INTRODUCTION: ARCHES AND CHAINS, SUPPORT AND MOBILITY

In anatomic as well as clinical literature, much attention has been paid to the specific anatomic and functional characteristics of the human foot. Its elastic vault structure combines a capability to bear loads passively with the possibility to adjust actively the position of its bones to an uneven walking surface or to maintain the body's equilibrium by small sideward displacements of the tarsus. Moreover, the foot's active mobility has an important function for deceleration during landing of the foot as well as in the acceleration of its push-off. This complex nature of the human foot is clearly reflected by its functional anatomy.

The Kinematic Chains of the Foot

In the concept of the foot's skeleton as a static, albeit elastic weight-bearing vault structure, the description as two assembled longitudinal arch systems seems attractive and appropriate indeed. From a kinematic point of view, however, the approach of longitudinal kinematic chains can be applied only to the distal part of the foot, comprising the metatarsals and phalangeal chains. In this part of the foot, the individual longitudinal chains can be moved in dorsal or plantar direction more or less independently and with a distally increasing freedom.

The Arches of the Foot

In many anatomic descriptions the vault structure of the foot is considered to be built up essentially by two longitudinal arch systems (Fig. 15–1). Although a single line of bones proximally, the arch systems split up distally. The lateral arch system is the lower and shorter one and is made up by calcaneus, cuboid, and metatarsals 4 and 5. It carries proximally the longer and higher medial arch system, which is composed of (calcaneus) talus, navicular, cuneiforms 1, 2, and 3, and metatarsals 1, 2, and 3. The arches are prolonged into the five shorter kinematic chains of the toes. These very mobile kinematic chains can also become stabilized actively to transmit forces between the foot and its supporting surface.

The arches, as far as they are seen as passive supporting structures, are connected by longitudinally running strong plantar ligaments, which prevent them from sagging under the load of the body's weight. Oblique and, on a lesser scale, transverse fibers, especially in the region of the navicular, cuboid, and cuneiform bones, and the bases of the metatarsals keep the parallel rows of the splitting arch systems together. Proximally, where the medial arch is mounted upon the lateral arch, mostly more vertically running fibers keep them together, and these belong not only to the talocalcaneal ligaments but also to the tarsocrural bands.

Figure 15–1. The vault structure of the foot conceived as two longitudinal arch systems. Proximally, the medial system is carried by the lateral system; whereas distally, both systems branch and are arranged side to side. (From Von Lanz T, Wachsmuth W: Praktische Anatomie, Part I, Vol IV. Berlin: Springer-Verlag, 1938.)
In the proximal part of the foot, composed of the tarsal bones, the motions are no longer described adequately by the mobility of longitudinal chains. In this part of the foot, the static longitudinal arch systems are integrated kinematically into what can be called a "closed kinematic chain," with a quite different mode of motion. As will be shown in a later section of this chapter, the relationship between the talar head and the anterior part of the calcaneus supporting it when it is loaded by the body's weight plays a significant role in the biomechanical behavior of the tarsus during inversion and eversion of the foot. As is discussed later, a similar dual functional character can be ascribed to the ligaments, which play an important role as kinematic constraints of the joints, apart from their share in force transmission to support the elastic vault structure of the foot.

THE JOINTS AND THEIR MOTIONS: A FUNCTIONAL ANATOMIC APPROACH

If during upright standing, invertor muscles, inserted distally to the line of Chopart, move the distal part of the loaded foot with respect to talus and calcaneus, a complex combination of motions occurs. Although they take place simultaneously, they are described successively, for clarity's sake, starting with the calcaneocuboid joint. Moreover, because the shape of the articular surfaces and the arrangement of the ligaments are determinant factors for these motions, both are considered in the following section.

Motions of the Cuboid

As the calcaneal surface of the calcaneocuboid joint is dominated by a bottleneck-shaped prominence in its dorsomedial corner fitting into a groove of the cuboid's articular surface, the latter bone is invited to pivot around this prominence with an inversion component (Fig. 15–2). This motion is further facilitated by a medially directed tongue-like elongation of the cuboid's articular surface running in the hollow circumference of the calcaneal prominence. In addition, this shallow groove curves medially into a proximal direction, which adds an adduction component to the rotation of the cuboid. Finally, the articular facet of the calcaneus has also a slight slant plantarward and posteriorly, adding to the inversion and adduction components of the cuboid's motion some plantar flexion (Fig. 15–3).

The calcaneocuboid joint has close-packed position in the neutral position of the loaded foot. During inversion, only a restricted contact is maintained between the articular surfaces, and the joint enters into loose-packed positions. This contact is insufficient to prescribe unequivocally the observed motion. It is therefore essential that the plantar calcaneocuboid ligament fibers also determine this motion by their special arrangement. The longest fibers of this ligament are located laterally, inserted on the calcaneus

Figure 15–2. Schematic frontal view of talus and calcaneus showing the more or less toroid shape of the articular surface of the talar head and the saddle-shaped calcaneal articular surface, with its bottleneck-shaped processus at the upper margin and the medially and proximally running shallow groove at its medial margin. Ligaments with a mainly vertical direction firmly secure the medial arch system upon its supporting lateral counterpart. (From Huson A: Een Onfeerstendig Functioneel Onderzoek van de Voetworpel [A functional and anatomical study of the tarsus]. PhD Dissertation, Leiden: Leiden University, 1961.)

Figure 15–3. A schematic representation of the shape of the articular surface for the cuboid on the calcaneus. S = the slanted plane of the articular face; i = the oblique insertion line of the plantar ligament fibers; h = the bottleneck-shaped processus around which the cuboid performs its inversion swing. R = transverse plane with respect to which the inclination of the slanted plane has been defined; V = an oblique vertical plane defining the trapezoid articular face. (From Huson A: L'articulation calcaneo-cuboidienne. C R Assoc Anat 132(30):540–547, 1965.)
The plantar bony relief of calcaneus and cuboid showing the robust longitudinal ridge on the calcaneus (A), which is the insertion site of the strong plantar ligaments (B). The ridge has an oblique anterior border (A) marking the gradual shortening in medial direction of the deep fibers of the short plantar ligament. (From Huson A: Een Ontleedkundig Functioneel Onderzoek van de Voetwiel [A functional and anatomical study of the tarsus]. Ph.D. Dissertation, Leiden: Leiden University, 1961.)

with respect to the joint cleft at a certain distance, but close to it on the cuboid. In medial direction, the fibers have a decreasing length and their calcaneal origin approaches the joint cleft ever more (Figs. 15–4 and 15–5). The shortest fibers lie close to the bottleneck-shaped and tongue-like prominences, locating at this place the motion axes of this complex motion. As is discussed in greater depth below, we can already note that a similar but mirrored arrangement can be observed in the plantar calcaneonavicular ligaments, with the longest fibers at the medial side of the foot. Therefore, both systems complete each other kinematically (Fig. 15–6).

**Motions of the Talus and Calcaneus**

For the time being, navicular and cuboid can be considered to constitute an immobile unit, which means that motions in the calcaneocuboid articulation bear immediately and forcibly on the talonavicular interaction and necessarily also on the talocalcaneal articulation. Thus the adduction and inversion components of the cuboid's motion have an abducting impact of the navicular bone on the talar head, which produces a turning moment on the talus as a whole, effecting an external rotation of this bone. As a result, the concave distal articular surface of the talus thrusts against the slope of the posterior joint facet of the calcaneus (Fig. 15–7). Because the talus is firmly fitted in the ankle mortise, it cannot follow this slope with a tilting motion as long as the leg maintains its vertical position, and it forces the calcaneus instead to give way by an inverting tilt underneath the talus. This increases the cuboidal inversion tilt till all joints involved have reached their terminal positions. In addition, apart from its inversion tilt, the calcaneus is also forced into an exorotation or abduction with...
Figure 15–6. Schematic dorsal view of the subtalar footplate demonstrating the arrangement of the longitudinally running plantar calcaneonavicular and calcaneocuboid ligaments. The shortest fibers are found in the midline of the foot, whereas the longest are found at the outer margins of the foot. This arrangement allows inversion and eversion motions of the navicular and cuboid with respect to the talus and the calcaneus (light arrows) combined with an adduction of the navicular and cuboid (heavy arrow). (From Huson A. Een Onthoedendkundig Functioneel Onderzoek van de Voetworta [A functional and anatomical study of the tarsus]. PhD Dissertation, Leiden: Leiden University, 1961.)

respects to its neutral position, which, however, is always less than the talar exorotation. Finally, the calcaneus goes into a slight dorsiflexion (Fig. 15–8).

The talocalcaneal joint also has its close-packed position in the neutral position of the loaded foot and goes through loose-packed positions during inversion. Therefore, also in this case its motion is not entirely prescribed by the shape of the complex talocalcaneal articular surfaces alone. The ligaments situated in the trumpet-shaped sinus and canalis tarsi play a similarly important kinematic role as has been described for the joints in the line of Chopart. Ligament fibers closing the posterior joint cavity anteriorly and the anterior joint cavity posteriorly become gradually shorter in a medial direction. Still more important are the strong strands, extending from lateral-anterior on the calcaneus medially and backward to the talus, as presented in Figure 15–9.

Several authors who described these ligaments extensively also discussed their functional role.7, 31, 53–55 Trying out the possible motions between the isolated bones, while keeping contact between the talocalcaneal articular surfaces as far as can be achieved, apparently three different modes of motion can be carried out. The inversely curved pairs of the talocalcaneal articular surfaces favor a shift along the axes of their curvatures according to a in Figure 15–10. The fibers of the talocalcaneal ligament in the sinus and canalis tarsi, however, permit this shift only for a very short distance, that is, as far as this shift coincides with a rotation around the main calcaneal insertion of this ligament (b). A rotation around the talar insertion (c) is obviously the best possibility and it is by this motion that the talus is forced to climb up the posterior articular facet of the calcaneus backward, as has been described before. It is this external rotation of the talus with respect to the calcaneus that becomes apparent in the exorotation of the (lower) leg when the foot is inverted over its lateral border.

It must be noted in this context that the complex talar motion as the result of a combination of several motion components, differing in direction, mode, and magnitude, makes it likely that talocalcaneal motion is

Figure 15–7. Lateral view of talus and calcaneus in the neutral position (A) and in Inversion (B). In the neutral position (A), the subtalar articular facets are in a close-packed position; whereas in inversion (B), the posterior parts of the articular facets have lost their contact and are therefore in a loose-packed position. Note that inversion forces the talus to climb up along the slanted calcaneal facet, which either brings the talus into an eversion tilt or, in case the talus is prevented from performing an inversion, brings the calcaneus into an inversion tilt. (From Huson A. Een Onthoedendkundig Functioneel Onderzoek van de Voetworta [A functional and anatomical study of the tarsus]. PhD Dissertation, Leiden: Leiden University, 1961.)
not the result of a simple hinge-like rotation, but is accomplished instead about a moving axis.

The Inversion Triad:
Three Characteristic Signs

Although the above-described motions of the talus, calcaneus, cuboid, and navicular with respect to each other, known as "tarsal inversion" (or "supination"), have been described in succession for clarity's sake, again it must be strongly emphasized, that they always occur simultaneously. This combined motion is marked by three signs, which together constitute the "inversion triad." These three signs, which can be established by inspection, by palpation, and by appropriate radiographs, are (Figs. 15–11, 15–12, and 15–13):

- a step between calcaneus and cuboid, visible and palpable at the dorsum of the foot;
- a prominence of the talar head, visible and palpable on the lateral side of the dorsum of the foot;
- a widening of the lateral entry to the tarsal sinus, visible on an appropriate radiograph.\(^{29,31}\)

The calcaneocuboid step is the immediate result of the cuboidal inversion tilt around the bottleneck-shaped and tongue-like prominences. The prominence of the talar head results from the laterally directed impact of the navicular on the talar head and the resulting talar rotation. The widening of the lateral entry to the tarsal sinus results from the relative talocalcaneal shift.
which emphasizes the deepening effect of the vault by the inversion components.

6. In order to keep contact with its supporting surface, the first metatarsal is brought into a plantar flexion. As is explained below, this causes a pronation twist of the forefoot compensating the tarsal inversion tilt, but again accentuating the deepening and torsional reshaping of the vault (see Figs. 15–8, 15–15, and 15–19).

**The Lower Leg As a Kinematic Chain**

The intimate relationship between longitudinal rotation of the lower extremity and inversion-eversion of the foot can be illustrated with a simple maneuver. If a person, sitting on a chair with flexed knees kept together, is asked to invert the feet, this motion is easily performed. The accompanying rotation of the lower leg, imposed on it by the inverting foot, clearly

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**Exorotation and Inversion in the Living Foot**

What can be seen further in the living foot during inversion and while the subject is standing on the floor, apart from the tarsal “inversion triad”? Briefly summarized, starting now from tibiotalar rotation (see Figs. 15–11, 15–12, and 15–13):

1. The leg exorotates, which is almost immediately followed by the talus, firmly grasped in the ankle mortise.

2. The heel inverts under the externally rotating talus, meanwhile shifting the talus as the supporting area for the leg laterally. Because of this shift, inversion can be used as a fine-tuning mechanism for sideward equilibrium (see Fig. 15–8).

3. Cuboid and navicular not only follow the inversion—abduction—dorsal flexion of the calcaneus but themselves perform an inversion—adduction—plantar flexion with respect to the calcaneus.

4. The combined inversion components of the calcaneus and the cuboideonavicular complex raise the medial longitudinal arch system and lower the lateral one. This becomes often visible by a small vertical upward shift of the leg and thus of the body.

5. The adduction component of the cuboideonavicular complex relative to the slightly abducting calcaneus bends the lateral border of the foot outward,

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**Figure 15–11. Schematic representation (lateral view) of the positions of talus, calcaneus, navicular, and cuboid in the neutral position during upright standing (A) and in the position of inversion (B). Note the laterally turned talar head, the widened sinus tarsi, and the upward-turned upper margin of the calcaneal articular facet relative to the cuboid: the inversion triad. (from Huson A: Het functioneel-anatomisch aspect van de bewegingen van de voet. Nederl Millt Geneesk T 18:37–43, 1965.)**

**Figure 15–12. Drawing of an osteotomogenous preparation of the foot in the neutral position (A) and in inversion (B), illustrating the characteristic features of the inversion triad.**
Figure 15-13. Radiographs of a foot in the neutral position (A) and in inversion (B). Note in the inverted foot: (1) the exorotation of the talus indicated by the relative shift of the circular margins of the talar trochlea and the widening of the entrance of the sinus tarsi; (2) the shift downward of the cuboid and fifth metatarsal bone, indicated by the more pronounced step-shaped line "calcaneus-cuboid-fifth metatarsal"; (3) the inversion of the calcaneus inferred from the upward displacement of the projection of the sustentaculum tali relative to the bottom of the sinus tarsi, and (4) the further inversion of the navicular and cuboid relative to the talus and calcaneus, indicated by the shorter projection of the dorsolateral dimension of the navicular as well as by the visible projection of the raised tuberositas ossis navicularis. (From Huson A: L'interdépendance des mouvements du tarse. C R Assoc Anat 51:505-514, 1966.)

takes place in the knee joint. However, after maximal exorotation of the feet in their neutral position, realized in the knee joint of both legs, inversion is entirely blocked. If subsequently the erect posture is assumed, while keeping the feet in the exorotated position, inversion of the feet is possible again. Now longitudinal rotation of the tibia together with the femur takes place in the hip joint, demonstrating the occurrence of a greater range of longitudinal rotation in this joint than in the knee. Finally, if now the extended legs are again maximally exorotated, inversion of the feet is blocked once more. When in the end the sitting posture is retaken, maintaining the exorotated position of the feet from stance, the flexed knees can be no longer brought together. Trying to do so will cause a strong everting stress, which can be felt in the feet. This close functional relationship of kinematic modalities in the entire chain of the lower extremity, demonstrated by the last part of the maneuver, throws an interesting light upon what happens in the legs of
patients suffering from cerebral palsy, leading to a spastic posture of knee flexion combined with an adduction in the hips. The feet will be subjected to a forceful evertin strain, as has been pointed out also by Fixsen and Lloyd-Roberts.17

The Talocrural Coupling

In the preceding sections, the relationship between rotation of the leg and inversion/eversion of the foot stood out as a characteristic mechanie feature. Therefore a few introductory words should be said about the proximal coupling between foot and lower leg—the talocrural joint. Plantar and dorsal flexion being its main mode of motion, this joint must transmit sideward tilting motions as well as longitudinal rotations of the leg to the tarsus, especially to the talus. Because the contact conditions of the talocrural joint surfaces hardly allow transmission of forces and motions through bone contact only—except in the extreme dorsiflexion position—the ligaments must play an important role in this respect. Longitudinal rotations of the leg, alone or in combination with sideward swaying motions, are converted by the tarsal mechanism into inversion and eversion motions of the foot. This means that an active use of the tarsal mechanism is an effective trick to counteract any internal or external rotating moment exerted by the leg on the foot. Again, in the transmission of a longitudinal rotation from the leg to the talus and vice versa by the talocrural joint, the ligaments are here crucial structural elements. This is especially true for the horizontally running fibers of the anterior talofibular ligament (Fig. 15–14).20, 40, 51

THREE DIFFERENT MECHANISMS
OF THE FOOT:
CONSTRAINT AND NONCONSTRAINT
MECHANISMS COOPERATE IN
INVERSION AND EVERSION

In the complex inversion/eversion motion of the foot, a number of different but closely cooperating osteoligamentous mechanisms are involved. At least three can be distinguished: (1) the tarsal mechanism; (2) the tarsometatarsal mechanism; and (3) the metatarsophalangeal mechanism.

With regard to different mechanisms with their own modes of motion, as well as of their cooperation, the following points should be noted. A mechanism that exists by virtue of the cooperation of a number of different joints can be constraint or nonconstraint.

In a constraint mechanism this cooperation is imposed by the passive structures and their kinematically relevant characteristics, which are: (1) the shape of the articular surfaces as well as the insertion pattern and length of the adjoined ligament fibers, both of which determine the degree of kinematic freedom of these joints; and (2) the number of the joints belonging to the mechanism, as well as the positions of these joints with respect to each other, which affect their kinematic interaction.30

If the mechanism is nonconstrained, however, either muscular or external forces are needed to determine the eventual modes of motion of these mechanisms. This holds also true for the cooperation of the different mechanisms.

The Tarsal Mechanism

The existence of these separate constraint and nonconstraint mechanisms in the human foot has not been recognized for a long time. In contrast, the relatively limited mobility of most joints in the foot has invoked many authors to stress only the contributions of these joints to the elastic properties of the foot's vault construction. It is mainly the subtalar and talocalcaneonavicular joints that received most attention in the mechanics of inversion and eversion motions of the foot, and these were conceived mostly as a structurally complex but mechanically simple hinge joint.10, 37 However small the motion ranges of many joints in the foot seem to be, careful measurements have shown that the range of tarsal motions is often much greater than is suggested in traditional descriptions.10 Moreover, these motions are coupled kinematically, and this feature points to the existence of a constraint mechanism in the tarsus, producing exactly defined and therefore predictable inversion and eversion motions. In humans, the tarsus has evolved to a comparatively large and mechanically elaborate part of the foot. It is able to transmit large forces by virtue of its mechanical constraints, while it can be controlled by a limited number of long tendons, which act mainly on its distal parts. Mechanically, it is a very stable component
intercalated between the lower leg and the more pliable and elastic distal half of the foot.

**The Tarsometatarsal Mechanism**

In contrast to this, the metatarsal bones seem to be movable in a more independent way, therefore forming in their turn a nonconstraint mechanism. This mechanism can be described as follows. At the level of the tarsometatarsal joints, a striking functional anatomic feature is the relative immobile connection between metatarsal (MT) 2 and the tarsus, whereas the other metatarsal bones are far more mobile. The base of MT-2 is solidly slotted indeed into a socket formed by the cuneiform bones. As a result of this, the distal half of the foot can be twisted around a longitudinal axis, formed by MT-2. This possible twisting mobility, which is mainly seated in the tarsometatarsal joints with a possible contribution from the talonavicular and calcaneocuboid joints, is known as the "supination and pronation twist" of the forefoot. This twisting change of shape of the metatarsal part of the foot is effected by motions with different ranges of the individual metatarsals in dorsal and plantar directions.

**The Metatarsophalangeal Mechanism**

The tarsometatarsal mechanism cooperates intimately with the still more mobile joints of the metatarsophalangeal (MTP) connection. Owing to the different lengths of the five metatarsal bones, the five joints of this connection are assembled in a horizontally curved configuration, offering the foot different possibilities to roll off during walking and running. Each of these possibilities has different "gear" characteristics, as has been shown by Bojesen-Møller. The actively stabilized phalangeal arches of the toes, which form the most distal kinematic chains of the foot skeleton, are of paramount importance for a proper function of this mechanism. Finally, the five MTP joints, together with their phalangeal chains, form again five separate nonconstraint mechanisms.

In the next sections, each of the three mechanisms in the foot is more amply discussed, with an emphasis on the tarsal mechanism.

**THE CONSTRAINT TARSAL MECHANISM: A BIOMECHANICAL APPROACH**

The tarsal mechanism comprises the movable connections between talus, calcaneus, navicular bone, and cuboid bone. It should be noted, however, that these movable connections do not correspond entirely to the anatomic joints between the just-mentioned bones. There seems to be a discrepancy between the mechanical (or kinematic) and the anatomic (or structural) categories of articulations that can be discerned in the foot. This is especially obvious in the talocalcaneonavicular and subtalar joints. The former, although characterized by a single joint cavity, comprises the connection between talus and navicular bone as well as part of the connection between talus and calcaneus, whereas the other part of this connection is formed by the subtalar joint.

**Incongruity of Joints and Interdependence of Motions**

Apart from these terminologic problems, the tarsal joints have puzzled their investigators because of other peculiar functional anatomic characteristics. As early as the second half of the 19th century, anatomists noted that during motion there is a striking incongruity between the corresponding male and female articulating facets of these joints. Moreover, they noticed that motions in these joints can occur only simultaneously. During the 20th century, such authors as Döntitz, Fick, Manter, and Huson endorsed this concept. The tarsal joints seem to operate in a strict mechanical interdependence: If one of them is blocked physically, the others are blocked too. The latter block, however, is functional. This particular mechanical feature indicates that the tarsal joints belong, as we have seen already, to a so-called constraint mechanism. This observation found a confirmation in the clinical experience—that the occurrence of a rigid connection (consisting of stiff cartilage or bone) between two tarsal bones, a so-called tarsal coalition, disturbs the normal function of the tarsal joints profoundly, which may lead to a "spastic" flatfoot. Moreover, this observation may provide a mechanical argument for the performance of a triple arthrodesis instead of a simple subtalar immobilization. Kinematically a simple monoarticular arthrodesis will also immobilize the other joints of the tarsal mechanism, but in this situation, force transmission must be expected to change profoundly, which may give rise to abnormal stresses in the other joints, as might be inferred from the occurrence of degenerative changes in cases of tarsal coalition.

In the balance of profit and loss, there may be, however, other arguments that contrarily favor a simple arthrodesis. As the shock-braking capacity of the foot seems to depend mainly on the energy-storing capacity of the ligaments, the plantar aponeurosis, and the long tendons running over the talocrural and intertarsal joints, the loss of each joint's mobility will diminish further this shock-braking capacity of the foot. In the long run, this may have an ill effect on the joints at a higher level in the limb. The problem is that it will be hardly possible with present methods to make such an objective balance.

**A Model of the Tarsal Mechanism: The Concept of a Moving Joint Axis**

Figure 15–15 shows a simple model of the tarsal kinematic chain as a constraint mechanism. In this
model, the navicular and cuboid bones are conceived as one single piece, whereas the calcaneus articulates with the talus as well as with the cuboid navicular piece by means of a separate hinge for each of them. The axes of these hinges are invisible, but the talocalcaneal axis has an oblique direction, as can be inferred from the visible "articulation," whereas the calcaneocuboid axis runs in a longitudinal direction of the foot. In the model, the articulation between talus and navicular (or rather the cuboid navicular piece), however, is complex. This complex mechanical connection allows for rotations about three axes as well as translations along two of them. Its complexity is a kinematic necessity; otherwise the chain would be immobile. Because there exists no biologic joint that allows for a combination of three rotations and two translations, such a trick can be realized only in a mechanical model. This becomes obvious if one notices that in fact the complex connection consists of at least three different mechanical connections, built together in this particular linkage.

In the foot, therefore, some rotations and translations, occurring in this specially devised linkage, must occur in the other tarsal joints, according to the theory of the closed articular chains. Thus, these joints cannot be just simple hinges, as was supposed in the model of Figure 15–15. Either they must be polyaXial joints instead, or they will rotate about moving axes, as in the case of the flexion axis of the knee joint.

Not visible in the photograph of the model, although it has been built in, is the boundary condition that starting from the neutral position the tarsal mechanism can perform only an inversion motion. This special feature was based on the observation seen in many living feet, that in stance the heel of a "normal" foot takes a vertical position, in line with the lower leg, whereas only feet with rather lax ligaments may show a heel sagging into an everted position, often in combination with a relatively low medial arch. Even in the unloaded, free-hanging foot this one-sided motion range of the tarsus could be clearly observed (Fig. 15–16). This point is discussed further in the section dealing with the tarsometatarsal mechanism.

**Experimental Support for the Moving Axis**

Using a roentgen photogrammetric method, which was developed by Spoor, Van Langelaan showed that the
motions of the tarsal joints can be described indeed by means of a fan-shaped or cone-shaped bundle of discrete axes, representing the successive positions of a particular moving axis.\textsuperscript{40, 48} A helical axis describes a finite spatial motion by the following kinematic parameters: the position and direction of the axis, and the rotation about, and the translation along, this axis. He found also that these successive positions followed fixed patterns, which were characteristic for the joint concerned. According to these results, axis bundles could be established for all the tarsal joints. All of them have an oblique direction with respect to the foot, and none of the axes belonging to different bundles coincides with another. Some of these bundles have a more or less flattened shape, lying mainly in a sagittal plane, whereas the others are more cone-shaped, having an additional mediolateral direction (Figs. 15–17 and 15–18).

It must be emphasized that Van Langelaan used an experimental set-up that allowed him to study the tarsal motions in a loaded cadaver foot, brought into inversion by an externally rotating moment applied to the tibial plateau. The foot was prevented from simply following the external rotation of the leg by an adjustable vertical support placed against the lateral border of the foot. The heel could move freely, being prevented from slipping only by the rough surface of its horizontal support, whereas the ankle was allowed to accompany these motions with any needed horizontal as well as vertical shift. In this way inversion and eversion, as performed by the living foot, could be simulated exactly (see also the section earlier in the chapter, "The Lower Leg As a Kinematic Chain"). He could observe under these experimental conditions that after inversion, the tarsal mechanism would go passively into eversion again under the influence of the vertical loading of the tibia, combined with an accompanying internal rotation of the leg. The terminal position of this motion, however, as well as the initial neutral starting position, was characterized by a vertical position of the calcaneus, and thus of the heel. Only a forced internal rotation of the leg could extend the returning eversion motion beyond its neutral position to a very limited extent. This observation was in agreement with the observed motions in the living foot (see Fig. 15–16).

Tables 15–1 and 15–2 give the total rotations about and translations along the helical axes as calculated by Van Langelaan in his experiments with a series of ten specimens for the total step from the
neutral position to the maximal exorotated position of the tibia. Maximal tibial exorotation varied between 30° and 35°.

The translations along the helical axes are fairly small. The talus translated with respect to the calcaneus in a posterolateral direction, whereas the navicular and the cuboid translated in a posterior direction. The talus translated with respect to the navicular in an anterior direction. The direction was seldom reversed during motion. These translations are mechanically coupled to the corresponding rotations. It should be realized, therefore, that they must be discerned

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**Table 15-1. Magnitudes of Total Range of Tarsal Rotations**

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Minimum (in°)</th>
<th>Maximum (in°)</th>
<th>Mean (in°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talocalcaneal</td>
<td>15.8</td>
<td>30.0</td>
<td>23.6</td>
</tr>
<tr>
<td>Calcaneocuboid</td>
<td>0.8</td>
<td>25.3</td>
<td>8.8</td>
</tr>
<tr>
<td>Talonaviculcar</td>
<td>29.9</td>
<td>50.7</td>
<td>43.1</td>
</tr>
<tr>
<td>Cuboldnavicular</td>
<td>3.9</td>
<td>9.9</td>
<td>6.8</td>
</tr>
</tbody>
</table>


*Measured with a roentgenphotogrammetric method in ten postmortem specimens.

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**Table 15-2. Magnitudes of Total Range of Tarsal Translations**

<table>
<thead>
<tr>
<th>Translation</th>
<th>Minimum (in mm)</th>
<th>Maximum (in mm)</th>
<th>Mean (in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talocalcaneal</td>
<td>1.0</td>
<td>2.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Calcaneocuboid</td>
<td>0.6</td>
<td>3.4</td>
<td>1.8</td>
</tr>
<tr>
<td>Talonaviculcar</td>
<td>0.4</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Cuboldnavicular</td>
<td>0.4</td>
<td>1.6</td>
<td>0.9</td>
</tr>
</tbody>
</table>


*Measured with a roentgenphotogrammetric method in ten postmortem specimens.
from the translations that can be induced in a joint by passive mobilization techniques as applied in physical therapy.

**Evidence From In Vivo Studies**

Benink\(^2\) showed that continuously performed motions of the tarsal bones had paths that were entirely similar to the interrupted or stepwise recorded motions in Van Langelaan’s experiments. It is most likely, therefore, that the kinematic parameters of these motions in terms of helical axes apply also to the continuously performed motions. Moreover, it can be concluded from Benink’s further experiments that the results of Van Langelaan’s kinematic analysis of preserved post-mortal preparations apply also to the tarsal motions in vivo. Finally, Benink found that, within the boundary conditions of his experiments, differences in vertical loading of the foot, as well as differences in the speed of motion, had no influence whatsoever on the motion in terms of differences in the established kinematic parameters. These findings concerning the absence of an influence of loading on the position of the talocalcaneal motion axis are supported by Engsberg.\(^11\)

Lundberg,\(^33, 41\) applying a similar roentgenphotogrammetric method in living subjects, and comparing the inversion and eversion effects of different input motions with each other, also found a far more extensive inversion response of the living foot to exorotation of the leg, starting from the neutral position, in comparison with a limited eversion response to endorotation. He also noted a relative exorotation of the talus during endorotation of the leg, indicating a talar delay, which can be explained as a “lock” of the tarsal mechanism, prohibiting further eversion. Furthermore, there is a general agreement between the directions of the talocalcaneal joint axes he found in his experimental subjects and the corresponding results of Van Langelaan’s cadaver experiments. The fact that Lundberg also found different (average) axes for different tracks of the total range of motion might support the idea of a moving joint axis, notwithstanding some methodologic differences.

**The Calcaneocuboid Joint: An Essential Contribution**

It is obvious from what has been demonstrated before concerning the bundles of helical axes as well as from what can be seen in the listed rotations (see Table 15-1) that the talonavicular joint and the calcaneocuboid joint not only have their own different bundles of discrete axes but also perform rotations that differ markedly in magnitude. Thus there is no such thing as a single functional Chopart joint, or midtarsal joint, or transverse tarsal joint.

Furthermore, the rotations appear to be much greater than suggested by mainly qualitatively oriented descriptions of the tarsal motions in most papers and textbooks. In these descriptions, emphasis is laid mainly on the motions in the subtalar and talocalcaneonavicular joints. The calcaneocuboid joint is often described as an amphiarthrosis, although in Van Langelaan’s results, this joint has its own motion pattern that is as specific as the motion patterns of the other joints.

There appeared to be also an appreciable, though restricted, mobility in the cubooidnavicular joint, which is indeed far more an amphiarthrosis than is the calcaneocuboid joint. The amount of rotation was too small to establish a bundle of successive helical axes, but it could be deduced from the compared first and last positions of the joint that its main motion component is an inversion-eversion tilt: During inversion of the foot, the navicular inverts with respect to the cuboid.

Van Langelaan’s findings concerning the calcaneocuboid moving axis are of special interest. Manter\(^46\) described two different axes for the “midtarsal” joint, one running mainly in a longitudinal direction with respect to the foot, the other having a far more slanted direction. In the model shown in Figure 15-15, the longitudinal axis was used, leading to the effect that during tarsal inversion, the lateral border of the sole of the foot maintains a straight outline. In reality, however, this border acquires an outward curving outline, as is shown by the footprints in Figure 15-19. If a more slanted calcaneocuboid axis is incorporated in the model, the resulting change in its lateral border during inversion is more realistic, as is shown by the

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*Figure 15-19. The outlines of the footprints of a foot in its neutral position (interrupted line) and in an inverted position (continuous line). Note the shortened medial arch and the outward-curved lateral border of the foot. (Redrawn from Huson A. De bewegingen van de voet als uitgangspunt voor klinische waarnemingen. Nederl Milit Geneesk T 18:1–9, 1965.)*
right model in Figure 15–20, as compared with the model on the left, which is the same model shown in Figure 15–15.

These changes in the shape of the foot during inversion have important consequences for the design of footwear. Shape as well as construction of a good shoe should allow for these changes in the outer shape of the foot.

Furthermore, Van Langelaan’s findings show that the tarsal joints do have a polyaxial nature and they offer an indirect functional anatomic explanation for the repeatedly described incongruity of the articular facets during motion of the tarsal joints.

**Different Input Motions and Their Implications**

The models of Figures 15–15 and 15–20 show the constraint nature of the tarsal mechanism. Constraint mechanisms are very well suited to transmit motions, whereas they may modify these motions during transmission. As such they have found a wide application in mechanical engineering. Familiar examples are the slider-crank mechanism of a steam engine and the gear box of a motorcar. In the description of their mechanical behavior, it is practicable to distinguish between an input and an output motion. In the first example, an alternating translation (the input motion) is changed into a continuous rotation (the output motion), whereas in the second example, the input rotation can be reversed, its speed can be changed, or both.

In the case of the foot, input and output motions are not easily recognized. Lundberg realized this, and in his study he compared the effects of several different input motions. Where he applied endorotation and exorotation of the leg as an input motion, his results are generally in agreement with Van Langelaan’s and Benink’s results. With the loaded foot and the subject in the upright body posture, motions of the body are transmitted downward to the foot through the talus. Because the talocrural joint allows mainly for a dorsoventral motion of the body, especially sideward swaying motions of the body as well as a longitudinal rotation of the leg force the talus into a particular input motion of the tarsal mechanism and then the other tarsal bones, belonging to this mechanism, follow. By virtue of the obliquity of all the moving axes of the tarsal joints, the input rotation of the talus about a vertical axis acquires inversion or eversion components.

As no muscles can move the talus directly, forces transmitted through the contact surfaces as well as the ligaments of the talocrural joint must impose the input motion on the talus. In this respect the horizontally running fibers of the anterior talofibular ligament play a crucial role in bringing the talus into an external rotation, which is converted into inversion by the tarsal mechanism. As is shown later, this mechanical feature has important consequences for the pathomechanics of the sprained ankle.

Accepting exorotation of the tibia as the input motion for inversion of the foot, it is worth noting that there are in the lower extremity at least two different levels at which muscles may produce this input motion. In the extended, upright-standing leg, exorotation is realized in the hip joint and effectuated by the exorotator muscles of the hip, whereas in the postures with flexed knees, endorotation and exorotation of the tibia take place at the level of the knee through the activity of such muscles as the hamstrings, the popliteus, and the medial and lateral vasti.

In the free-hanging foot, the input motion of the tarsal mechanism must be imposed on other tarsal bones and not on the talus. But also in the upright position with the foot loaded by the body’s weight, muscles acting on the navicular and cuboid, or even farther distal, may impose an input motion on the distal elements of the tarsal mechanism. In this case the direction of motion transmission through the tarsal mechanism is reverse in comparison with the earlier-described situation. It can be inferred from several theoretical considerations as well as practical observations that there are several muscles that could be used in this reverse transmission. Thus, in stance, as far as the long foot muscles are concerned, the tibialis posterior is an effective inverter, together with the flexor digitorum longus, whereas the peronei and the extensor digitorum longus have the opposite effect. Under these conditions, the tibialis anterior seems to be a less effective inverter. The abductor hallucis muscle is an example of an intrinsic foot muscle acting indirectly on the tarsal mechanism through its more distal ele-
ments in combination with the calcaneus, and with a notable inversion effect.1,10

Therefore, both muscle groups, the proximally situated muscles in the thigh or around the hip, acting through longitudinal rotation of the leg upon the talus, as well as the more distally situated extrinsic and intrinsic foot muscles, acting upon the distal part of the tarsal mechanism, can at least assist each other, thereby reinforcing their mechanical effects. This may be an important point in a heavily loaded part of the locomotor system such as the lower extremity. It offers support to the clinical experience that patients with a permanent ligament defect after injury may regain a stable joint function through specific and careful muscle training. It underlines above all that the question of input and output motion of the tarsal mechanism should be approached with much care. Indeed, the more favorable dynamic conditions for force and motion transmission through the tarsal mechanism in either a proximodistal or a distoproximal direction may vary widely, depending on the likewise widely varying loading situations of foot and leg. There is still a strong need for a suitable model to analyze these situations adequately to gain more insight into the role played by different muscles during motor control of the foot.

**Talar and Tarsal Delay**

Van Langelaan noted in his specimens under study that during the initial phase of exorotation of the tibia the talus did not follow the tibia immediately, and he spoke of a tibiotalar delay to characterize this phenomenon. The magnitude of this delay varied among individuals. This phenomenon may be ascribed to a variable laxity in the horizontal talocural ligament fibers, and it is supposed that these fibers have to build up an initial tension before they can transmit the pulling forces from the leg to the talus. After this initial delay, talar rotation increases generally and may even surpass the magnitude of tibial rotation. In most cases, after having reached a plateau, talar rotation decreases again during the last phase of tibial rotation. Figure 15–21 shows this typical rotation pattern. Generally, this pattern is also characteristic of the rotation behavior of the other tarsal bones, and it can be briefly described as an initial acceleration followed by a deceleration, which is induced, however, by a constant tibial rotation. This “delay” is quite different from the rotation deficit described by McCullough and Burge,45 Fraser and Ahmed,18 and Johnson and Markolf,56 although both phenomena are caused by the elastic properties of the horizontal talocural ligament fibers. The last-named authors recorded the strain of these fibers occurring predominantly at the end of the motion range.

This behavior is very interesting from a mechanical point of view. It has been said already that the tarsal bones move simultaneously as if they are part of a constraint mechanism. Because the different bones simultaneously perform rotations with different magnitudes, as is presented in Table 15–1 according to Van Langelaan, their mechanical behavior can be compared with the behavior of a tooth-wheel gearbox.55 This becomes apparent as soon as the corresponding percentages of total rotation are calculated and compared with each other. These percentages are entirely similar for each tarsal bone, as in the case of a frictionless tooth-wheel transmission (Table 15–3).

<table>
<thead>
<tr>
<th>Bone</th>
<th>TI</th>
<th>TA</th>
<th>CA</th>
<th>CU</th>
<th>NA</th>
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<td>15</td>
<td>15</td>
<td>15</td>
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<td>15</td>
</tr>
</tbody>
</table>


*Mean values calculated from the data of seven postmortem specimens of the ten specimens studied by Van Langelaan. These seven specimens were selected because of their similar total motion range of 30°. (TI = tibia; TA = talar; CA = calcaneus; CU = cuboid; NA = navicular.)
ately as soon as the input motion is imposed. It means, however, also that the speed of the gear system as a whole changes continuously during motion, and the mechanical cause for this behavior might be found in the mechanical characteristics of the talocrural coupling.

As has been pointed out already, it is very likely that the anterior talofibular ligament plays an important role in this remarkable mechanism of talocrural transmission. This was further corroborated by the experiments of Fiévez and Spoor who studied the kinematic consequences of lesions of the lateral ligaments of the ankle joint. The lateral capsular structures and ligaments of the ankle in fresh and embalmed foot-leg preparations were cut systematically, and always in the order according to the most frequently occurring sequence of tears in an inversion trauma of the ankle with increasing severity (Fig. 15–22). Using roentgenphotogrammetry and a specially designed set-up, which allowed an axially loaded tibia to rotate externally or internally in combinations with flexion forward (dorsiflexion) and backward (plantar flexion) of the leg with respect to the foot, Fiévez and Spoor found two characteristic patterns of changes as the extremes in the kinematic behavior of their preparations, with a number of intermediate patterns within between.

At one side of the range, patterns were seen in specimens with rather lax talocrural ligaments. These were characterized by a delay that was greatest in the first exorotation steps from 0° to 10° of the tibia, and increased with the increase of plantar flexion. After injury of the ligaments, a delay was seen also in the other exorotation steps.

The other type of patterns was seen in specimens with rather stiff talocrural ligaments and was characterized by a delay occurring mainly at the end of exorotation, and especially in 25° and 35° of plantar flexion. Ligament injuries had smaller effects, and again, they became especially notable in the more plantar-flexed ankle joint.

It is important to realize that after severing the anterior talofibular ligament with its adjacent capsular structures, tibiotalar delay increased markedly. Feet belonging to the first group may be more accident-prone and tend to have a recurrent inversion sprain after ligament injury. In the pathomechanics of lateral ankle ligament injuries from an inversion trauma of the foot, the mechanical compliance of the tarsus in response to tibial exorotation is an important factor.

Arch Height and Biomechanical Behavior: The Tarsal Index

Benink studied this mechanical compliance, recording the magnitude of the input moment required for the tibial rotation inducing inversion. The moment curves were recorded as a function of the amount of exorotation. Benink found very characteristic patterns, which varied from a curve with two inflection points and a high intermediate maximum, which is followed.
Figure 15-23. In these graphs, the magnitude (Nm) of the input moment (upper graphs) and the vertical rise (mm) of the tibia (lower graphs) have been given as a function of the exorotation angle (ext. rot.) of the tibia for a normal foot (A), a low-arched foot (B), and a foot of the cavus type (C). (From Benink R. The constraint mechanism of the human tarsus. Acta Orthop Scand 56(Suppl 215):1985.)

by a rather deep minimum via flatter curves, to a curve that showed no maximums or minimums. Moreover, there appeared to be a relationship between these different types of curves and the height of the vault of the foot, especially with respect to the medial arch. The first type (Fig. 15-23B) corresponded to feet with relatively low arches (the flatfoot type), and these feet showed the greatest vertical rise of the tibia. The flatter curves were produced by feet with relatively high arches (the pes cavus type), and these feet showed the smallest amounts of vertical rise of the tibia (Fig. 15-23A). Finally, Figure 15-23C shows an intermediate curve, corresponding to feet with an average height of their arches.

Benink defined a so-called tarsal index to characterize the type of foot using geometric parameters obtained from standardized mediolateral x-rays of the foot (equation).

\[ i_t = 100 \times \frac{P_C}{L_t} \times \tan \epsilon TC \]

In this equation, \( i_t \) is Benink’s tarsal index, \( P_C \) the extent of overlap between the talar head and the upper side of the processus anterior calcanei, \( L_t \) the length of the talus, and \( \epsilon TC \) the angle between the horizontal and the lower side of the talus (Fig. 15-24).

Using a mathematical characterization of the obtained curves, Benink found a high correlation between this index and the type of the obtained moment curves. He supposed (1) that a biomechanically hollow foot (low value for \( i_t \)) is less stable than a biomechanically flat foot (high value for \( i_t \)), and suggested (2) that a lateralizing calcaneal osteotomy would increase the tarsal stability and in this way decrease the tendency to sprain.

THE TARSOMETATARSAL MECHANISM

The Nonconstraint Nature of the Tarsometatarsal Mechanism

As has been pointed out earlier, this is a nonconstraint mechanism, comprising the five metatarsal bones and their connections to the tarsus with differing ranges of motion. Therefore, motions occurring in this mech-
anism take place mainly in the joints lying in the line of Lisfranc, whereas motions occurring in the joints of Chopart’s line are kinematically integrated in the constraint tarsal mechanism.

The motions of the tarsometatarsal mechanism are characterized by their main dorsal and plantar flexion components. Because the motions of the joints in the line of Chopart, operating in dependence on the other tarsal joints, also have dorsal and plantar flexion components as has been shown before, and as the two mechanisms act mostly in close cooperation, it may be difficult to distinguish the contributions of each of them to the comprehensive motions of the foot. Indeed, most muscles that have an effect on inversion or eversion, such as the tibialis posterior and anterior, the peroneal muscles, and the long flexors and extensors of the toes, insert distally to the line of Lisfranc and thus have a mechanical effect on both mechanisms. Moreover, in his electromyographic study of the long foot muscles, Ambagsheer showed that it is possible to evoke an isolated plantar and dorsal flexion of the joints in Chopart’s line to a very limited extent, if deliberately a simultaneous inversion and eversion action by the appropriate muscles is exerted on the foot. He called the effectuated motion a “clawing motion.” In the light of these arguments, any distinction between these two mechanisms may seem to be of academic interest only. Therefore, let us reconsider this matter in somewhat more depth.

**Tarsal and Metatarsal Cooperation**

It is obvious indeed that, because of its constraint nature, the tarsal mechanism should be considered as an independent functioning component of the whole mechanical system of the foot. However, it is also obvious that for a proper function within this mechan-

ical system, the tarsal mechanism must act in close cooperation with the tarsometatarsal mechanism.

For a clear understanding of this cooperation in relation to the discrete nature of each mechanism, two points mentioned before should be noted again.

The first point is that MT-2, tightly connected to the tarsus, is almost immobile and acts as a sort of spoke for the tilting tarsal mechanism as long as the metatarsus keeps contact with its supporting ground. As soon as the tarsal mechanism goes into inversion, MT-2 is forced to follow this motion with an accompanying inversion tilt. Consequently, the underlying supporting surface will push the metatarsals laterally from MT-2 upward into dorsal flexion, with an increasing range from MT-3 to MT-5, and to the extent allowed by their tarsometatarsal connections. On the other hand, MT-1 must move into plantar flexion if the medial arch is to maintain its distal point of support. As soon as these different tarsometatarsal motion ranges are exhausted, the foot will tilt over its lateral border, that is, MT-5. Likewise, one may expect that eversion of the tarsal mechanism will evoke a reverse motion pattern. MT-1 must move into dorsal flexion, whereas MT-3 to MT-5 must flex plantarward. The opposite dorsal and plantar flexion motions of the metatarsals at both sides of MT-2 have been described as a torsional twist of the metatarsus known as “supination and pronation” twist of the foot. The above-described description suggests the existence of a symmetric motion pattern. Yet, the situation appears to be more complex than may be apparent from what has been said previously.

In order to explain this, the second point should be noted now. The second point implies the observation already mentioned—that the tarsal mechanism starting from the neutral position of the loaded foot essentially has only a one-sided motion range into inversion and back. In this view, eversion is the return motion from (maximal) inversion to the neutral position, and as the loaded foot has a strong tendency to go into eversion under the influence of the body’s weight, this motion finds its terminal position in the passively girded vault. Construction of the osteoglen-メンous skeleton of the foot. Eversion is accompanied by an internal rotation of the leg, which forces the talus into adduction, stretching the strong plantar calcaneonavicular ligament as well as the talonavicular fibers reinforced by the tibionavicular strands of the deltoid ligament. In other words, the girding system of the medial longitudinal arch system is brought under tension to withstand a further lowering of its (minimal) height. Indeed, Van Langelaan saw in his experiments that even this isolated system was capable of supporting passively a vertical loading of the foot, without the help of the plantar aponeurosis (as it had been removed before). It is very likely, however, that in the complete, living foot, part of this arch-stretching load is carried passively by the plantar aponeurosis, actively by muscle action through a forceful depression of MT-1, or both.
**Differences in Mobility of the Five Metatarsal Rays**

In light of the two foregoing points, the following conclusions can be proposed with respect to the cooperating mechanisms:

The weight-bearing foot, having a tarsal mechanism with a one-sided inversion range starting from its neutral position during standing, and tilting about MT-2 as the fixed spoke of its tarsometatarsal mechanism, requires a less stiff anterior beam of its most medial arch (MT-1), which is especially capable of flexing plantarward, as well as less stiff beams laterally (MT-3 to MT-5) capable of a compensatory dorsiflexion. On the other hand, eversion of the tarsal mechanism beyond its neutral position is very limited and leads almost directly to an eversion tilt of the entire mechanism over its anteriorly supporting spoke, MT-2. This would require a compensatory dorsiflexion of MT-1, but this seems to be blocked also very soon by the passive medial and plantar girding systems of the medial arch. Only the lateral beams, MT-3 to MT-5, are capable of adjusting their position by means of an appropriate plantar flexion. This means that also the medial half of the tarsometatarsal mechanism seems to have a one-sided motion range in this respect, corresponding to the asymmetric motion range of the closely cooperating tarsal mechanism.

The characteristic fixed position of MT-2 relative to the tarsus, creating a second longitudinal arch as the most rigid of the five, has yet another consequence. If the foot is conceived as an elastic vault carrying the body weight, a sideward shift of the body's center of gravity may evoke a small torsional twist of the metatarsal part of the foot by an elastic flattening of the less stiff longitudinal arches at either side of this stiffest second arch. This means that the forefoot rolls over the distal point of support of the second arch, and if this mechanism acts only passively, vertical forces exerted by the body weight are transmitted mainly through the head of MT-2, until the other passively load-bearing arches have been stretched maximally. However, a more favorable distribution of load transmission over the arches can be achieved by an attuned arch-stabilizing muscular action (extrinsics as well as intrinsics). An insufficient muscular balance, due to a disease or to wearing bad footwear, may lead to an overloading of the less robust second arch, and this may explain the observed predilection site of calluses just underneath the second or third metatarsal head. Such a functional explanation seems more appropriate than the supposed fallen transverse arch, which as we have said already lacks a sound structural base.

Finally, as soon as the heel is raised and the total area of support shifts to the ball of the foot, the increased activity of the calf muscles together with the increased moment arm of the body's gravity center pulls the calcaneus still more forcibly into plantar flexion. This would increase the arch-flattening tension in the plantar ligaments enormously, if no other girding system were available. In the first place, there are the long and short muscles that span the plantar side of the foot arches and that are activated at the same time. In the second place, the accompanying dorsal flexion of the toes, especially of the big toe, brings the windlass action of the plantar aponeurosis into play, which adds also a passive contribution to the plantar girding elements.24

Many observations of the changes in the pressure distribution underneath the foot during normal walking show a peak during push-off under the head of MT-1, and this seems to fit very well the dominance of the part of the plantar aponeurosis under the medial longitudinal arch.8,17 In this context it is interesting to note the highly organized structure of the sole of the foot in the metatarsal region (Figs. 15–25 and 15–26).

**THE METATARSOPHALANGEAL MECHANISM**

**Differences In the Transverse Relationships**

In the preceding section, the asymmetry of the torsional tarsometatarsal mobility at both sides of MT-2 has been emphasized. This particular asymmetry can also be recognized in the structural relationship between the five metatarsal heads as an anatomic base of the metatarsophalangeal mechanism. In contrast with the classical description of the transverse meta-

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*Figure 15–25. The arrangement of the finer texture of the fibroseptal reinforcement of the sole of the foot in the metatarsal region. Its pattern suggests an adaptation to torsional movement forces. At the medial side, the connections with the superficial strands of the plantar aponeurosis become visible.*
Moreover, it has been well documented in the literature that there are bursae between the heads of the metatarsal bones. Remarkably, this holds true for all of them although it must be admitted that the bursae between MT-1 and MT-2 are rather extensive. The occurrence of these bursae has been documented in fetal feet, thus in feet that could not have been influenced by the constraints of footwear.

In relation to the special position of the first metatarsal head, another important structural feature should be mentioned. De Wilde has pointed out that on the basis of ridge pattern formation, the anlage of the first digit should have three phalanges. In his view, the first metacarpal is not an ontogenetic homologue of the other metacarpals, but it must be the homologue of the basic phalanx of the other fingers.

As an additional argument, De Wilde mentioned the position of the growth plate of the first metacarpal, which is located at its base as in the other phalanges, whereas the other metacarpals all have subcapitally located growth plates.

De Wilde found a similar developmental pattern of the cutaneous ridges in the foot as he had observed in the hand. Likewise, a similar arrangement of the growth plates can be found in the metatarsals and phalanges as has been described for the hand. It seems to be very likely, therefore, that MT-1 has a particular position in the construction of the foot comparable to that of MC-1 in the hand.

**The Stabilization of the Toe Arches**

Finally, studies of the pressure distribution under the sole of the foot during walking have established more than once the load-bearing role of the toes during push-off. This means that muscles must be able to stabilize the toe arches for proper force transmission.

The stabilization of the multiarticulated chain against external forces has been elaborately studied in the human fingers, and there is no reason to assume that the stabilization of the toes is basically different. Therefore, both the flexor digitorum brevis and the interossei are essential to obtain a stable arch. It is obvious that the interossei, and also the other intrinsics, stabilize the metatarsophalangeal joints. Particular demands are put on the metatarsophalangeal joint of the great toe, a major force-generating structure in the take-off. The extremely powerful abductor, adductor, and flexor hallucis brevis not only are present for stabilization of the first metatarsophalangeal joint but, by virtue of their remarkably far proximally located origin, have also a stabilizing effect on the metatarsocuneiform connections and even more proximal joints. In this respect it is significant to note that the interossei, unlike those in the hand, have their proximal origin beyond the metatarsals from the tarsal ligamentous meshwork, so that "the pull of the interossei is transformed across the tarsometatarsal joints . . ." (p. 90). These authors suggest the possible role of the interossei as stabilizers of the forefoot, "rendering the tarsometatarsal joints rigid when
Figure 15-27. Three transverse sections of the foot of a fetus of 115-mm crown-rump length (approximately, 14 weeks) made at the level of the MTP region. In A the most distal parts of the transverse head of the adductor hallucis muscle can be seen, together with the tendon of the oblique part. In B the plantar pads of the MTP joints 4 and 5 are more clearly visible; likewise in C the plantar pads of 2, 3, and 4 but now also the deep transverse metatarsal ligaments in the interdigital spaces between MT-2, -3, and -4 are present. Note the different situation in the interdigital space between MT-1 and -2! At the level of the transverse metatarsal ligaments between MT-2, -3, and -4, the space between MT-1 and -2 is occupied by a large synovial bursa, and only a much thinner layer of connective tissue, which can be seen in all three sections, splits off into a more superficially located plantar connection at the level of the flexor tendons.
weight is carried on the ball of the foot" (p 91). It is, therefore, certain that dropout of the intrinsics, as in leprosy or diabetics, not only affects the metatarsal joints but also deprives more proximal joints of a plantar stabilizing force.

THE PLANTAR APONEUROSIS: ITS ROLE IN THE COOPERATION OF THE THREE MECHANISMS IN THE FOOT

The cooperation of the three mechanisms described in the foregoing paragraphs is achieved by the activity of extrinsic and intrinsic foot muscles, as well as by the plantar aponeurosis as a most crucial passive component in this respect.

The plantar aponeurosis bowstrings all three mentioned mechanisms and is connected to their bony parts as well as to the sole of the foot in an anatomically complex way.6 This bowstringing anchorage enables it to exert a windlass action, raising the longitudinal arches of the foot when the toes are dorsiflexed as well as stiffening the fibrous skeleton of the ball of the foot during push-off.6 This effect is most evident in the medial arch, and thus it can be seen also by dorsiflexion of the great toe only. This maneuver is known as the great toe extension test in the diagnosis of flatfoot.50 Because inversion of the tarsal mechanism mostly leads to a rise of the medial longitudinal arch, raising the arch by the aforementioned maneuver is mostly accompanied by a slight inversion of the tarsus and exorotation of the leg.

Finally, the plantar aponeurosis is an important intermediate structure in the transmission of forces between the sole of the foot and the foot skeleton. In relation to these structural features it is no surprise that many investigators who studied force distribution under the loaded normal foot have found a weight-bearing function for all the metatarsal heads in stance as well as in gait.8,15,50 Therefore, the older idea of a three-point support of the foot, consisting of the tuber calcanei and the first and fifth metatarsal heads should be definitely abandoned.

If this view is accepted, it should have consequences for the term "transverse arch," which is often used in relation to the clinical condition of a so-called flatfoot. It is unclear what could be meant by a transverse arch in the human foot. The apparent signs on the sole of the foot of an abnormal local pressure under one of the metatarsal heads cannot be designated adequately by a fallen transverse arch, as there has not been such an arch before. It seems to be more reasonable to adopt the opinion of Kelikian,41 who describes flatfoot as a condition in which essentially the first and fifth metatarsal heads have shifted outward with respect to the midline of the foot. This would be in good agreement with the structural differences mentioned in the section of this chapter entitled "Differences in the Transverse Relationships."

REFERENCES


