THE ANATOMY AND PHYSIOLOGY OF THE FOOT

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When considering this subject it must be remembered that feet are housed in shoes during the waking hours of the owner. Such an apparatus may affect the physiology and will be discussed.

Longitudinal Arch.

In books and papers on affections of the foot, great prominence is given to the arches, yet in a series of two hundred cases of painful feet not more than 20 per cent could possibly be labelled as due to flattening of the arch. The reason is that the term "flat foot" is used very loosely and without due appreciation of the anatomy of the foot.

The classical medial longitudinal arch is described as consisting of the os calcis, astragalus, navicular, the three cuneiforms and 1st, 2nd and 3rd metatarsals, its summit is the superior articular surface of the astragalus and its chief characteristic is its elasticity. Its weakest part is the joint between the astragalus and the navicular, which is braced by the plantar calcaneo-navicular or spring ligament.

A lateral arch is described as consisting of the os calcis, cuboid and 4th and 5th metatarsals.

This classical description is not correct, for, in an amputated leg, the arch will not flatten even if the ligament is cut through. The error has arisen because the skeleton of a foot is usually incorrectly articulated, with the tarsus spread out flat, whereas in life it is not spread out, but the cuboid lies beneath the lateral cuneiform. In many books the illustrations depict such a flattened tarsus, the most glaring example being one purporting to show the outward direction of the foot relative to the axis of the knee. The mal-articulation of the tarsus in this skeleton is the reason the foot points outwards. If properly articulated the foot would point straight forward, as is normal clinically. If a radiograph of a normal foot is examined A.P. view, it can be seen that the tarsus is not spread out but that the lateral cuneiform is superimposed upon the cuboid, and that the navicular overlaps the cuboid. Fig. 1 illustrates this. Fig. 2 illustrates a case of extreme pes plano-valgus, and far more nearly resembles the usual illustrations of what is meant to be a normal foot.

The articular facet on the cuboid for the lateral cuneiform is usually described as being on the medial surface, whereas this facet is really on the supero-medial surface, and is in fact more horizontal than vertical.

This should alter our conception of the architecture of the foot. The medial and lateral longitudinal arches are not separate entities but are one and support each other. When the foot is standing the lateral cuneiform carrying the navicular, intermediate and medial cuneiforms rests firmly on the cuboid, which in turn is supported by the base of the 5th metatarsal which is on the ground.

When the heel is raised, as in running or walking, so that the base of the 5th metatarsal is no longer supported, the arch is still strong because, instead of being a single arch of the old-fashioned stone bridge, it is a double arch, one superimposed upon the other as in modern girder construction. Such an arch can withstand a vertical pressure, but will give way with a lateral thrust on the upper span.

Similarly in the foot, for the arch to flatten, the lateral cuneiform must be forced medially and down, on to the facet on the cuboid. When this happens the whole shape of the foot is altered, the navicular becomes prominent on the medial border and the condition of pes plano-valgus, or the pronated foot, is produced. There is, therefore, no such condition as a pure pes planus but only a plano-valgus.

This is borne out by the illustrations of imprints of the sole in any textbook. Those labelled normal show the external border of the foot on the ground, thus showing that the cuboid is normally supported when standing, while those labelled flat show the bulge on the medial border produced by the navicular in the valgus position.

This deformity can be produced in two ways: first by a rotation of the astragalus on the os calcis; secondly by eversion of the os calcis into the talipes valgus position.

FIG. 1.—Tracing of a radiograph of a foot, A.P. view, to show that the tarsus is not spread out, but that the lateral cuneiform is superimposed upon, and therefore supported by, the cuboid. It is also partially obscured by, and therefore is supporting, the middle cuneiform.

FIG. 2.—Tracing of a radiograph of a foot in a case of extreme pes plano-valgus. The lateral cuneiform has moved medially in relation to the cuboid, and all three cuneiforms are clearly visible.

The articular facets on the os calcis for the astragalus are a concave facet anteriorly and a convex one posteriorly, set obliquely with the interosseous ligament in the middle, so that the only movement that can occur is a slight rocking in an oblique axis, combined with rotation, so that the head of the astragalus moves medially. When this occurs it carries the navicular and cuneiforms medially into the valgus position as described. Out-toeing appears to be the chief cause of rotation of the astragalus, for if a person walks with the foot pointing out, unless he is walking with nearly straight knees, he must have the knee pointing straight forward in order to bend it. As the astragalus is gripped firmly by the malleoli, this must tend to be rotated straight forward, and therefore medially, in relation to the foot.

The mechanics of the second cause of this deformity, eversion of the os calcis, are simple. The cuboid articulates with the os calcis by a saddle-shaped articulation in which rotation is not possible, therefore if the os calcis is everted the cuboid must be as well, and in that position it has rotated so that the facet on it for the cuneiform has moved medially and down. This produces two results: first, the lateral cuneiform carrying the others is moved medially and down into the valgus position; secondly, depending upon the extent to which the facet on the cuboid becomes less horizontal and more vertical, it ceases to be such a direct support under the lateral cuneiform.

Talipes valgus occurs frequently in children, probably the remains of a packing deformity in utero, and may persist into adult life. The most extreme form of pes plano-valgus occurs with rotation of the astragalus in a foot in which the os calcis is already everted. This is seen frequently in children who have been fitted with special built-up shoes to correct a talipes valgus. As such shoes are heavy and will not bend, the child finds it impossible to walk in

them normally, so he turns his feet out and plods. The out-toeing rotates the astragalus medially, with this disastrous result.

Although it is not possible for the arch to flatten, provided the feet are parallel and the os calcis vertical, some increase occurs normally when the person stands on tiptoe. In lateral radiographs taken of the two positions it was found that the movement was almost entirely one of flexion of the metatarsals on the tarsus.

Forepart of the Foot.

In the series quoted before, 60 per cent of the cases complained of pain in the region of the heads of the metatarsals, so that this is an important part of the foot.

The first consideration is the question of a transverse arch, for, although not generally described, it is firmly believed in by all the public and many in the profession.

The chief anatomical fact in this region is that the metatarsal heads are not in a straight line, but resemble the fingers in that some are longer than others.

If a hand is resting flat on a table all the finger tips will rest on the table, but if the wrist is raised one to two inches, then only the tip of the third finger, which is the longest, remains on the table unless the others are depressed. In the same way with the foot, when the heel is raised, as by the heel of a shoe, only the head of the longest metatarsal would be on the ground unless the others were depressed.

Now Morton and Mennell consider that normally the first metatarsal is the longest and should be the bearer of weight, and state that many foot troubles are due to a short 1st metatarsal.

On analysis of one hundred radiographs of normal feet it was found that the 1st metatarsal was equal in length to the 2nd in 53 per cent, whereas it was longer in only 19 per cent, and shorter in 28 per cent. These figures agree roughly with Lake's.

As regards the remaining metatarsals, the lengths again are variable but the 2nd is more commonly longer.

FIG. 3.—Tracing of a radiograph of a foot in which the 1st metatarsal is equal in length to the 2nd, and the 2nd is longer than the 3rd. This is the commonest type. The patient complained of pain under the head of the 2nd metatarsal, so that the straight line probably represents the floor when standing in a heeled shoe, and upon it only the 2nd metatarsal is resting fully.

Fig. 3 is a tracing from the radiograph of the foot of a patient complaining of pain under the head of the 2nd metatarsal. The line of the metatarsal heads is the commonest one, and the 1st metatarsal is equal in length to the 2nd. As can be seen in such cases, the 2nd appears to be the most prominent.

As just described, when such a foot is standing flat all the metatarsal heads can rest on the floor, but when the foot is standing with the heel raised an inch or two by the heel of the shoe, the transverse line represents floor upon which the 2nd metatarsal only is fully resting, the remaining metatarsals must either not take full weight or be depressed varying degrees to be weight bearing.

Thus we see that a transverse metatarsal arch is a case of wishful thinking, for if there was one, a foot would be better adapted to fit a shoe.

Fig. 3 is a similar tracing of a case with pain under the heads of the 2nd, 3rd and 4th metatarsals, and the transverse line represents the floor, as the heel stands in a heeled shoe.

The next consideration is weight distribution in a standing foot. Morton states that half the weight is taken by the heel and half by the forepart of the foot, but he does not discuss the height of the heel. In order to find out the effect of a heel his experiments were repeated, though with less accurate instruments. Volunteers stood first in their shoes, and the weight on heel and forefoot was recorded, then they stood barefooted and it was recorded again. The results in shoes were fairly constant, the results barefooted were extremely variable, suggesting that the sudden change over from high heels to flat made balance difficult, so that no reliance could be placed on these readings.

In 74 per cent of women in high-heeled shoes greater weight was taken on the heel than forefoot, the average ratio being $5\frac{1}{2}$ on heel to 4 on forefoot. In males with a $\frac{1}{2}$ -inch heel or less, the average ratio was 7 on heel to 4 on forefoot.

These results do suggest that a high heel increases the proportion of weight on the forepart of the foot.

Muscles.

The muscles of the foot consist of the extrinsic and intrinsic, the latter usually being described in four layers. The table below puts them into groups according to their main action during walking and normal use.

1. *Plantar flexors of ankle.*

Gastrocnemius. Soleus. Plantaris. Flexor digitorum longus. Flexor hallucis longus.

2. *Dorsiflexors of ankle.*

Tibialis anticus. Peroneus tertius. Extensor digitorum longus. Extensor hallucis longus.

3. *Muscles that form a brace on each side of the tarsus, prevent inversion or eversion and render the foot stable.*

Peroneus longus et brevis. Tibialis posticus.

4. *Toes.*

Plantar flexors of proximal phalanges on metatarsals.

Lumbricales. Interossei dorsales et plantares. Flexor brevis hallucis. Flexor brevis minimi digiti. Adductor hallucis. Abductor hallucis. Abductor minimi digiti. Flexores longus et brevis digitorum, but only when the phalanx is not dorsiflexed.

5. *Flexors of interphalangeal joints.*

Flexores digitorum longus et brevis. Quadratus plantæ. Flexor hallucis longus.

6. *Dorsiflexors of proximal phalanges on metatarsals.*

Extensores digitorum longus et brevis. Extensor hallucis longus.

7. *Extensors of interphalangeal joints.*

Lumbricales. Interossei dorsales et plantares. Extensores longus et brevis digitorum if assisted by above. Extensor longus hallucis.

If the everyday use of these muscles is considered, it can be seen that:—

1. The plantar flexors of ankle are used fully daily.

2. The dorsiflexors of ankle are also used but, as pointed out by Crisp, the extensor longus digitorum is used in many cases more than the tibialis anticus, so that the toes are pulled into the clawed position at the same time as the ankle is dorsiflexed. Although the extensor digitorum should not be the prime mover, the interossei and the lumbricales should prevent the clawing, as will be discussed later.

3. Those that brace the tarsus should be used in normal walking but often are not used fully, in such sloppy gaits as the "heel and flap," to be discussed later.

As regards the movement of the toes, these are restricted by the shoe. There is usually room for flexion of the interphalangeal joints but that is about all.

The action of the muscles in group 4, flexors of proximal phalanges, is severely limited because of the presence of the sole of the shoe, which limits the movement. The matter is made worse because in an ordinary heeled shoe the toes are permanently dorsiflexed owing to the angle the metatarsals make with the ground. Fig. 4 represents a tracing of a metatarsal and

FIG. 4.—Tracing of a metatarsal and phalanges from a radiograph of a foot in a shoe with cuban heel, lateral view. The metatarsal is placed horizontally to make the dorsi-flexion of proximal phalanx more obvious.

phalanges from a radiograph, lateral view of a foot in a shoe with an ordinary cuban heel. The metatarsal is placed horizontally to make the dorsiflexion more obvious. Even in a male shoe with a lower heel than the above the dorsiflexion is considerable owing to the upward curve of the forepart of the sole.

In the case of the 1st toe these intrinsic muscles are inserted into the base of the proximal phalanx, so can still act efficiently although the phalanx is dorsiflexed. This applies also in the case of two out of the three muscles of the 5th toe.

As regards the others, the lumbricales and interossei are inserted into the sides of the base of the proximal phalanges and the expansion of the extensor tendons, so that when the toes are dorsiflexed these muscles are working at a mechanical disadvantage.

There is another consideration as regards the majority of these muscles, in that their prime action is adduction or abduction movements, not possible in a shoe or practised by many out of one.

Now running in a light shoe all these muscles are used. Running in a heavy stiff boot the foot is used less and the heel more. This is demonstrated well in professional soccer players whose quadriceps are overdeveloped and the muscles of the foot underdeveloped.

In walking in a heeled shoe the average woman's gait can best be described as "heel and flap." The heel is brought down to the ground and the toes just flap down in a toneless fashion. In such a gait muscles exercising ankle control do some work but, as there is no active push off by the toes, the intrinsic muscles are not used.

As regards the skeleton of the foot, such a gait must cause a minor degree of trauma to the head of the most prominent metatarsal or metatarsals (and sometimes a "march fracture"). Whereas in a gait with active use of the forepart of the foot, the motion is more in the nature of a roll across the metatarsal heads, starting from the 5th.

We thus see that these muscles in group 4 can be fully developed in few people, and in

many must suffer some degree of disuse atrophy, the interossei and lumbricales being chiefly affected.

The result in many cases is clawing of the toes, as the extensors cannot extend the interdigital joints without the assistance of these muscles. The result produced is comparable in appearance in many cases to the 4th and 5th fingers with an ulnar nerve lesion and complete paralysis of the lumbricales and interossei to those fingers.

The factors just discussed have an important bearing on the production of that very common deformity, splaying of the metatarsal heads, which again is the most important antecedent of hallux valgus.

Anatomically the structures binding together the heads of the metatarsals are the transverse metatarsal ligament, which connects the plantar ligaments of the metatarso-phalangeal articulations; the adductor hallucis transversus, which is the only muscle directly connecting the metatarsal heads; lastly the dorsal interossei which arise from adjacent sides of the metatarsal shafts and so would assist in holding them together to some extent.

These structures are not very strong, but in standing flat no strain would be put upon them. In a heeled shoe, however, not only is a strain thrown upon the metatarsal heads, but the only muscles that can resist that strain are in the group of those most atrophied.

Bursae.

The most common situation is over the 1st metatarso-phalangeal joint when this is enlarged from a hallux valgus or rigidus.

Two bursae occur about the heel. The tendo Achillis is inserted into the middle of the posterior surface of the os calcis, and between the tendon and the upper half of the posterior surface is a pad of fatty bursal tissue. In some persons the upper posterior part of the os calcis projects further back so that the tendon forms a prominence passing over it. In such cases a bursa will form beneath the skin over this prominence, from the rub of the shoe.

Another bursa is not uncommonly found over an enlarged joint between the medial cuneiform and 1st metatarsal. This results from the 1st metatarsal riding up on the cuneiform, and the articular surface of the bone enlarges to accommodate it.

Summary.

In a properly articulated skeleton of a foot the articular facet on the cuboid for the cuneiform is nearly horizontal, so that the lateral cuneiform rests firmly upon it. The medial and lateral longitudinal arches are not separate entities but are one. The medial arch cannot be directly depressed, and can only flatten if the cuneiform moves medially on the cuboid, in which case a valgus deformity of the foot is produced.

The intrinsic muscles of the foot are of great importance, but tend to a disuse atrophy as a result of footwear. A raised heel throws greater weight and strain on the forepart of the foot, the head of the longest metatarsal being particularly affected.

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