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CHANGE OF FORM OF THE FOOT AND THE FOOT SKELETON UPON MOMENTARY WEIGHT-BEARING

By

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An often discussed question is that which concerns the behaviour of the arch of the foot and of the foot skeleton during weight-bearing of the foot. The answers to this question which can be found in the literature are by no means uniform. Benninghoff states, for example, in his book on anatomy, 1949, that the navicular bone is depressed on weight-bearing of the foot by 6.5 mms, on average. Fick mentions in this respect the figure 8 mms and adds that the bones of the whole foot are depressed but that their mutual positions do not change when the foot bears weight. According to the investigations of H. Virchow¹, the foot arch prolonged 19 mms within the second ray and 8 mms within the fifth ray upon weight-bearing. At the same time the foot becomes broader so that the distance between the bases of the first and fifth metatarsals increases by a mean figure of 8.5 mms. In a radiological study of the foot's change of form over a short and long period of weight-bearing Weitmauer considered that he was able to demonstrate that X-rays taken of a weight-bearing and a non-weight-bearing foot were identical or almost identical. If any difference existed it consisted in a minor elevation of the foot arch when the foot bore weight. At the same time the foot's length became somewhat less. This change in shape was explained by saying that when the foot bore weight the short plantar foot muscles were activated together with the posterior tibialis muscle, the flexor hallucis longus and the peroneus longus. By means of this muscle action the arch of the foot was apparently main-

¹ According to *G. Hohmann*: Fuss und Bein, fünfte ergänzte Auflage. Verlag J. F. Bergmann, München, 1951.

tained and even elevated upon weight-bearing. Electromyographic studies of later years showed however that upon static weight-bearing of the foot, *e.g.*, in an upright symmetrical rest position, none of the foot's muscles were in action. Static weight-bearing of the foot must therefore signify an increased load on the ligamental apparatus of the foot. How the ligamental apparatus behaves upon receiving large, momentary loads has not previously been investigated.

In order to obtain information concerning this and to form an independent view of the change in the normal foot on momentary weight-bearing,—since the literature could not provide satisfactory details of this—a radiological and anthropometric study of a series of clinically normal feet was undertaken. Moreover the Swedish shoe industry had put the question to the authors of this article of whether and how the form of a healthy foot was changed upon momentary weight-bearing, *e.g.*, when trying on shoes. The problem was therefore of both anatomical and practical economic interest.

MATERIAL AND METHOD

Nineteen students of the Royal Gymnastic Central Institute in Stockholm were examined, 10 of these students were male and 9 were girls. Their age varied between 19 and 22 years and their body weights between 50.7 and 96.8 kgs. None of those taking part in the tests had any foot trouble nor had anyone experienced it previously. Clinically and orthopaedically these individuals exhibited certain variations in the shape of the foot but these were of such slight degree that the test group could be regarded as forming a normal series.

X-rays were taken of the left foot as the test individual stood upright on both feet. As underlying support for the left foot a 2 cms thick plate of plastic was employed which was fixed horizontally above a force plate (Figure 1 b) (Carlsöö 1962). Between the plastic plate and the force-plate there was a narrow gap large enough to accommodate an X-ray plate. Two metal wires were inserted into the plastic plate at right angles to each other, the one longitudinally and the other transversely so that their point of intersection lay approximately at the centre point of the plastic plate. The metal wires formed a coordinate system. Three X-ray tubes were firmly directed towards this coordinate system. Longitudinally along one side of the plastic plate and transversely along one short side there were placed two cassette holders for lateral (1 d) respectively axial (1 c) radiographs. In the former cases the rays passed in a latero-medial direction and in the latter case in an anterior-posterior direction. On the film lying beneath the plastic plate frontal pictures were taken. A lead indicator about 2×2 mms in size was fixed to the skin above the tuberosity of the navicular bone. The foot was positioned on the plastic plate in the angle formed by the two upright cassettes and with the heel and the medial aspect of the foot in contact with the cassettes (Figure 1). The longitudinal axis of the foot then lay approximately directly above the longitudinal wire in the

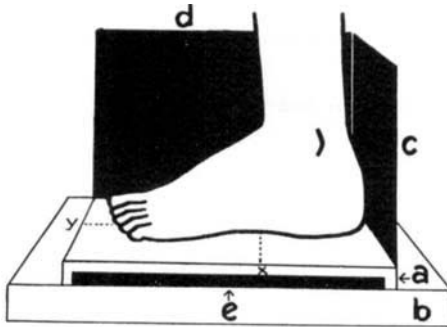


Figure 1. Diagram of foot and position of X-ray plates. a) plastic plate supporting foot, b) force plate, c) d) e) X-ray plates.

plastic plate and the tuberosity of the navicular bone was in the same frontal plane as the transverse wire. The focus-film distance was 100 cms for all three projections. In the lateral projection the central ray passed horizontally and at right angles to the film 6 cms above the supporting surface of the foot and on a plane with the transverse wire in the plastic plate, *i.e.*, through or very close to the lead indicator above the tuberosity of the navicular bone. The central rays of the other two X-ray tubes were ranged on a plane with the longitudinal wire in the plastic plate and thus with the longitudinal axis of the foot. Both tubes were placed in front of the test individual. The focus on the X-ray tube with which the axial picture was taken lay 7 cms higher than the intersection point between central ray and film. It was calculated that the ray would pass through the talo-crural joint and thus form an angle of approx. 4° with the horizontal plane through the joint. The axial pictures were not however utilised in drawing up the results given below. The central ray of the frontal picture passed a point on the longitudinal wire in the plastic 9 cms before the point of intersection between the two wires and making a forward, open angle with the horizontal plane of 85° .

As a support for the right foot a wooden bench was placed about 30 cms from the force plate and level with the plastic plate on the force plate.

That part of the weight of the body which was borne by the left foot and thus by the force plate was recorded on a Honeywell Viscicorder. In quick succession three pictures were taken, one by each of the X-ray machines, when the test individuals stood in the following three positions, a total therefore of nine pictures. The first three pictures were taken in a *symmetrical* standing rest position with the body weight evenly distributed over the right and left foot. With this foot position maintained, almost the whole of the body weight was then transferred to the right foot by means of a careful inclination of the body to the right. This position is called below asymmetrical rest position A and the left foot is regarded as *unloaded*. Afterwards body weight is transferred in a similar way to the left foot and this position is called asymmetrical rest position B and the left foot is designated *max. loaded*.

In order to obtain a preliminary understanding of the changes in position of the bones of the foot with the various loads the X-rays were examined in a stereocomparator. Two pictures were placed in this apparatus, the one picture of an unloaded foot and the other of the same foot *max.loaded* or *symmetrically loaded*. Even if the identification of various skeletal points is not completely exact this procedure

is nevertheless far superior to a two dimensional reading (*Hallert 1953*). The points and contours which were utilised as measuring points are shown in Table 1.

Table 1. Measuring points on radiographs of the foot and the distal end of the leg.

Lateral pictures

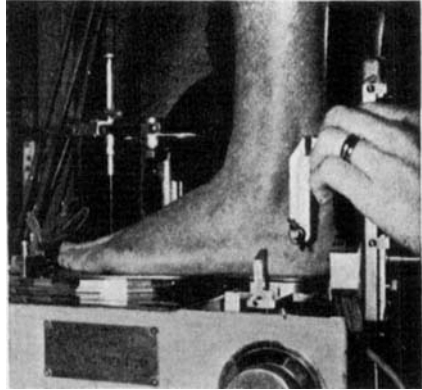
- 1 Furthest anterior point of tibia.
- 2 Furthest posterior point of tibia.
3. The most proximal point of the trochlea of the talus.
- 4 Proximal-anterior tip of the head of the talus.
- 5 Furthest anterior point of the head of the talus.
- 6 Distal tip of fibula.
- 7 Furthest posterior point of calcaneus.
- 8 Furthest plantar point of calcaneus.
- 9 Furthest anterior point of calcaneus.
- 10 Proximal-dorsal point of navicular bone.
- 11 The dorsal-proximal tip in the joint-cavity in the carpo-metacarpal joints.
- 12 The dorsal-distal tip in the joint-cavity in the carpo-metacarpal joints.
- 13 Furthest distal point of the cuboid.
- 14 Furthest plantar point of the base of the 5th metatarsal bone.
- 15 Furthest plantar point of the head of the 5th metatarsal bone.
- 16 Furthest dorsal point of the head of the 1st metatarsal bone.
- 17 Furthest anterior point of the head of the 1st metatarsal bone.
- 18 Furthest plantar point of the head of the 1st metatarsal bone.

Frontal pictures

- 1 Furthest medial point of the head of the 1st metatarsal bone.
- 2 Furthest medial point of the head of the 2nd metatarsal bone.
- 3 Furthest medial point of the head of the 3rd metatarsal bone.
- 4 Furthest medial point of the head of the 4th metatarsal bone.
- 5 Furthest medial point of the head of the 5th metatarsal bone.
- 6 Furthest lateral point of the base of the 1st metatarsal bone.
- 7 Furthest lateral point of the base of the 2nd metatarsal bone.
- 8 Furthest lateral point of the base of the 3rd metatarsal bone.
- 9 Furthest lateral point of the base of the 4th metatarsal bone.
- 10 Furthest lateral point of the base of the 5th metatarsal bone.
- 11 Furthest medial point of the cuneiform bone.
- 12 Furthest medial point of the navicular bone.
- 13 Furthest lateral point of the cuboid.
- 14 Furthest distal point of the head of the talus.
- 15 Furthest distal point of the calcaneus.

The measurements in the stereocomparator showed that the changes in position of the measuring points in the lateral pictures were considerable. Differences of up to 5 mm often occurred. On the other hand the differences in the frontal pictures were small. These conditions show that, as was expected, the changes of position occur principally in a craniocaudal direction. A completely satisfactory measurement

Figure 2. Foot measuring instrument by Haraldson with force plates mounted, type Wetzenstein



of the size of these craniocaudal displacements as well as sagittal displacements cannot be carried out however. Certain rotatory movements may arise in weight-bearing of the foot which make difficult and indeed impossible an identification of the measuring points which is free from objection. Nevertheless a precisely executed measurement of the lateral pictures can produce values which are sufficiently reliable to be used as a basis for an evaluation of the change in form of the foot skeleton in those individuals examined who were given the varying loads.

In measurements of radiographs taken on two different occasions, in one case on three different occasions and in one case on five different occasions—the values were almost identical. No variations in the readings occurred of such magnitude that they could affect the conclusions to be drawn from the investigation, if the distal tip of the fibula is excepted, *i.e.*, point 6 on the lateral pictures. These variations are due to changes in the position of the ankle joint.

In the measurements of the lateral pictures an orthogonal coordinatograph was used of the type Simonson and Klintmalm. The coordinate system was placed over the radiograph so that its *y*-axis passed through the dorsal top of the lead indicator above the tuberosity of the navicular bone and its *x*-axis coincided with the weight-bearing plan of the foot (more precisely, the longitudinal wire inserted into the plastic plate).

The external shape of the foot and the contour changes were measured by Haraldson's foot measuring instrument (SFI publication, 1954) under the same weight-bearing conditions as in the radiological studies, *i.e.*, with a symmetrical and maximally loaded foot and also with an unloaded foot. Two force-plates were used to record the foot loading, one for the heel and one for the fore-foot, (Figure 2), (Wetzenstein 1964, Carlsöö 1964). In this way it could be checked that the percentage distribution of weight on the heel and fore-foot remained unchanged when the total loading was changed. Of the measurements taken with Haraldson's measuring instrument, foot length, ball breadth and the circumference of the ball were utilised. By ball breadth is meant the external distance between the medial border of the head of the 1st metatarsal bone and the lateral border of the head of the 5th metatarsal bone. The circumference of the ball was measured level with these two measuring points. The accuracy of the method was tested by two investigators with four double measurements. The difference was never more than 1 mm.

so insignificant—a mean of 0.15 mms—that one cannot speak of any true changes in the form of the foot skeleton during weight-bearing of the foot.

The anthropometric measurements showed no significant difference in either foot length or ball breadth in differing loadings of the foot. The average difference did not extend to 1 mm. On the other hand there was a systematic difference in the circumference of the ball upon various loads with an average difference of + 4.9 mms between unloaded and maximally loaded foot, and + 2.5 mms between unloaded and symmetrically loaded foot. Foot length and ball breadth are principally skeletal measurements while the circumference of the ball is a soft tissue measurement. These anthropometric measurements coincide fully with the radiological, *i.e.*, the foot skeleton does not undergo any demonstrable changes in position in the sagittal and transverse direction when the foot bears weight. The increase in width within the region of the ball of the foot, *i.e.*, within the region of the metatarsal heads, which arises on weight-bearing of the foot, seems therefore to be a soft tissue change. When the foot bears weight, the subcutaneous tissue is pressed together and displacements in a medial and lateral direction occur and produce stretching of the tissues so that measurable increases in volume arise.

Since the muscles of the foot do not seem to be in action on static weight-bearing in a symmetrical standing rest position (*Basmaijan & Bentzon* 1954, and others), then this must mean that the ligamental mechanism and plantar aponeurosis play a decisive role in the stability of the foot skeleton even if the passive resistance of the muscles to stretching and the internal positional relationships of the skeletal parts may contribute to stability. The fact that the foot skeleton is considerably more depressed in passing from unloaded to symmetrically loaded foot than from symmetrically loaded to maximally loaded foot is in full accordance with the rheological qualities of the connective tissue, even though the increase in load is the same on the whole in both cases. Thus studies of stress-strain behaviour in specimens of ligament, tendon and other connective tissue structures show that the degree of stretching is not proportional to the load but decreases considerably with increased load. Therefore the passive forces in the material studied can fix the different joints of the foot so powerfully that when the foot bears weight, no true depression of the foot's longitudinal arch takes place.

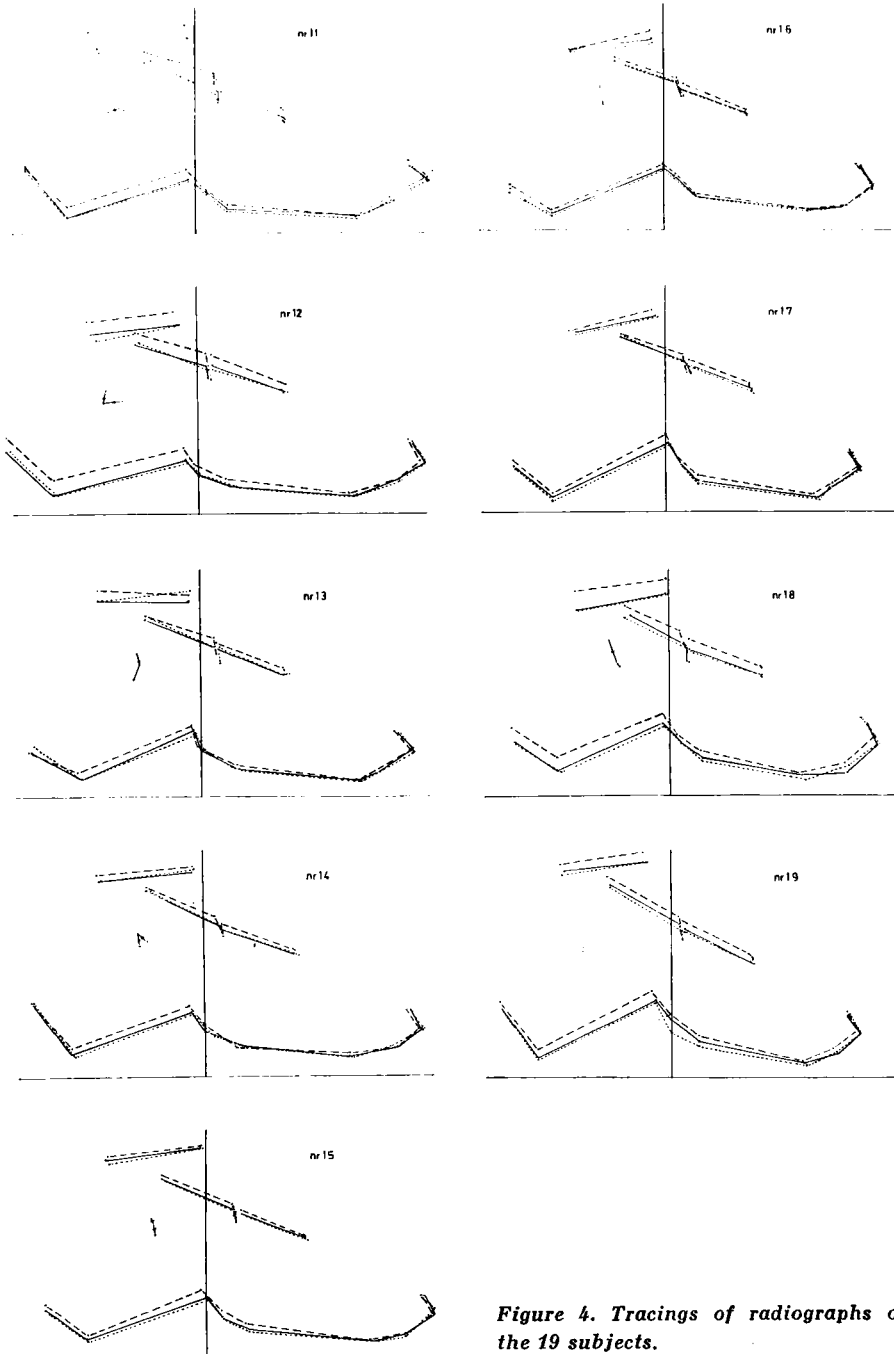
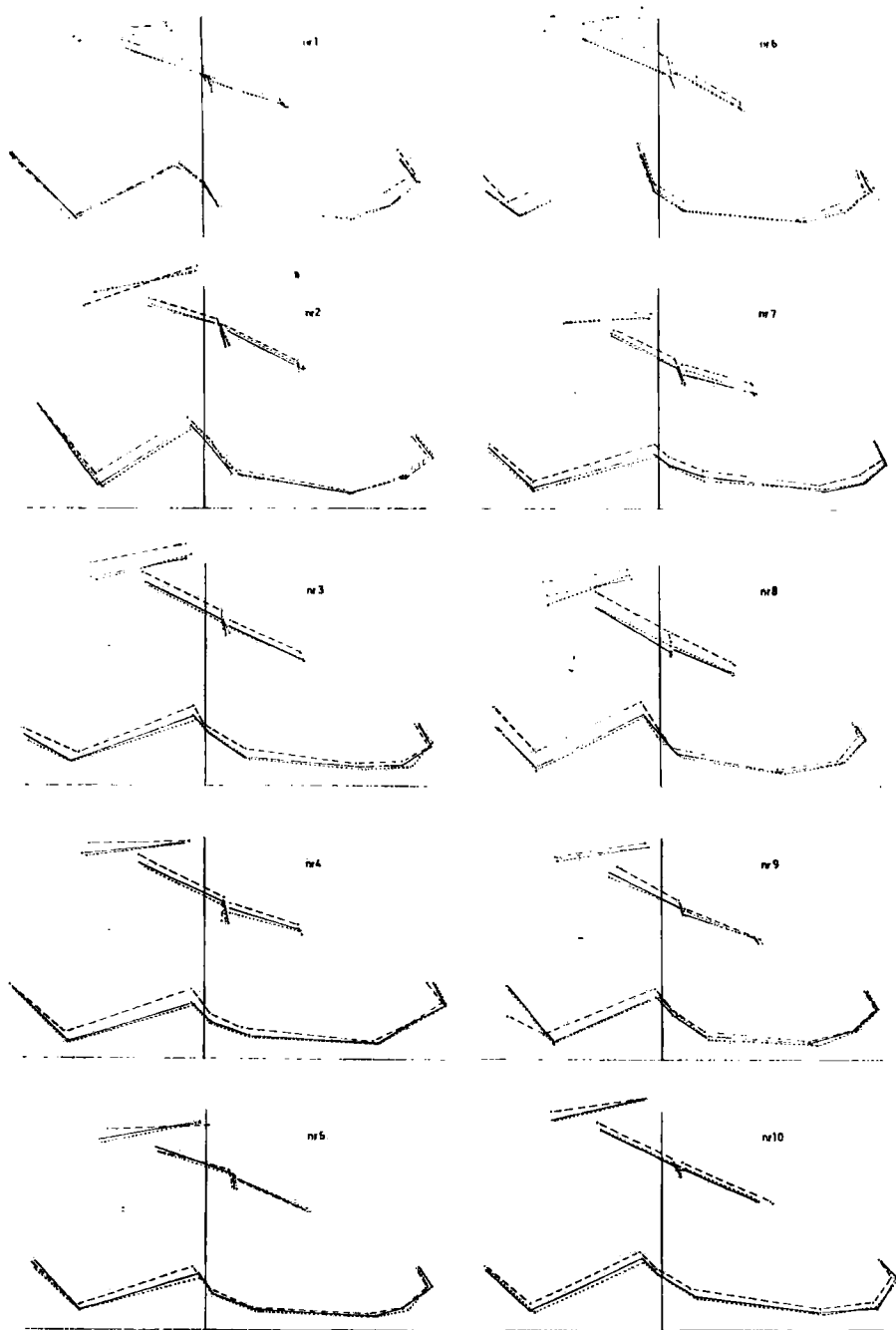


Figure 4. Tracings of radiographs of the 19 subjects.



SUMMARY

A radiological and anthropometric investigation into changes of form of the foot and the foot skeleton on weight-bearing was carried out on 19 students. Clinically and orthopedically the series is considered to be normal series. No changes in the form of the foot skeleton could be demonstrated. The external changes in form of the foot which arise when the foot bears weight are due to alterations and displacements of soft tissues. The active and passive supporting mechanism of the foot is discussed.

RESUME

Un examen radiologique et anthropométrique du pied et des modifications du squelette du pied dans des épreuves de charge a été effectué chez 19 étudiants. Au point de vue orthopédique clinique, les sujets doivent être considérés comme un matériel normal. Il n'a pas été possible de constater une déformation du squelette du pied. Le changement extérieur de la forme du pied qui apparaît sous la charge est dû à une déformation et à un déplacement des tissus mous. Il est discuté de l'appareil de choc actif et passif du pied.

ZUSAMMENFASSUNG

Eine röntgenologische und antropometrische Untersuchung der Formveränderung des Fusses und Fusskelettes bei Belastung des Fusses wurde an 19 Studenten vorgenommen. Klinisch orthopedisch ist das Material als ein Normalmaterial anzusehen. Irgendwelche Veränderungen des Fusskelettes konnte man nicht nachweisen. Die beobachteten äusseren Formveränderungen des Fusses bei der Belastung beruhen auf Deformierung und Verschiebung der Weichteile. Die aktiven und passiven Stützapparate des Fusses werden besprochen.

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REFERENCES

- Basmajian, J. V. & Bentzon, J. W. (1954) An electromyographic study of certain muscles of the leg and foot in the standing position. *Surg. Gynec. & Obst.* **98**, 662-666.

- Benninghoff, A. (1949) Lehrbuch der Anatomie des Menschen. Vierte Auflage. Urban und Schwarzenberg, Berlin-München.
- Carlsöö, S. (1962) A method for studying walking on different surfaces. *Ergonomics*, Vol. 5, No. 1.
- Carlsöö, S. (1964) Influence of frontal and dorsal loads on muscle activity and on the weight distribution in the feet. *Acta orthop. scand.* 34, 299-309.
- Hallert, B. (1953) Fotogrammetri, P. A. Norstedt och Söners Förlag, Stockholm.
- Hohmann, G. (1961) Fuss und Bein. Fünfte ergänzte Auflage. Verlag von J. F. Bergman.
- SFI publikation (Åke Norlander) (1954) Foten, lästen och skon. Emil Kihlström AB, Stockholm.
- Weitnauer, H. (1954-55) Formveränderungen des Fusses bei Ermüdung. (Zugleich ein Beitrag zur operativen Behandlung des Knickfusses). *Zschrift Orthopädie* 85, 119-127.
- Wetzenstein, H. (1964) Eine Untersuchung der Fersenbelastung beim Gehen. Eine Methode für die Messung der Fersenbelastung in Schuh. *Acta orthop. scand.* Suppl. 75.