THE MECHANICS OF THE FOOT

II. THE PLANTAR APONEUROSIS AND THE ARCH

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INTRODUCTION

In a normal living foot that is weight-bearing, as in ordinary standing, passive extension of the big toe at the metatarso-phalangeal joint will be observed to result in the following effects:

(i) the arch appears to rise (Pl. 1, figs. 1, 2);
(ii) the posterior part of the foot assumes an 'inverted' position (supinates);
(iii) the leg rotates laterally;
(iv) there appears a tight band in the region of the plantar aponeurosis (Pl. 1, figs. 2, 3).

It has been explained in a previous paper (Hicks, 1953) that (i) is synonymous with flexion of the first ray. The terms 'flexion of the ray', 'rising of the arch' and 'downward movement of the metatarsal head' will therefore be used alternatively throughout the present paper. It was also explained that (ii) and (iii) occur whenever individual flexion of the first ray—and in consequence pronation twist of the forefoot—takes place in the standing foot. The short terms 'flexion' and 'extension' are being used for a movement which has previously been shown to be really flexion-pronation extension-supination. The present discussion is not invalidated by this approximation.

When the load is light or when it is being borne mostly on the heel, toe extension to its limit (about 90° to the line of the metatarsal) can be brought about with comparatively little force, and in these circumstances the subject's own extensor hallucis longus muscle will succeed in bringing about the action. A few trials will reveal, however, that as a greater proportion of body weight falls on to the anterior part of the foot the toe extension requires greater force, the extensor muscle becomes inadequate, and the subject experiences an almost painful feeling of tightness in the sole. At this stage he tends to invert his foot voluntarily to relieve this painful sensation. These effects, however, also occur in the dead or the paralysed foot, so it is evident that the action of the invertor muscles of the foot is not necessary.

The four observations listed above also hold in toe-standing (Pl. 1, fig. 3), the metatarso-phalangeal joints in this case being caused to extend by pressure of the toes against the ground. This is a familiar test in the clinical examination of the foot, the usual, though erroneous, interpretation being that the arch-raising muscles have thereby been proved to be working satisfactorily.

When the foot is free, the arch-rising effect is manifested as a movement of the metatarsal head downward relative to the fixed posterior part of the foot. An attempt to oppose this will reveal that—so long as metatarso-phalangeal extension is achieved—the downward shift of the metatarsal head is irresistible. It is demonstrable in lesser degree in the second, third and fourth rays, a prominence of the metatarsal head in the ball of the foot being the manifestation of its downward shift relative to the rest of the foot. This prominence disappears and the metatarsal head recedes into line with its neighbours when the toe is released and allowed to flex. The effect is almost absent in the fifth ray.

Although the association of arch-rising with toe-extending is recognized by orthopaedic surgeons no attempt has been made to explain it and its existence receives no more than an incidental mention in the literature (Jack, 1953). A short version of the present work has appeared previously (Hicks, 1951).

In the standard anatomical text-books no reference is made to the plantar aponeurosis as an agent in raising the arch, although several text-books (Buchanan (1949), Cunningham (1951), Gray (1949)) include it amongst other structures, e.g. plantar ligaments and muscles, which maintain the arch, likening it to the string of a bow. Concerning the anterior attachment of this bow-string there is general agreement that, having divided into five digital processes, the main part of the plantar aponeurosis becomes attached to the sesamoid bones, the deep transverse ligament of the sole and the fibrous sheaths of the flexor tendons and hence to the proximal phalanges. The importance of the mechanical effect of the attachment to the phalanges will be explained in this paper.

MATERIAL AND METHODS

The material described by Hicks (1953) was used.

I. The effects of extending the toes at the metatarso-phalangeal joints were observed in the experimental foot in the natural conditions of standing.

II. Dissection was carried out to identify the tight band observed in the sole and to examine its mechanical effects. This involved a study of the plantar aponeurosis and especially of its anterior attachments. The aponeurosis was ultimately divided to determine whether or not it was essential to the arch-raising mechanism.

III. Before dissection had proceeded far enough to interfere with the mechanism radiographic examination was made to demonstrate it in action. The aponeurosis, the process going toward the toe, and the plantar pad of the metatarso-phalangeal joint were marked by metal clips. Radiographs, both with toes flexed and toes extended, were taken using techniques designed to demonstrate changes in arch height.

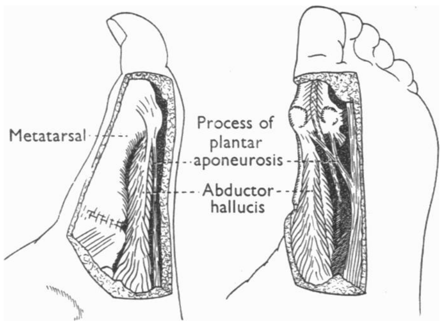
IV. Analysis of the metatarsal movement was made by the method of the artificial axis (Hicks, 1953).

V. The living foot was examined in action by cinematography and radiography, and the movements occurring at the heel-raising phase of walking were identified with those observed in the specimen.

OBSERVATIONS AND INTERPRETATIONS

I. All the effects described on p. 25 in the living foot were observed to occur in the specimen. It was concluded, therefore, that the mechanism is independent of muscles.

II. Dissection revealed that two structures play an important part functionally. They are the plantar pads of the metatarso-phalangeal joints and the plantar aponeurosis which is attached to them through its five digital processes. The plantar pad is the thick conjoined tendon and capsule on the plantar aspect of each joint. The name is adopted from a paper by Haines (1947), although, as will presently become clear, it is not fully appropriate, suggesting as it does the function of a cushion rather than that of a cable. Each plantar pad with its attached process of plantar aponeurosis was seen to constitute a continuous strong band forming a direct connexion between the proximal phalanx and the calcaneum like a tie or bow-string. Each tie was observed to become tense when an attempt was made to push the corresponding metatarsal head upwards and all became tense in standing. This tension appeared just as the ray reached its limit of extension, which is to say when



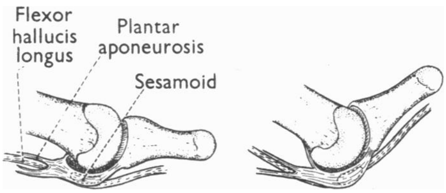
Text-fig. 1. Semi-diagrammatic drawings of a dissection of the arch-raising mechanism.

the arch reached its limit of flattening. If the toe to which it was attached was first held in extension, the tie was observed to become tense at an earlier stage, i.e. it prevented the ray from reaching its usual limit of extension. Alternatively, if the ray was initially pushed into the fully extended position and then the metatarso-phalangeal joint was extended, the ray became forcibly flexed, being pulled into flexion by a progressive shortening of the tie.

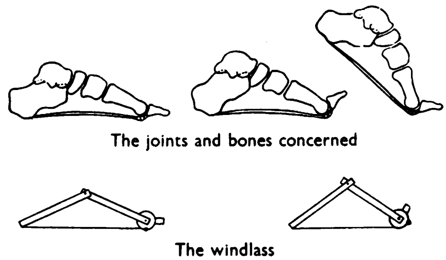
To explain these phenomena the following details of structural anatomy are necessary. Although made independently they are in close conformity with the description given by Haines whose other observations are also fully confirmed.

The five strong processes into which the plantar aponeurosis divides, each split into two slips which straddle the toe flexor tendons (Text-fig. 1). The larger part of each slip fuses with the plantar pad near to the sesamoid thickening. The insertions were of substantial size in the specimens quoted (though less obvious in certain senile feet), being comparable with the adjacent insertions of the short muscles. The plantar pad (Text-fig. 2) is broad and thick. It is connected very firmly to the base of the proximal phalanx, not only to the lower rim of the articular facet but also blending with the periosteum on the inferior surface. Its superior aspect is an articular surface continuous with that of the proximal end of the phalanx and forming two-thirds of the total surface for articulation with the metatarsal head. It moves with the phalanx, being free to slide anteriorly and posteriorly underneath the metatarsal head. At the same time the toe flexor tendons slide equally freely underneath the plantar pad and have no direct mechanical action upon the mechanism. The part of the joint capsule attached to the neck of the metatarsal and closing the joint cavity proximally is lax and tenuous allowing of free movement but having little mechanical strength.

Haines has pointed out a continuity of ligamentous tissue over the surface and around the sides of the sesamoids, and it is apparent that together with the plantar aponeurosis the plantar pads provide a continuous band of ligamentous tissue between calcaneum and proximal phalanges suitable to the transmission of a mechanical pull to or from the phalanges.



Text-fig. 2. Mechanical detail at the metatarso-phalangeal joint.



Text-fig. 3. The windlass.

The toe-extending arch-raising effect was seen to occur as follows. When the toe was extended, the phalanx, sliding on to the dorsum of the metatarsal head, pulled after it the plantar pad which thereby came to lie anterior to the metatarsal head and this in turn pulled upon the attached process of the plantar aponeurosis. The effect was as though a cable had been wound one-quarter of a turn on to the drum of a windlass (Text-fig. 3; Pl. 1, figs. 4, 5), the drum of the windlass being the head of the metatarsal, the handle which does the winding being the proximal phalanx and the cable which is wound on to the drum being the plantar pad and the plantar aponeurosis. The effective length of the cable was shortened by, in the case of the first ray, about 1 cm. Actually the aponeurosis did not shift distally because of its attachment to the calcaneum; instead it was the windlass which shifted, being pulled 1 cm. proximally towards the calcaneum (cf. Text-fig. 4) and the arch was thereby made shorter and higher. When one toe alone was extended the corresponding metatarsal head was found to be moved by the mechanism posteriorly and downwards out of line with its neighbours in the ball of the foot and to remain there as a prominence resistant to all pressure until the metatarso-phalangeal joint was allowed to flex again.

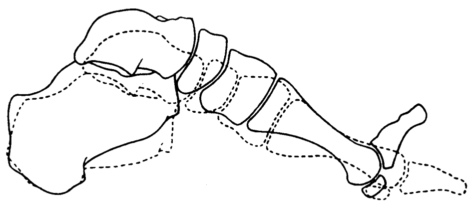
To confirm that the 'cable' is strong enough to perform this function, tests were made in four specimens outside the series. It was found that the total breaking strain of the mechanism to the five toes ranged from 1·7 × to 3·4 × body weight.

When the plantar aponeurosis was cut across, the arch-raising action almost disappeared.

No muscle is directly concerned in the mechanism which is entirely bony and ligamentous, the work of raising the arch being done usually by body weight. The action is analogous to the 'tendon action' of muscles that cross two joints described by Elftman (1939).

III. The radiographs (Pl. 1, figs. 4, 5) demonstrate this flexion of the ray which results when the toe is extended, the metal clips showing up the windlass effect. Radiographs of the living foot revealed similar effects, and tracings from these, superimposed (Text-fig. 4), demonstrate the approximation of metatarsal head to calcaneum, also the ray flexion or increase in height of the arch. The sesamoid shadow acts as a guide to the position of the plantar pad as the metal clips do in the experimental foot.

IV. The measured range of movement as brought about by the windlass varied in different specimens but the findings averaged about half of the full range of which the joints were capable, being about 10° for the first ray (full range = 22°) and about 5° for the lateral rays (full range = 10°). This range was from a position of full extension to one of semi-flexion. The movement took place at the naviculo-cunei-



Text-fig. 4. Tracings from radiographs of a living foot, standing. Dotted line: toe-flexed low-arch position. Continuous line: toe-extended high-arch position.

form and cuneo-metatarsal articulations and movement at other articulations did not occur when the foot was free. (The movement at the talo-navicular articulation, which can be detected in the tracings (Text-fig. 4), is a manifestation of talo-calcaneo-navicular joint movement, viz. supination-adduction-flexion ('inversion') which is one of the secondary movements that occur when the foot is standing.)

Although this mechanism exists in each of the five rays its effects are most marked in the first ray. Thus, when all the toes are equally extended, the first ray shows the greatest degree of flexion and the fifth the least. This is pronation twist of the fore-foot (Hicks, 1953). The consequences of fixed pronation twist of the forefoot when standing have been described in the previous paper as supination of the posterior part of the foot and lateral rotation of the leg.

V. The mechanism functions each time a step is taken. During the phase when the foot is rising on to the toes the toes are being extended by pressure against the floor. A cinematograph film was made of the foot of a person walking, and it was seen that the arch does rise during this phase. The effect of the ray flexion in walking is to increase the range and speed of flexion over and above that which occurs at the ankle alone and to provide a foot which does not yield to the increasing forces at the toe-rising phase but which tends to flex and thrust downwards with an additional 'flick' on taking off. The new concept which emerges is that the arch-raising is not necessarily the result of action by arch-raising muscles but is a movement that must inevitably occur in every foot, even if dead or paralytic, every time the toes are extended. This, however, must not be taken to imply that muscles never have an action upon the arch.

The mechanism should also work in reverse, i.e. the effect of body weight should tend to flatten out a raised arch, the flattening of the arch should tend to unwind the windlass, and the unwinding of the windlass should tend to flex the toe at the metatarso-phalangeal joint. Experiment showed this to be the case. When the foot, dead or living, is made to bear weight the toes are found to press upon the ground by a flexion action arising at the metatarso-phalangeal joints. This pressure, in the experimental specimen, was found to vary with body weight. The effect disappeared when the plantar aponeurosis was divided. It can be concluded, therefore, that part at least of the 'gripping action' of toes on ground so often referred to in discussions on walking is not due to the action of the toe flexor muscles.

SUMMARY

1. The plantar aponeurosis at its distal end is attached through the plantar pads of the metatarso-phalangeal joints to the proximal phalanges. The attachment is mechanically very strong.

2. When the toes are extended they pull the plantar pads and hence the aponeurosis forward around the heads of the metatarsals, like a cable being wound on to a windlass. The arch is caused to rise because the distance between the metatarsal heads and the calcaneum is thereby shortened.

3. The toes are forced into an extended position in toe-standing and walking by the action of body weight, and the arch is caused to rise by this ligamentous mechanism without the direct action of any muscle.

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EXPLANATION OF PLATE 1

Figs. 1, 2, and 3. Normal living foot.

Fig. 1. Relaxed flat standing. The arch is at the lower limit of normal range.

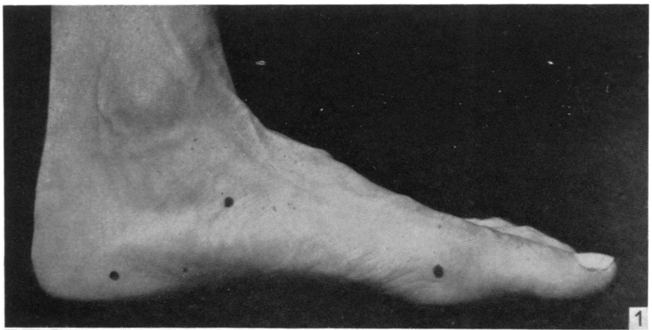
Fig. 2. Extension of the toe causing the arch to rise.

Fig. 3. The same effect occurring in toe-standing. The tight band of the plantar aponeurosis is seen in the sole.

Figs. 4, 5. Radiographs of the windlass mechanism in the experimental foot. Metal clips have been fixed to the plantar aponeurosis, to its process going towards the big toe and to the plantar pad of the metatarso-phalangeal joint. (The upward convexity of the main part of the aponeurosis is due to the intermuscular septum attached deeply.)

Fig. 4. Toe-flexed low-arch position.

Fig. 5. Toe-extended high-arch position.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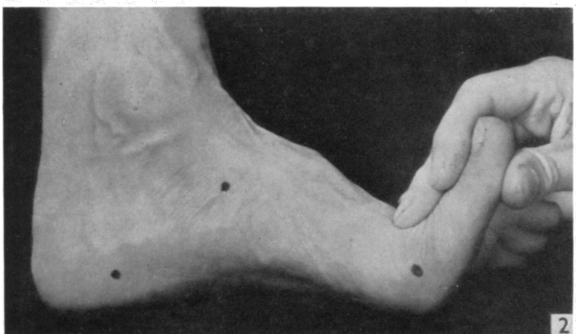
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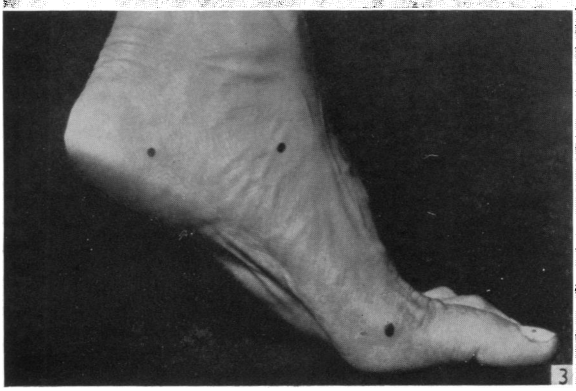
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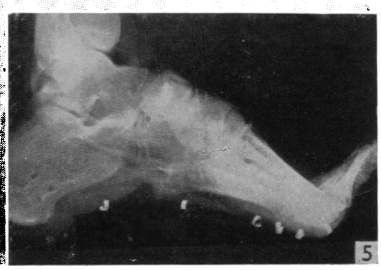
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