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Calcaneocuboid joint and stability of the longitudinal arch of the foot at high and low gear push off

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INTRODUCTION

The forward prominence of the second metatarsal bone in the human foot allows the push off to be performed about two alternative axes: either (1) a transverse axis through the heads of the first and the second metatarsal bone, or (2) an oblique axis through the second to the fifth metatarsal heads, which also are in line (Fig. 3). In a previous study of the leverage of the foot it was found that the transverse and oblique axes are used for a high and a low gear push off respectively, and that the leverage ratio averages 6:5. It was a difference in the length of the resistance arm of the foot which was found significant. The length of the force arm of the triceps surae was found to be nearly equal in the two kinds of push off (Bojsen-Møller, 1978).

Movements between the foot and the shank occur at the talocrural and subtalar joints. With the toes on the ground and the foot rising, dorsiflexion of the toes about one of the two axes at the metatarsophalangeal level is accompanied by compensatory plantar flexion in the ankle joint. Thus, with the transverse axis the compensation occurs mainly in the talocrural joint, while with the oblique axis, it also involves the subtalar joint. Because of the peculiar orientation of the axis of the subtalar joint, the shank is allowed to move in a sagittal plane despite the inversion of the foot that occurs in this latter case (Jones, 1945; Wright, Desai & Henderson, 1964; Inman & Mann, 1973; Inman, 1976).

Movements between the forefoot and the hind foot occur at the transverse tarsal joint, which consists of the talonavicular and the calcaneocuboid joints. In these the forefoot can be pronated and supinated in relation to the hind foot as well as it can be adducted and slightly plantar flexed.

The subtalar and the transverse tarsal joints are connected, however, through the talonavicular joint and the cervical and bifurcate ligaments, so the positions of the forefoot, the hind foot and the leg are not totally independent. A plantar flexion–adduction–inversion of the foot is a concerted action of all the joints in which they become loose packed and in which the stability of the foot and its arches is decreased (Elftman, 1960; Inman, 1969).

The purpose of the present investigation was to study the movements of the joints and ligaments of the mid-foot and to assess their importance for arch support and foot stability at high and low gear leverage.

OBSERVATIONS

The calcaneocuboid joint

The calcaneocuboid joint was studied in the skeletons of 25 human feet, of two gorillas (*Gorilla gorilla beringei*), of six chimpanzees (*Pan troglodytes*) and of three orang utans (*Pongo pygmaeus*). The movements of the joint and their restraints were further studied in ligamentous specimens of ten human feet fixed in formalin.

The calcaneocuboid joint is a concavoconvex joint. In man its articulating surface on the cuboid is shaped, not as a saddle, but as a sector of one end of an hour-glass shaped surface of revolution with the axis oriented longitudinally in the foot through the calcanean process of the cuboid (Figs. 1, 2, 4*a*). This process extends posteriorly from the medial part of the cuboid, undershooting the calcaneus. The articulating surface covers the dorsolateral aspect of the process and continues into a flat peripheral part which reaches the lateral limit of the bone and eventually is extended inferiorly as a tongue-like projection.

The adjoining distal surface of the calcaneus is shaped reciprocally, and a great deal of congruence exists between the two. The calcanean process of the cuboid is thus lodged in a little recess on the medioplantar aspect of the calcaneus, where it is held in position by the strong plantar calcaneocuboid ligament, and the flat peripheral part has an inferior extension similar to that on the cuboid.

The calcanean process of the cuboid is of varying size, however, and in two of the 25 specimens it was virtually non-existent (Fig. 4*b*). The recess on the calcaneus was correspondingly flat, and the joint could be classified as of the plane variety.

In the common concavoconvex type the arrangement allows the cuboid to rotate on the calcaneus with the calcanean process as the pivot, and with the flat peripheral part of the joint surface as a guiding flange. In neutral position the tongue-like inferolateral extension of the cuboid joint surface is unopposed by the calcaneus, but at pronation it slides upward until the joint reaches its close packed position. The movement is stopped by the dorsal border of the calcaneus which overhangs the cuboid, and by a tightening of the plantar, lateral and dorsal calcaneocuboid ligaments (Fig. 1). In the intermediate positions of the joint, movement of the forefoot about a secondary axis is allowed as the cuboid with the calcanean process slides posteromedially on the convex curvature of the calcaneus (Fig. 3). The

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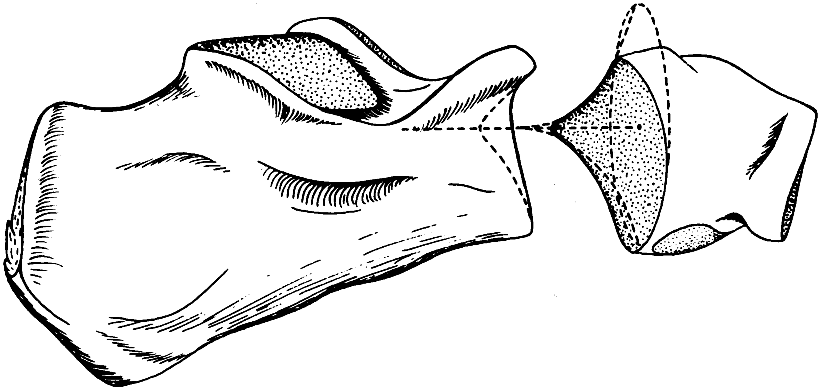
Fig. 1. Diagram showing a right sided calcaneocuboid joint. The joint surfaces are shaped as sectors of one end of an hour-glass shaped surface of revolution. The main axis is oriented longitudinally in the foot. The cuboid is grooved for the tendon of the peroneus longus, and a contraction of this muscle results in a pronatory, pivotal movement of the cuboid. The movement will be stopped by the calcaneus which overhangs the cuboid dorsally, and the joint is thereby brought into its close-packed position.

Fig. 2. Diagram showing two concavoconvex joint surfaces, both of which are parts of an hour-glass shaped surface of revolution. The saddle-shaped surface on the left has a waist, and is extended in both directions from this mid-point. The calcaneocuboid joint (on the right) is part of one end of the figure only. The main axis (x) is shown together with two secondary axes ($y+y'$).

Fig. 3. Diagram showing movements about the secondary axis of the calcaneocuboid joint. The axis passes through the lateral part of the calcaneus in a mediocranial direction. In relation to the fixed forefoot, the hind foot can be adducted and plantar flexed (dashed). The tuber of the calcaneus along with the origin of the plantar aponeurosis is thereby approximated to the first metatarsophalangeal joint. The aponeurosis becomes slack, and the medial arch raised.



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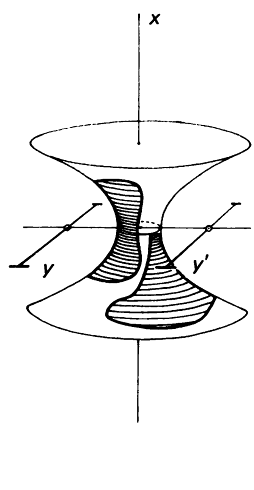

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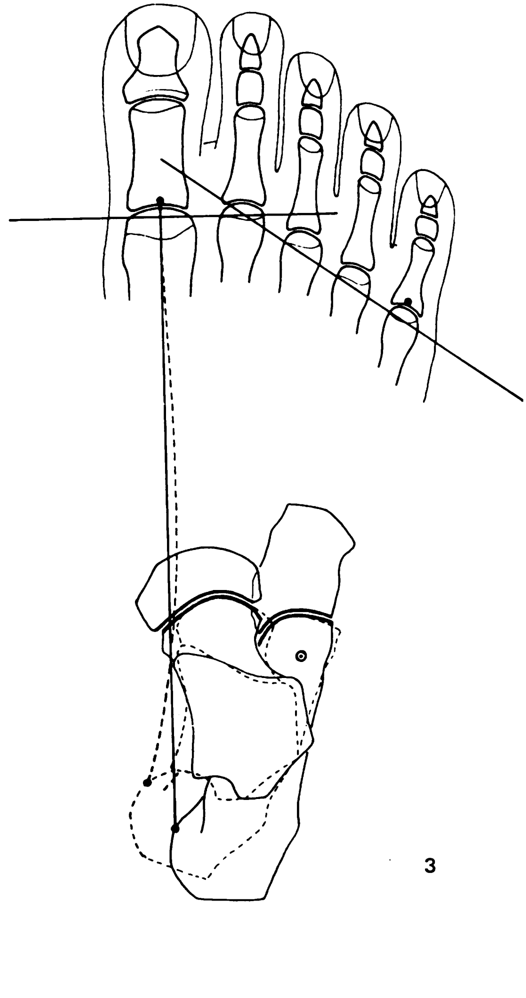

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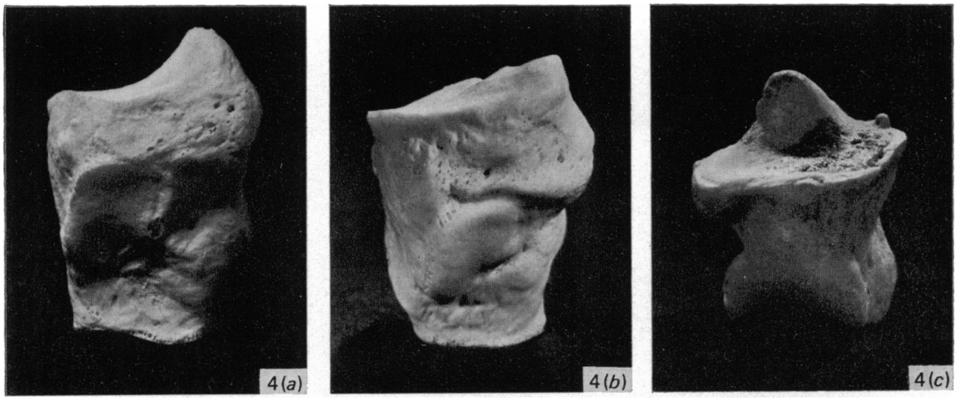
4(a)
4(b)
4(c)


5(a)
5(b)

navicular follows the cuboid in a medial movement on the talus. The fit between the two surfaces of the calcaneocuboid joint is, however, soon lost, and the movement is limited by tension in the tarsal joint capsules and ligaments. Finally, at full supination of the calcaneocuboid joint, the calcaneocuboid ligaments become taut again, thereby limiting further movements. The joint is locked, but not in a close packed position, as the articulating surfaces only oppose each other partly.

In the apes the concavoconvex form of the calcaneocuboid joint was evident also. There appeared, however, two differences when compared with the human joint. The nearly flat variety was found in six of the eleven specimens, and seems thus to be more frequent. The guidance of the movements was correspondingly less precise. Secondly it was found that the calcanean process of the cuboid had a median position on the bone, and a flat, articulating periphery on its medial side in addition to the dorsal and lateral sides (Fig. 4*c*). The calcaneus was shaped correspondingly and, in contrast to the human bone, had its anteromedial corner extended anteriorly to articulate with the medial part of the cuboid (Fig. 5). Because of this symmetry of the joint, and because the calcaneus did not overhang the cuboid dorsally, there appeared to be no close packed position.

High and low gear push off

The performance of the foot at high and low gear push off was studied on a walk-way in which a glass plate was inserted. The progress of the contact area could be followed through an underlying mirror, and the footprint was enhanced by illuminating the glass plate with UV-light through the rear edge (Grundy, Tosh, McLeish & Smidt, 1975). The events were filmed with a Milliken high speed camera at 120 frames per second and with an Ectachrome V.N.F. film developed to 1500 ASA.

At high gear push off, over the transverse metatarsophalangeal axis, the contact area was transferred from the heel to the medial part of the ball of the foot and on to the great toe. The forefoot was observed to be pronated in relation to the hind foot, and the lateral part of the ball was elevated very early from the ground. The plantar aponeurosis became tensed and could be seen through the skin (Fig. 6*a*). The tensed tendon of the peroneus longus was visible on the lateral aspect of the foot.

At low gear push off, over the oblique axis, the contact was transmitted from the heel to the lateral part of the ball of the foot. The push off continued as a rolling action over this part while the lateral toes were forced into dorsiflexion and the great toe stabilized the foot on the medial side. The leg became externally rotated, the foot inverted at the subtalar joint and the forefoot adducted in relation to the

Fig. 4(*a*). Right cuboid from man. Dorsomedial aspect, showing the contour of the proximal joint surface with the calcanean process, and the flat peripheral part of the concavoconvex joint. (*b*) Right cuboid from man. Dorsomedial aspect. The proximal joint surface possesses no calcanean process, and the calcaneocuboid joint can, in this case, be classified as a plane joint. (*c*) Right cuboid from chimpanzee. Dorsolateral aspect. The calcanean process is pronounced and is surrounded on three sides by a flat peripheral joint surface.

Fig. 5. Right calcaneocuboid joint from (*a*) man and (*b*) gorilla. Plantar aspect. The calcanean process (arrow) extends posteriorly into a recess on the calcaneus. In man the process is located asymmetrically, with the joint surface on its lateral and dorsal sides only. In the anthropoids the calcaneus and the cuboid are extended in a medial direction (asterisk). The calcanean process assumes thereby a median position, with the joint surface on its medial, dorsal and lateral aspects.

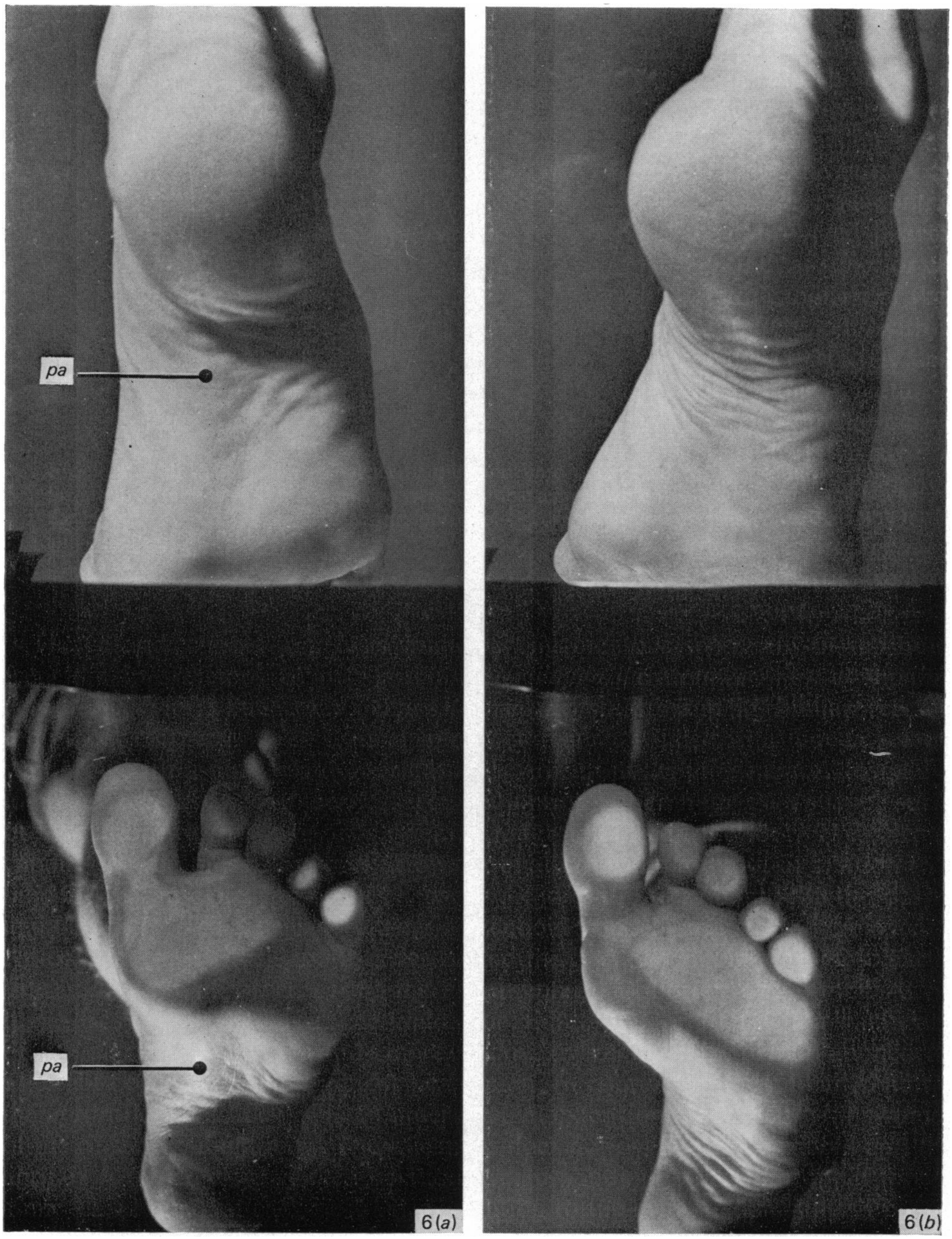

Fig. 6. Right foot performing a push off about the transverse axes (*a*) and about the oblique axes (*b*). The foot is placed on a glass plate, and the sole with the footprint can be seen through an underlying mirror. In (*a*) the lateral edge of the foot is raised and the forefoot is slightly pronated. The medial part of the ball and the great toe have the contact and the plantar aponeurosis (*pa*) is tensed and can be seen through the skin. In (*b*) the foot is inverted and the contact lies on the central and lateral parts of the ball. The hind foot is adducted and plantar flexed in the transverse tarsal joint, and the plantar aponeurosis is slack and can neither be seen nor felt through the skin.

hind foot, i.e. in the transverse tarsal joint. The medial arch became high, but neither the plantar aponeurosis nor the peroneus longus could be seen through the skin (Fig. 6*b*).

Observations on ligamentous specimens

Ligamentous specimens of ten human feet were prepared by removing skin, muscles, tendons and all other soft tissues except the joint capsules and the extra-capsular ligaments. In three specimens the plantar aponeurosis was also preserved with its deep connexions through the ten sagittal septa to the proximal phalanges of the five toes (Bojsen-Møller & Flagstad, 1976). Metal rods were inserted *in lieu* of the transverse and oblique metatarsophalangeal axes, and with these alternately fixed to the ground the two kinds of push off were studied by elevating and rotating the two crural bones.

Movements about the oblique axis were thus brought about by an elevation and an external rotation of the crus, involving inversion of the foot. The calcaneocuboid joint became loose packed, with the hind foot adducted and flexed in relation to the forefoot. Consequently, the distance from the tuber calcanei to the metatarso-phalangeal joints became shorter, and the plantar aponeurosis became slack and unable to support the arch (Figs. 3, 7*a*).

Push off about the transverse axis was simulated by an elevation and an internal rotation of the crus. The calcaneocuboid joint became close packed, and this was especially evident if the cuboid was rotated (pronated) by a pull in the peroneus longus tendon. The short plantar ligaments became taut, and the transverse tarsal joint was locked and stable. As the foot became straight in the transverse tarsal joint, the plantar aponeurosis became tensed and able to tie the anterior and posterior pillars of the longitudinal arch even before the heel had left the ground and the windlass function of Hicks (1954) was initiated (Fig. 7*b*).

The plantar aponeurosis inserts anteriorly on the proximal phalanges of the toes. When the toes are dorsiflexed, in specimens or in living feet, the aponeurosis is wound around the heads of the metatarsal bones. The two extremities of the longitudinal arch are thereby approximated and the arch is tied together. This is called the windlass mechanism (Hicks, 1954).

The effectiveness of the windlass depends on the length of the plantar aponeurosis in relation to the arch, and on the radius of the drum.

At high gear push off, where the aponeurosis is pre-tightened, the windlass can build up tension in the aponeurosis as soon as the heel leaves the ground and the toes become dorsiflexed, while at low gear push off the windlass first must take up the slack in the aponeurosis as described above.

The radius of the drum, i.e. the radius of the metatarsal heads, was measured in the specimens by dorsiflexion of the toes through one radian. The distal displacement of each of the insertions of the plantar aponeurosis against its metatarsal head equals hereby the radius for that joint. In the ten specimens the displacement, and thus the radius for the first and third toe, was found to average 15 mm and 8 mm respectively. The head of the first metatarsal bone is not only the biggest, but its radius is further enlarged by the presence of the two sesamoid bones. Consequently it is more effective as a windlass than the four lateral metatarsal heads (Fig. 8).

At high gear push off there is thus a combination of a pre-tightening of the plantar aponeurosis and an engagement of a drum with a bigger radius in the windlass

7(a)

7(b)

Fig. 7. Ligamentous specimen of a human right foot. The plantar aponeurosis extends from the tuber of the calcaneus and is connected through deep septa to the proximal phalanges of the toes. In the upper Figure the crural bones are externally rotated. The hind foot is thereby adducted in the transverse tarsal joint and the plantar aponeurosis becomes slack and wavy. In the lower Figure the crural bones are internally rotated. The foot becomes straight in the transverse tarsal joint, and the aponeurosis is pre-tightened and ready to support the arch.

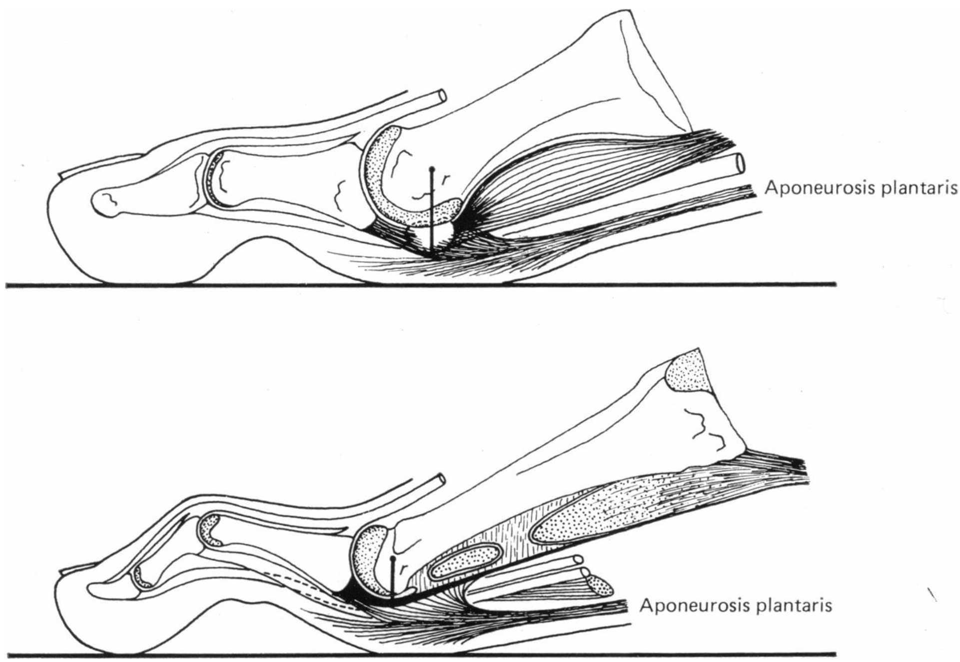

Fig. 8. Diagram showing the first and third metatarsophalangeal joints. The fibres of the plantar aponeurosis are divided in the ball of the foot into superficial fibres for the skin and deep fibres which proceed through the sagittal septa to a facet on the base of each proximal phalanx. The size of the radius (*r*) is decisive for the effectiveness of the windlass which winds the plantar aponeurosis around the metatarsal heads when the toes are dorsiflexed. In the first metatarso-phalangeal joint the radius is approximately twice as big as in the lateral ones because of the size of the head and the presence of the two sesamoid bones.

mechanism. In addition, the calcaneocuboid joint is close packed and the total support of the arch is therefore maximal.

DISCUSSION

Concavoconvex joints were named saddle joints by A. Fick (1854). He and R. Fick (1911) conceptualized them as a symmetrical, saddle-shaped section of a rotation hyperboloid (Fig. 2). For small movements the joints were described as two-axial, and this has since become accepted. The first carpometacarpal and the calcaneocuboid joints are the two typical examples of saddle joints given in human anatomy textbooks.

Du Bois-Reymond (1895) observed, however, that the number of degrees of freedom of a joint depends also on the congruency between the surfaces. He found for the first carpometacarpal joint that the convex curvature on each of the adjoining surfaces had a smaller radius than its opposing concave surface, and that the contact therefore was confined to a point. This incongruency gives the thumb a freedom to rotate on itself, and the first carpometacarpal joint is therefore three-axial, at least at all intermediate positions (Bojsen-Møller, 1976).

The calcaneocuboid joint is shaped like an asymmetrical sector of an hour-glass shaped surface of revolution with a very high degree of congruency between the opposing surfaces (Fig. 2). Consequently, the joint is two-axial as originally described. Its main axis is located longitudinally in the foot while the secondary axis passes through the lateral part of the body of the calcaneus in a mediocranial direction (Manter, 1941; Shephard, 1951). Important for the function of the joint in man is that it has a close packed position where the longitudinal arch is stabilized and so a mid-tarsal break is prevented. Prerequisite for this locking of the joint is that the calcanean process fits closely into its recess, and that the dorsal border of the calcaneus overlaps the cuboid and stops the pronation of the forefoot. These conditions were not found in the flat variety of the cuboid, probably indicating a less effective locking mechanism in these joints. It could not be determined from the specimens whether such joints were associated with flat feet.

It is the part of the cuboid medial to the calcanean process that is missing in man, resulting in the asymmetry of the joint (Fig. 5*a*). It is probably these medial parts of the calcaneus and the cuboid which, in a few cases, emerge as apophysial, supernumerary ossicles in the area between the calcaneus, the cuboid and the navicular. The ossicles are registered as the calcaneus secundarius and the cuboideum secundarium (Pfitzner, 1895–6; Trolle, 1948).

During low gear push off the foot is raised somewhat on its fibular edge, as shown in Figure 6(*b*), and the stresses are absorbed across the five rayed foot plate. This is similar to the phylogenetically ancient way of using the foot, and it can be compared in present living animals with the propulsive use of the hind limbs of amphibians and reptiles and with that of the climbing foot in arboreal primates (Morton, 1964; Lessertisseur & Saban, 1967). Characteristic of these uses are that the foot is inverted, that it is its postaxial, fibular edge that is exposed to the forces, and that it receives no support from the plantar aponeurosis (Fig. 9).

On the ground the anthropoids must undo the inversion of their feet to obtain a plantigrade position. The stiffness of the now flattish foot is lost and a mid-tarsal break appears at each step. The foot keeps its pliancy, but becomes less effective as a lever, as there is no locking of the calcaneocuboid joint.

This is all changed in man, who has developed a fast, ground covering gait in which the feet are kept parallel and moved about transverse axes.

In the evolutionary remodelling which has given stability to the polysegmented forefoot in this new mode of use, the great toe and its metatarsal bone have been adducted and incorporated in the forefoot, the lateral metatarsal bones have been twisted (pronated) so that their heads and the pulp of the toes rest against the ground, the calcaneocuboid joint has changed as described above, and the forefoot as a whole has been pronated, bringing into existence the arches (MacConaill, 1944–5; Morton, 1964; Preuschoft, 1971).

A general pronation of the hind limb is seen in its evolution from the transverse to the parasagittal position (Lessertisseur & Saban, 1967). The above-mentioned structural pronation of the forefoot is a further step in this process, occurring at the transition from arboreal to terrestrial life. The functional pronation of the human forefoot for the high gear push off is the final step in the process of producing a fast and efficient lever for propulsion. Among the muscles the peroneus longus becomes a key member, as it pronates the forefoot, locks the calcaneocuboid joint, and assists in the internal rotation of the crus which forces the foot to use the transverse axes.

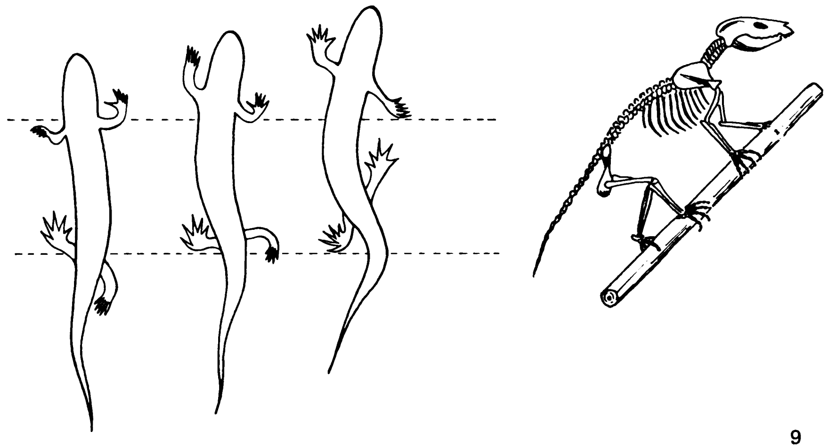

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Fig. 9. The postaxial, fibular border of the hind limb is exposed to the propulsive forces in primitive tetrapods with transversely oriented limbs, as well as in tree-climbing mammals where the legs are swung into a parasagittal position. (Redrawn after Lessertisseur & Saban, 1967, and Morton, 1964.)

SUMMARY

The calcaneocuboid joint was studied in ligamentous specimens of ten human feet, and in skeletons of two gorillas (*Gorilla gorilla beringei*), six chimpanzees (*Pan troglodytes*), three orang utans (*Pongo pygmaeus*) and 25 human feet. The movement of the transverse tarsal joint was further studied in a living foot on a walk-way with a glass plate inserted, and with an underlying mirror. In man the joint is shaped as an asymmetrical sector of one end of an hour-glass shaped surface of revolution with its main axis oriented longitudinally in the foot. The calcaneocuboid joint becomes close packed by a pronation of the forefoot in relation to the hind foot because of a congruency between the joint surfaces obtained in this position and because the calcaneus overhangs the cuboid dorsally and stops the movement. At low gear push off the foot is inverted and the calcaneocuboid joint loose packed. The stresses are absorbed across the fibular, postaxial border of the foot. At high high gear push off there is a functional pronation of the forefoot with a stabilization of the transverse tarsal joint and a more effective tightening of the plantar aponeurosis. The foot becomes a rigid lever for propulsion. In contrast to the human condition, the anthropoid calcaneus has an anteromedial extension associated with symmetry of the calcaneocuboid joint. The calcaneus does not overhang the cuboid and there appears to be no close packed position. Correspondingly, the anthropoid foot has a mid-tarsal break at each push off in addition to the metatarsophalangeal break.

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