

The reaction force R can be measured and its magnitude and direction are known. However only the direction of TS is known and the only information we have about TC is that it must pass through the axis of the talocrural joint (tc).

We start by drawing the force R on the force diagram and continue downwards with the action line of TS as is shown in Figure 1a. The point 0 is chosen quite freely and is connected to the head of R by means of line 1 and

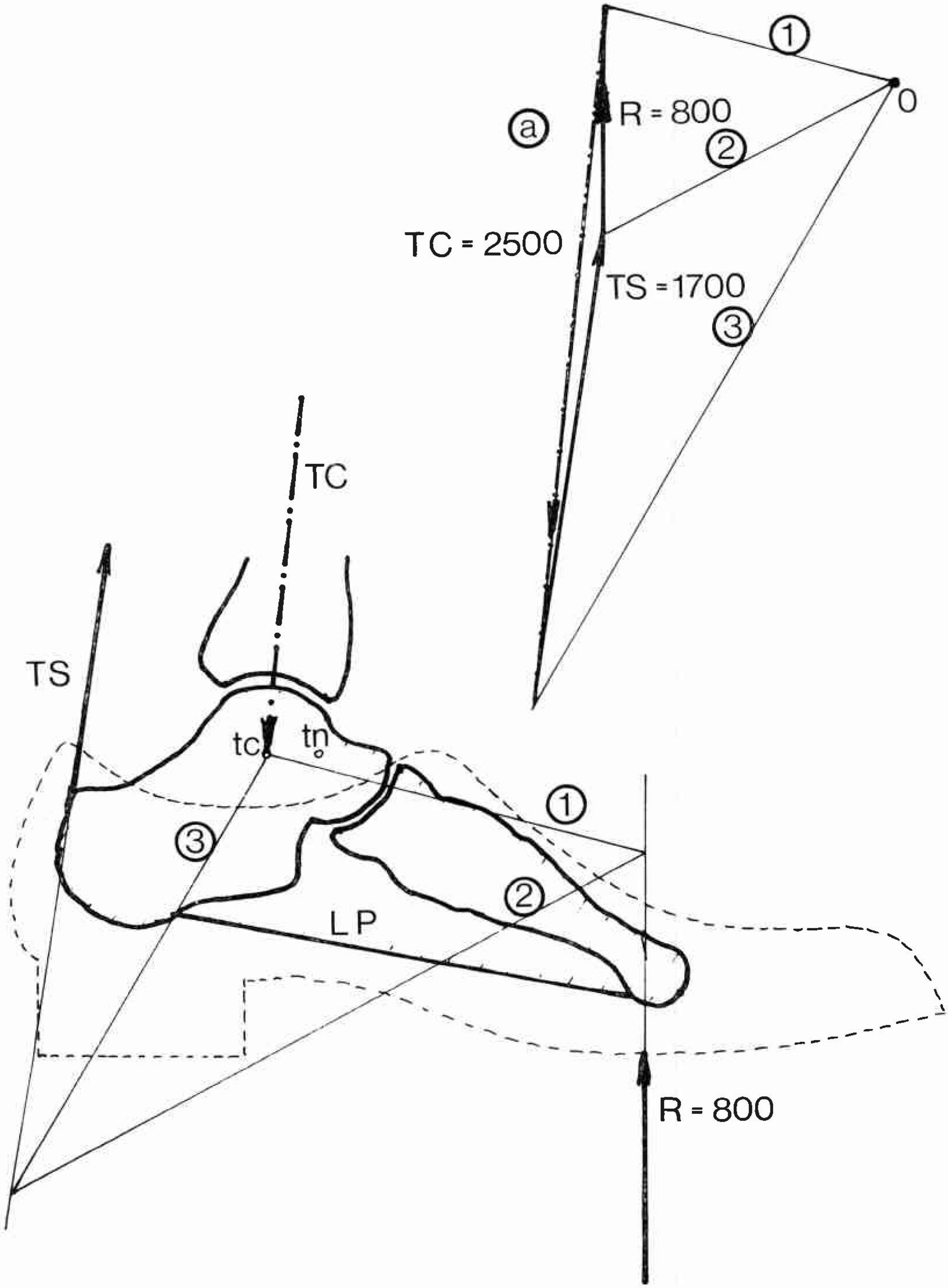

Fig. 1. Forefoot bearing the total body weight. (Foot considered as a single body.)

to the tail of R by means of line 2. On the schematic architectural diagram of the foot we start from the axis of the talocrural joint (tc) and construct line 1 parallel to the above mentioned line until it crosses the action line of R. From this point there must be drawn a construction line parallel to the line 2 on the force diagram. The intersection point on the action line of TS must be connected to the starting point tc which results in construction line 3. A parallel to this

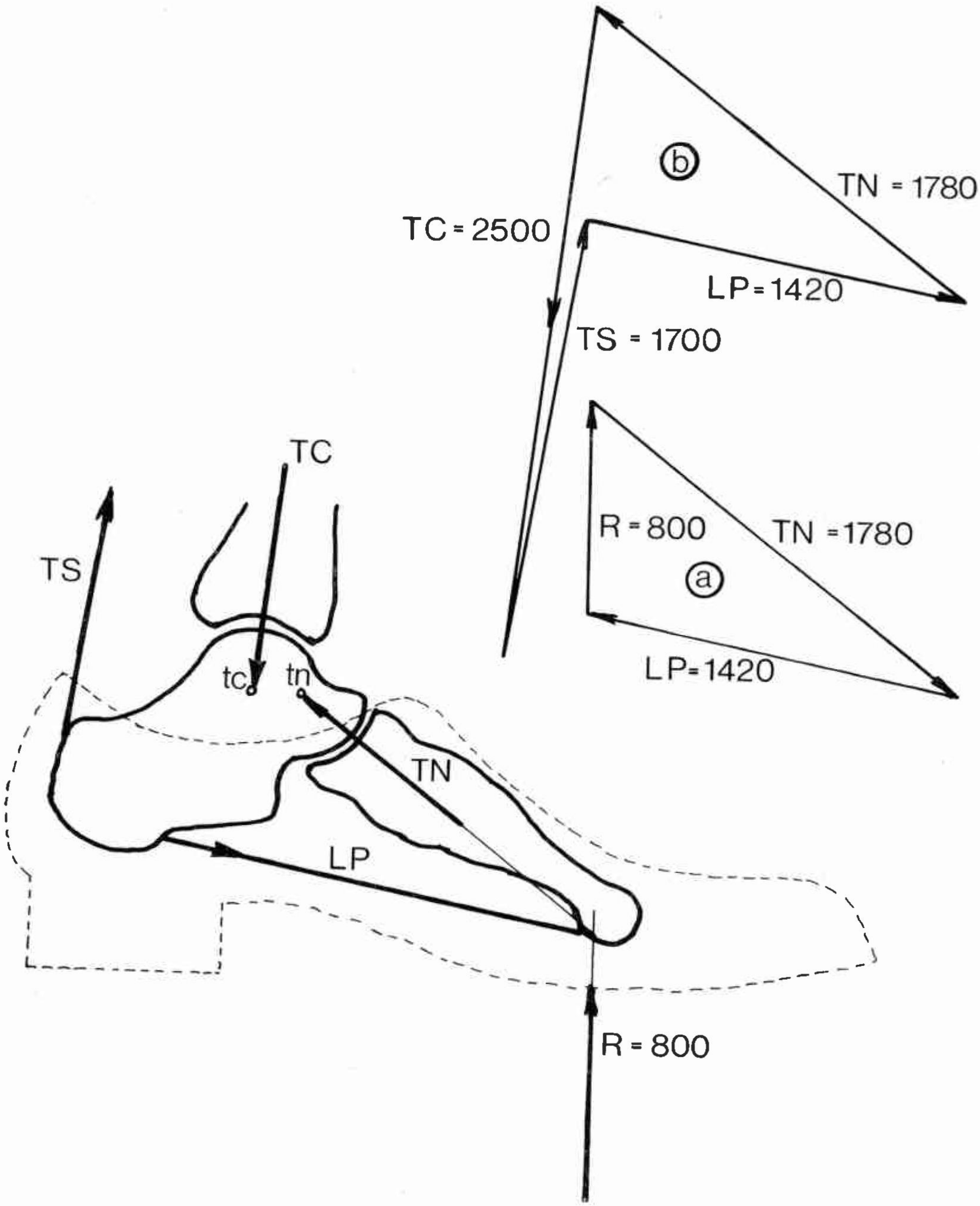

Fig. 2. Forefoot bearing the total body weight. (Foot considered as a two-member body.)

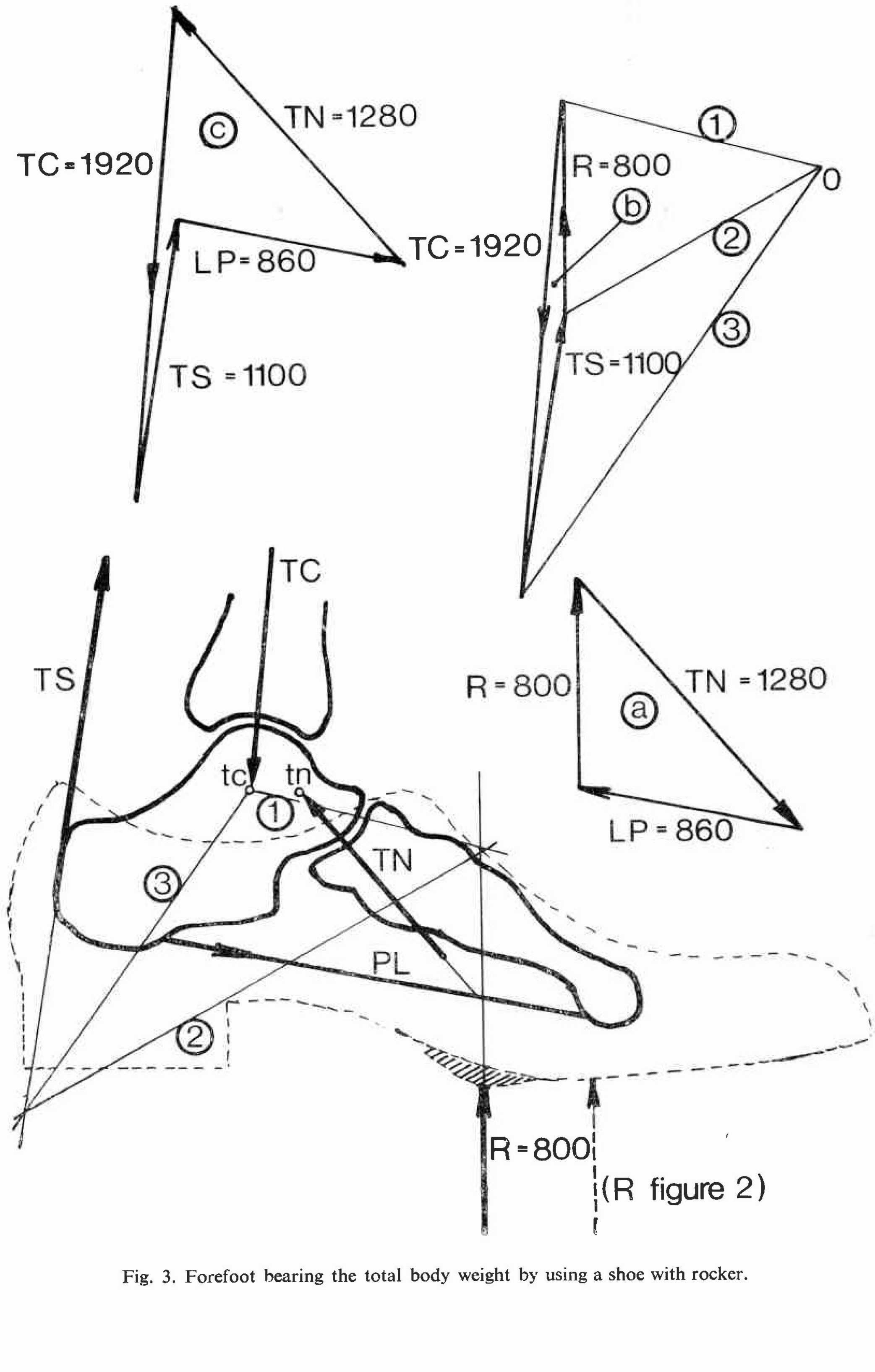

Fig. 3. Forefoot bearing the total body weight by using a shoe with rocker.

from point 0 on the force diagram will cut out the correct length of the force TS. By closing the force diagram we can obtain the magnitude and direction of the unknown force TC and the unknown magnitude of the force TS.

Figure 2 shows the same situation as before, but we now take into consideration the existence of the talonavicular joint. In this way the "foot" consists of a solid hindpart and forepart which are linked together on the plantar side by means of the idealized plantar passive structure, ligament LP. The forefoot is acted upon by three coplanar forces. The equilibrium in this case demands that these must have a common intersection point. This immediately gives the direction of the load on the talonavicular joint which must pass through the axis of the joint (tn).

The force diagram of the forefoot as a free body in equilibrium can be constructed as shown in figure 2a.

Similarly the force diagram of the hindfoot is shown in figure 2b. The directions of forces TN and LP are changed in relation to figure 2a, because these are now taken into consideration as forces acting on the hindfoot.

The directions of the forces acting on the hindfoot are shown in the figure of the schematic foot architecture.

It is interesting to observe that the load on the talocrural joint is about three times greater than the total reaction force.

The foot orthotist can reduce the large internal loads on the foot by using a rocker on the sole of the footwear. Figure 3 shows a rocker which moves the reaction force R posteriorly by a distance of about 15 per cent of the length of the footwear compared with the R shown in figure 2. At first we handle the foot as one solid single free body acted upon by the forces R, TC and TS. By analogy with the graphical method applied in figure 1 we can get the load TC and TS (fig. 3b). Figure 3a shows the force diagram of the forefoot and figure 3c the same for the hindfoot. The rocker reduces the load on the talocrural joint by about 20 per cent and on the idealized plantar ligament by about 40 per cent.

It is informative to take a look at the foot when it is loaded externally, but with a moderate

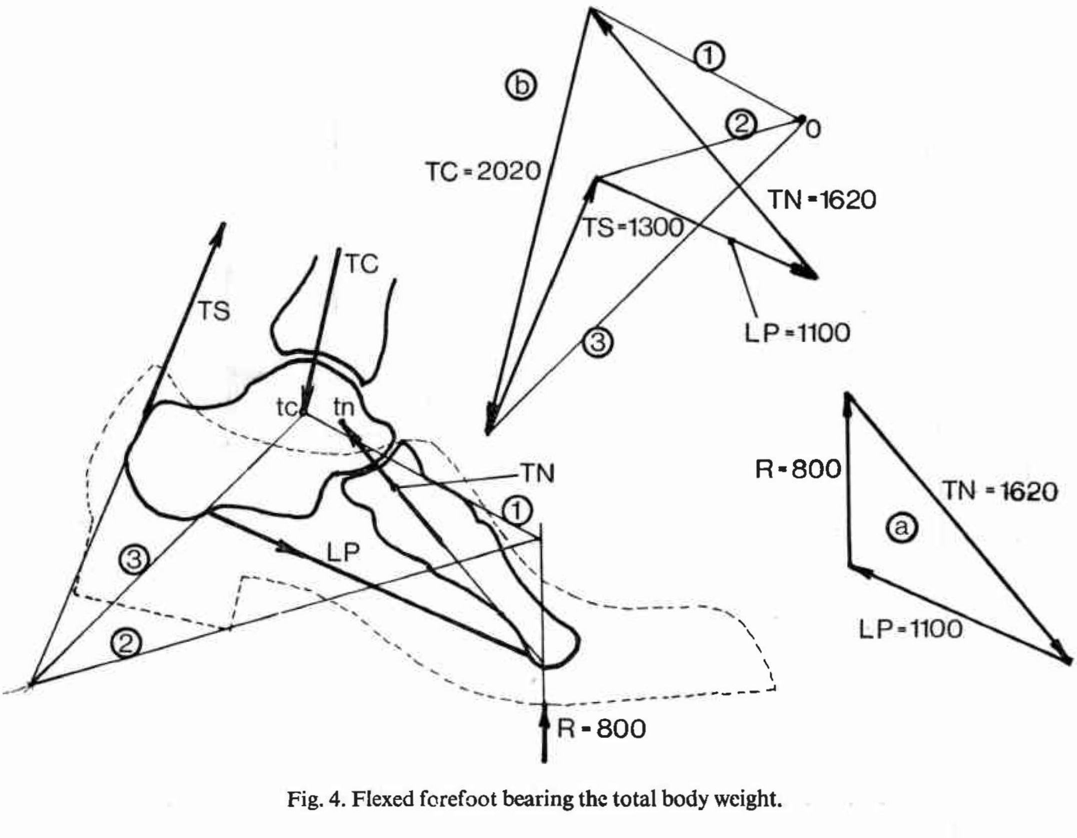

Fig. 4. Flexed forefoot bearing the total body weight.

flexion as shown in figure 4. The graphical analysis gives the force diagram for the forefoot (fig. 4a) and for the hindfoot (fig. 4b). Note that the flexion in this configuration decreases the internal forces, for example the load on the talocrural joint falls by about 20 per cent.

Figure 5 indicates how the internal load distribution will change in the case of pes planus. The pes planus situation is approximated by moving the axis of talocrural and talonavicular joints distally (tc^1 and tn^1) compared with the normal foot (tc and tn). Figure 5a shows the force diagram of the forefoot. In this approximation we maintain the form of the foot and therefore the loads TC and TS are the same as in the case of the normal foot. (On the schematic architecture of the foot the forces are shown as they act upon the forefoot).

The results of the four cases we have discussed can be most conveniently compared by looking at table I.

	R	TC	LP	TS	TN
Normal sole, nonflexed	800	2500	1420	1700	1780
Normal sole, flexed	800	2020	1100	1300	1620
With rocker, nonflexed	800	1920	860	1100	1280
Pes planus	800	2500	1700	1700	2040

Table I. Comparison of internal loading in different circumstances as a result of externally loading the forefoot (all values are given in Newtons).

The externally loaded hindfoot

It is also important to know how the load on the hindfoot affects the internal load distribution. Let us examine the case when standing on a stair with the heel as shown in figure 6. We assume that the foot as a solid free body is acted

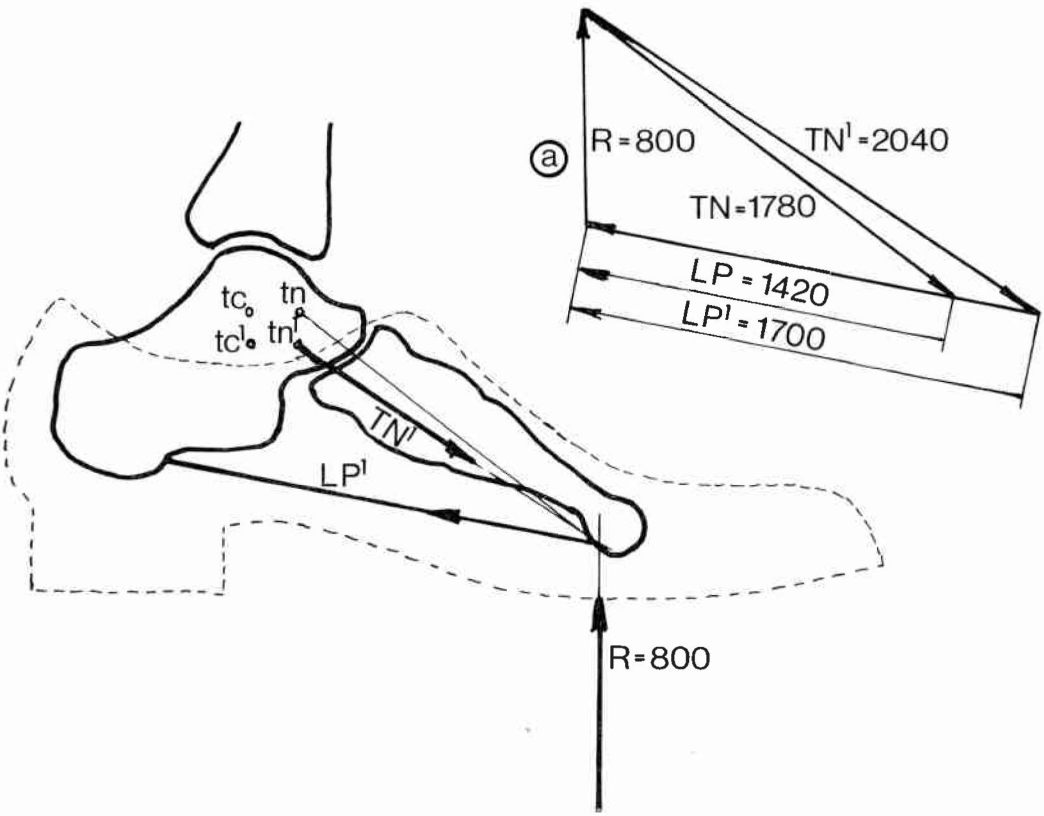

Fig. 5. Forefoot bearing the total body weight in the case of pes planus.

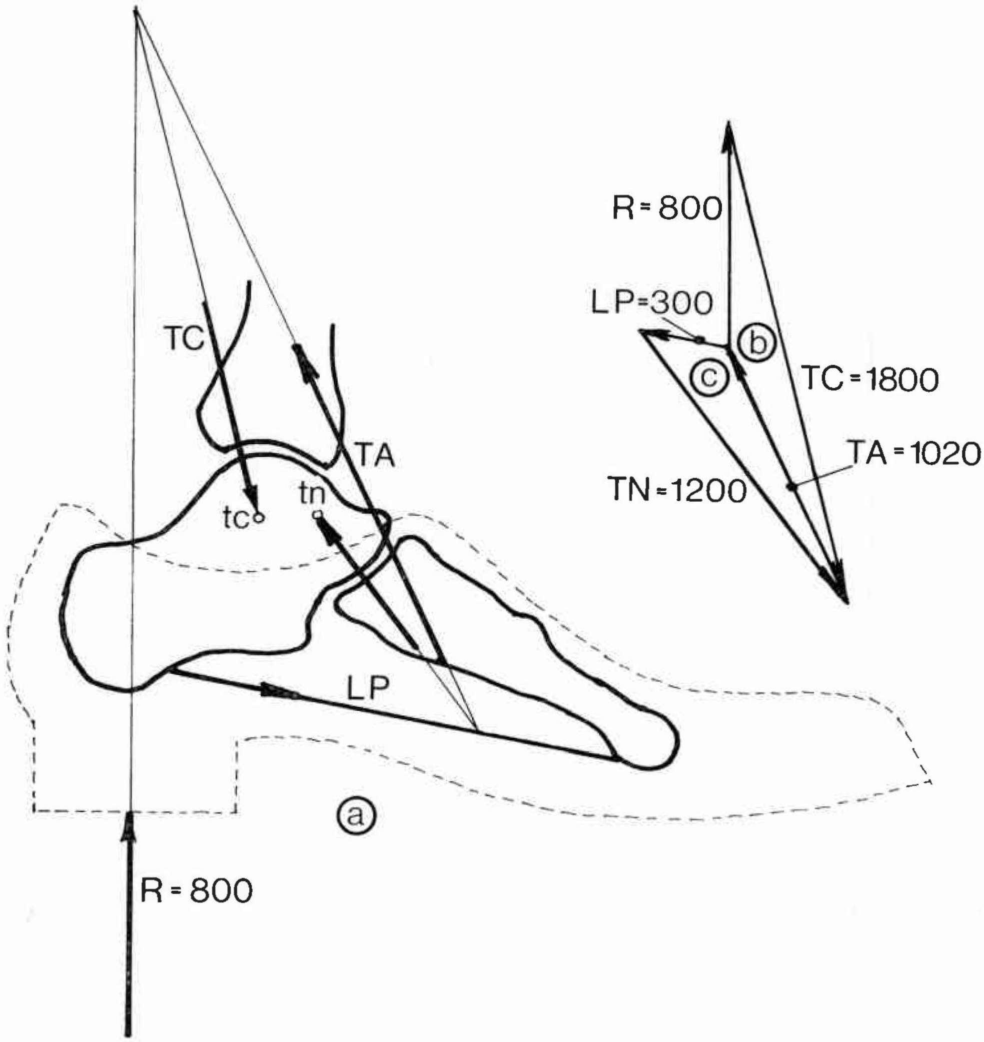

Fig. 6. Hindfoot bearing the total body weight.

upon by three coplanar forces and that the muscle tibialis anterior (TA) is the only dorsiflexor. The equilibrium demands a common intersection point for the three forces. This gives the force diagram in figure 6b. In the same way we can find the intersection point for the three coplanar forces of the forefoot which leads to the force diagram in figure 6c. In figure 6a all the forces are directed as if they are acting on the hindfoot with the exception of TA which is acting on the forefoot.

The foot orthotist is able to moderate the internal loads also in this case. He adjusts the heel giving it a profile (fig. 7d) which moves the reaction force anteriorly, as the R^1 indicates on figure 7, for example by about 5 per cent of the total length of the shoe. The corresponding internal loads are indexed in the same way, for example LP^1 or TN^1. Figure 7b is the force diagram for the foot as one solid free body. (The force diagram in figure 7c shows the loads acting upon the forefront as a free body).

The modern fashion with a heel profile (fig. 7e) can move the reaction force posteriorly counteracting the work of the foot orthotist. Such a reaction force is represented by R^{11} which is displaced posteriorly by about 5 per cent of the total length of the shoe compared with the normal situation (R). The corresponding internal forces are indexed in the same way, for example LP^{11} or TN^{11}.

The internal load distributions for externally loaded hindfoot situations are shown in table II.

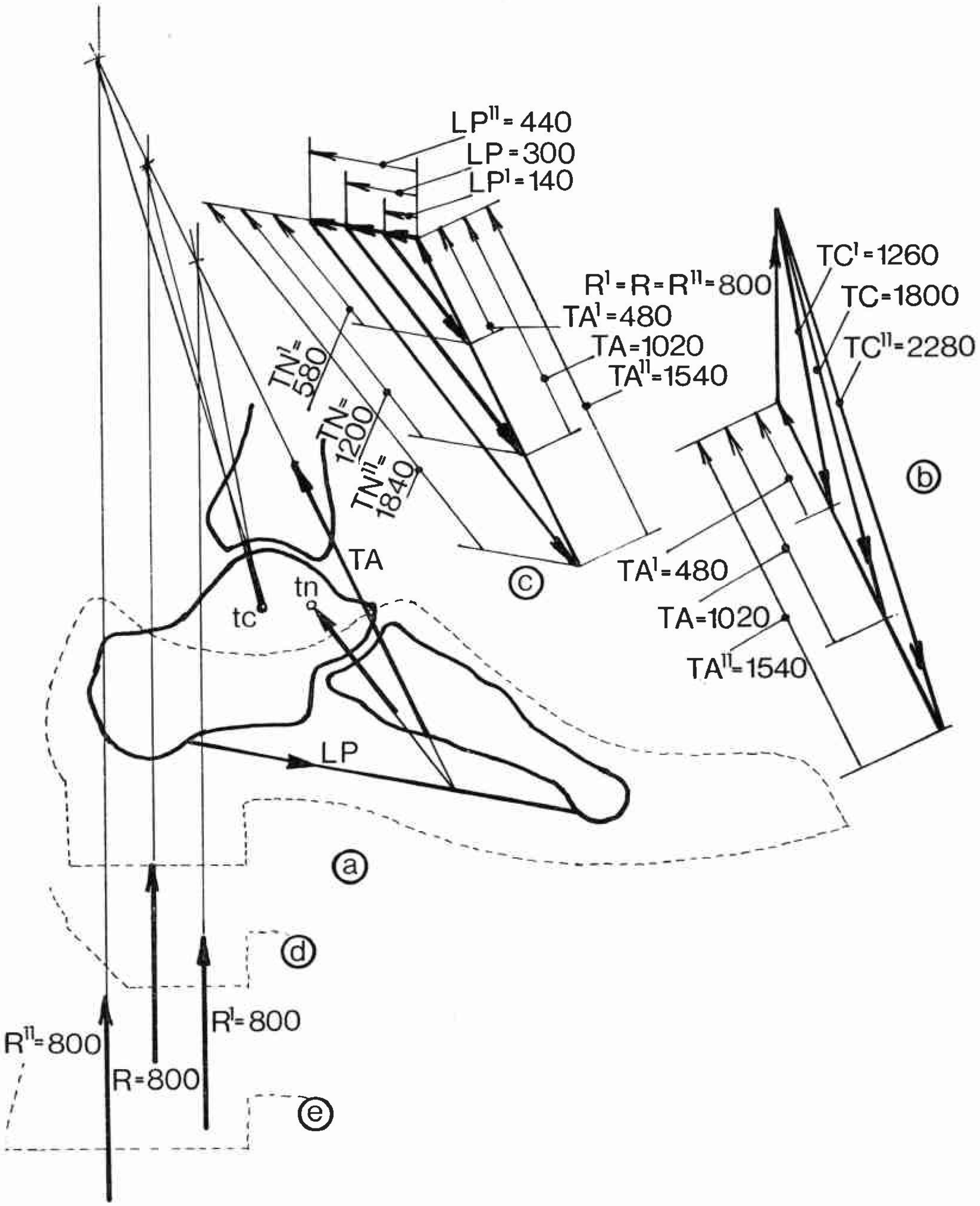

Fig. 7. Influence of the heel profile variation on the internal force distribution when the hindfoot is bearing the total body weight.

	R	TC	LP	TA	TN
Normal heel profile	800	1800	300	1020	1200
Shortened heel profile	800	1260	140	480	580
Extended heel profile	800	2280	440	1540	1840

Table II. Comparison of internal loadings using different heel profiles when externally loading the hindfoot (all values given in Newtons).

The simultaneously externally loaded hindfoot and forefoot

The graphical construction methods applied previously can be useful in analysing the internal load distribution in a situation when the reaction force is acting simultaneously on the forefoot and the hindfoot. Such a case is shown in figure 8 with symmetrically divided equal partial loads (each 400N).

In the first step we determine the loads acting on the foot as a one-piece solid body and we consider the total reaction force $R = R_1 + R_2$ and construct the force diagram in figure 8a. In this

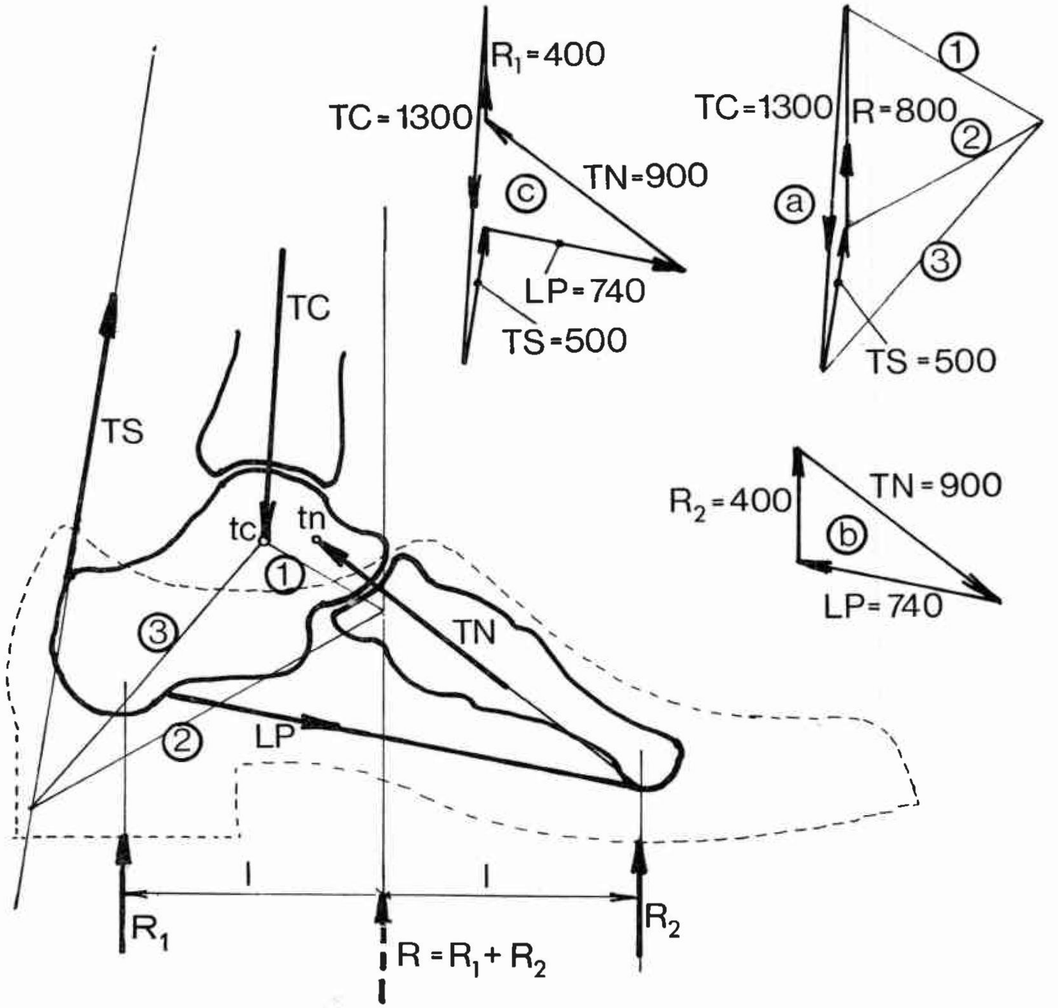

Fig. 8. Symmetrically loaded forefoot and hindfoot.

way we can determine the forces TC and TS. In the next step we can find the loads acting on the forefoot as is done in figure 8b. Figure 8c shows the force diagram of the hindfoot. (The forces on the schematic architecture of the foot are directed as they are acting on the hindfoot).

How a pes planus will behave in this combined externally loaded case is shown in figure 9. The pes planus situation is indicated in the same way as in figure 4. The graphical construction method is similar to the one that is used before. It is worth noticing that the load in the idealized ligament increases in this case by one fourth compared with the normal situation.

The foot orthotist helps the patient by applying an inlay sole and moving the hind partial reaction anteriorly as shown in figure 10, the unchanged total reaction force R will be divided into partial reaction forces in inverse ratio to their distance from R. The construction of force diagrams are similar to the ones we have used before. A significant reduction in the magnitude of the internal load is obtained.

The results of the investigations on the foot

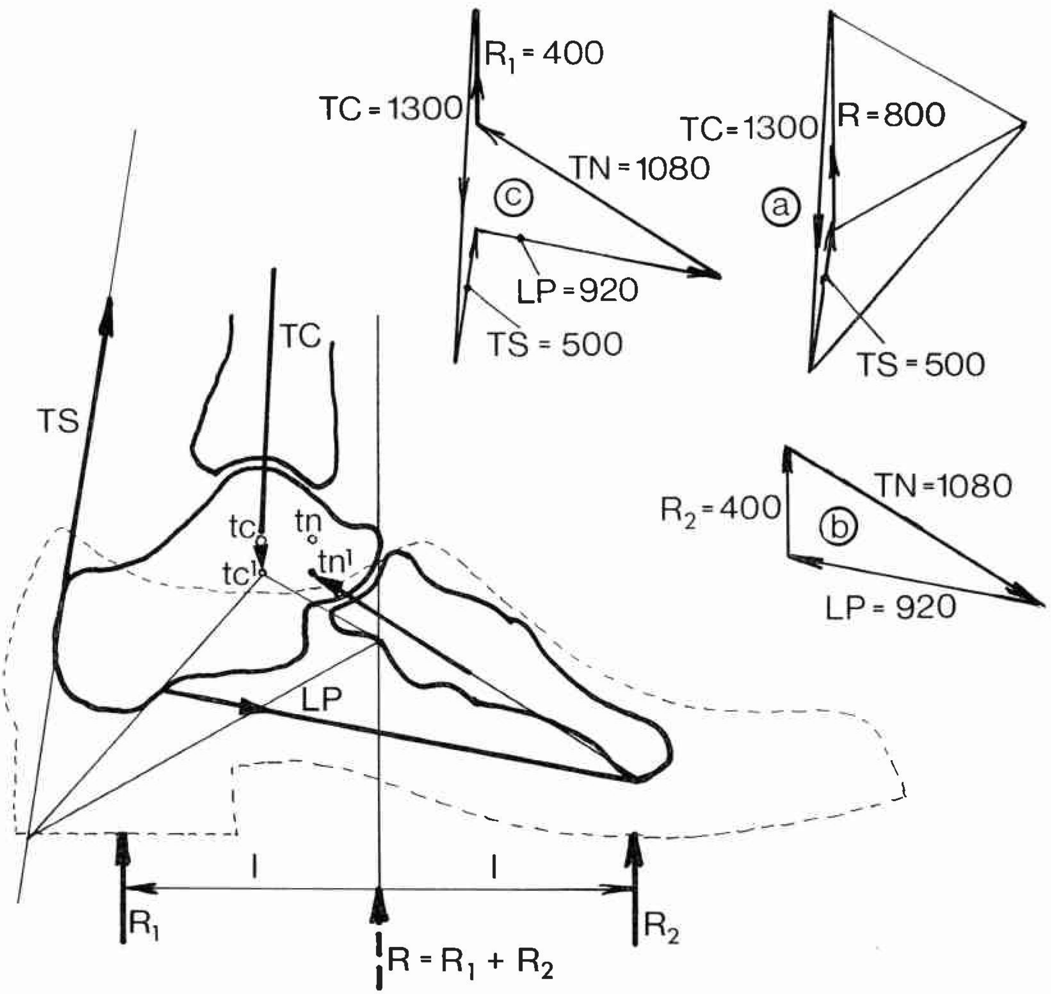

Fig. 9. Influence of pes planus configuration on the internal forces of the symmetrically loaded forefoot and hindfoot.

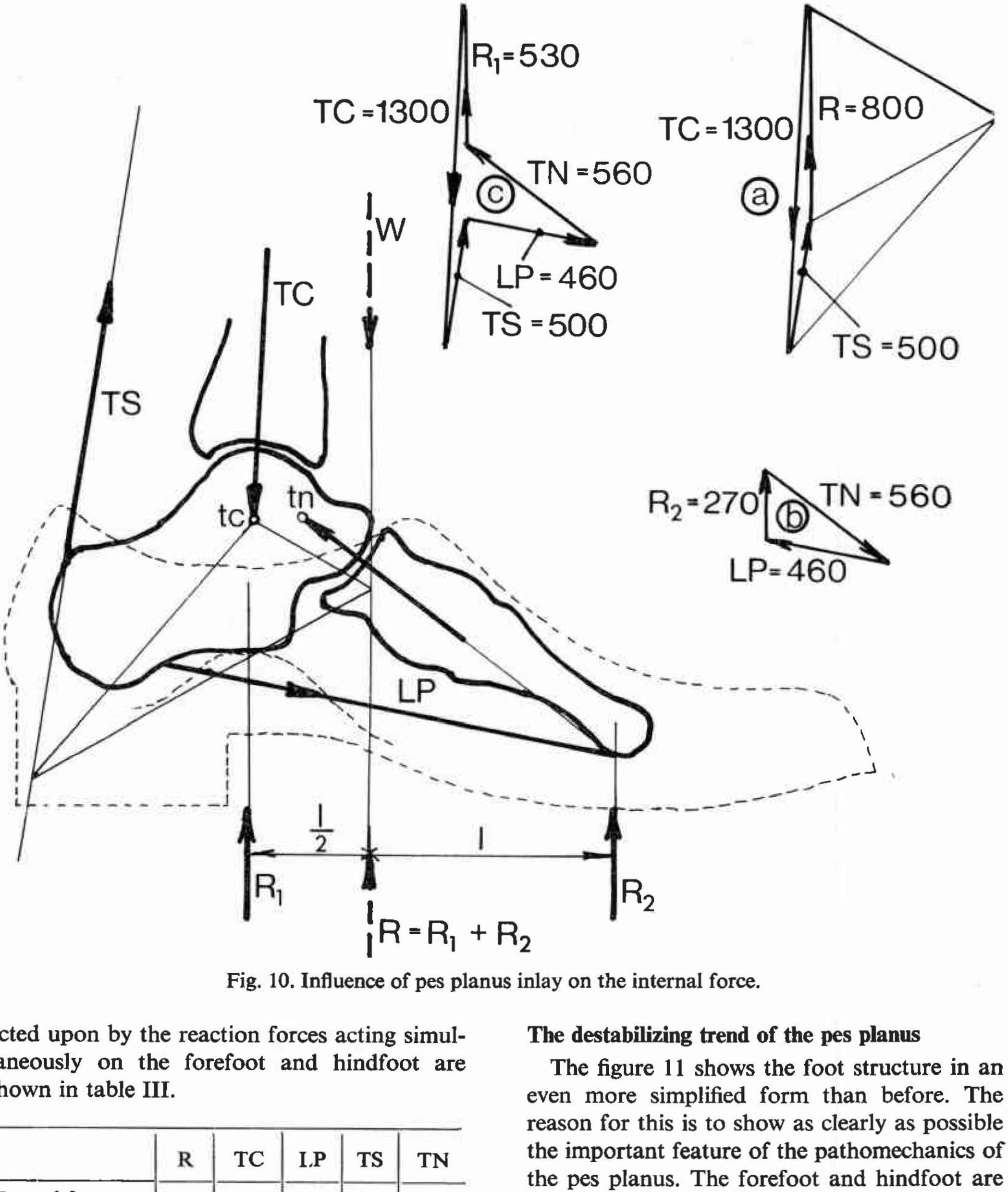

Fig. 10. Influence of pes planus inlay on the internal force.

acted upon by the reaction forces acting simultaneously on the forefoot and hindfoot are shown in table III.

	R	TC	LP	TS	TN
Normal foot without inlay	800	1300	740	500	900
Pes planus without inlay	800	1300	920	500	1080
Pes planus with medial support	800	1300	460	500	560

Table III. Comparison of internal loading in different circumstances as a result of simultaneously loading the forefoot and the hindfoot (all values given in Newtons).

The destabilizing trend of the pes planus

The figure 11 shows the foot structure in an even more simplified form than before. The reason for this is to show as clearly as possible the important feature of the pathomechanics of the pes planus. The forefoot and hindfoot are substituted by solid bars articulating at one idealized ankle joint and held together by the idealized plantar ligament. We assume that only the passive structures are engaged to maintain equilibrium with the external load.

Figure 11e shows the model of the normal foot. The force diagram in figure 11a belongs to the hindfoot and in figure 11b to the forefoot of such a model.

If the plantar passive structure in any way is

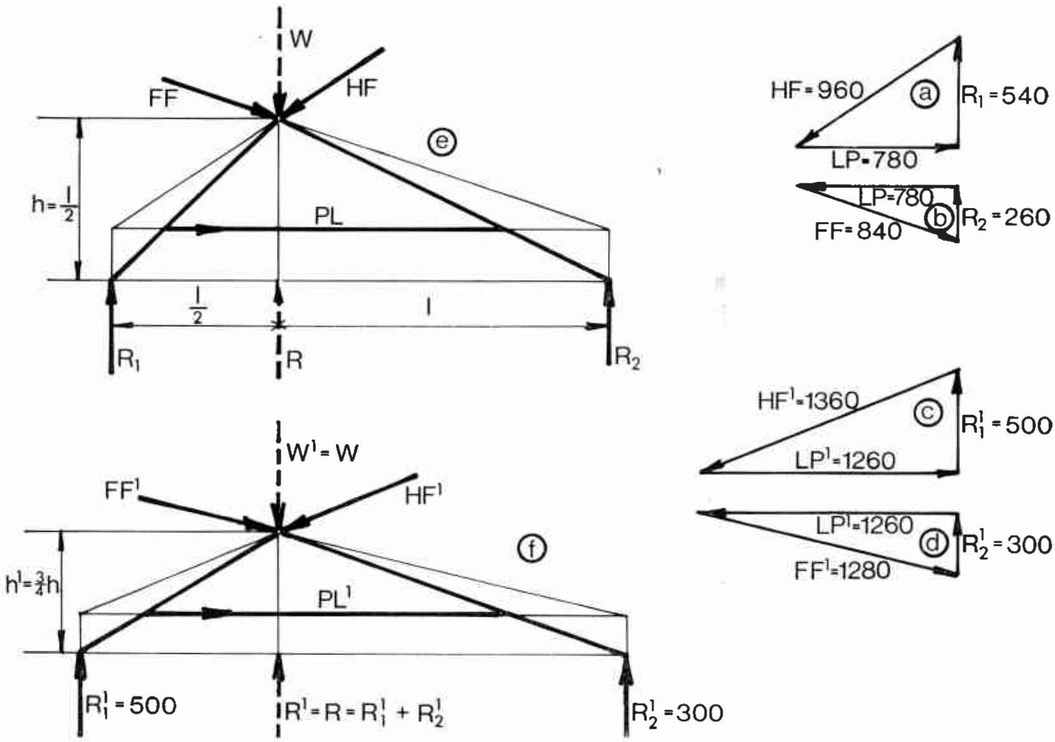

Fig. 11. Diagram showing the destabilizing effect of pes planus.

too weak to resist the load acting on it, the structure will give way and be lengthened. This lengthened passive plantar structure causes a pes planus architecture where the lengths of the solid forefoot and hindfoot are constant, but the height of the ankle joint will fall as shown in figure 11f. The forces acting on the forefoot in this case are shown in figure 11d and on the hindfoot in figure 11c. The load on the plantar passive structure in this case increases by about 60 per cent compared with the normal foot. This means that if the plantar passive structure is unable to resist a normal load it will cause an architectural change which results in an even greater load on the same structure. This is a runaway trend which should be stopped.

In closing it must be remembered that all these analyses are carried out by reducing to the utmost the complex situation to get an easy method which gives the relative magnitude and directions of these loads depending on various situations.