Dynamic Structure of the Human Foot

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THE FOOT is one of the most dynamic structures in the human body. The lively interplay of forces which makes its function possible is easily forgotten and it is too often treated like the graven image of a static structure. The success of modern therapeutic measures in solving other problems has owed much to close cooperation between Nature working from within and assistive devices from without. The forces within the foot can be powerful allies in such a partnership.

The human foot acts in concert with the rest of the body during standing and movement. It provides man with his most effective physical contact with the environment and is especially responsible for successful regulation of initial and final contact of the body with the ground. The foot must also provide adjustable support during the characteristic human occupations of manipulating the environment or of simply standing in line.

Human bipedality was made possible by the redesign of an ancestral foot with five long toes used for the grasping of the limbs of trees. We still testify to our heritage by having a big toe larger than the rest but no longer opposable. The heel bone was brought down into contact with the ground to provide additional area of support. Each of these changes traded an old advantage for a new one and the barter is still going on.

THE FOOT IN MOTION

Walking is more characteristic of human movement than running, since man has substituted cunning in the management of external devices for fast movement of body parts when speed is desired. The foot must constantly adjust to the varying loads imposed upon it. Particularly important are the stresses it must withstand at the initiation of contact with the ground and again at its termination.

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INITIATION OF CONTACT

The heel is the first part of the foot to touch the ground in walking. It is consequently entrusted with the delicate mission of gradually bringing the foot to rest on the ground. In running this can be done without the help of the heel since the limb is already in the midst of its backward swing with respect to the body and the ball of the foot can touch the ground at zero velocity.

In walking, the advanced leg has barely started its backward swing with respect to the body when the heel touches the ground. The initial velocity of the ankle after contact is only slightly less than that of the hip joint, making heel-roll imperative. As the ankle approaches zero velocity at ball contact, the forward velocity of the hip joint is preserved by ankle and knee flexion (Fig. 1). Failure to do this properly is one of the most common deficiencies of assistive devices.

The normal human heel is specialized for the part it plays in walking. Resilience is supplied by the construction of the connective tissue under the heel. The collagenous fibers are arranged so as to produce cylindrical compartments filled by more fluid tissues. Since the fluid changes volume only slightly in compression, pressure is accommodated by elastic deformation of the surrounding connective tissue. While

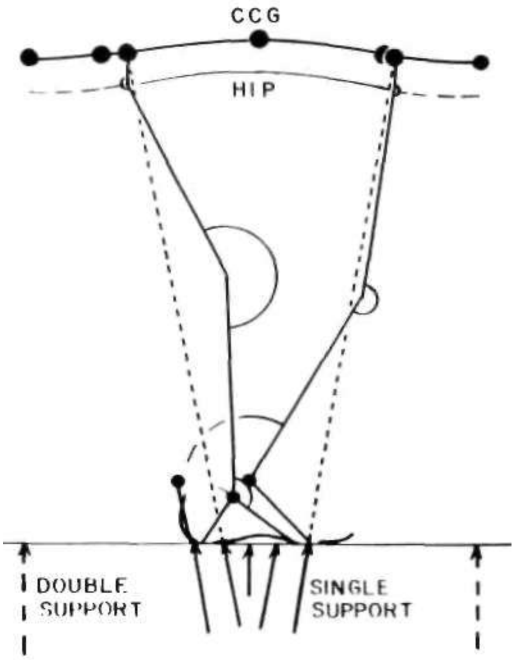

Fig. 1. Forces acting on the foot during two important phases of its activity: (1) completion of heel roll; (2) initiation of rolling off on the hall. *From Elftman, 1967.*

this elastic deformation is taking place the foot rolls forward on the heel. The character of this movement is determined by the contour of the calcaneous combined with the shape which the heel-pad assumes under pressure. Artificial heels can be of assistance if properly shaped, usually achieved when wear erases original design.

TERMINATION OF CONTACT

Although the foot moves only slightly in the interval between ball contact and heel rise, it is subjected to constantly changing stresses. As the body moves forward over the ankle until the knee becomes almost straight, tension is built up in the calf muscles in preparation for the critical events which terminate ball and toe contact. In this phase of walking the transformation of the ape foot into a human foot shows its functional worth. With grasping no longer the chief function of the toes, they have been shortened and the connective tissue pad beneath the ball has become stronger. The great toe has lost its opposability and is permanently aligned parallel to the others. This relieves the peroneus longus muscle of its ancestral responsibility of adducting the hallux and enhances the aid which it gives to the tibialis posterior in resisting splaying of the foot. The first metatarsal and its attendant phalanges retain the size which they had attained in the ape. This led to the accentuated use of this toe during push-off and the important role which the flexor hallucis longus plays in terminal contact with the ground.

Rolling over the ball of the foot has a function similar to that of the heel but acting in reverse. It must control the gradual acceleration of the ankle so that the lower limb as a whole is moving forward with body speed close to the time at which the advanced heel makes contact and double support begins. Here again knee flexion adjusts the relative velocities of the limb segments and allows the calf muscles to push off the limb as it begins its forward swing.

CONTROL OF FOOT POSITION BY HIP AND KNEE

Primary control of foot position is exercised at the hip joint with assistance from the knee when it is flexed. After the primary position of the foot is determined by these distant factors, fine control is added by joints of ankle and foot. The forces and moments which act on the foot are largely determined by the disposition and accelerations of other parts of the body. The importance of knee and hip joints in controlling the spatial relationships of the foot is emphasized frequently by unwelcome responses in these joints to abnormal stresses in the foot.

FUNDAMENTAL ARCHITECTURE OF THE FOOT

The foot consists of 26 bones controlled by 42 muscles and is held together by an almost unbelievable number of ligaments. Fortunately, in the normal performance of its major functions, many of these parts co-operate so closely that an initial workable concept of the foot can be based on very few units. The talus is the uppermost of these. When it is removed, the subtalar part of the foot reveals two major divisions: the calcaneus and, articulating with it by the calcaneocuboid joint, a semirigid constellation of bones terminating in the ball of the foot. This leaves the toes jutting out, to become of importance in activities which require forward extension of the base of support beyond the ball.

THE ANKLE-JOINT COMPLEX

The talus is a bony meniscus which allows the movements of the foot with respect to the shank to be divided between a pair of articulations: the subtalar below and the ankle joint above. Since the same external forces act on both joints, the normal body is interested in their combined movement but the clinician is frequently faced with the results of differential insult.

In the ankle joint, normal pressure is transmitted from the tibia to the trochlear surface of the talus and lateral bending moments are resisted, within limits, by the malleoli and ligaments. When the joint is compressed, as in weight bearing, the instant axis is determined by the curvatures of the surfaces in contact at the moment. The classical concept of an invariant axis passing horizontally through the lateral malleolus to emerge just below the medial malleolus has been revised in recent years. Barnett and Napier (1952) have described the difference in curvature between the parts of the talus used as movement progresses. Close and Inman (1952) have emphasized a component of vertical rotation conforming to the curved lateral surface of the talus. Both of these factors are sufficiently variable to require assessment in each individual.

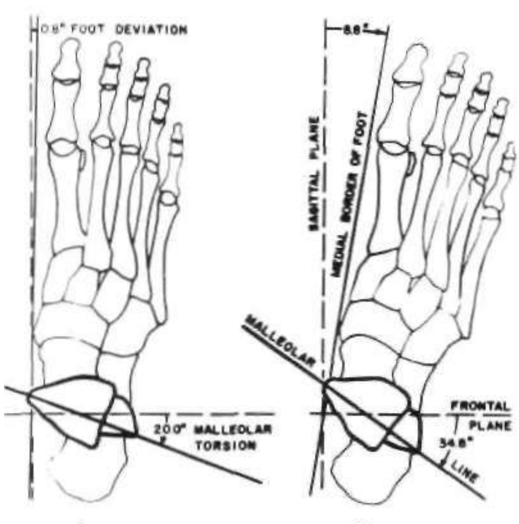

Fig. 2. Range of variation in the orientation of the axis of the ankle joint. Two-thirds of the individuals measured were within the limits shown here. *From Elftman, 1945.*

Even more variable is the orientation of the axis of the ankle joint with respect to the foot and to the transverse axis of the knee. The situation in any individual can be estimated by observing the position of the malleoli; the results of such measurements recorded by Elftman (1945) are shown in Figure 2. It is obvious that the orientation of the ankle joint determines the plane in which dorsi- and plantar flexion occur and this influences the amount of movement required in the subtalar joint.

The subtalar joint is guided in its movement, when it is under compression, by the areas of contact between the calcaneus and the lower surface of the talus. These surfaces are beautifully sculptured to form parts of a helical or screw-shaped surface. The helix is right-handed in the right foot; the resulting advance of the talus during eversion is important for the control of the transverse tarsal joint, but may be neglected during consideration of the ankle. For this purpose the major axis of the helix, also called the compromise axis, suffices. Its position in one foot is shown in Figure 3. This axis emerges from the talus so as to pierce the tendon of the tibialis anterior; its other end is variably located on the lateral surface of the calcaneus. The movements about this axis are called inversion and eversion.

The obliquity of this axis confers on the subtalar joint its most significant proper-

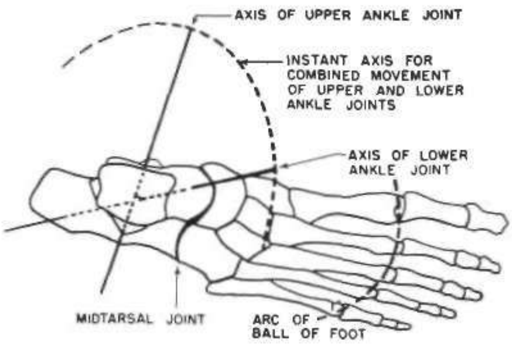

Fig. 3. The instant axis for the combined movement in the upper ankle joint and the subtalar joint lies in the thin disc represented by the dashed circle. Attention is also called to another variable functional feature, the arc of the ball of the foot. *From Elftman, 1954.*

ties. Indispensable for our ancestors in tree climbing, it is still our chief accommodation to rough terrain. Its large component of vertical rotation gives us the possibility of transverse rotation at the ankle under gravitational control.

Since the ankle joint and the subtalar joint are not subject to independent regulation, the resultant movement when the two are combined is of greater practical value than the separate components. The location of this resultant axis is indicated in Figure 3. If the two joint axes actually intersected, the resultant would lie in the plane determined by the two axes. Since they almost intersect, but not quite, the resultant is confined within a thin disc which may be treated as a plane for practical purposes. Once this plane is determined, the problem of substituting new artificial axes for the old ones is simplified.

Movement in the ankle-joint complex is controlled by: (1) moments due to the ground reaction; (2) constraints due to joint surfaces and ligaments; and (3) moments produced by the leg muscles which pass over the ankle. The part played by the ankle muscles can be studied quantitatively from the data shown in Figure 4. This is essentially an oblique section through the ankle oriented so as to include the axes of the ankle joint and the subtalar joint. The lever arms of the muscles with respect to these axes can be read from the diagram; the relative maximum strengths of the muscles are proportional to the areas of the circles which represent them. The resultant moment of various muscle combinations can then be found. Important points to note are: (1) the tibialis anterior is a dorsiflexor and not an invertor in this position; (2) the gastrocnemius and soleus are strong invertors as well as plantar flexors; (3) the peroneal muscles are stronger for eversion than for plantar flexion.

TRANSVERSE TARSAL JOINT

The part of the foot which lies immediately in front of the talus and calcaneus forms a semirigid unit articulating with the rear part of the foot by means of two joints, the calcaneocuboid and the talonavicular. Since they act together much of the time, it is convenient to call the combination the transverse tarsal joint.

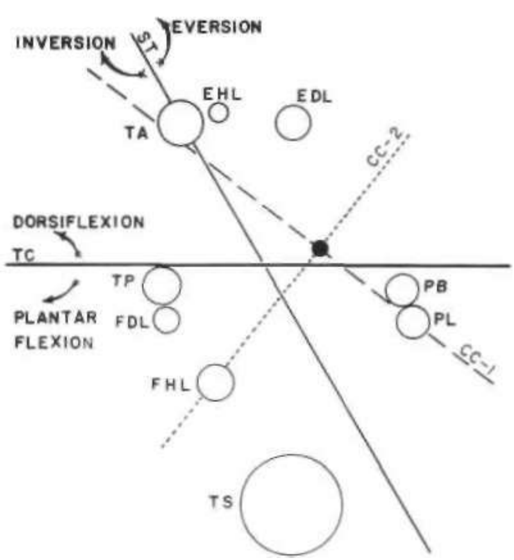

Fig. 4. Muscular control of the ankle. The figure is essentially a section through the right ankle in the plane of the disc shown in Figure 3 and includes the ankle-joint axis *(TC)* and subtalar axis *(ST).* The circles representing the muscles are proportional in area to the physiologic cross sections. The muscles may be identified by their initials, *e.g.,* triceps surae *(TS). From Elftman, 1960.*

The calcaneocuboid joint was described as a saddle-shaped joint by Adolf Fick in 1854; only one other joint of this type is present in man, at the base of the first metacarpal. More than a century elapsed before an adequate description of this joint was provided by Elftman in 1960. For practical purposes a simplified description will suffice. The principal axis (labeled CC in Fig. 5) passes obliquely through the calcaneus in such a fashion that an extension of it would almost intersect the subtalar axis in the neck of the talus. Associated with the major movement of rotation about this axis is a slight translation parallel to the axis. The total movement is known as supination and pronation. The man in the street calls these raising and lowering of the arch.

The talonavicular joint is the controlling element in the transverse tarsal joint complex. The head of the talus is a cam of ellipsoidal shape which is not concentric about the subtalar axis but makes a considerable angle with respect to it. As a consequence of this, rotation of the head of the talus during rotation about the subtalar axis changes its orientation, and movement in the transverse tarsal joint ensues to bring the navicular concavity to a conformable position. The important thing to remember is that inversion produces supination and eversion causes pronation. At the extremes of this range of association, the transverse tarsal joint becomes independent of the subtalar in extremely pronated (flat) feet and the subtalar motion can occur alone at extreme supination.

BALL OF THE FOOT

The structures which allow the heads of the metatarsals to transmit pressure to the ground consist of connective tissue and skin which have been modified in the human foot to spread the pressure in the hope of preventing painful concentrations. When weight is not borne by this region, a transverse metatarsal arch is visible. Even slight pressure is sufficient to bring the heads of the metatarsals in alignment with the ground and the arch disappears. The extreme variability in the lengths of the metatarsals has important consequences for foot action. The distribution of pressure as the heel is raised is very closely dependent on the contour of a line connecting the metatarsal heads, as shown in Figure 3. Morton (1935) has stressed the difficulties resulting from first metatarsals

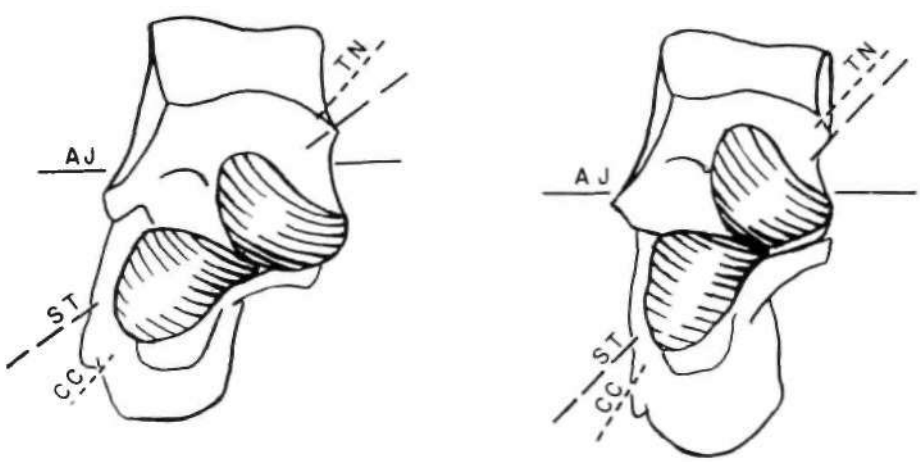

Fig. 5. Transverse tarsal joint, pronated at left, supinated at right. The joint axes are labeled as follows: *AJ,* ankle joint; *ST,* subtalar; *CC,* calcaneocuboid; *TN,* talonavicular. When the heel is placed on the ground in the supinated position, inversion in the subtalar joint restores the vertical orientation of the shank and rotates the head of the talus so as to lock the transverse tarsal joint.

which are short or have posteriorly located sesamoids. Equally disastrous effects can come from contours which are sharply curved or hairpin in shape.

Among a number of variable features in this part of the foot is the extent to which the base of the fifth metatarsal transmits weight to the ground. Another condition, splaying of the foot, can result when the cooperative efforts of the tibialis posterior and the peroneus longus are insufficient to give transverse stability.

TOES

Although human toes can be used for grasping when occasion demands, their customary use is accessory to the ball of the foot which lies behind them. The toes are the anchors for the long flexors which play an important part in managing the ankle-joint complex. By differential contraction of the flexors of the toes it is possible to adjust the distribution of pressure between parts of the ball of the foot. Because of the strength of the big toe and the long flexor attached to it, this part of the foot is usually the last to leave the ground and contributes the final touch to the control of movement.

CONTROL OF THE FOOT BY THE HEEL

When the body rolls forward on the heel until the foot rests on the ground, the position which the foot assumes is determined by the manner in which the calcaneous rolls forward. Proper contouring of the sole of the shoe where the heel nests in it will not only provide assistive forces but will also originate sensory feedback to stimulate better foot alignment.

If the heel cup is so constructed that its anteromedial quadrant is elevated, the calcaneus will come to rest with a predetermined amount of inversion about the subtalar axis. This places the contact area of the calcaneus more nearly under the vertical thrust of the body, decreasing its rotational moment. Since the ankle-joint axis strives for a horizontal position, the talus is forced into inversion and this drives the transverse tarsal joint into supination. Sensory feedback, in the course of a few steps, will encourage the hip joint to bring the foot down in a slightly toed-in position, thus restoring the knee joint to its usual orientation.

The details of the sculpturing of the heel cup need not be left to chance since the desired conformation of the internal

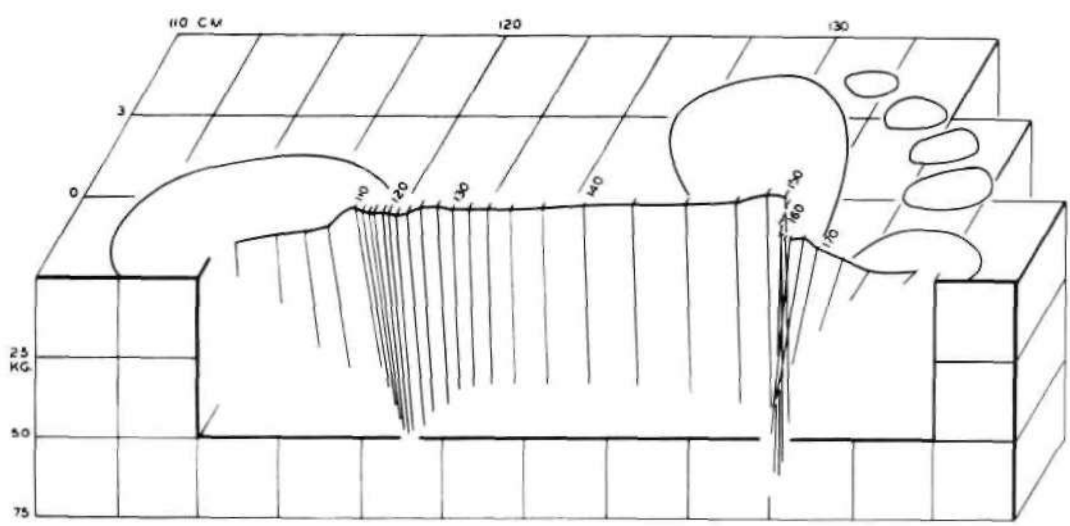

Fig. 6. Force plate record of the ground reaction acting on the foot of J. T. Manter during a step described by Elftman, 1939.

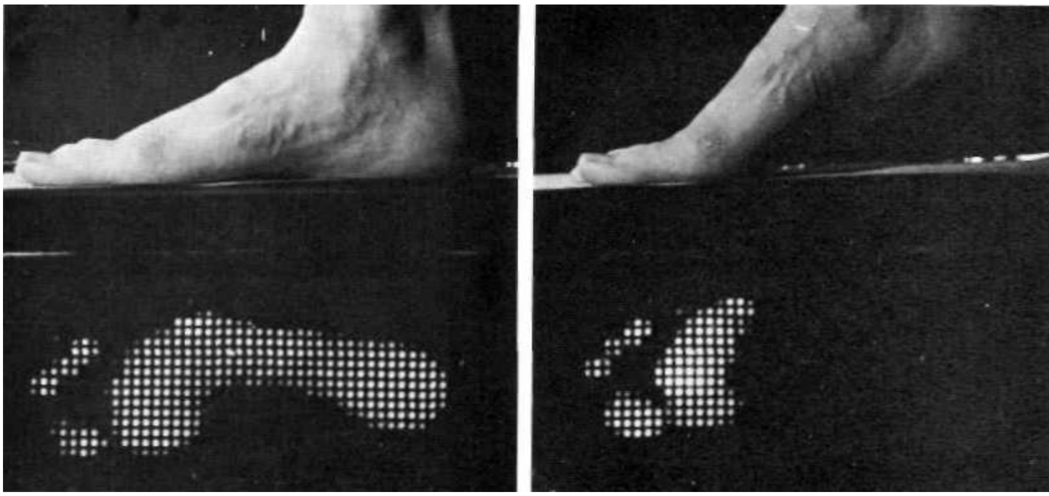

Fig. 7. Barograph record of the distribution of pressure at two phases of the step.

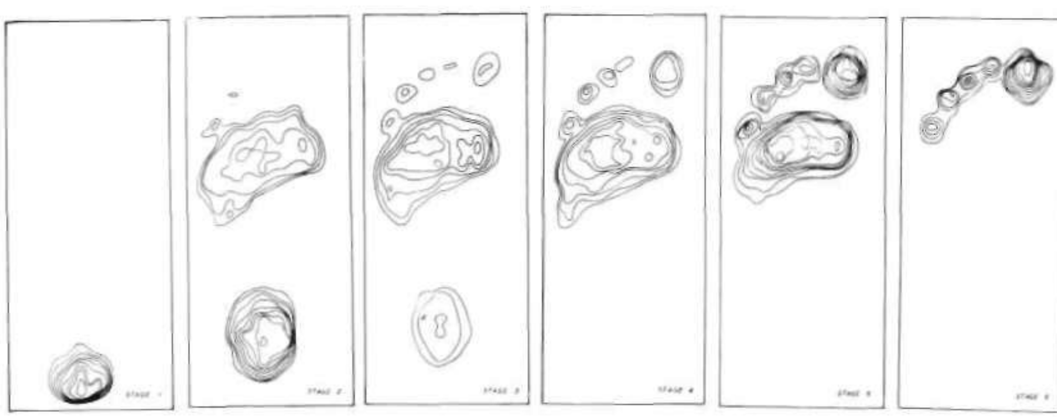

Fig. 8. Load distribution on the human foot during one step of J. T. Manter. (Isobars at 4 lb. per sq. in.) The records made on the original barograph and published in Elftman, 1934, were measured after calibration of the pressure transducer.

architecture of the foot is almost identical with that which it assumes when the subject stands on an inclined plane. Instant orthotics can be achieved by placing the proper compound in the shoes and having the subject stand in them, with heels supported at a proper elevation, to impress the functional shape.

MEASUREMENT OF FOOT FUNCTION

The foot is sandwiched between the pressure of the ground below and the weight and inertia forces of the body above. Since these are the forces to which the foot must accommodate, their measurement assumes primary importance.

The total pressure of the ground on the foot and the point at which its resultant is applied can be measured easily when the individual is standing. The only equipment needed consists of three reasonably accurate scales and a ruler. The usefulness of the information which can be obtained should not be underestimated; it is sufficient to tell whether many therapeutic devices achieve their objectives.

When the body is in motion, measurement of the ground reaction is more important and becomes more difficult. This can be accomplished by means of force plates, the earliest results of which are shown in Figure 6 from Elftman (1939). From data such as this and photographic determination of the location of joint axes, muscle moments and joint forces can be obtained.

In foot problems the distribution of the ground reaction over the foot is frequently of greater interest than its total value. Many interesting methods of making such measurements have been recorded and some are still useful; they have been reviewed by Elftman (1934). Since the distribution of pressure changes in the course of movement, instantaneous recording is of value. This can be accomplished by means of the barograph, introduced by Elftman in 1934. The changes in area of a pressure transducer placed under the foot are recorded photographically. Figure 7 shows two phases of a step; when the pressure is on the ball of the foot the structural characteristics of this region reveal themselves. Calibration of the pressure transducer allows the derivation of quantitative data from the photographic record. In Figure 8 it is even possible to recognize the concentration of pressure under the sesamoid bones beneath the head of the first metatarsal.

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