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SIGNIFICANCE OF FREE DORSIFLEXION OF THE TOES IN WALKING

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Dissection reveals that the ball of the foot contains a connective tissue framework with transverse, vertical, and sagittal fibers, all connecting the skin with the proximal phalanges of the toes. Dorsiflexion of the toes tightens the framework and thereby restricts passive movements of the skin, enabling shear forces to be transferred to the skeleton. An electromechanical oscillator was constructed that applied oscillatory shear forces of constant amplitude (±0.2 N) to the skin and at the same time measured the resulting motions. It was found that the toes should be dorsiflexed by 35–40° to restrict skin mobility to 50 per cent and by 50° to restrict it maximally. The results were compared to actual dorsiflexions of toes during walking. These dorsiflexions were measured on slow motion film and with still pictures with light tracks formed by light emitting diodes. Maximal dorsiflexion during push off was found to be 60° for feet walking without shoes, 45–50° for feet walking in soft shoes, and 25–30° for feet walking in a stiff shoe of the minus-heel type. Dorsiflexion was further found significant for arch support and for the mechanics of the forefoot during push off.

Key words: biomechanics; foot; gait; ligaments; metatarsophalangeal joint; photography

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The ball of the foot consists of three transverse zones, each with a specific connective tissue frame (Figures 1 and 2): 1) a distal zone mainly with transverse lamellae, 2) an intermediate zone, in which vertical fibers form a connective tissue cushion below each metatarsal head, and 3) a proximal zone in which ten sagittal septa pass the deep fibers of the plantar aponeurosis to the proximal phalanges of the five toes (Henkel 1913, Bojsen-Møller & Flagstad 1976). Fat lobules are enclosed between the elements of the framework, and the two tissues endow the ball with softness and great internal strength.

The lamellae, the cushions, the septa and the plantar aponeurosis are all attached to the skin as well as to the proximal phalanges. At each dorsiflexion of the toes the slack of the fibers is therefore taken up, causing the soft and pliable ball to be transformed into a firm pad that can resist tangential, or shear, forces. This happens twice during the stance phase: at foot contact, where there is a stopping of the forward movement of the foot, and at push off, where the foot transmits a backward force against the ground (Napier 1957, Close et al. 1967). It is the purpose of the present paper to describe and illustrate the dorsiflexion of the toes and its functional significance in walking, including how tangential forces are intercepted and how shoes can affect the function.

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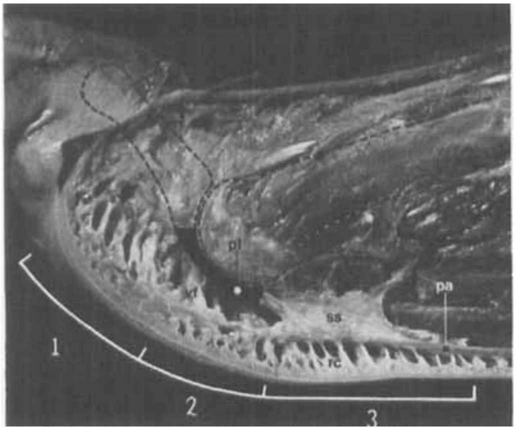

Figure 1. Sagittal section through the second interosseous space of a left foot. Fat is removed to show the connective tissue framework of the ball of the foot. The metatarsal bone, the proximal phalanx and the plantar ligament (pl) are outlined. The ball consists of 1) a distal zone with 4–5 transverse lamellae and the insertion in the skin of the plantar aponeurosis (pa), 2) an intermediate zone in which vertical fibers (vf) form a cushion below the metatarsal head, and 3) a proximal zone in which retinacula cutis (rc) and the deep fibers of the plantar aponeurosis are connected through sagittal septa (ss) to the plantar ligament. The fibers of all three zones are ultimately attached to the proximal phalanx and become tensed when the phalanx is dorsiflexed.

Duration and range of the dorsiflexion

Two gait cycles for each of 21 students with normal feet were filmed at 200 frames per second using a 16 mm ciné camera placed at ground level. A few cycles were also filmed at 400 frames per second. The students walked barefooted with cadences and step lengths of approximately 100 steps per minute and 65 cm, respectively. The film was analyzed frame by frame and the duration and range of the dorsiflexion of the toes were measured.

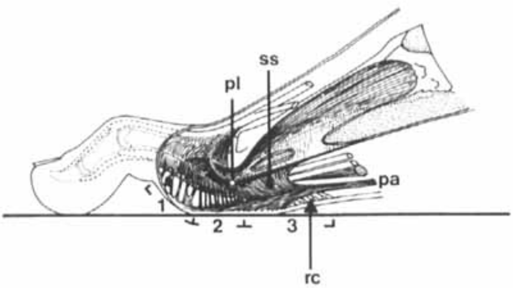

Figure 2. Diagram showing the connective tissue framework of the three zones of the ball of the foot. Abbreviations as in Figure 1.

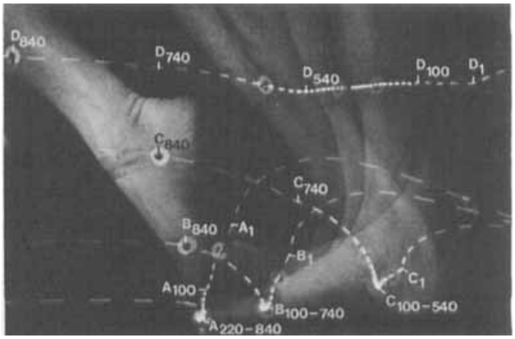

Figure 3. Stance phase of right foot. Medial aspect. Light emitting diodes placed at the tip of the great toe (A), at the metatarsophalangeal joint (B), below the medial malleolus (C), and on the medial side of the shank (D) form four light tracks. Each light-dark period represents 20 ms. They are numbered consecutively from time 1 at heel strike to lift off 840 ms later. The positions of the foot and leg are further shown for each 200 ms. The shock absorbing calcaneograde phase lasted 100 ms. From time 100 to time 540 the foot has rested with its sole on the ground while the shank has rolled forward and reached an inclination of approx. 20°. During the following digitigrade phase of the push off (from time 540 to time 740) the heel has circled 60° about an axis at B and the shank has accelerated in a forward and slightly upward direction. At time 740 the axis has been advanced to position A and for the next 100 ms the digit has circled 90° about this point while the metatarsophalangeal joint has been stretched gradually.

The events were further studied by means of still pictures with interrupted light tracks formed by light emitting diodes fixed to the foot and leg at four different sites (Figure 3). The diodes were placed at the tip of the great toe, at the metatarsophalangeal joint, on the heel below the medial malleolus and on the middle of the shank. The diodes flashed with a frequency of 50 Hz giving a 20 ms periodicity on the pictures. A strobe light showed the position of the foot at every tenth

Table 1. Duration of and joint movements in the four phases of the stance phase for twelve push offs analyzed with light emitting diodes as shown in Figure 3

	range	mean	1.st.dev.	% of total
calcaneograde phase ms	60–100	87	15.6	10.3
plantigrade phase ms	320–440	375	33.2	44.4
digitigrade phase ms	200–320	267	37.5	31.6
unguligrade phase ms	100–140	116	14.4	13.7
total ms	760–900	844	38.0	100.0
maximal metatarsophalangeal dorsiflexion at heel strike	20°–30°	25°	3.0°	
digital delay at heel strike ms	40–120	110	74.6	13.0
tibial inclination at heel rise	10°–25°	21°	4.2°	
maximal metatarsophalangeal dorsiflexion during push off	50°–60°	58°	3.4°	

flash of the diodes, enabling the light periods of all four tracks to be identified and numbered consecutively from heel strike to lift off. Twelve stance phases of the same foot walking with approximately the same speed were analyzed with this technique (Table 1).

During midswing the toes were slightly dorsiflexed to clear the ground. At heel strike the great toe was dorsiflexed 20–30° and reached the ground 40–120 ms later than the ball, which itself touched down 60–100 ms after heel strike. Toe contact was established either by all five toes at the same time or by the first and fifth toes together with the ball, followed by a delayed contact of the second, third and fourth toes.

During the following plantigrade phase in which full contact was maintained with the ground, the leg rolled forward on the foot and reached a forward inclination of 20–25°. The plantigrade phase lasted on average 375 ms or 45 per cent of the total stance phase. After that period the push off started with rising of the heel. Using terms from comparative anatomy the push off could be divided into a digitigrade and an unguligrade phase each lasting 32 per cent and 14 per cent of the stance phase, respectively. In the former phase the toes rested on the ground while the heel circled 60° about an axis at the metatarsophalangeal joints (Figure 4 axis B). The latter phase started with a sudden displacement of the axis to the tip of the great toe, and while the toe and the metatarsophalangeal joint circled 90° about this distal point (Figure 4 axis A), the relative dorsiflexion of the toes was undone, allowing the hindfoot to follow a more gently curved or straighter path. At the conclusion of the unguligrade phase only the tip of the great toe and its nail had contact with the ground, and the foot was straight and formed an angle of approximately 90° with its position at the beginning of the push off. Finally, the foot continued forward and slightly upward with a translatory movement into a new swing phase.

Heel rising is initiated when the shank has a forward inclination of 8–25° (Table 1) (Wright et al. 1964, Close et al. 1967, Lamoreux 1971). This is well before the joint has reached its maximum possible dorsiflexion and is therefore caused by tension built up in the triceps muscle and not by tension in the capsule or the ligaments. For the same reason it is tension built up in the flexor hallucis longus which causes the elevation of the ball of the foot after a submaximal dorsiflexion of the toes in the digitigrade phase.

Effects of free dorsiflexion on the mechanics of the foot

Compared to a rigid lever, the foot with its intermediate break at the metatarsophalangeal level has several advantages for smooth accomplishment of the vertical and horizontal accelerations that are necessary for initiation of the swing phase of walking:

a) In the first interval, where the acceleration is mainly antigravitational, the resistance arm of the foot is diminished by nearly 30 per cent as the distance from the ankle to the metatarsophalangeal joint relates to the total length of the lever (ankle to tip of great toe) as 5 : 7 (Figure 4, CB:CA = 5 : 7). The

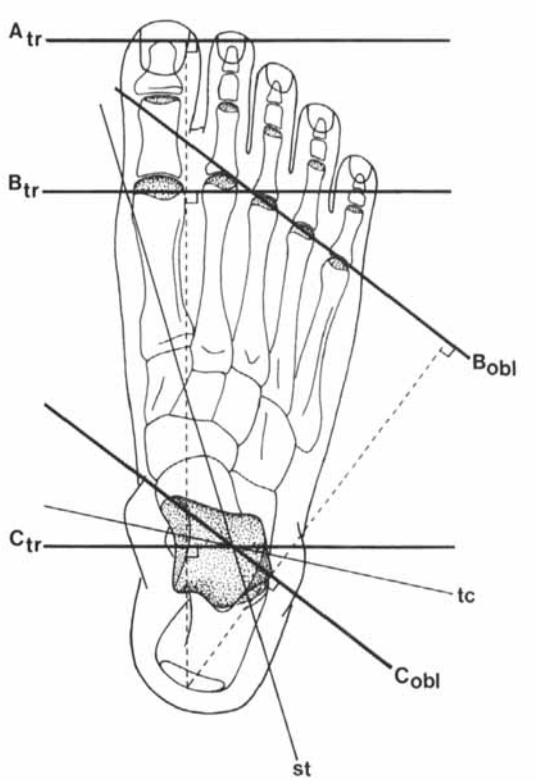

Figure 4. Diagram of right foot showing the location of the axes. During push off the two mechanical axes of the ankle joint complex (tc and st) combine into axes (C_{tr} and C_{obl}) which are parallel in the horizontal plane with the primary axes (B_{tr} and B_{obl}) at the metatarsophalangeal level. The push off can thus be performed about a set of transverse axes or a set of oblique axes. With the transverse axes the foot is a divided lever with C_{tr}-B_{tr} as the resistance arm in the first phase of the push off and C_{tr}-A_{tr} as the resistance arm in the final phase (compare with Figure 3). With the oblique axes the resistance arm C_{obl}-B_{obl} is shorter and there is no advanced axis.
tc: mechanical axis of the talocrural joint.
st: mechanical axis of the subtalar joint.

demands upon triceps surae are thereby reduced.

b) The fact that the resistance arm of the foot increases as the horizontal speed of the foot increases allows the triceps to provide useful forces over a longer period of time, thereby reducing the peak forces required to achieve the necessary horizontal speed at toe-off.

c) The flexor hallucis longus is stretched, and therefore reaches a higher tension for its work, which is to force the great toe back to a neutral position and deliver the final thrust.

In the human foot the second metatarsal bone is characteristically the longest one (Wood Jones 1944). As a consequence two different axes exist at the metatarsophalangeal level: one passing transversely through the heads of the first and second metatarsal bones and the other obliquely through the heads of the second to the fifth metatarsal bones (Figure 4). The two axes can be used for different mechanical purposes as their distances to the ankle joint complex, and thus the resistance arms of the foot, are different. In a previous work (Bojsen-Møller 1978) it was thus found that the resistance arm of the foot is 20 per cent longer in the digitigrade phase when the push off is performed about the transverse axis than when it is performed about the oblique. With the transverse axis the leverage is further stepped up with the final advancement of the axis to the tip of the strong first toe, while with the oblique axis the push off continues more as a roll over the ball of the foot with the lateral toes yielding dorsally, unable to establish an unguligrade phase of their own.

The two metatarsophalangeal axes with their long and short resistance arms can be used for different mechanical demands such as fast level walking and uphill walking, respectively. They can further be used to adjust the direction of the propulsion in accordance with the requirement for balance and the requirements of an uneven ground. Free mobility of the five metatarsophalangeal joints is, however, a prerequisite for the forefoot to exploit these options.

Effect on arch support

The plantar side of the joint capsule of each metatarsophalangeal joint is reinforced by a *plantar ligament,* which is attached to a prominent facet on the base of the proximal phalanx, while it is connected to the metatarsal bone by a synovial fold only. The five plantar ligaments continue across the foot as the deep transverse metatarsal ligament and proximally into the fascia covering the adductor hallucis and the interossei. The plantar aponeurosis is connected by its deep fibers in the ten septa to the plantar ligaments and thus to the proximal phalanges (Figures 1 and 7).

Hicks (1954) pointed out that the plantar aponeurosis acts as a tie for the longitudinal arch of the foot. In normal standing position and in the phase where the foot has full contact with the ground, the aponeurosis is slack and unable to support the arch. When the toes are dorsiflexed, however, a pull is exerted on the plantar aponeurosis by a "windlass action" where the head of the metatarsal bone acts as the drum. The mechanism springs into action as soon as the heel leaves the ground, and the stress on the arch becomes augmented (Figure 7).

Transfer of shear forces from the skin to the skeleton

Relaxed, the ball of the foot is a soft and pliable pad. The plantar skin can be moved from side-to-side and proximo-distally. Dorsiflexion of the toes changes this situation; the ball becomes tense, firm and pale, and mobility of the skin becomes greatly reduced. This stiffening ensures that shear forces resulting from accelerations, decelerations or twists are not carried by the skin alone, but are conveniently taken up by the underlying connective tissue frame and transferred to the skeleton.

To permit objective measurement of the rigidity of attachment of plantar skin, an electromechanical oscillator, or vibrator, was constructed that applied oscillatory shear forces to the skin and measured the amount of skin motion that resulted. The shear forces were of constant sinusoidal amplitude and were applied at a relatively high frequency (40 Hz) to allow the mass of the foot itself to minimize skeletal movement, thereby eliminating the necessity for rigid fixation of the foot to an external reference structure. The rigidity of the skin over the underlying structures was characterized by the peak-to-peak magnitude of skin motion caused by the constant-amplitude shear forces. Forces were applied to the skin by the end of a lightweight tubular aluminium arm, 50 mm long and 8 mm in diameter. This arm was rigidly mounted at a right angle to the shaft of an oscillatory torque motor (MFE Model T4–150A) capable of generating torques up to ± 0.075 Nm over a range of ± 15°. In use, the peak force at the tip of the arm was arbitrarily set to ± 0.2 N, which caused skin movement of ± 5 mm or less, corresponding to maximum torque motor rotations of ± 6°. Motion of the shaft is sensed by a rotary variable differential transformer (Shaevitz Model R30D). The electrical output is calibrated in terms of displacement of the tip of the arm, in mm.

The free end of the vibrator arm was attached to the skin by double-sided adhesive tape, and measurements were made on 27 students with normal feet at four selected points: 1) in the intermediate zone of the ball of the foot between the first and the second metatarsophalangeal joint, 2) at the fourth metatarsophalangeal joint, 3) at the departure of the deep fibers of the plantar aponeurosis and 4) over the central compartment of the sole (Figure 8). Measurements were made for each 10° of dorsiflexion of the toes and, in accordance with the two kinds of push off, for dorsiflexion of the first and second toes (transverse axis) and for the second to the fifth toes (oblique axis).

The results are shown in Table 2 and Figure 9. It was found that the restriction of the skin movements is more influenced by dorsiflexion of the first and second toes than by dorsiflexion of the second to the fifth toes, except over the lateral part of the ball (site 2). It was further found that a relatively large dorsiflexion (35–40°) was needed to achieve a 50 per cent restriction of the amplitude. This means that a moderate restriction of the freedom of the toes, imposed by a shoe, will hinder the tightening of the connective tissue framework and thus the normal transfer of shear forces. It was finally found that the skin of the lateral part of the ball was the least movable. This is paralleled in the hand where the skin was found less movable over the ulnar part of the palm than over the radial

Table 2. Skin displacement in mm at the four locations shown in Figure 8. For each site are shown, for 27 persons, a mean value together with one standard deviation for dorsiflexion through 50° of the first and second and of the second to the fifth toe, respectively

Site no.		Dorsiflexion of the toes					
		0°	10°	20°	30°	40°	50°
1.	1st–2nd toe	1.87 (0.58)	1.66 (0.63)	1.45 (0.70)	1.19 (0.64)	0.90 (0.52)	0.8 (0.54)
	2nd–5th toe	1.88 (0.57)	1.73 (0.66)	1.56 (0.66)	1.26 (0.63)	1.00 (0.53)	0.83 (0.38)
2.	1st–2nd toe	1.46 (0.49)	1.31 (0.49)	1.11 (0.47)	0.97 (0.44)	0.83 (0.40)	0.89 (0.47)
	2nd–5th toe	1.43 (0.51)	1.16 (0.48)	0.96 (0.47)	0.79 (0.39)	0.61 (0.30)	0.53 (0.29)
3.	1st–2nd toe	2.81 (1.00)	2.49 (1.05)	2.12 (1.11)	1.63 (1.04)	1.3 (0.90)	0.98 (0.71)
	2nd–5th toe	2.88 (1.00)	2.47 (1.04)	2.1 (1.01)	1.75 (0.93)	1.37 (0.85)	1.97 (0.86)
4.	1st–2nd toe	3.27 (0.97)	3.01 (1.11)	2.64 (1.12)	2.24 (1.07)	1.78 (0.95)	1.28 (0.75)
	2nd–5th toe	3.46 (0.98)	3.15 (1.06)	2.86 (1.09)	2.42 (1.01)	2.16 (1.01)	2.04 (0.84)

(Bojsen-Møller & Lamoreux, unpublished data). Individual differences in skin mobility were pronounced, as can be seen from the standard deviations. The differences were not related to the size of the foot and apparently neither to certain shoe habits.

At the time the ball made contact with the ground and became involved in the deceleration of the foot, the proximal phalanges were dorsiflexed 25–30° (Table 1). At that instant, therefore, the skin mobility at site 3 of an average foot would have reached half of its maximally obtainable restriction. During push off the toes became dorsiflexed through 55–60°. Maximal restriction of the skin mobility at sites 1 and 2, which in this phase have the ground contact, is reached already at 45–50° dorsiflexion. The skin and its underlying connective tissue framework are thus well adapted to take up the shear forces of the final rapid acceleration.

It should finally be noted that the direction of the collagenous fibers in the different zones of the ball are in keeping with the direction of the forces they shall intercept (Figures 1 and 2). At push off the skin of the ball will tend to slide anteriorly, but is prevented from doing so by the superficial fibers of the plantar aponeurosis, which insert in the distal zone and thereby are able to transmit the forces to the calcaneus. At braking, it is the proximal zone which has the ground contact, and the posterior pull is intercepted by anteriorly sloping fibers which proceed from the retinacula cutis through the sagittal septa to the proximal phalanges.

Effects of shoes

Using the light-track technique, two shoes of different stiffness were tested on the same foot performing push-offs about the transverse axes.

In Figure 5 a shoe (Trimsko®) with a soft upper and soft rubber sole is shown. In the decelerative phase of the heel strike the great toe is dorsiflexed 12°. In the digitigrade phase of the push off the heel point C circles for 200 ms about the metatarsophalangeal axis while the great toe reaches a maximal dorsiflexion of 45–50°. The axis is then transferred to the tip of the great toe and the dorsiflexion is undone with a gradual increase of the resistance arm of the foot as a consequence. This shoe imposes hardly any restrictions on the performance of the foot.

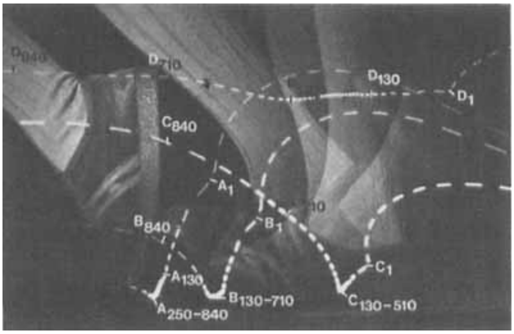

Figure 5. Stance phase of a right foot with a soft shoe. The light tracks are marked as in Figure 3. At heel strike the toes have been dorsiflexed 12°. During push off the heel point C has circled around the metatarsophalangeal point B for 200 ms (C_{510}-C_{710}) and the toes have reached a dorsiflexion of 45–50°. The axis has then been advanced to A allowing C to follow a straighter path and the resistance arm of the foot to increase its length.

The sole of a minus-heel shoe is

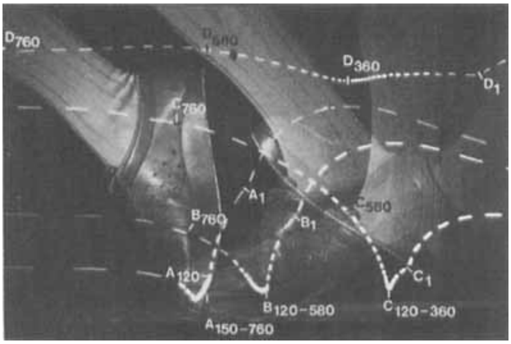

Figure 6. Stance phase of a minus-heel shoe. Maximal dorsiflexion in the metatarsophalangeal joint was 0–5° at heel strike and 25–30° at push off. Mainly due to the rocker sole the heel point C has followed a spiral shaped path with increasing radius during the push off.

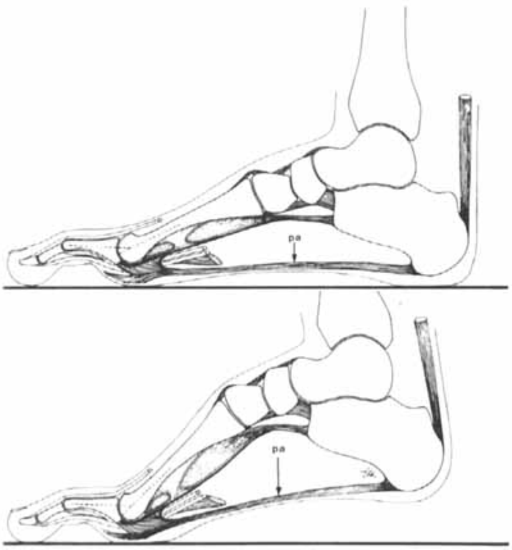

Figure 7. The plantar aponeurosis (pa) reaches from the calcaneus to the proximal phalanges of the toes. It acts as a tie for the longitudinal arch held in reserve while standing, but tensed when the heel is lifted and the toes wind its distal part around the metatarsal heads (Modified after Hicks (1954)).

characterized by a thin heel and a stiff, built-up forepart. It is a rocker sole with a resistance arm that increases smoothly and continuously during the push off as the shoe rolls forward toward the tip of the sole. The path of the heel point C is therefore a curve with gradually increasing radius (Figure 6). Significant for foot function is that the maximal dorsiflexion of the metatarsophalangeal joint is reduced to 25–30°. At heel strike the dorsiflexion is nil. By its stiffness, the minus-heel shoe reduces the function of the forefoot.

Conclusion

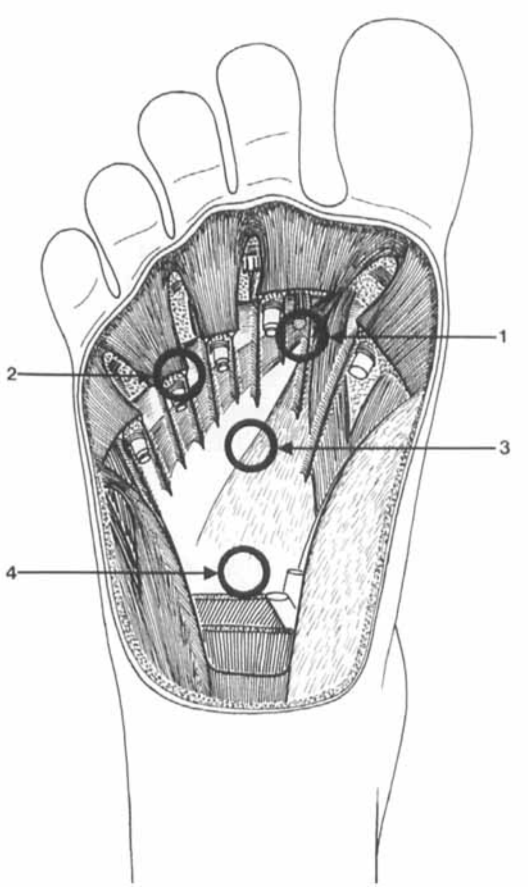

Figure 8. Plantar aspect of right foot, with the connective tissue framework exposed. Shown are, in the proximal zone of the ball: the ten sagittal septa, in the intermediate zone: the five cushions protecting the metatarsal heads, and in the distal zone: the insertion of the superficial fibers of the plantar aponeurosis and a few of the transverse fibers. The four sites, where the skin mobility was tested, are indicated.

In a nonprehensive foot such as the human, the range of motion of the toes lies in dorsiflexion, rather than plantar flexion, of the metatarsophalangeal joints. In this respect the toes differ from the fingers, whose working range lies between the neutral and the flexed position. The cartilage of the metatarsal heads is, in accordance with this, continued further dorsally on the bone than it is on the metacarpal heads.

Dorsiflexion occurs twice during the stance phase of walking. An active dorsiflexion starts just before heel contact and continues until after the ball of the foot contacts the floor. A passive dorsiflexion occurs after the heel leaves the floor prior to push off, as the toes are forced dorsally by the weight of the body.

Free dorsiflexion is essential for the

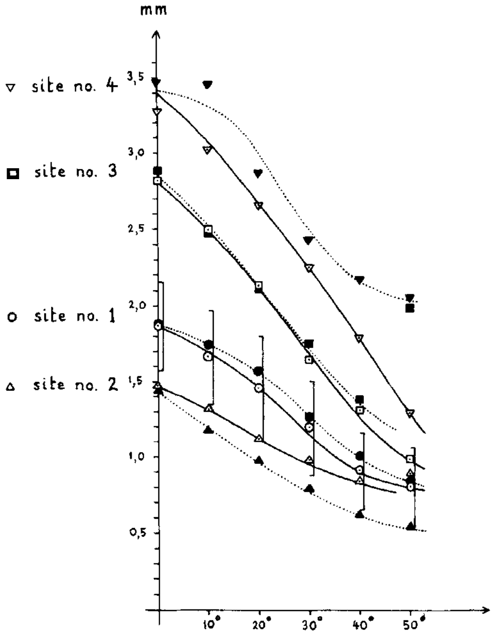

Figure 9. Average skin mobility in mm at the four sites of the planta shown in Figure 8. For each site is shown the restriction in skin mobility by dorsiflexion through 50° of the first and second toe (full line with open marks) and of the second to the fifth toe (dashed line with filled marks). For site 1 one standard deviation is shown.

function of the foot. It secures support to the longitudinal arch at peak loads, and it enables the ball to withstand the tangential forces to which it is exposed. Dorsiflexion also allows the foot to take advantage of different leverage ratios to suit different conditions, resulting in a more efficient propulsion. Dorsiflexion seems even to have an effect on venous return flow as it squeezes the cutaneous and subcutaneous venous plexus, which is well developed in the ball of the foot (Spalteholz 1893).

The sole of a shoe should be as soft as possible for its particular use. The aim is that the shoe shall protect the foot without interfering unnecessarily with natural movements of the joints. This was not found to be the case with one of the shoes tested as its sole, and especially the forepart, was stiff and thick. It thereby halved the natural dorsiflexion of the toes and it further prevented a free selection between the transverse and the oblique metatarsophalangeal axes.

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