The Influence of the Foot-Ankle Complex on the Proximal Skeletal Structures[1]

Verne T. Inman, M.D[2]

Since the human foot seems to have evolved concomitantly with bipedal locomotion, it seems unreasonable to study its functions isolated from those of the remaining segments of the lower extremity *(3).* It is my belief that a complete understanding of the foot can only be obtained by relating it to the other segments of the lower extremity.

Walking is more than merely placing one foot before the other. There occurs a series of axial, rotatory movements which can be measured in a horizontal plane; many of these are familiar to any observant person. I call your attention to the obvious rotations of the pelvis and the shoulder girdle. What is not so apparent is that similar horizontal rotations occur in the femoral and tibial segments of the extremities. The tibiae rotate about their long axes internally during swing phase and into the first part of stance phase and rotate externally during the latter part of stance; this motion continues until the toes leave the ground. The amount of these rotations is subject to marked individual variations. The minimal amount of horizontal rotation of the tibia in space was recorded in our series of twelve male subjects to be 13 deg. and the maximal to be 25 deg., with an average of 19 deg.

These rotations are particularly interesting when one reflects that a great portion of this rotation occurs when the foot is firmly placed on the floor; normally, the shoe does not slip but remains fixed. The rotations, however, generate a torque which can be recorded from force plates. This torque is of considerable magnitude, being measured at 60 to 75 in.-lb.

We are now confronted with several observations which require an explanation. First is the measured horizontal rotation of the tibia of 19 deg. (plus or minus) about its long axis while weight is being borne on the foot. Second is the fact that the foot does not slip on the floor, although it may on a slippery surface. Finally, there is a measurable torque that may be recorded. A mechanism which would explain all three of these observations would have to have the following characteristics: It would permit the above-mentioned rotations to occur, but it would offer resistance to them of a magnitude such that they would be transmitted through the foot to the floor and would be recorded on the force plate as torques.

The question immediately arises whether all or a portion of this mechanism is located in the ankle joint. Without presenting all the data concerning the mechanics of the ankle joint, one can state that the plantar flexion and dorsiflexion of the ankle joint which occur during the stance phase of walking do produce relative rotations of the talus in relation to the tibia. These rotations, however, are in the opposite direction to absorb the horizontal rotations of the leg.

[1] The research on which this paper is based was supported by Easter Seal Research Foundation grants VJ-29 and N-6618 and by Veterans Administration Contract V1005M-2075.

[2] Biomechanics Laboratory, University of California, San Francisco and Berkeley, and the Department of Orthopaedic Surgery, University of California School of Medicine, San Francisco, Calif.

The structure that permits the leg to rotate upon a fixed foot is the subtalar joint. From the viewpoint of descriptive anatomy, the subtalar joint appears to be a complicated structure. Functionally, it is simple. It is a single-axis joint and its major movement is essentially that of a mitered hinge. In normal standing, the axis of the subtalar joint is inclined at a little less than 45 deg. to the horizontal (studies of small numbers of cadaver specimens by both Manter (9) and Isman and Inman *(4)* have shown their averages to be about 42 deg.).

A simple mechanical model may be constructed consisting of two pieces of wood attached to each other at a right angle by means of a hinge whose axis is at 45 deg. (Fig. 1). Rotation of one board causes rotation of the other. In a similar way, rotation of the leg about the longitudinal axis is transmitted to the foot, imposing rotation on it about its long axis. The opposite is also true. Rotation of the foot from a pronated to a supinated position results in a horizontal rotation of the leg through its longitudinal axis.

We have now identified a mechanism located within the foot which is nicely designed to permit the horizontal rotations of the leg as measured. The next step is to determine the behavior of this mechanism during locomotion and its effect upon the remaining structures in the foot.

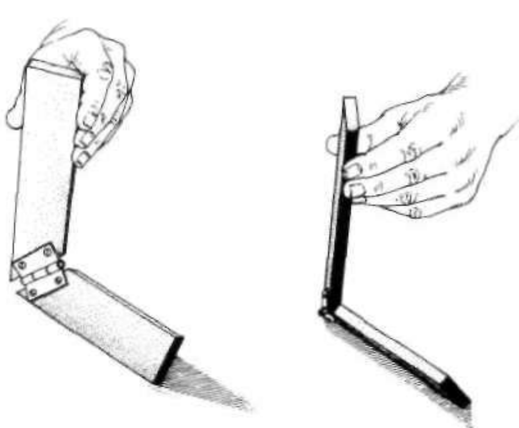

Fig. 1. Simple mechanical model constructed to show motion about the subtalar joint.

However, many events are occurring in the leg, ankle, and foot during stance phase. These events are sequential and interdependent. The behavior of each anatomical part is dependent upon some immediate prior event. This makes the presentation extremely complex and difficult. In an attempt to simplify it, the entire stance phase, from heel-strike to toe-off, will be divided into three periods. The first and third periods are when both feet are in contact with the floor (double weight bearing). The second period is when the foot is flat on the floor and weight is borne solely on that foot (single weight bearing). The first and third periods are naturally equal in length if the gait is symmetrical, and the third period equals the time of the swing phase of the opposite leg. The time of the *second* period is twice that of the first or the third and is equal to the sum of the first and third.

The first period extends from the moment of heel-strike to full weight bearing, which occurs when the toe of the opposite foot leaves the ground. The impact of the heel as it contacts the floor and the rapid loading of the foot result in a vertical floor reaction, which exceeds the total body weight by over 20 per cent. The suddenness of this impact is partially absorbed by lowering of the body through plantar flexion of the ankle. The entire leg continues to rotate internally during the loading of the foot, or through this entire first period. The internal rotation of the leg, through the action of the subtalar mechanism, causes the foot to pronate.

During this first period no muscular activity in the leg or foot is recorded by the EMG except in the anteriorly placed extensor group which is acting to prevent "foot slap" (Fig. 2) *(8).* The degree of pronation that occurs in the foot is dependent solely on the ranges of motion in the intrinsic articulations of the foot and on the laxity of the ligamentous structures.

Before turning our attention to the second period of stance phase, some further

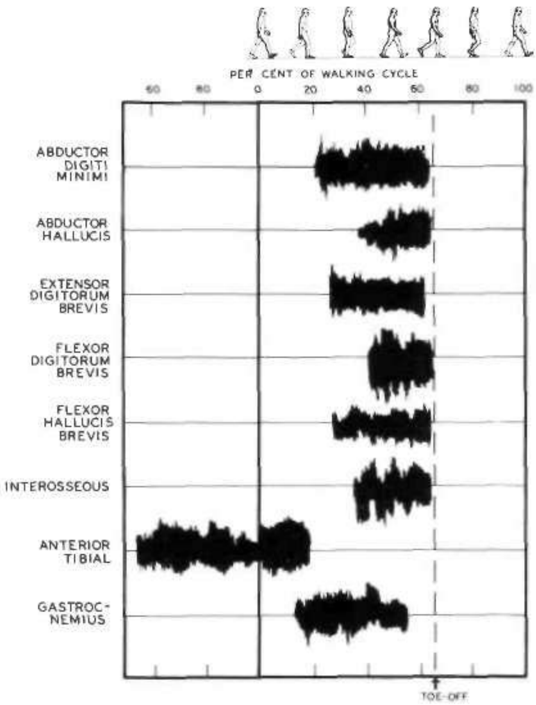

Fig. 2. Recordings of myoelectric signals of muscles of the leg during the stance phase of walking. *Courtesy J. Bone JointSurg.*

remarks are necessary concerning the subtalar joint. If the axis of the subtalar joint is inclined at 45 deg. to the horizontal, the angular rotation of the leg will be the same as the angular rotation of the foot about its long axis (pronation and supination). If, however, the axis of the subtalar joint is closer to the horizontal, the same amount of angular rotation of the leg will impose a greater motion upon the foot. Conversely, if the axis of the subtalar joint is closer to the vertical, then the same amount of rotation of the leg will produce less pronation and supination of the foot. This may be the explanation why in flat-footed individuals, in whom the axis may be more horizontal, the same amount of rotatory movement of the leg requires a greater amount of pronation and supination. Conversely, in persons with a cavus foot, in which the axis is more vertically placed, the same amount of rotation of the leg requires less pronation and supination of the foot.

Pronation of the foot seems to reduce all the inherent skeletal stability of the foot. Maximal motion of the midtarsal

Fig. 3. The foot becomes a pliant structure when it is placed in pronation.

joint is easily demonstrated to occur with the foot pronated. In this position the greatest dimension of the articular surface of the head of the talus is parallel to the transverse axis of the calcaneocuboid joint. Furthermore, since no muscular activity can be detected to add support, the foot becomes a pliant structure able to mold itself to irregularities of the walking surface (Fig. 3).

The second period of stance phase is characterized by vigorous muscular activity. Almost simultaneously, all the intrinsic muscles of the foot, together with the calf musculature, contract (see Fig. 2). The leg reverses the direction of rotation and begins to rotate externally (Fig. 4). The arch of the foot is elevated and the foot supinates with concomitant motion in the subtalar joint. Whether the supinating

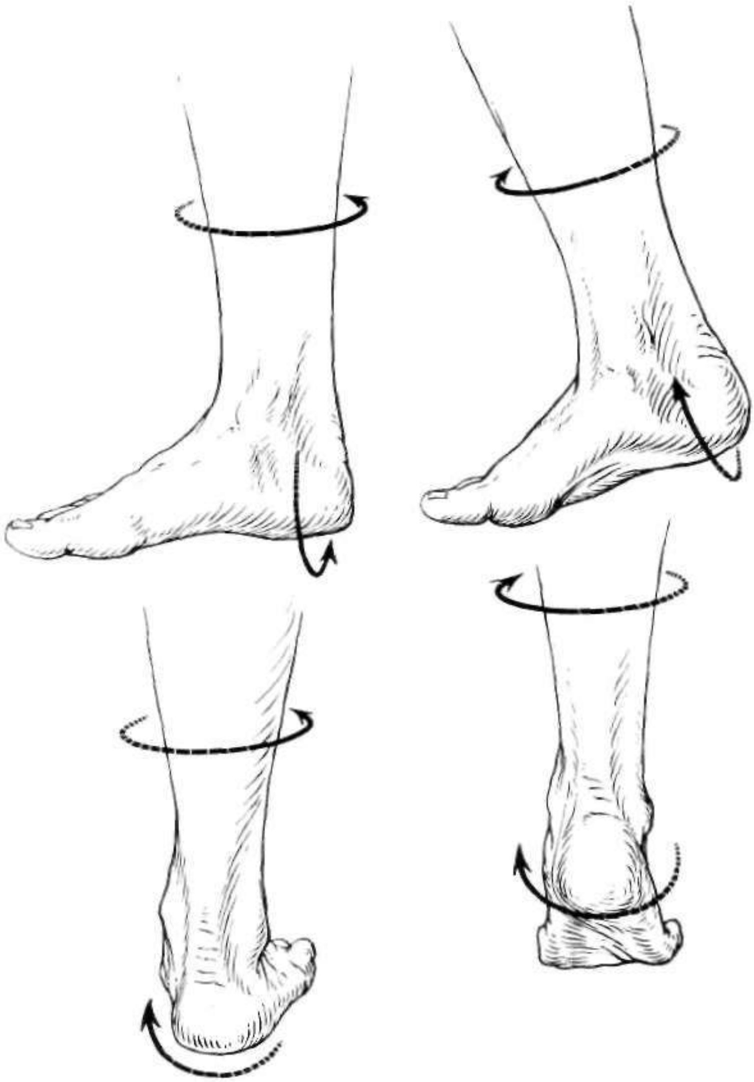

Fig. 4. Sketches showing the reversal of motions that occur between the first and second phases of stance phase.

foot, through the subtalar linkage, initiates the external rotation of the leg or whether it is independently controlled by the external rotator muscles of the hip is not definitely determined. The probability is that both contribute. Certainly some rotating force is imposed from above, since in amputees the same horizontal rotations are discernible in the prosthesis and measurable by a suitable device in the prosthetic ankle.

The amount of motion occurring in the subtalar joint has been measured by Wright *et al.* *(12).* Although this rotation is not as apparent as ankle-joint motion to the casual observer, it should be noted that the angular movement of the subtalar joint, as measured in degrees, approaches that of the ankle (Fig. 5).

The orthopaedic literature has recently furnished us with experimental evidence of the relative importance of the subtalar joint.

Surgical arthrodesis of this joint has been a frequent and favorite orthopaedic procedure. This procedure has been carried out for stabilization of the flail foot in poliomyelitis, as well as for the relief of flaccid flatfoot and of traumatic arthritis of the subtalar joint after fractures of the calcaneus. Granted that this procedure does give stability and better appearance to the foot, but the effects of the loss of subtalar motion upon the ankle joint have only recently been evaluated.

In 1959 Robins *(11)* reported on a series of 60 patients with flail feet resulting from poliomyelitis who had all had subtalar fusion. They had been followed for a minimum of 10 and a maximum of 25 years. It is interesting to note that when this procedure was carried out on younger individuals they tended to develop a "ball-and-socket" ankle joint (Fig. 6) which had increased rotation to replace the function of the lost subtalar mechanism. Many of these feet were asymptomatic; a few became so unstable as to require braces, and several others showed early but asymptomatic arthritic changes in the ankle joint.

The orthopaedic literature also contains isolated observations on congenital synostoses, between the tarsal bones, which suppress motion of the subtalar joint. Lusby (7), del Sel and Grand *(2),* Jacobs

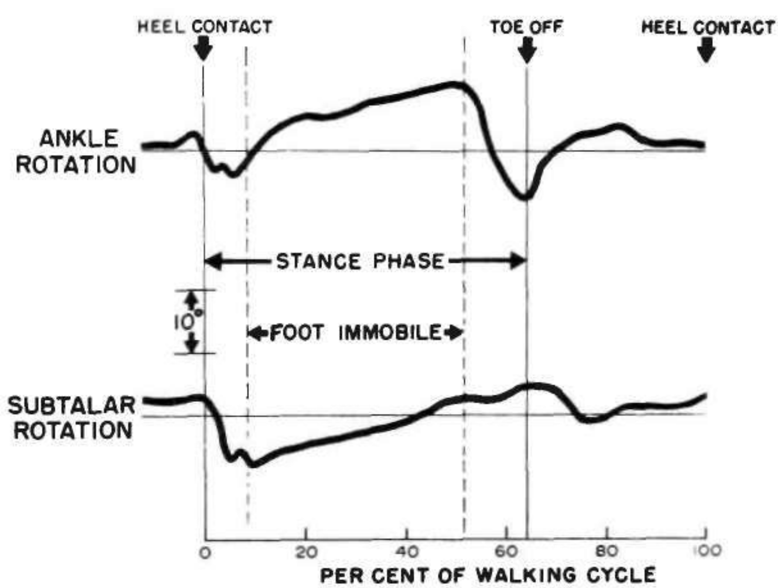

Fig. 5. Rotation about ankle and subtalar joints during the stance phase of walking. *Courtesy J. Bone Joint Surg.*

Fig. 6. The "ball-and-socket" ankle joint produced as a result of earlier fusion of the subtalar joint.

(5), Brahme *(1)*, and Lamb (6) all report late effects on the ankle joint caused by the loss of subtalar motion. It seems quite characteristic that such congenital abnormalities also result in ball-and-socket ankle joints. It appears that the failure to provide subtalar motion in the growing child is reflected in the maldevelopment of the ankle joint which must accommodate for the lost subtalar motion.

When a subtalar or a triple arthrodesis is carried out in adults there is a frequent complaint that pain is referred to the lateral side of the ankle. Povacz *(10)* in 1965 reported on a series of 27 patients who had had subtalar arthrodesis; more than half complained of discomfort on the lateral side of their ankle joints.

Because subtalar motion is not as obvious as ankle-joint motion during walking, the importance of this joint has been overlooked. However, all evidence, both experimental and clinical, emphasizes its importance in normal locomotion. This evidence indicates that loss of subtalar motion in congenital abnormalities of the foot or operative procedures designed to obliterate motion in this joint causes, in the child, the development of a ball-and-socket ankle joint with ankle instability. In the adult, surgical arthrodesis of the subtalar joint may result in pain and arthritic changes in the ankle joint.

Because even a ball-and-socket ankle joint cannot absorb all the rotatory movements transmitted through the femur and the tibia, and because a fused subtalar joint may change the pattern of transmission of forces to and from the foot, there may well be effects on the proximal musculoskeletal structures; it should therefore behoove us to watch for them.

LITERATURE CITED

1. Brahme, F., *Upper talar enarthrosis,* Acta Radiol. (Stockholm), 55: 221-224, March 1961.
2. del Sel, J. M., and N. E. Grand, *Cubo-navicular synostosis: A rare tarsal anomaly,* J. Bone Joint Surg., 41B:149, February 1959.
3. Inman, V. T., *The human foot,* Manitoba Med. Rev., 46:513-515, October 1966.
4. Isman, R. E., and V. T. Inman, *Anthropometric studies of the human foot and ankle,* Biomechanics Laboratory Technical Memorandum, University of California (San Francisco and Berkeley), in press.
5. Jacobs, P., *Some uncommon deformities of the ankle and foot,* Brit. J. Radiol., 35:776-782, November 1962.
6. Lamb, D., *The ball and socket ankle joint—a congenital abnormality,* J. Bone Joint Surg., 40B:240-243, May 1958.
7. Lusby, H. L. J., *Naviculo-cuneiform synostosis,* J. Bone Joint Surg., 41B:150, February 1959.
8. Mann, R. A., and V. T. Inman, *Phasic activity of intrinsic muscles of the foot,* J. Bone Joint Surg., 46A:469-481, April 1964.

9. Manter, J. T., *Movements of the subtalar and transverse tarsal joints,* Anat. Rec., 80:397-410, August 1941.
10. Povacz, F., *Nachuntersuchungsergebnisse von 27 Arthrodesen des unteren Sprunggelenkes bei Fersenbeinbruchen der Gruppe V bis VIII,* Zbl. Chir., 90:91-96, January 16, 1965.
11. Robins, R. H. C, *The ankle joint in relation to arthrodesis of the foot in poliomyelitis,* J. Bone Joint Surg., 41B:337-341, May 1959.
12. Wright, D. G., S. M. Desai, and W. H. Henderson, *Action of the subtalar and ankle-joint complex during the stance phase of walking,* J. Bone Joint Surg., 46A:361-382, March 1964.