Electromyography and Cinematography of Leg and Foot ("Normal" and Flat) during Walking

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ABSTRACT Electromyography with fine-wire electrodes and special equipment for synchronized motion pictures were used to study six muscles of the leg and foot during walking in five different ways in ten "normal" and ten flatfooted subjects. Detailed analyses and comparisons of the two groups are described and discussed.

Tibialis Anterior has two peaks of activity at heel-strike and toe-off of the stance phase; is inactive during mid-swing and middle of the stance phase; is active at full-foot in flatfooted subjects, and generally more active during toe-out and toe-in walking. *Tibialis posterior* is inactive through the swing phase. In flatfooted persons it becomes activated at heel-strike and more active at full-foot during level walking. The toe-out position reduces its activity. *Flexor hallucis longus* is most active in mid-stance; during toe-out walking, activity increases in both phases, generally being more active in "normal" persons. *Peroneus longus* is most active at mid-stance and heel-off and generally more active in flatfooted persons. *Abductor hallucis* and *Flexor digitorum brevis* are generally more active in flatfooted persons. An important regular pattern of inversion and eversion during the walking cycle is described. Contingent arch support by muscles rather than continuous support is the rule, muscles being recruited to compensate for lax ligaments and special stresses during the walking cycle.

In spite of substantial research over the past fifty years, a clear understanding of the functional anatomy of the foot remains elusive. Various studies have provided information of its static functions, but such information is incomplete because the foot is also a dynamic structure. Even the old theory that the arches of the foot — as arches — are of vital significance calls for re-examination.

Acceptable definitions of a "normal" and a flat foot do not exist, with dictionaries lamely defining flat foot as "a condition in which one or more of the arches of the foot have flattened out." Most descriptions of a "normal" foot suggest an idealized structure with lateral and medial longitudinal arches and a transverse arch, the last supposedly crossing the heads of the five metatarsals (Inkster, '64`

Even though the medial arch is peculiar to man, some persons lack one that is externally visible (Jones, '44). Whether one considers this normal or not, when a medial arch is not evident the term "flat foot" is appropriate. Unfortunately, a flat foot has become associated in the clinical literature with a painful foot. Jones and later Perkins ('47) warned against this prevailing attitude, but the real benefits of possessing a medial arch have never been investigated scientifically. Often a depressed or low arch, although organically efficient, will be called a flat foot simply because of pain arising from other causes (Hauser, '50).

"Toe-out" or "toe-in," which describe the angle made by the feet in reference to the line or path of walking, have given similar concern in the past. In a long series of subjects, Morton ('52) found that the average toe-out during walking was 7.5°. Observing that a flatfooted person toes out markedly in his walking, Howorth ('60) maintained that it is an "inefficient" manner of walking. But Lapidus ('63) recognized that excessive toe-out may have some purpose and therefore he questioned the rationale of efforts to "correct" it.

Arch supporting mechanisms

After extended study, Hicks ('55, '61) described three different interdependent supporting mechanisms: a "beam," a "truss," and a "muscle mechanism." Experiments with leg and foot preparations from cadavers established that strong ligaments in the sole of the foot uniting neighboring bones make the foot behave like a solid curved beam. The "truss" theory

(Lapidus, '43) proposes that the plantar aponeurosis acts as a tie to prevent separation of the two ends of the arch. Further, through a windlass effect, the plantar aponeurosis is tensed by passive dorsiflexion of the great toe. Hicks claims this mechanism provides an adjustable arch during walking, especially when the heel is raised off the ground and the body weight shifts onto the ball of the foot. Finally, the "muscle mechanism" stabilize a constantly changing position of the line of weight of the body while standing.

Muscular function in the foot

Keith ('29) formulated the theory that muscle actively hold up the arches: otherwise a flat foot would result. This theory, based on extensive phylogenetic evidence, received support from Willis ('35) who concluded from tension experiments in cadavers that the tibialis posterior and peroneus longus muscles keep the medial arch from collapsing. He claimed that the tibialis posterior maintained the normal relationship of the navicular and talus near the summit of the medial arch and so prevented distortion of the front part of the foot in a lateral direction, i.e., an abducted forefoot.

Morton ('24) disagreed with the Keith's theory although his evidence was also indirect, largely the evolutionary changes in the foot. He emphasized the firmness of bones and the strength of ligaments. Supporting him experimentally, R. L. Jones ('41) found that the tibialis posterior and peroneal muscles can support only 15 to 20% of the body weight. In addition, Harris and Beath ('48) concluded from an extensive survey that a balance exists between the ligament in the sole and the active contraction of muscles in both leg and foot. They placed greater importance on the ligaments but thought the muscles would be quick to respond if the ligaments failed. They defined a stable foot as one which has interlocking articular processes at joints that are firmly joined by ligaments, and a less stable foot as one that needs muscular support because it lacks ligamentous support. Independently, F. Wood Jones ('44) had also concluded that there is an equilibrium between the passive ligaments and the active muscles in support of the arches of the foot, fallen arches resulting if this balance were upset. However, he believed that all the muscles, both intrinsic and extrinsic, are in a steady state of partial contraction.

This was the confused state of affairs until electromyography became available, offering hope in resolving the controversy. Using needle electrodes, Basmajian and Bentzon ('54) investigated the tibialis anterior, peroneus longus, and intrinsic muscles of the foot, concluding that these muscles take no part in support of the arches during standing, regardless of any role they may have during locomotion. Because their subjects had normal feet, they reserved judgement on the muscles in flat foot.

At the same time, Smith ('54) investigated the anterior, posterior and peroneal muscles of the leg with skin electrodes. He too found the muscles were inactive in a standing position although they were active while walking. In a later investigation Basmajian and Stecko ('63) studied six leg and foot muscles electromyographically with their subjects seated and loads (up to 400 pounds) applied at the knee. Again emphasizing that muscles are not significant in providing static support, they concluded that muscles provide a dynamic reserve especially during the take-off phase of walking.

Sheffield et al. ('56) studied the pattern of muscular activity during walking in twelve muscles of the leg and foot. They reported that the anterior leg muscles were active throughout the walking cycle, with peak activity at heel-strike and again when the foot leaves the ground; the posterior muscles, when the entire foot was on the ground. However, Close and Todd ('59) found that the anterior crural muscles were active during walking only while the foot was off the ground, although they agreed that the posterior muscles were active while the foot was on the ground. Subjects were able to repeat their pattern of activity on repeated tests for the same muscle. Using radiotelemetry, Battye and Joseph ('66) confirmed earlier findings but also revealed a basic similarity in the EMG patterns of various people.

Mann and Inman's ('64) study of phasic activity revealed that the actions of the intrinsic muscles are related to the axes of the subtalar and transverse tarsal joints of the foot. They believed that the intrinsic muscles stabilize the joints, i.e., the foot may act at times as if it did not have any joints. Flatfooted subjects required more activity of the muscles apparently to hold the joints of the foot in a rigid position, but the intrinsic muscles are not needed in the standing position.

While studying the plantar flexors of the leg for their effect on stabilizing the knee, Sutherland ('66) concluded that their chief function was deceleration of rotation of the tibia on the talus. However, the ability of the plantar flexors to stabilize the knee indirectly was confirmed by motion pictures and electromyography. He emphasized the importance of muscles in providing stability of the lower limb.

Definitions of the walking cycle. Walking forward, in effect, is a process of losing and regaining of body balance (Scott, '63). A "gait cycle" is the period from the time one of the feet strikes the ground until the same foot makes contact with the ground again (fig. 1). The gait cycle has two subdivisions, the "stance" and the "swing" phases.

The stance phase is when the foot is on the ground. It is divided into "heel-strike", "full-foot", "mid-stance", "heel-off", and finally "toe-off". At the point of "mid-stance" in the cycle the body weight is entirely over the foot (Edelstein, '65).

The swing phase is divided into the following three parts: "acceleration", "mid-

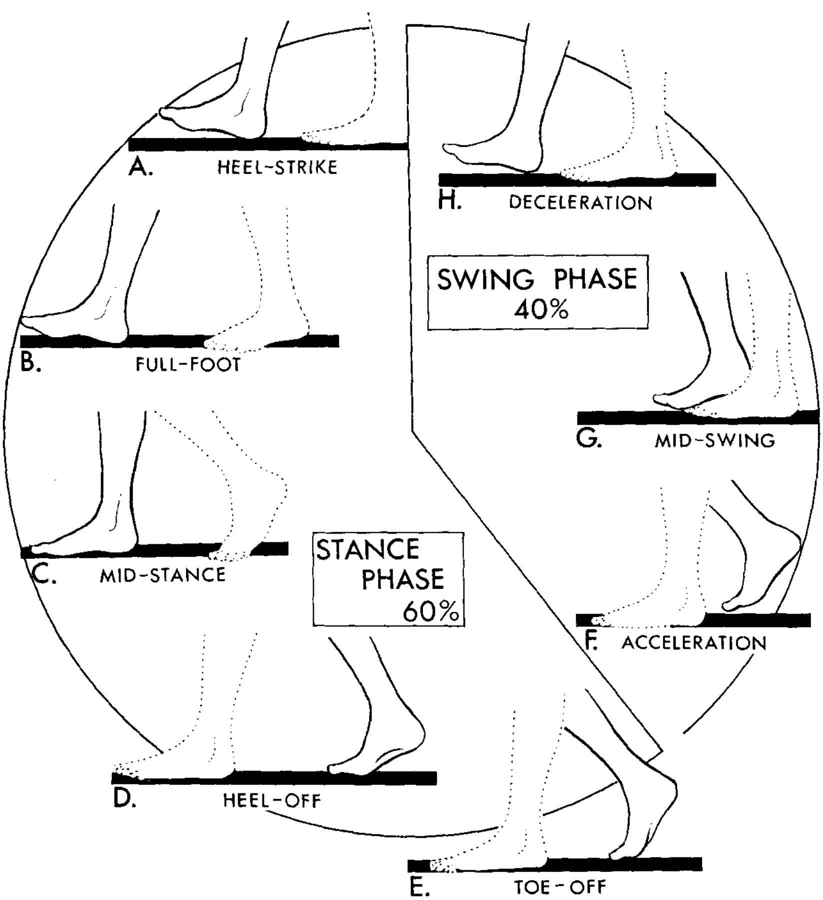

Fig. 1 A single walking cycle on the horizontal surface (60%, stance phase; 40%, swing phase): tracings of photographs to show the right leg and foot in the eight "moments" (A to H).

swing", and "deceleration" (fig. 1). At the moment of acceleration the leg is behind the trunk: at mid-swing directly under; and at deceleration, well in front, ready to make contact with the ground at heel-strike.

About 60% of a gait cycle is occupied by the stance phase and 40% by the swing phase (Drillis, '58), the speed of walking governing the time each leg will remain in contact with the ground (Edelstein, '65). There is a time at the beginning and at the end of each cycle when both feet are on the ground (Joseph, '64). These times are prolonged at slower speeds (Schwartz, '64).

MATERIAL AND METHODS

Twenty young adult volunteers (19 men and 1 woman) were studied. They were medical, graduate and undergraduate students at Queen's University. Ten had an evident medial arch, no obvious deformities, and "normal" function of the foot. In contrast, ten had no apparent medial arch of the foot and, though symptom-free, were considered flatfooted as previously defined.

The six muscles studied were: tibialis anterior, tibialis posterior, peroneus longus, flexor hallucis longus, abductor hallucis and flexor digitorum brevis. The right leg and foot were investigated in all cases for convenience and consistency. To provide electric signals of contacts of the foot to the ground to be recorded with the EMGs, three specially devised "contact switches" were taped to the sole of the subject's own right shoe (at the outer edge of the heel, across the area of the ball of the foot, and at the toe of the shoe). When stepped upon, these send signals to three channels of the electromyograph.

Electrodes, EMG apparatus and cinephonic camera

Bipolar fine-wire electrodes were put into the middle of each of the six muscles studied by means of a hypodermic needle (through a small skin-wheal of 1% procain in some cases). The special electrodes (Basmajian and Stecko, '62) combine the maximum of comfort with accuracy in recording of the electrical activity of the muscles during locomotion; they are made from a nylon-coated, Karma-alloy wire with a diameter of 25 μ.

The wires from all six pairs of electrodes were connected to the amplifiers by means of a twelve-foot length of "Cicoil" flexible multiwire cable, a valuable new commercial product used here for the first time in electromyography. A highly flexible, extremely light-weight ribbon containing 24 separate, parallel wires (Basmajian, '67), it almost completely removes movement artifacts from the recordings.

The apparatus is a six-channel electromyograph (Basmajian, '58, '67) which provides photographic traces on 35 mm linograph film along with a time marker.

A Fairchild Cinephonic Camera was specially adapted to record pictures of the foot along with taperecording of individual EMG channels on its magnetic-tape edge; normally it is an 8 mm movie camera with a built-in electronic sound system. The final film made with it is a 100-foot length of 8 mm color film with a magnetic sound-strip along one edge. To record EMGs on the magnetic strip, the receptacle on the camera (which is normally connected to a microphone) was connected to individual monitoring outlets of the electromyograph during filming.

Experimental procedure

The first part of a session was spent on filming the activities (described below) with simultaneous recording of the EMGs on the sound film. The cinephonic camera was mounted on a tripod with flood-lights arranged to follow the movement of the camera while photographing the subject in action. The camera and operator were located 15 feet lateral to the midpoint of the walkway. Five types of walk were recorded:

I. Level walking: accustomed foot position. From an erect stance a subject walked the length of the walkway, coming to a halt with one foot beside the other. The length of the walkway allowed a recording of three full walking cycles.

II and III. Level walking: toe-out and toe-in foot positions. The subject walked with his feet turned out laterally to 45°.

This was repeated with the feet turned medially 45°.

IV and V. Walking up and down an incline (12°): accustomed foot position.

Analysis of movies and EMG records

The developed sound film was analyzed in fast and slow motion, the audiospeaker outlet of the projector having been adapted to allow the EMG recorded on the magnetic strip to be either viewed on an oscilloscope or heard on a loudspeaker. Use of a hand-operated movie editor also allowed a frame-by-frame analysis of the performance of the activities.

By visual interpretation of the linagraphic EMG records one can relate activity of the muscles to the foot-switch traces which mark the five events or "moments" of the stance phase and the three "moments" of the swing phase of the walking cycle. Each EMG was examined for the starting, ending and level of electrical activity during each "moment". The following levels of activity were employed: *nil*, slight, moderate, and marked (there being no case of very marked activity in any of the muscles during walking). For tabulation, averaging, and analysis of data, numerical values were assigned to the four levels of muscular activity as follows: *nil* = 0; slight = 1; moderate = 2; marked = 3.

For each locomotor exercise, a detailed chart was made showing the mean muscular activity (with standard deviation) during the seven parts of the walking cycle. An average was made of three complete steps whenever there was any variation (always slight); in fact about half the subjects showed identical muscular patterns for all steps. The muscular effort to initiate and complete a walk was disregarded, in keeping with the advice of Wright et al. ('64).

After examination of mean values and standard deviations of the "normal" and flatfooted subjects, two main questions arose. Are the means of the flatfooted subjects significantly different from the means of the "normal" subjects? Are the means of the "normal" and flatfooted subjects during level walking significantly different from means in the same subject during toe-out, toe-in, and walking up and down an incline? A "t" test was applied to answer the above questions; the levels of significance, "P", being obtained from the Fisher and Yates table (Croxton and Cowden, '55). Generally the conventional $P = 0.05$ level was adopted: here the mean difference is judged to be significant if the "t" values place "P" at or beyond the 0.05 level of confidence.

OBSERVATIONS

I. Level walking: Accustomed foot position. During the early part of the stance phase, at heel-strike, the foot in each case was inverted (fig. 2), and so remained through heel-strike and full-foot. At midstance it assumed a neutral position between inversion and eversion. At heel-off the foot was inverted, and then assumed a more neutral position again at toe-off.

At the beginning of the swing phase the ankle joint was dorsiflexed but the foot remained essentially in the same position as at toe-off. Near the end of acceleration the foot began to evert and the position of eversion was maintained through midswing; but at the end of the swing phase (deceleration) the foot became inverted.

The tibialis anterior was the only muscle active during the swing phase (fig. 3). During the three central moments of the stance phase it was inactive except at full-foot in the flatfooted subjects. In contrast, the other five muscles were active only in the stance phase, responding primarily around mis-stance in "normal" subjects. However, in the flatfooted subjects all the muscles except flexor hallucis longus showed slight to moderate mean activity at heel-strike and maintained this level through most of the stance phase.

II. Level walking: Toe-out position. During exaggerated toe-out walking, the response of tibialis anterior was the same for both "normal" and flatfooted subjects. Generally there was more activity at heel-off with the toe-out position than with the accustomed position in "normal" subjects (the difference between the mean activities being significant beyond the 0.05 level of confidence). Some subjects showed continuous muscular activity through the entire cycle.

Tibialis posterior at heel-strike was about the same in "normal" and in flatfooted subjects. The mean activities at heel-strike

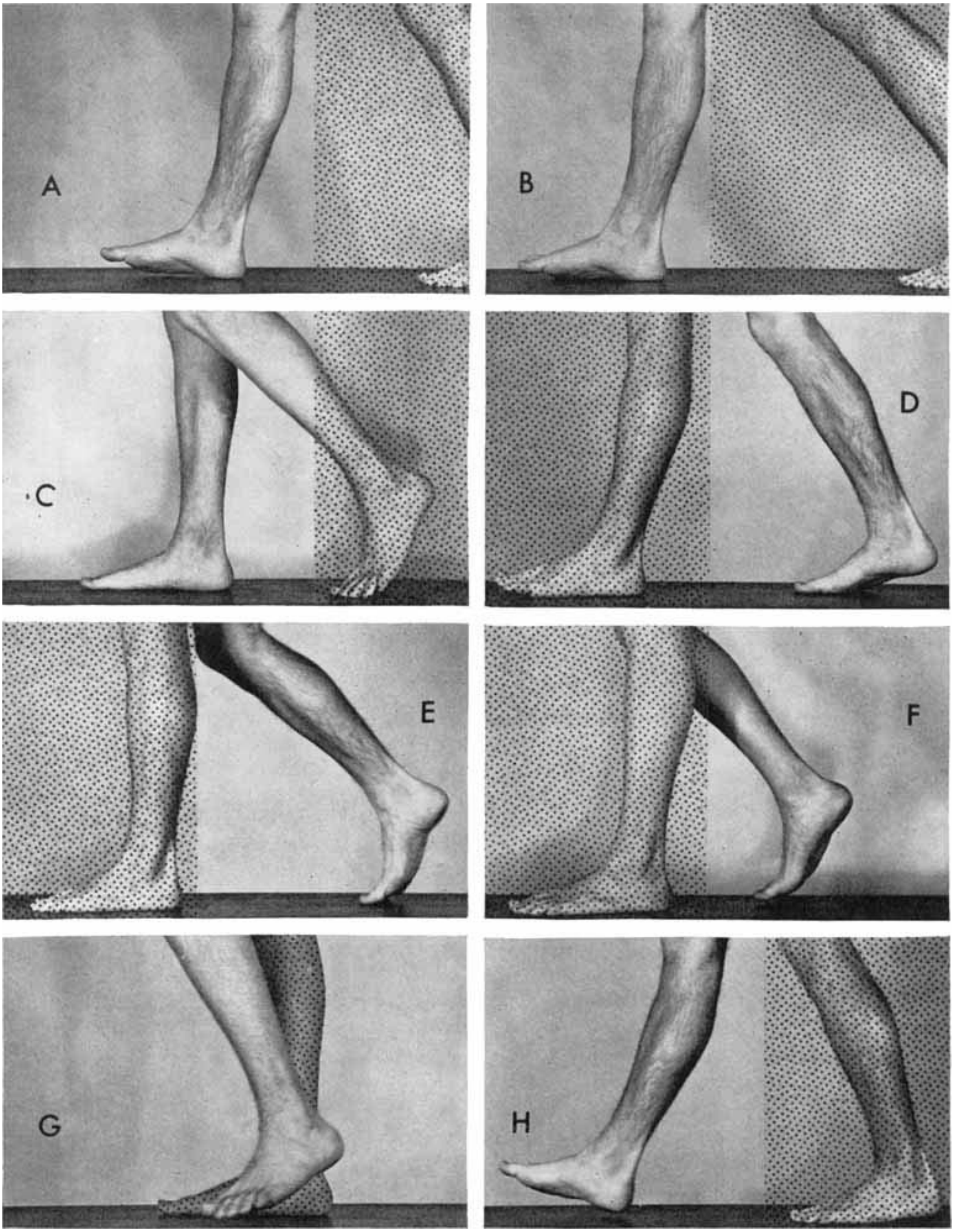

Fig. 2 Photographs of normal and flatfooted subjects to show special features of the right foot (except in frame G) during the walking cycle. A. heel-strike (sole of normal forefoot turned medially); B. full-foot (normal; lateral border and heel make contact); C. mid-stance (flat foot; in neutral position); D. heel-off (normal; heel turned medially); E. toe-off (normal); F. acceleration (flat foot); G. mid-swing of LEFT flat foot; H. deceleration (sole of right normal forefoot turned medially).

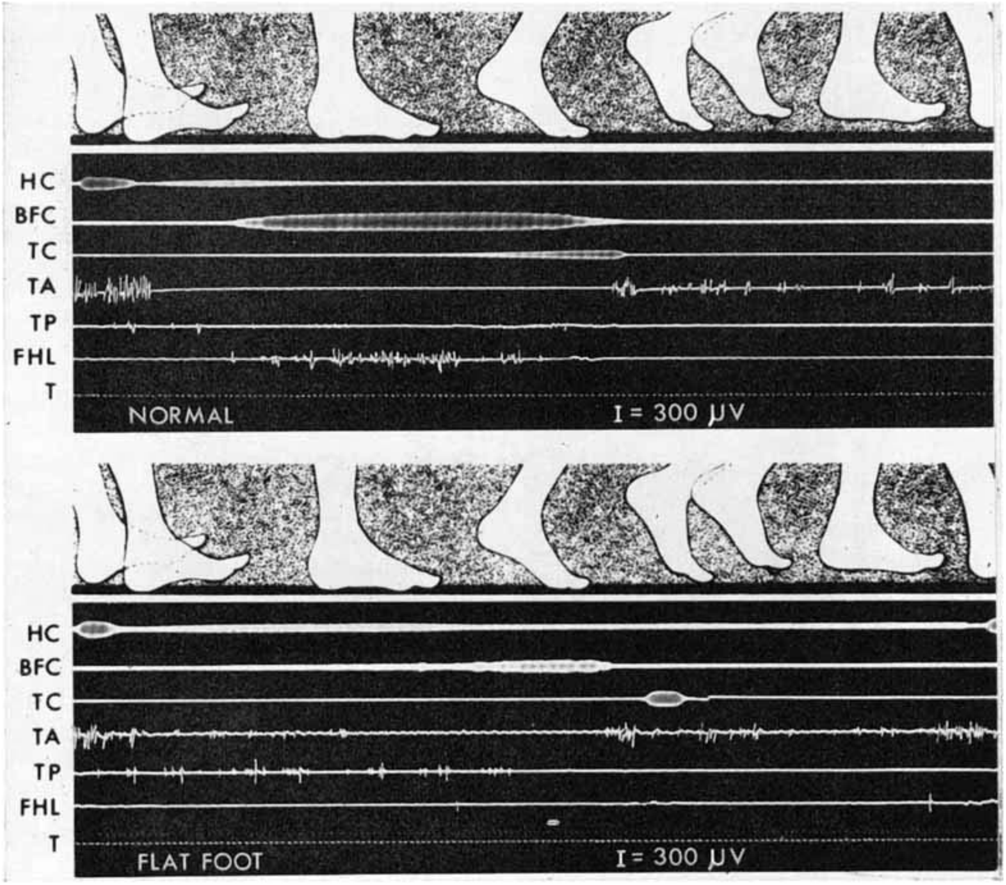

Fig. 3 EMGs of tibialis anterior (TA), tibialis posterior (TP) and flexor hallucis longus (FHL) during level walking with an accustomed foot position in a "normal" (upper set) and flatfooted subjects (lower set). Diagrams of foot positions are generalized; the exact positions are indicated by records of heel contact (HC), ball of foot contact (BFC) and toe contact (TC). Time marker (T): 10 ms intervals.

and mid-stance for the accustomed and toe-out positions in "normal" subjects show a significant difference (at the 0.05 level) only at heel-strike. In the flatfooted subjects a significant difference exists at full-foot (at the 0.05 level) between accustomed and toe-out positions.

The flexor hallucis longus was active in both the stance and swing phases in some subjects. The "normal" subjects had a higher mean activity than flatfooted ones except at heel-off when they were the same. Toe-out foot position tended to affect the activity of the flexor hallucis longus to a greater degree in "normal" subjects; at heel-strike and full-foot in "normal" subjects, the change was clear-cut (beyond the 0.01 level of confidence).

The peroneus longus responded throughout most of the stance phase, with only negligible differences between the "normal" and flatfooted subjects.

Except at full-foot when both "normal" and flatfooted groups were the same, the abductor hallucis showed greater mean activity in flatfooted subjects. In "normal" subjects the activity was increased at heel-strike and full-foot and was lowered at mid-stance. In flatfooted subjects the responses remained unchanged at mid-stance and were only slightly affected at heel-strike and full-foot.

For the flexor digitorum brevis the moment of mid-stance had the highest mean activity in both groups of subjects. The toe-out position did not greatly influence its action in "normal" subjects. When full-foot and heel-off for accustomed foot position and toe-out were compared in flatfooted subjects, significant changes were found for both moments (beyond the 0.01 level of confidence).

III. Level walking: Toe-in position. Tibialis anterior showed a typical pattern of muscular activity during toe-in walking with peaks at the beginning and end of stance and swing phases. The "normal" subjects had higher levels of activity at full-foot and mid-swing. When the mean activities for accustomed foot position and toe-in walking are compared at full-foot, there is a significant difference between the two types of walking in the "normal" subjects but none in the flatfooted subjects (at the 0.05 level).

The other five muscles were very much alike in the patterns of activity with the exception of the abductor hallucis. The flexor hallucis longus and flexor digitorum brevis were similar in that their levels of activity were about equal. In the tibialis posterior the flatfooted subjects had higher levels of activity.

Comparison of toe-out with toe-in foot position

Toe-out and toe-in did not alter the basic pattern of muscular activity in level walking to any great extent. Whilst they prolonged the action of the tibialis anterior in "normal" subjects into the stance phase, they had less effect in flatfooted subjects.

Tibialis posterior was unaffected by toe-out at mid-stance in both groups of subjects and at heel-strike for flatfooted subjects. It did affect the "normal" subjects at heel-strike and flatfooted subjects at full-foot. In general toe-in did not affect the level of activity of tibialis posterior in flatfooted subjects but did increase it in "normal" subjects.

Flexor hallucis longus was most influenced by toe-out in "normal" subjects; but toe-in had no appreciable effect on the muscle in either "normal" or flatfooted subjects.

The peroneus longus in the flatfooted subjects was affected more by toe-in walking, which shifted the peak activity from mid-stance to toe-off. In normal subjects toe-out and toe-in affected the peroneus longus in different ways. Toe-in walking initiated activity at heel-strike but for some subjects the muscle was totally inactive during the stance phase. On the other hand, toe-out induced greater activity at the early parts of the stance phase without affecting the peak of activity at mid-stance.

Toe-out walking had more effect on the abductor hallucis of "normal" subjects, raising the level of response at heel-strike and full-foot and lowering it at mid-stance. Toe-in walking affected the early stance phase in "normal" subjects and recruited activity during the swing phase.

Toe-out and toe-in did not alter the action or pattern of the flexor digitorum brevis in "normal" subjects, but in flatfooted subjects they raised the level of activity at mid-stance and lowered it at other parts of the stance phase.

IV. Walking up incline: Accustomed foot position. Walking up an incline recruited tibialis anterior activity in both phases of the gait cycle but the mean activity at the beginning and end of stance and swing phases were less than for level walking (fig. 4). When means of level and up-incline walking are compared for "normal" subjects, there is a significant difference (at the 0.05 level of confidence) only between the means at mid-stance.

The other five muscles were very much alike in their pattern of muscular activity, and there were only small differences between "normal" and flatfooted subjects. However, peroneus longus does become active in the swing phase with no significant differences between "normal" and flatfooted subjects. Tibialis posterior in both groups of subjects showed significant change at heel-off (at the 0.01 level).

V. Walking down incline: Accustomed foot position. The tibialis anterior showed a pattern that was very similar in walking both up and down an incline, the differences at particular moments being negligible. Compared with level walking, the tibialis anterior was affected by walking

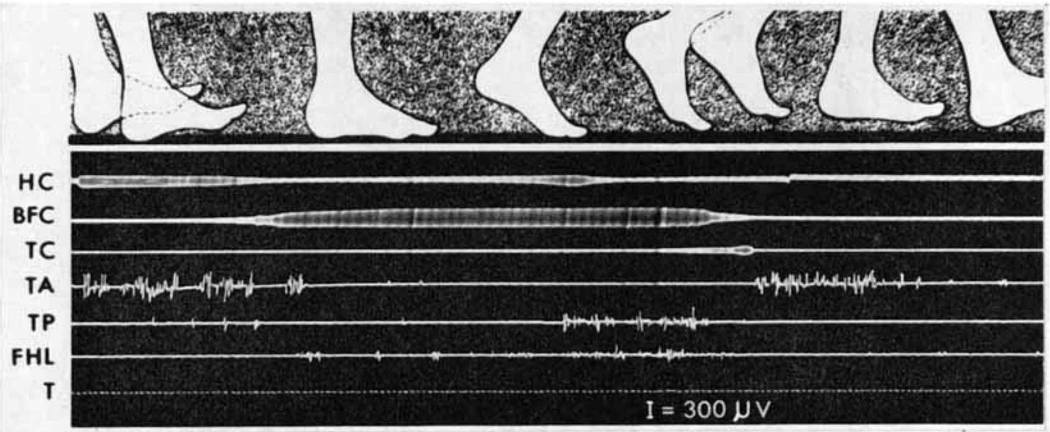

Fig. 4 EMGs of tibialis anterior (TA) tibialis posterior (TP) and flexor hallucis longus (FHL) during walking up an incline (with an accustomed foot position) in a "normal" subject. Diagrams of foot positions are generalized; the exact positions are indicated by records of heel contact (HC), ball of foot contact (BFC) and toe contact (TC). Time marker (T): 10 ms intervals.

up and down an incline mostly during the central moments of the stance phase.

The peroneous longus and abductor hallucis were active in some subjects during the swing phase. All the muscles were active to some degree through the stance phase except tibialis posterior and flexor digitorum brevis. During the swing phase, walking up an incline initiated activity in the peroneus longus but walking down an incline initiated activity in abductor hallucis. The flexor hallucis longus was not affected to any great extent.

Walking up an incline changed the pattern of tibialis posterior, while walking down changed the flexor digitorum brevis. Compared to the levels recorded during level walking, walking up and down an incline produced the greatest effect in these muscles during the early and late parts of the stance phase.

DISCUSSION

Level walking: Accustomed foot position

Tibialis anterior

Because tibialis anterior has been a favored object of attention, some of our observations are not original here. Nevertheless, better techniques and a comprehensive approach permit an integration and explanation of its role during walking. Using skin electrodes, Sheffield et al. ('56) first reported peak EMG activity at heel-strike of the stance phase, suggesting that this decelerates the foot to provide a controlled approach to the ground, i.e., to stop the foot from slapping the ground. Close and Todd ('59) and Battye and Joseph ('66) made similar EMG observations, and our present study with indwelling electrodes again confirms the peak of activity at heel-strike in all subjects. Our movies show the foot to be inverted and dorsiflex at this time, confirming the opinion of Hardy ('59) and Wright et al. ('64).

Notwithstanding the above, there has been no general agreement as to the function of tibialis anterior at heel-strike. Without offering direct evidence, Carlin ('63) suggested only that it counteracts forces applied to the heel by the ground. Sheffield et al. ('56) considered the tibialis anterior only from the standpoint of dorsiflexion. Finding activity carried into the stance phase beyond heel-strike, they proposed that the tibialis anterior decelerates the foot at heel-strike and lowers it to the ground by gradual lengthening (eccentric contraction). Perhaps the clinical condition known as "drop-foot" due to paralysis of the tibialis anterior influenced their conclusions.

During the more central moments of the stance phase (full-foot, mid-stance and heel-off) Sheffield et al. recorded a continuous slight level of activity; but with modern techniques we recorded none in "normal" subjects. Our flatfooted subjects and those of Battye and Joseph were like the "normals" except for extended activity into full-foot. Curiously, the movies of our flatfooted subjects show the foot staying inverted during full-foot. Apparently the action of tibialis anterior supports the foot during full-foot by maintaining inversion in order to distribute the body weight along its lateral border.

The peak of EMG activity observed at toe-off of the stance phase is apparently related to dorsiflexion of the ankle, presumably to permit the toes to clear the floor. This reaffirms the work of Sheffield et al., Close and Todd, and Battye and Joseph.

Although Sheffield et al. and Close and Todd believed there is a slight fall in the activity of tibialis anterior at mid-swing, we agree instead with Battye and Joseph that there is, in fact, a period of electrical silence at mid-swing. Battye and Joseph did not explain the period of silence but attributed the foot's not dropping to inertia. Now an explanation emerges from our movies which show the foot everting at the end of "acceleration" and remaining everted through mid-swing. (This eversion, previously noted by Hardy ('59), was not explained by him.) The eversion of the foot at mid-swing allows for adequate clearance while the inactivity of the invertor fits the concept of reciprocal inhibition of antagonists. We conclude that the brief period of electrical silence of tibialis anterior is essential.

The peak of activity at toe-off tapers to a slight-to-moderate mean level of activity during acceleration of the swing phase. Conversely, prior activity in deceleration of the swing phase builds up to a peak of activity at heel-strike. Thus, one may see that the pattern of activity of tibialis anterior is biphasic. Apparently, tibialis anterior is in part responsible for dorsiflexion during acceleration and for inversion of the foot during deceleration of the swing phase.

The pattern of activity of tibialis anterior suggests that it does not lend itself to direct support of the arches during walking. At heel-strike, when the muscle shows its greatest activity, the pressure of body weight is negligible (Hicks, '55). Conversely, during maximum weight-bearing at mid-stance when all the body weight is balanced on one foot, the tibialis anterior is silent. When the activity resumes at toe-off, the weightbearing of the involved foot is minimal.

Tibialis posterior

Tibialis posterior during ordinary walking shows activity at mid-stance of the stance phase. The movies show the foot remaining inverted throughout full-foot and turning to a neutral position (between inversion and eversion) just before mid-stance. First, the fourth and fifth metatarsal heads make contact; then, as the foot everts increasingly toward neutral, more of the ball of the foot makes contact at mid-stance until the entire contact-area of the foot is applied. Although the tibialis posterior is an invertor in non-weightbearing movements of the foot, its role at "mid-stance" appears to be a restraining one to prevent the foot from everting past the neutral position.

The above observations of tibialis posterior confirm the deductions of R. L. Jones ('41, '45) and the more recent findings of Sutherland ('66). Jones showed in human cadaveric preparations that the tibialis posterior distributes body weight among the heads of the metatarsals. In living subjects he showed that a lateral torque on the tibia results in an increase or shift of body weight onto all but the first metatarsal head; a medial torque has the opposite effect. He concluded that by inverting the foot the tibialis posterior increases the proportion of body weight borne by the lateral side of the foot. Sutherland concluded that the plantar flexors, including the tibialis posterior, have a restraining function to control or decelerate medial rotation of the leg and thigh observed at mid-stance; by controlling the eversion of the foot at mid-stance, the tibialis posterior provides an appropriate placement of the foot.

In our flatfooted subjects, the EMG activity of tibialis posterior in the early stance phase is consistent with the maintenance of an inverted position during full-foot. By maintaining inversion the foot is supported in order to keep the body weight on the lateral border of the sole. The latter observations essentially support the opinion of Harris and Beath ('48) who suggested that muscle would be needed if the bones and ligaments failed. They considered the tarsal bones of a flatfooted person less favorably placed in relation to each other for weightbearing than in persons with a "normal" medial arch.

The foot must be inverted to accomplish lateral weightbearing in the early "moments" of the stance phase. This of course is because the middle part of the medial border of the foot does not bear body weight in "normal" subjects (Heath, '65); the lateral border with its strong plantar ligaments is well equipped to bear the stresses of body weight in walking (Napier, '57).

Tibialis posterior is usually considered to be a plantar flexor of the ankle (O'Connell, '58), but during level walking with an accustomed foot position, it showed *nil* activity at heel-off (when plantarflexion of the ankle takes place to raise the heel) (fig. 2). This confirms the opinion of R. L. Jones and Sutherland who doubted that the tibialis posterior participated in raising the heel during level walking. (This is not to deny that tibialis posterior may be a plantarflexor of the ankle when more powerful contractions are needed.)

Flexor hallucis longus

At mid-stance, when the entire body weight is concentrated on one foot, flexor hallucis longus shows its greatest activity, reaffirming the earlier electromyographic work of Sheffield et al. ('56) and Close and Todd ('59). Flexing the big toe apparently positions and stabilizes it during mid-stance. During heel-off, our movies shows the big toe hyperextended. Napier ('57) felt that the flexor hallucis longus helps maintain overall balance and prevent instability induced by excessive extension of the big toe. But our EMG observations support this only for the flatfooted subjects and then with little enthusiasm: there is a slight activity during heel-off which may be related to preventing overextension and so giving a better balance. In contrast, the "normal" subjects show negligible activity. Consequently, one may conclude that the flexor hallucis longus is not needed in most "normal" subjects to play this role.

Peroneus longus

The pattern of activity of the peroneus longus confirms the findings of Sheffield et al., Close and Todd, and Sutherland. The last-named and others have suggested that the peroneus longus helps to stabilize the leg and foot during mid-stance. Our movies and electromyograms show how the peroneus longus and tibialis posterior, working in concert, control the shift from inversion during full-foot to neutral at mid-stance. Thus the opinion of R. L. Jones is again confirmed; from static studies, he inferred that peroneus longus is related to eversion of the foot at mid-stance during level walking. Sutherland further concluded that peroneus longus, like tibialis posterior, is involved in controlling rotatory movements at the ankle and foot. We found that eversion of the foot and medial rotation of the lower limb occur together. One may conclude that the peroneus longus is in part responsible for returning the foot to, and maintaining it in, a neutral position at mid-stance. The conclusion by Sheffield et al. that the activity of peroneus longus is due to stretching at mid-stance must be rejected because stretching of muscle does not itself produce EMG activity (Leavitt and Beasley, '64).

Throughout most of the stance phase, peroneus longus is generally more active in flatfooted subjects than in "normal" subjects. This appears to be a compensatory mechanism called forth by faulty architecture.

During heel-off, our movies showed some inversion while peroneus longus, an evertor, is active, and the invertors are relaxed. Mann and Inman ('64) who also believe the foot inverts at this time (agreeing with Duchenne, 1867) suggest that the inversion is caused by triceps surae—a possibility which we have not tested. We believe the activity in peroneus longus affords stability by preventing excessive inversion, thus maintaining appropriate contact with the ground.

In flatfooted subjects, the interplay of activity between peroneus longus and tibialis posterior appears to play a special role in stabilizing the foot during mid-stance and heel-off. At mid-stance the tibialis posterior is notably more active, but at heel-off the emphasis shifts to peroneus longus.

Abductor hallucis and flexor digitorum brevis

These two show similar patterns of activity, and generally our findings confirm those of Sheffield et al. ('56), Hardy ('59) and Mann and Inman ('64). They showed that the two muscles become active at mid-stance and continue through to toe-off in "normal" subjects. In addition, Mann and Inman reported EMG observations from three flatfooted subjects. Although their observations for abductor hallucis, which showed activity from heel-strike to toe-off, was confirmed, their conclusion that the flexor digitorum brevis had the same pattern of activity in "normal" and flatfooted subjects is incorrect. In our larger group of flatfooted subjects, seven of ten showed activity from heel-strike to toe-off; this is patently different from the pattern of "normal" subjects.

Sheffield et al. suggested that perhaps the flexor digitorum brevis and abductor try to grip the ground since they are flexors of the toes. Although Mann and Inman (and others) were not opposed to this idea, they believed that the muscles are also in an ideal location to help support the arches. Our findings tend to confirm this opinion only for flatfooted subjects because they showed higher mean levels of muscular activity.

Toe-out and Toe-in Foot Position (Level Walking)

A parallel position of the feet during walking has been advocated by some physicians and physical educators for therapeutic reasons and by others for esthetic reasons. What is the correct position of the feet during walking? Actually, most individuals toe out slightly (at an angle of 7.5°, according to Morton, '52, and Murray et al., '64); but some walk with the feet in a toe-in position. We found that our exaggerated toe-out position affects the mean levels of activity more than toe-in does. Nevertheless, the muscles retain their basic pattern of activity seen with the accustomed foot position. The notable changes in mean levels of activity —some are increases, some decreases— occur in the early part of the stance phase.

The toe-out or toe-in position determines the manner in which the heel strikes the ground at the beginning of the stance phase. When one walks with the feet pointed straight ahead the heel strikes the ground near its midline, but the toe-out position of 45° places the extreme lateral edge of the heel on the ground first. Conversely, the medial side of the heel strikes the ground first when walking with the foot in the toe-in position (Elftman, '34).

Although the toe-out position is manifested in the foot, it is chiefly the result of lateral rotation of the hip joint (Morton '52). With the toe-out position the lateral border of the foot is effectively placed on the ground from the very onset of the stance phase. Whilst one might guess that the muscles which can invert the foot (and so set it on its lateral border) should show less activity at full-foot, yet they generally show higher activity (e.g., tibialis anterior). This must be because they are in a better position to lower the foot to the ground in the toe-out position.

At heel-off, the increased activity of flexor hallucis longus is consistent with that expected from the pressure studies of Elftman ('34). He found that the pressure from body weight during toe-out walking was concentrated on the first metatarsal of the big toe. However, with the accustomed foot position, the pressure is distributed better across the five metatarsal heads. Thus the flexor hallucis longus should be more active in maintaining balance at heel-off during toe-out walking.

The toe-in position is also mainly the result of rotation at the hip joint and not in the foot. Walking with the foot in the toe-in position generally shows lesser changes in the levels of muscular activity than in the toe-out position when both are compared with the accustomed position. However, some of the activity in the toe-in position may be due to inversion resulting from the effort of keeping the foot in a toe-in position.

In flatfooted subjects, levels of muscular activity are generally less affected by walking in the exaggerated toe-out or toe-in positions than is the case for the accustomed foot position. Harris and Beath ('48) thought that flatfooted individuals had a greater degree of movement between the bones of the foot than "normal" individuals, and Close ('64) confirmed their opinion. He found a greater freedom of movement in the joints while walking, especially the subtalar joint, when compared to "normal" subjects. Perhaps the greater freedom of movement in the bones allows the flatfooted subjects to assume the toe-out and toe-in position more easily while the relationship of bones is retained.

The toe-out and toe-in foot positions during walking affect the levels of muscular activity in various ways when compared with the accustomed foot position; but it does not necessarily follow that one foot position is more advantageous than another during walking. We can agree with Morton that the position of the foot during walking is an individual characteristic.

Walking Up and Down an Incline

Muscle action is not the only factor which determines the movement of the body while walking. Amongst others, the force of gravity and a purposeful loss of body balance are influential (Steinberg, '66). Even walking downhill at 5.5° or more, the force of gravity is not an aid but a handicap; additional effort is required to overcome the reverse effect of gravity. We found that some muscles show obvious changes.

Walking up an incline modifies the manner in which the foot strikes the ground. Rather than the usual type of heel-strike found in level walking, the foot is practically "placed" on the ground. Dorsiflexion and inversion of the foot are superfluous in this modified placement of the foot, and therefore tibialis anterior shows correspondingly less activity.

The increased activity of tibialis anterior at full-foot and mid-stance may be related to maintaining the position of the leg so that the body can be balanced over the leg and foot by mid-stance. In static studies, O'Connell ('58) found the tibialis anterior of subjects standing on an incline active to keep the leg poised over the foot as a base of support. Thus, although the tibialis anterior acts on the foot when only a part of the foot is on the ground, it may be acting on the leg when the sole of the foot is on the ground (Hall, '65).

The tibialis posterior showed activity at heel-off in more than half of our subjects; here the tibialis posterior is probably acting as a plantarflexor in response to the additional muscular effort needed to walk up an incline. Howorth ('60) thought that if one leaned farther forward to create a further imbalance of the body when walking up an incline less effort from the muscles would be needed. Perhaps those subjects who show *nil* activity unconsciously make use of this change of body position.

Some subjects show activity in peroneus longus during the swing phase when walking up an incline. When compared to level ground, the inclined surface offers an additional obstacle. Although it would be possible for the foot to clear the floor by greater flexion of the more proximal joints (such as the knee and hip), nevertheless, the foot everts; apparently this provides a smoother and more efficient gait.

One would expect some changes in levels of activity in muscles of the lower limb when walking down an incline since gravity is now acting positively on the body. Indeed all the muscles (with the exception of tibialis anterior) generally show lower mean levels when compared to level walking. It appears that gravity has made the performance of walking easier as far as movements and muscular activity of the foot are concerned. One may argue that perhaps these changes are due to a modified placement of the foot, but the movies do not confirm this, showing the foot making similar movements in both level walking and walking down our incline of 12°.

The acceleration due to gravity increases the walking speed. This suggests that some muscles are necessary to control the descent down the incline. In the early stance phase the tibialis anterior may help to resist excessive walking speeds.

General considerations

The tibiales anterior and posterior, flexor hallucis longus, peroneus longus, abductor hallucis and flexor digitorum brevis are all concerned with both movements and restraints in the foot during walking. The inversion of the foot seen at heel-strike appears primarily to be related to the activity of tibialis anterior, although tibialis posterior, abductor hallucis and flexor digitorum brevis show slight mean activity in flatfooted subjects. All except flexor hallucis longus may be attempting to maintain inversion in flatfooted subjects during full-foot. However, maintenance of inversion in most "normal" subjects may be due to factors not yet studied.

Dorsiflexion and inversion which occur at acceleration and deceleration, respectively, are in part related to the action of tibialis anterior during the swing phase. However, none of the muscles studied could be credited with producing the movement of eversion that occurred at about mid-swing.

"Foot-flat" of the stance phase, as used by Radcliffe ('62) and Edelstein ('65) is the same as our full-foot. It was so named because they believed that the entire sole of the foot was on the ground. In fact we find that the contact part of the sole does not make contact with the ground until the beginning of mid-stance. Edelstein stated that at heel-strike the foot is perpendicular to the leg and moves to nearly 20° plantarflexion at "foot-flat" (full-foot). Then the leg or shank dorsiflexes over the foot, returning the ankle by mid-stance to the neutral position between dorsiflexion and plantarflexion. In other words, Edelstein believes the only difference between full-foot and mid-stance is the changing angle between the leg and foot. However, because the entire contact surface of the sole of the foot is *not* on the ground until the beginning of mid-stance, a term like "partial-foot" is more appropriate than both "foot-flat" or "full-foot". Although the latter term is so widely used that we could not avoid it, it is a misnomer.

During toe-in and toe-out walking or when the floor is inclined or declined, the muscles respond to these conditions whilst retaining their basic pattern seen in ordinary level walking. Indeed, these modes of walking have served as a test for the validity of the patterns of activity seen in level walking with the accustomed foot position. They also show that the muscles respond individually to situations where the demands upon them differ.

Arch Support

The most controversial function of the muscles that traverse the foot is the support of the arches. Our observations on the flatfooted subjects confirm the opinions of Harris and Beath regarding what we would call the contingent support of the foot by muscles. They thought that a flatfooted person needs active muscular support during walking, and our flatfooted subjects show statistically significant differences from "normal" subjects in mean activity early in the stance phase. Moreover, the slightly higher mean levels of muscular activity generally seen in these subjects suggest that they may be actively supporting the arches of the foot. Several investigators (Oota, '56; Mann and Inman, '64; and Gresczyk, '65) reported activity from leg and foot muscles of flatfooted subjects even during standing. It appears, then, that besides providing movements of the joints of the foot, propulsion of body and stability of joints as in "normal" subjects during walking, the muscles of flatfooted subjects may also help to support (or attempt to support) the arches of the foot during locomotion.

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