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# The Function of the Muscles of the Lower Leg in Relation to Movements of the Tarsus

BY

J. B. T. AMBAGTSHEER

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INTRODUCTION

This study was designed to obtain more information regarding the function of the lower leg muscles in relation to the movements of the tarsus. For this purpose functional-anatomical and electromyographic investigations were employed. Until now, no quantitative data have appeared in the literature concerning the movements of the tarsal bones; we began, therefore, with an investigation of these latter movements.

The functional-anatomical descriptions of the movements of the foot, pronation and supination, are presented as qualitative descriptions of the movements of the entire foot. The quantitative information concerning these movements is restricted to global data regarding the range of the excursions of the heel, toes and edge of the foot or to a description of the position of the sole. The pronation and supination movements, however, are very complicated and consist of combinations of movements of the skeleton of the foot. There is no quantitative information concerning the movements of the individual tarsal bones.

Since previous authors had not succeeded in locating precisely the position of the joint axes an entirely different approach to the problem was employed. We decided to measure the rotations of the tarsal bones (talus, calcaneus, navicular and cuboid) in three

perpendicular planes. In order to obtain further quantitative and qualitative data with respect to these rotations of the tarsal bones, the tendon slips following the lengthening and shortening of the lower leg muscles were measured. All these measurements were performed in anatomical specimens during selected movements.

The activities of the lower leg muscles were recorded electromyographically in experimental subjects during the same selected movements.

Electromyography can be used

1. qualitatively,
  - a. for the registration of muscular activity in functional anatomy,
  - b. for clinical purposes, in the diagnosis of disturbances of the neuromuscular system.
2. quantitatively,  
for investigations into the dynamics (force and work) of functional anatomy.

In our study the electromyographic signal is used only for qualitative interpretation (mentioned in 1a) in the presence or absence of muscular activity.

An association between certain combinations of muscular activity and the results of measurements of the tendon slips became apparent. One of the questions foremost in our mind throughout the investigation was whether or not it might be possible to deduce electromyographic activity from alterations in tendon slip. In fact, a demonstrable association between certain combinations of muscular activity could be related to the recordings during more combined movements and to the phases of the walking movement.

The selection of the movements in vivo and in vitro was based upon functional arguments. In our opinion it was more appropriate to study the supination and pronation movements of the foot under weight-bearing conditions than in the case of the free hanging foot.

Under these weight-bearing conditions it might be possible to isolate combinations of active muscles which could be recognized as components of combinations of active muscles during walking.

For a clear understanding of the functional anatomy of the foot we began with the findings of Huson (1961). This author gave an extensive description of the movements of the tarsal bones and stressed the following points:

- these movements are combined movements of the tarsal bones,
- it is impossible to introduce fixed axes into the description of these movements.

The bones involved in this combined movement of the tarsus are the talus, the navicular, the cuboid and the calcaneus. Huson demonstrated how these bones form a closed kinematic chain (p. 6 and 7). The axes of motion of this chain are not fixed axes, but moving ones, so-called instantaneous axes.

Huson described how the supinatory movement of the tarsus and the raising of the medial arch of the foot are accompanied by external rotation of the lower leg. At the same time, the calcaneus moves, relative to the tarsus, in a slight endorotation with some lateral tilt, leading to a readily discernible varus position of the heel, the so-called supinatory remodelling of the hind-foot. Without plantar flexion of the metatarsals and consequent bearing of their heads on the floor, this movement would result in elevation of the medial edge of the foot from the floor while standing upright. A pronation twist of the forefoot occurs normally as a compensatory mechanism. (Of course, it is also possible that the forefoot follows the supination of the cuboid and navicular, and that only the lateral edge of the sole of the foot remains in contact with the floor, while the lower leg attains maximal exorotation.) This mechanism of

supinatory remodelling is used unremittingly in man to maintain balance during walking. A painful disturbance of this mechanism, therefore, as in tarsal osteoarthritis, manifests itself during walking, especially on an uneven floor.

The scheme of investigation was divided into two phases,

1. Quantitative measurements in post-mortem specimens of the lower leg and foot: -
  - a. the movements of the tarsal bones during supination,
  - b. the tendon slip of the lower leg muscles during movements of the tarsus and ankle-joint.
2. Electromyographic registration of the activity of the muscles of the lower leg in living subjects.

1. Quantitative measurements in post-mortem specimens.

- a. The movements of the tarsal bones during supination.

The analysis of the tarsal movements by Huson was a qualitative one and we endeavoured to measure these movements quantitatively. For this purpose the lower leg and foot were stripped of all their muscles. The leg, with its remaining inserting tendons, was mounted in an apparatus with the sole flat on the bottom, in such a way as to allow of

- external rotation of the leg combined with supination of the tarsus, or
- internal rotation of that leg coupled with pronation of the tarsus.

Pins were placed in the tarsal bones and four consecutive positions (0, 1, 2 and 3) of the tarsus were photographed from three different directions at right angles to each other. In this way twelve pictures were obtained from each leg. *These consecutive positions were selected phases in the gradual supinatory remodelling of the tarsus. They were selected in such a way that they are all*

*well defined and reproducible.*

Angular displacements could be measured in the three projections from the photographs. It is, however, only possible to obtain values from the degrees of rotation of the tarsal bones, the translation components remaining unknown.

- b. Tendon slip of the lower leg muscles during movements of the tarsus and the ankle-joint.

The displacements of the tendon ends of the cut muscles were measured in the same specimens when the foot moved from the starting position to the other positions noted as  $0 \rightarrow 1$ ,  $0 \rightarrow 2$  and  $0 \rightarrow 3$ . These values could then be related to the rotational changes of the bones when they passed through the same positions. *In addition to the positions 0, 1, 2 and 3, we selected three further positions, A, B and C, two (A and B) imitating a balancing movement on the ball of the foot (foot in plantar flexion), the third (C), being a position in which only the heel was in contact with the bottom of the cage (foot in dorsiflexion).*

In this way data were obtained from the relationship between the changes in length of the lower leg muscles and the movements of the tarsal bones. With this information a better understanding of the myographs was to be expected.

2. Electromyographic registration of the activity of the muscles of the lower leg in living subjects. The activity of eleven lower leg muscles and of one foot muscle was recorded in living subjects.
  - a. Performing the following standard movements, (these movements were chosen in such a way as to pass through the same selected positions as used in the post-mortem experiments),
    - the movements  $0 \rightarrow +1$  and  $0 \rightarrow 2$ ,
    - the so-called clawing movement, (heightening of the arch without rotation of the lower leg),

- a more combined supinatory movement (+ 1) starting from pronation (- 1).
- b. Performing the rolling movement. (a combination of movements - 1 → 0 → + 1 → 2 → B → P → A → - 1 → 0.)
- c. During walking on a *trottoir roulant*. (In chapter 4 the movements mentioned under 1 and 2 will be described further.)

Surface electrodes were used for the superficial muscles and wire electrodes for the deeper muscles.

From the myographs of the standard movements (see 2a) we obtained characteristic combinations of muscular activity, and with the knowledge of these characteristic combinations, we studied the myograms of the walking subjects.

- - -

The closed kinematic chain.

As mentioned above, Huson (1961, 1973) described the tarsus as a closed kinematic chain. The implication of this term will be summarized briefly since it is necessary to understand how endorotation and exorotation of the lower leg in the weight-bearing positions can produce pronation and supination of the tarsus.

A kinematic chain is formed by a number of rigid bodies which are linked to each other by movable connections. In biomechanics these rigid bodies are bones but under certain conditions non-rigid bodies may also function as links in the chain (Huson, 1973).

We have to distinguish open from closed chains. An open chain has a freely moving end, e.g. the freely moving arm and hand. In a closed kinematic chain, every part is linked to at least two other parts. An open chain can be closed and reopened. This is precisely the way in which the open chains in the limbs of man and animals are frequently used. During walking, the pelvis, the two legs and the floor form alternately a closed (bipedal phase) and an open (monopedal phase) chain. Moreover, some parts of the limbs (or even

joints) are constructed as permanently closed chains.

In the case of the tarsus, a closed chain is formed by the talus, calcaneus, cuboid and navicular. It is possible to construct a closed chain which has only one pattern of motion; movement of one link implies that the others also move according to this specific pattern. Such a chain is said to have a constrained motion. In engineering, these closed chains are often used to guide or transform certain motions, e.g. the slide and crank mechanism of a steam engine. The tarsal chain is also movable according to one pattern only. The chain is said to have a constrained motion with only one degree of freedom. In our case, external rotation of the leg in the cage induces a specific motion of the tarsal bones, and it is in fact sufficient to know the amount of rotation in order to determine the position of the tarsal bones. Closed kinematic chains can be further differentiated into planar and spatial chains.

In planar chains, the rotations of the links are rotations around parallel axes. The entire path of motion, therefore, can be projected into a single plane which is perpendicular to the axes of rotation.

In spatial chains, the movements take place around non-parallel axes. The tarsal chain is an example of a spatial mechanism. The talus, calcaneus, cuboid and navicular form together such a spatial closed kinematic chain with constrained motion.

Movements of a kinematic chain are described with respect to a fixed link, the reference link, which is considered as a part of the stationary surrounding. Furthermore, we discern an input link, that is the link to which the moving force is applied.

In the tarsus one has to face the problem of determining the reference bar. Huson (1961) used in his description of the tarsal movement the calcaneus as the reference link. In the weight-bearing foot however, there is in fact no reference bar: all the bones move. For this reason Huson had to "translate" his qualitative description of the movements of the tarsal bones with respect to the fixed calcaneus (which was in fact an artificial motion pattern) in order to confront them with his observations of the tarsal movements as seen in radiographs of the living, weight-bearing foot. On the other hand, with the foot hanging free at the lower leg, the talus can be used as a reference bar provided there is no plantar flexion or dorsal flexion of the talus in the ankle-joint. But in this case it is not clear which of the bones can be used as a suitable input link through which motion can be induced in a simple way. Moreover, we feel that the movements of the loaded foot might be more important from a functional point of view. For this reason we chose the experimental set-up of a weight-bearing lower leg. External rotation of the leg - which could be measured easily - was used as the input motion applied to the talus as the input link. The rotations in three perpendicular planes of the other bones could now be measured.

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CHAPTER 2

DEFINITIONS OF TERMS USED IN THE TEXT



## CHAPTER 2

### DEFINITIONS OF TERMS USED IN THE TEXT

In functional anatomy there exists considerable confusion regarding terminology, for which reason the definitions employed in our work are elaborated hereunder. The anatomical position was taken as the starting position. In the anatomical position the body is erect with the head, eyes and toes directed forwards, the upper limbs hanging by the sides, and the palms of the hands facing forwards. Our definitions are basically in accordance with the International SFTR - Sagittal, Frontal, Transverse, Rotation - method (Russe and Gerhardt, 1975).

The various terms of functional anatomy employed in this thesis are as follows: -

Exorotation of the leg:

Movement around a longitudinal axis. The ventral side is turned outwards.

Endorotation of the leg:

The opposite movement.

Adduction of the leg:

The term which describes the movement of a body around a more or less sagittal axis. The distal part moves in a mainly frontal plane in the direction of the main body axis.

### Abduction of the leg:

The opposite movement. The distal part moves away from the main body axis.

### Adduction of the forefoot:

The forefoot moves in the direction of the main body axis, while rotating around an axis more or less parallel to the body axis.

### Abduction of the forefoot:

The opposite movement.

In French literature the terms "torsion en dedans" and "torsion en dehors" are encountered for supination and pronation respectively. In English literature inversion and eversion are often used as a synonym of supination and pronation respectively.

Warwick and Williams (1976), in their most recent edition of Gray's Anatomy, differentiate between these terms. They use the terms pronation and supination of the foot only when the foot is bearing weight. The terms pronation and supination may be applied both to the hand and to the foot. In the case of the foot pronation infers downward rotation of the medial border with inclination of the great toe towards the ground; supination is the reverse movement in which the lateral border of the foot returns to a position of plantigrade contact.

### Extension of the foot = Dorsiflexion:

This term describes a movement of the foot around a more or less transverse axis. The distal part of the foot moves in the direction of the dorsum of the foot and in a mainly sagittal plane, i.e. extension resulting from activity of tibialis anterior, extensor digitorum and extensor hallucis as prime movers.

### Flexion of the foot = Plantar flexion:

The opposite movement. The foot moves in the direction of the foot-sole, i.e. flexion in the strict meaning of the word.

### Supination of the foot:

The term which describes the complex movement of the foot when the medial edge of the foot is elevated.

### Pronation of the foot:

The movement opposite to supination. The medial edge moves in a plantar direction.

Supination is also used to describe the rotation of the hand. There exist, however, fundamental differences between supination of the hand and supination of the foot. Supination of the hand takes place at the radio-ulnar joint around a more or less longitudinal axis, the radius carrying the hand as a whole, whereas supination of the foot comprises a combination of movements in several tarsal joints around different axes. Each of these motions can be referred to as a supinatory movement. The effect of supination is a supinatory remodelling of the outer shape of the foot, or parts of the foot such as the hindfoot or the tarsus.

Synergists:

Muscles working with a similar mechanical effect in a given movement in our laboratory experiments.

Antagonists:

Muscles working with an opposing mechanical effect.

These definitions imply that synergists can act together simultaneously or alternately, to achieve a given movement. Simultaneous activity of synergists and antagonists to stabilize a joint is also possible; indeed, such a combination of muscle activity is necessary for proper control of movement.

The following three, generally accepted mechanical terms are also used in our text: -

Rotation:

The movement of a solid around an axis. The distance of each point of the solid with respect to all points on the axis remains constant, whether or not this axis crosses the solid.

Translation:

The movement of a solid along a defined line. The distance between each point of the solid and this line remains constant, whether or not the line crosses the solid.

Helical movement:

That special combination of rotation and translation which involves rotation around an axis and a certain constant translation along the same axis.

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CHAPTER 3

HISTORICAL NOTES

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3.2. Functions of the lower leg muscles with respect to the tarsal movements. . . . .	26



## CHAPTER 3

### HISTORICAL NOTES

Since our investigation could be divided into firstly, measurements of the rotations of the tarsal bones, and, secondly, the function of the lower leg muscles with respect to movements of the tarsus, the ensuing historical review is divided into corresponding sections.

#### 3.1. Movements of the tarsus.

The movements of the tarsus have interested research workers for the last two centuries. During the eighteenth century and up to the beginning of the nineteenth, the ankle and tarsal joints found their place in the simple classification of ball and socket joints, hinge joints and saddle-shaped joints (Winslow, 1732 and Sabatier, 1777, according to Huson, 1961).

A detailed analysis of the tarsal movements was still to come. Henke (1855), in the second half of the nineteenth century, considered the tarsus as a functional unit comprised of the talus, calcaneus, cuboid and navicular. The result of the simultaneous movements of these bones is pronation or supination. Henke defined only one axis for these movements. Other investigators have tried to define still more axes for each of the separate tarsal joints.

In most cases the joint surfaces are considered as a part of the surface of a solid of revolution. Alter-

natively, if the surfaces of a joint, either totally or partially, form the surfaces of a solid of revolution turning around its axis of revolution, they must be congruent to each other in such a way as to exclude gaping of the joint cleft. And gaping is exactly what does occur! At the beginning of the twentieth century, it became obvious to Robert Fick (1911) that it is impossible to indicate a single fixed axis for the complex movements of the tarsus. He has therefore defined a so-called compromise-axis as a hypothetical possibility. This hypothetical axis of Fick passes obliquely through the talus and he describes the movement of the tarsus as an impure hinge movement.

Subsequent investigators have indicated the relationship between the medial arch of the foot, the position of the tarsus and the position of the first metatarsal bone.

Wiles (1934) described the movements of the tarsus and forefoot as being composed of adduction with supination, and abduction with pronation. He explained that the abduction-adduction movement of the foot on a vertical axis, in the case of the free-hanging foot, is the same as the exo-endorotation of the lower leg in a fixed foot. What we do have to determine is which part of the moving system is fixed, the lower leg or the foot.

Manter (1941) made a further attempt to localize the axis of motion of the tarsal joints. According to this latter worker, the axis makes an angle of  $45^{\circ}$  with the horizontal plane, an angle of  $16^{\circ}$  with the sagittal plane, and passes through the tuber calcanei and the head of the talus.

Jones (1945) confirmed the findings of Wiles concerning the relationship between the rotation of the lower leg and the postural change in the tarsus. He concluded that this rotation of the leg makes possible a transfer of weight-bearing on the foot from the medial to the lateral side and vice versa.

Levens, Inman and Blosser (1948) demonstrated with the cinematograph the rotations of the leg while walking. They did not, however, relate their findings to the postural change in the tarsus.

Hicks (1954) gave a description of the movements of the tarsal bones and the resultant remodelling of the hindfoot. He asserted that these movements are based on rotation around a fixed axis. The tarsal joints are thus hinge joints from a functional point of view. Hicks related these tarsal movements to those of the forefoot, the so-called pronation twist and supination twist. Moreover, he considered the torsion of the forefoot as secondary to the movements in the tarsus. Pronation twist of the forefoot, therefore, takes place concurrently with elevation of the medial arch and descent of the lateral arch. Hicks' conception of the forefoot twist was presented as follows:

Hick's Scheme concerning the fore foot twist.

<u>Foot standing</u>	<u>Talo-calc. nav. joint</u>	<u>Mid-tarsal joint.</u>	<u>First ray</u>	<u>Fifth ray</u>
Arch high	supination adduction flexion	supination	fl.pronat.	ext.pronat.
			"pronation twist"	
Arch low	pronation abduction extension	pronation	ext.supinat.	fl.supinat.
			"supination twist"	

The character of this remodelling of the forefoot, which Hicks calls a twist, becomes clear on looking at a model of the skeleton. A rectangular wooden block represents the tarsus with the cuneiform bones. The fore-front of this block is connected to five small wooden beams of varying length, as indicated below (fig. a).

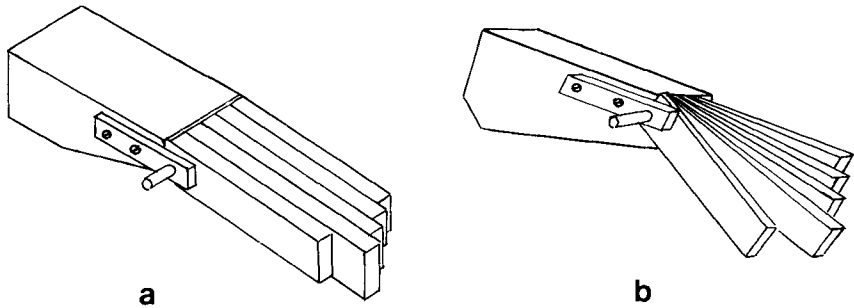


Fig.1. Model adapted from Hicks. Only tarsus and metatarsus are represented.

In a supinatory movement of the block (representing the tarsus), the beams are taken along with it in supination. When the free (distal) ends (representing the metatarsus) of the beams are turned towards the floor, the phenomenon of the twist becomes evident ( b ).

There exist, according to Hicks, two axes for the so-called mid-tarsal joint. These axes determine the movements between the forefoot and the hindfoot. The same author stated that these axes almost coincide, and that we ought, therefore, to regard these as one single axis only. Moreover, a third axis exists for the talo-calca-neo-navicular joint. This axis determines the pronation and supination movements of the foot. Further to the description of these three axes, he showed the influence of the tension in the plantar aponeurosis (= fascia plantaris) on the shape of the medial arch. This aponeurosis is inserted proximally at the plantar side of the calcaneus and distally into the capsule of the metatarsophalangeal joints, as well as into the first phalanx of the hallux. Due to this latter fact, dorsiflexion of the hallux winds up the aponeurosis, the basal phalanx working as a winch and bending the medial arch

like a bow, thus raising it. The arched form of the foot is essential to the combination of the functions of support and mobility. Hicks showed the ways in which the chains of bones forming longitudinal arches in the foot are loaded and demonstrated these principles in relation to the foot. On loading the foot, the aponeurosis becomes taut and the arch of the metatarsal bones becomes lowered due to their flexibility. Furthermore, Hicks (1955) investigated the foot as a support. He quoted Elftman who showed how the foot transmits weight to the ground mainly through the heel and the ball of the forefoot. The skeleton of the foot receives weight from above at any intermediate point in its length and can behave, presumably, either as an arch or as a beam (fig. 2).

In the foot, the plantar aponeurosis becomes tightened by dorsiflexion of the hallux and of the toes by a windlass mechanism. In this case the support of the foot acts like a truss. The arch of the foot now rises and the intersegmental ligaments become relaxed. When the toes are plantar flexed, the plantar fascia becomes relaxed, the arch of the foot is lowered and the intersegmental ligaments become taut. The foot now functions like a beam until the aponeurosis prevents further flattening.

Hicks constructed an apparatus with which he was able to measure the bending forces of the metatarsal bones and the tension in the plantar fascia. He conducted his experiments with the aid of six fresh amputation specimens as follows:

- A. with the foot undissected;
- B. with the plantar aponeurosis divided, the small muscles remaining intact, and
- C. with both plantar aponeurosis and small muscles divided.

He calculated that a total load of 100 lbs is supported as follows,

	<u>A</u>	<u>B</u>	<u>C</u>
Beam	24 lbs	55 lbs	81 lbs
Arch	60 lbs	13 lbs	6 lbs
Unaccounted	16 lbs	32 lbs	13 lbs

(A part of the load unaccounted for is borne by the base of the fifth metatarsal).

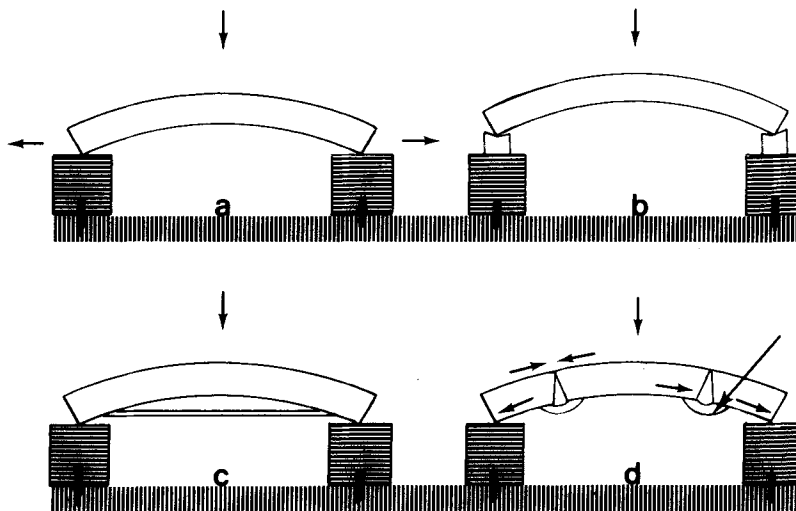


Fig.2

A weight on an arch-shaped structure - the arch-shaped beam, tends to thrust the ends of that structure further apart (fig.2a). The strength of a true arch is assured by preventing the ends from separating still more. This can be achieved by means of an embankment at either end (fig.2b), or by a connection between the ends of the arch (fig.2c). In the foot we know that the plantar fascia functions as a cord fixed to the ends of the arch. When the ends are not prevented from separating further, the structure behaves as a beam. The strength of such a beam lies in its breaking strain. The foot is a structure comprised of several parts with, on the under surface, tense intersegmental ties (fig.2d). On weight-bearing these ties are taut at their limit of extension and the foot functions as a beam until the plantar fascia prevents further flattening of the arches. Weight-bearing of the foot involves, therefore, both functions, that of an arch and that of a beam (Hicks, 1955). The large arrow indicates the intersegmental tie. The smaller arrows indicate the direction of compression and tension forces.

We cannot divorce these findings from the experimental methods employed. Much of the merit of Hicks' work lies in the fact that it lent stimulus to the young science of biomechanics. But he measured the bending of only a part of the beam, the metatarsals.

There occurs, however, a change in the structure of the arch when the plantar aponeurosis is divided. The changes, occurring in the intersegmental ligaments, remain unknown. Hicks defined precisely the mechanism of supination in the tarsus during arch-raising combined with external rotation of the lower leg.

Although he described the tarsal joints with respect to their functions as hinges, he left the question untouched regarding the shape of the joint surfaces, namely whether they are to be considered as parts of solids of revolution or not. Nor did he enter into the rôle played by the ligaments in guiding movements in the tarsus, an extremely important point as has been demonstrated by Huson (1961). Nevertheless a reasoned explanation for the coordinated movement of the tarsal joints, as presented in Hicks' elaborated study, was still lacking.

Lovett and Cotton (1898), and later Elftman (1960, 1966), also described the phenomenon of raising and lowering of the medial arch combined with, respectively, external and internal rotation of the whole leg, in subjects standing erect. According to Elftman, raising of the arch occurs in the so-called "transverse joint", known as Chopart joint. In this articulation, the cuboid and the navicular are functioning as one bone. Elftman (1960) regarded the transverse tarsal joint as part of the ankle complex. This ankle complex he regarded as a kind of kinematic chain, consisting of the calcaneus, the talus and the cuboid-navicular. (The junction between the cuboid and navicular bones is virtually rigid.) He did not abandon at any time, however, the

concept of the movements described by fixed axes.

To analyse the motion in feet of different types, Close and Inman (1953) used metallic pins as targets which were drilled into two tarsal bones, and calculated the angular motion of the calcaneus with respect to the talus during stance-phase of locomotion from the varying positions of these pins. The pins were inserted into the lateral aspect of the calcaneus and the lateral aspect of the talar neck in such a way as to form an angle in a plane perpendicular to the talo-calcaneal axis. This angle was recorded in two perpendicular planes by 35 mm. film projection, employing a film speed of 50 frames/s. The results from three individuals were as follows: -

- a. very little motion in a normal foot,
- b. in the moderately pronated foot,  $5^{\circ}$  or  $6^{\circ}$  of rotation around the subtalar axis,
- c. in the flexible flat foot,  $11^{\circ}$  or  $12^{\circ}$  of rotation between the calcaneus and the talus.

(When considering the axes, one must not neglect the ability of the ankle to move in more than one plane.) The same workers also demonstrated considerable horizontal torque between the lower leg and the foot in normal subjects during walking. This torque is hardly changed in the amputee or in the patient with a triple arthrodesis.

Huson (1961) pointed again to the remarkable relationship between tarsal movements and rotation of the lower leg. He asserted that the talus adopts a principal rôle in the performance of these movements.

The talus is a bone to which no muscle is attached. Huson denies the validity of the concept of "solids of revolution" as a mechanical principle for the guiding function of these joint surfaces. Far from functioning like hinges, these joints are instead poly-axial. He ascribes to the ligaments an essential function in the "steering" of movements in such joints. An additional

point is the fact that these joints perform their function in the closest cooperation. He points out that the tarsal bones form a closed kinematic chain. The mobility of this chain becomes annihilated almost completely after blocking even one of the tarsal joints. This phenomenon suggests that there is only one degree of freedom for the tarsal mechanism as a whole.

The movement described by Huson reads thus:

a. With the calcaneus fixed.

During exorotation of the talus the talar head tends to move laterally out of the socket of the navicular. This motion is followed by a dorso-lateral movement in the calcaneo-cuboid joint.

b. With the calcaneus free.

During exorotation of the talus the edge of the foot bulges laterally, since the calcaneus also, but to a lesser extent, follows this movement. An additional agent here is the fact that the anterior process of the calcaneus becomes directed more laterally. Concurrently the cuboid assumes a more adducted position in relation to the calcaneus.

c. The forefoot tilts in pronation.

Exorotation of the talus of a fully weight-bearing foot produces slight dorsiflexion of the talus and calcaneus accompanied by inversion of the calcaneus itself and of the navicular, together with plantar flexion of the first metatarsal. In this way the medial arch is raised. At the same time, the cuboid and the proximal part of the fifth metatarsal are tilted in a plantar direction, resulting in lowering of the lateral edge of the foot. During supination of the tarsus exorotation of the talus may be considered as the principal starting movement (the foot resting on the floor and the position of the lower leg being vertical). External rotation of the talus is produced by an exorotation of the leg. Such

a rotation of the whole leg can be effected in the hip, with the knee extended, or by rotation of the lower leg in the flexed knee-joint. In the same way as tarsal movements are induced by rotation of the tibia, the converse is also conceivable, namely that tarsal movements produced by the lower leg muscles induce rotation of the lower leg.

### 3.2. Functions of the lower leg muscles with respect to the tarsal movements.

In 1862, Duchenne of Boulogne published his book, entitled, "Physiologie des Movements". He studied the effect of the muscles in relation to the joint on which they are acting. He investigated this effect by faradic stimulation of separate muscle bundles, as well as on isolated whole muscles during life or shortly after death. He did not, however, investigate the lower leg and foot in the functional loaded position. He completed his experiences with findings in patients with paretic and paralytic muscles.

In 1892 R. Fick published his work under the title: "Ueber die Arbeitsleistung der auf die Fussgelenke wirkenden Muskeln". His work was based upon the work of A. Fick (1885) who calculated the work performed by muscles. A. Fick showed that it is sufficient to know the distance of muscle shortening and the tension of the muscles. Tension is estimated by correlating the cross-section and the weight-bearing of a given muscle.

The muscle shortenings of R. Fick bear some relevance to our own measurements. The results of R. Fick are represented in tables 1a and 1b. Table 1a represents the tendon slip when the foot was supinated at the talocalcaneal joint. The other tarsal joints were locked (see also p.28 and the sections 5.1.2.1. and 5.1.2.3.

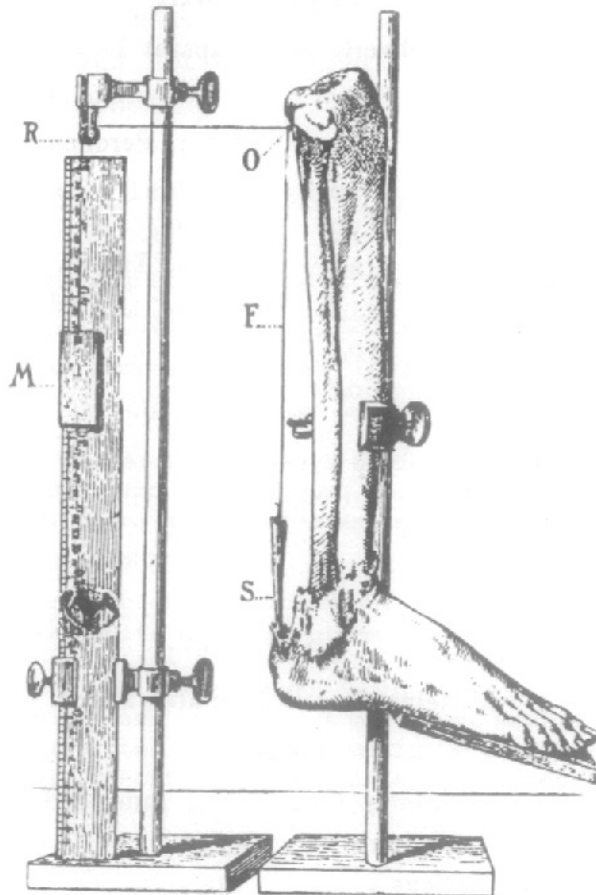


fig.3. Apparatus used by Fick to make tendon measurements (see text p.26,27).

R.Fick carried out measurements on three different legs stripped of all muscles. At the origin of the muscle a strap was put into the bone. A string was fixed to the proximal end of the tendon and led through the strap. At the other end of the string a weight of 58 grams was suspended. The string represented the average direction of the muscle tension. On moving the foot, the shift of the tendon end was measured as indicated (fig.3) by the weight moving along a graduated scale. Such measurements were carried out for movements in each of the joints of the foot and ankle. The entire weight of the individual

**Tabelle XII.**

**Mittelwerte aus Präparat I—III.**

Supinatoren:		Pronatoren:	
1. Tibialis posticus	21,5	1. Peroneus longus	24,5
2. Flexor digit. comm. 1.	19,3	2. „ brevis	22,8
3. Soleus fibularis	13,0	3. „ tertius	22,6
4. Flexor hallucis	12,2	4. Extens. digit. comm. 1.	19,4
5. Soleus tibialis	11,5	5. „ hallucis long.	9,0
6. Gastrocnemius	10,8		
7. Tibialis anticus	0,8		

table 1a. Measurements obtained by Fick. Shortening in mm. Average tendon slip of three preparations calculated with respect to the tarsus. The ankle-joint was locked.

**Tabelle IV.**

**Mittelwerte aus Präparat I—III.**

**Beuger:**

1. Ext. digit. comm. long.	36,1 mm	Verkürzung
2. „ hallucis long. . . .	33,6	„ „
3. Tibialis anticus . . . .	32,5	„ „
4. Peroneus tertius . . . .	30,4	„ „

**Strecker:**

1. Soleus caput fibul. . . .	45,7 mm	Verkürzung
2. „ „ tibiale . . . .	43,7	„ „
3. Flexor hallucis long. . . .	21,3	„ „
4. Flexor digit. comm. long.	13,2 mm	Verkürzung
5. Peron. longus . . . . .	12,8	„ „
6. Tibialis posticus . . . .	7,7	„ „
7. Peroneus brevis . . . . .	6,7	„ „

table 1b. Measurements obtained by Fick. Shortening in mm. Average tendon slip of three preparations calculated with respect to the ankle.

Beuger = Flexors; Strecker = Extensors.

muscle of one leg and the largest cross-section of these same muscles were measured. The legs were lean and the muscles themselves not excessively developed. They were preserved in alcohol.

In 1924 Scherb investigated the function of the contracting lower leg muscles by careful palpation during locomotion. He found that the use of these muscles follows a regular pattern and speaks of a "myokinetische Partitur" (fig.4). His book, published in 1952, included results of electromyographical investigations performed by Arienti and himself in the period after 1946 following the introduction of electromyography as a research tool. Concerning his results Scherb writes as follows:

- gastrocnemius muscle:

The triceps surae muscles are exclusively stance phase muscles. The gastrocnemius starts its activity at heel strike but gains its first maximal contraction at the moment when the toes come into contact with the floor. In the part of the stance phase immediately following, there is less activity. A period of maximal activity occurs shortly after heel lift. This activity decreases rapidly and terminates at toe-off. (In his writings, however, Scherb does not describe the phenomenon of push-off.)

- soleus muscle:

Start and finish coincide with those of the gastrocnemius. The maxima, however, are of lesser degree. The character of the contraction is less differentiated but nevertheless very strong.

- tibialis posterior muscle:

The curves of the myokinesigram are of the same shape as those of the gastrocnemius. Scherb, however, very often found deviations such as a failure to display differences in maxima and periods of lower activity.

- flexor digitorum longus and brevis muscles:

The action of these muscles starts at the moment when the metatarsal heads make contact with the floor. There is an increase of activity during the stance phase and a maximum shortly before toe-off. Scherb found the same pattern for the abductor hallucis muscle.

- peroneus longus muscle:

Scherb calls this muscle the lateral homonym of the tibialis posterior, also with regard to its activity, although the pattern of activity is more constant than that of the tibialis posterior.

- peroneus brevis muscle:

Die einzelnen Muskeln im Myokinesigramm

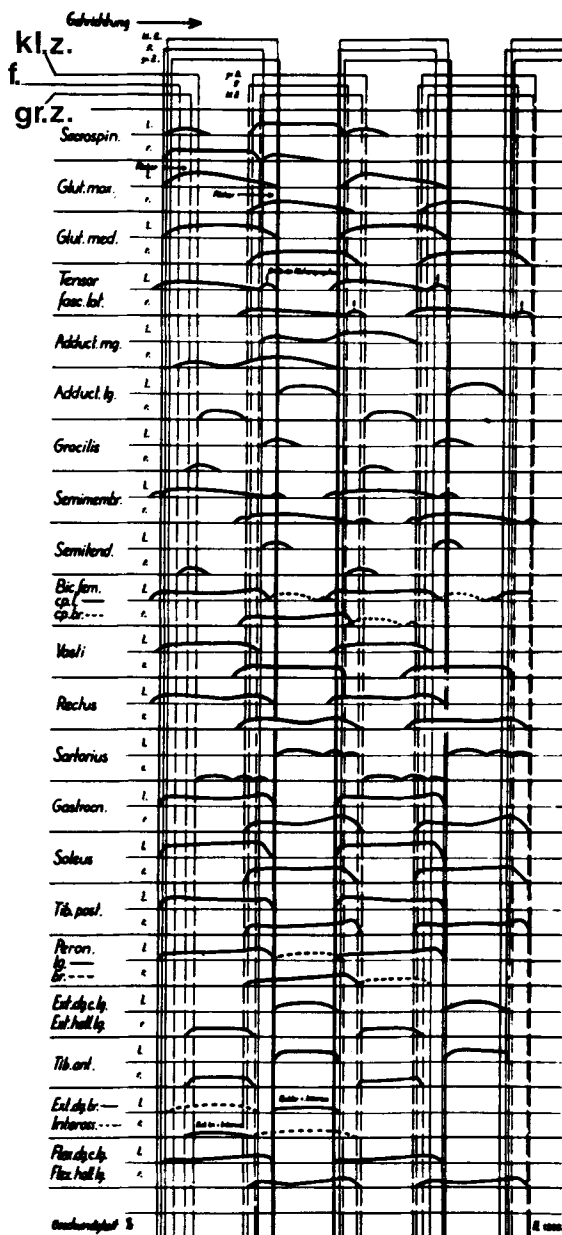


Fig.4. The myokinesigram during walking, according to Scherb.  
 f = moment heel strike  
 kl.z. = moment dig. V contacts the floor  
 gr.z. = moment hallux contacts the floor  
 The figure has to be read from left to right. By courtesy of Ferdinand Enkle Verlage from Scherb R.: Kinetische-diagnostische Analyse von Gehstörungen. Beilage zur Zeitschrift für Orthop., BD 32, S. 49, Abbildung 18 (1952).

The peroneus brevis muscle is principally a swing phase muscle, in contrast with the peroneus longus. The pattern of activity is individually variable, so that the stance phase activity may be lacking.

- Extensor digitorum longus and brevis and tibialis anterior muscles:

The long and short extensors of the toes and the tibialis anterior are defined as swing phase muscles. The activity starts shortly before toe-off, increases till half completion of the swing phase, and finishes at the moment the forefoot contacts the floor.

Hicks published a paper in 1953 concerning the action of the muscles of the foot in the upright position. As we have noticed already, he considers all the movements in the foot to be pure rotations. The action of any muscle can be determined from its moment at all the joints it crosses.

The moment of forces acting at a joint depends on the algebraic sum of the moments of all the passing tendons at the joint and the body weight. Starting from the localized position of the joint axes, the radii of action of all muscles at the major points in the foot could be determined by Hicks. Obliquity of a tendon with respect to the plane of rotation of a hinge joint reduces its effect. He obtained a table of effective radii of action of the tendons at joints and concluded that muscles can act on the foot in two ways:

- a. by direct action on the mid-tarsal and ray joints of the foot;
- b. by indirect action through their effect on the position of the line of the body's centre of gravity.

During quiet standing, the line of the body's centre of gravity is continually changing its position. There are anterior-posterior movements (observed in the ankle-joint), and side to side movements (in the talo-calcaneo-navicular joint).

Direction of shift of the point of balance can be determined theoretically by plotting the appropriate radius values from Hicks' table (balance-point of Hicks =

place where the force representing body weight and a given pull of a given muscle are in balance with a reaction force under the footsole in Hicks' experimental set-up). He shows how these changes in position of the line of centre of gravity of the body affect the arch-flattening force in the foot and how these balancing muscles act indirectly on the foot as a result.

Hicks' explanation of the indirect action of the muscles upon the arch of the foot is as follows: -

The arch-flattening effect of the body weight varies with the position of the point of balance. The effect is zero when the point of balance transects the heel and rises to almost twice the body weight when the point of balance penetrates the ball of the foot. The muscles which determine the position of the point of balance, determine indirectly the tension in the plantar aponeurosis. The plantar flexors of the ankle-joint increase the arch-flattening force and the dorsiflexors of the same joint diminish it towards zero. With a forward displacement of the point of balance, brought about by a pull on the tendo calcanei, the tension of the plantar aponeurosis was found to increase. It has to be confirmed that the muscles which display the point of balance medially also increase the arch-flattening force on the medial arches and lessen this force on the lateral arches and vice versa. With regard to direct action upon the arch, Hicks stated that any muscle that has a radius of action at a ray joint also has a direct action upon the arch. Crossing above the axis it will be an arch-flattener, and crossing below that axis, it will act as a raiser.

In 1962, W.G.Wright published her book, "Muscle Function". In her investigation of movements of the foot, the muscles of the lower leg were palpated during movement of the free hanging foot. Prior to testing the supination of the foot, the subject lay on his right side with the right knee slightly flexed and the muscles in a state of complete rest. The right foot was now raised from the table with its own weight as the sole force of resistance; only the tibialis posterior muscle was felt to contract. If the movement was carried out against strong resistance, the tibialis anterior, gastrocnemius and soleus all came into action as well. The adduction component of this supination is strong during the first part and during the latter part of this movement.

She describes, moreover, the supination action on the foot of the flexors hallucis longus and digitorum longus, but these muscles are active only when either the movement is strongly resisted or when the supinators are paralysed. Thirdly, these flexors are active while standing and during weight-bearing, when flexion of the toes is prevented. Maintenance of the arch of the foot is assisted by contraction of the flexors of the toes.

To test the opposite movement, namely pronation of the right foot, the subject lay on his left side and lifted his foot against gravity. The peroneus longus and brevis now contracted. The peroneus starts this movement. The action of the peronei alone tends to pronate the foot and brings it into slight plantar flexion. In pronation from a position of dorsal flexion, the tibialis anterior acts together with the peroneals. The weak plantar flexion action of the peroneals is no serious check to the dorsal flexion action of the tibialis anterior muscle. The weak supinator action of the tibialis anterior cannot prevent pronation by the peroneals.

Basmajian and Bentson (1954) and Sheffield et al. (1956) investigated the function of the tibialis anterior and the peroneus longus with respect to their function in supporting the arches of the foot. These muscles are inactive in the standing position. Basmajian concluded that the main resistance against a flat foot is provided by the ligaments.

Basmajian and Stecko (1963) studied the influence of the intrinsic foot muscles upon the arches, employing needle electrodes. They concluded that the muscles are also inactive during standing. There is, however, considerable activity of these muscles at push-off and while standing on tiptoe.

Close (1973), too, mentioned the phasic activity of the lower leg muscles during walking. He stressed the value of electromyographic studies in the further

development of orthopaedics. According to Close, in cases of muscle transfer it is especially important to analyse the function of the muscle before and after operation. The E.M.G. is of great value in measurements concerning time and extent of muscle activity.

According to Close, the axis of the subtalar joint enters the lateral aspect of the tuber calcanei and emerges from the dorsal aspect of the head of the talus, passing through the centre of the spherical portion of the talar head. The position of this axis is subject to individual variation and influences the effect of the tibialis anterior, peronei, tibialis posterior, extensor hallucis longus, and extensor digitorum longus.

Mann and Inman (1964) investigated the movements about the subtalar axis on walking horizontally, up a slope, down a slope, or up and down stairs, together with the phasic activity of the intrinsic muscles of the foot. They reminded one that external rotation of the tibia causes a movement of the talus which in turn transmits a force to the tarsus, thus raising the arch without the use of muscle power. The conclusion of their study is that the intrinsic muscles of the foot act synchronously as a functional unit. The electrical activity of all these intrinsic muscles of the foot corresponds with the progressive supination at the subtalar joint during walking on a horizontal plane, up slope and down slope. Moreover, there is a functional anatomical relationship between the intrinsic muscles and the subtalar and transverse joints, so that they may be considered to play the principal active rôle in the stabilization of the foot during propulsion. In the pronated foot (pes valgus), greater muscle activity is employed to achieve stabilization than in the normal foot. When a person is standing at rest, activity in the intrinsic muscles is absent, as has been shown by Basmajian and Stecko (1963). This supports the concept that muscular activity is not

necessary to support the arches of the fully loaded foot  
at rest.



CHAPTER 4

METHOD

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## CHAPTER 4

### METHOD

In the introduction it was explained that the investigation was divided into two phase: -

1. Quantitative measurements in the post-mortem specimens of the lower leg and foot of,
  - a. the movements of the tarsal bones during supination,
  - b. the tendon slip of the lower leg muscles during movements of the tarsus and ankle-joint.
2. Electromyographic registration of the activity of the muscles of the lower leg in living subjects.

In this chapter the methods will be presented in the same sequence.

#### 4.1. Measurements in the post-mortem specimens of the lower leg and foot.

- 4.1.1. Measurements of the rotations of the tarsal bones in the lower leg of anatomical specimens.

The measurements were carried out on anatomical specimens of the lower leg. For this purpose, the stiff skin of the lower leg and foot was removed right to the base of the toes. Thereafter, the lower leg muscles were removed, the tendons from a point 10 cm. above the ankle-joint remaining in situ.

Neither the joints of the ankle and the tarsus nor the the insertion of the tendons and their sheaths were

disturbed. The surfaces of the joint cartilages were smooth, and the ligaments flexible and not stiffened or hardened by conservation.

The junction between the tendon and tendon sheath, the mesotendon, however, was found to be shrunken. These junctions had to be disturbed in such a way as to allow the tendons to slip easily in their sheaths. The prepared legs were placed in position in the iron frame which we call the cage. This cage was a metal frame in the form of a cube. The upper and lower surfaces were 50 cm. square and the height was 60 cm. The foot under investigation rested on a plate placed on the bottom of the cage (fig. 5).

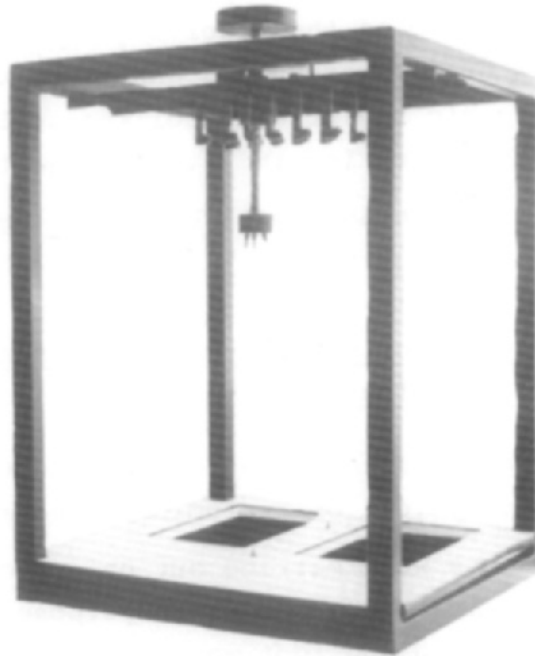


Fig.5. The cage

In this bottom plate, on either side of the area where the foot rested, two windows (see also fig.6) were cut. A pin, rising from the area for the heel, was pressed into

that part of the calcaneus in contact with the floor during normal standing. In this way the calcaneus could be tilted without risk of its slipping sideways (because the spongy bone offers less resistance to the pin than the cortical bone which is more solid).

In the upper plane of the cage was a vertical axis. At the upper end of this axis was a disc calibrated in degrees and at the lower end of the axis sat a knob with three pins. These pins were driven into the tibial plateau. The lower leg, set up vertically in the cage, could now rotate on its longitudinal axis and the tarsus was able to follow this rotation with the characteristic supination and pronation. After a chosen exorotation the axis was locked and measurements could be performed.

The arch of the foot was elevated by the supinatory remodelling and the lower leg raised. Thus we set up the vertical axis at the top in such a way as to permit rotation and translation (see table IV, p. 85). The forefoot was supported at the lateral side, at the head of the fifth metatarsal, in order to avoid sideways movement of the forefoot.

Pins were now placed in the tarsal bones and in the malleoli, so allowing the rotations of the tarsal bones and the malleoli to be followed. The distance object - photographic plate was in all cases 1.5 m.

We made photographs from three directions perpendicular to each other; the three planes of projection and the rotations of the bones in these planes of projection could now be measured. These photographs give no information about the translations. To describe tarsal movement precisely, it is necessary to measure the translation as well. The momentary axes can only be defined from measurements of the rotations and the translations. For measurements of this kind we require the opportunity to determine exactly the position of each bone. A radio-photogrammetric system with computer analysis was thus

devised in the anatomical department (van Langenlaan, Spoor, Huson, 1974). Results will be reported in the near future elsewhere.

Four characteristic positions of supination are defined as follows: -

Position 0: "foot flat position"

Position at the start of the movement. There was maximal contact between the foot sole and the base of the cage. The medial arch was as low as possible.

Position 1: "incomplete supination"

First movement in supination. The lower leg was rotated externally to a point of elevation of the medial arch, the head of the first metatarsal still resting on the bottom of the cage. The forefoot made, therefore, a pronatory movement, a twist.

Position 2: "complete supination"

Maximal supination of the tarsus. The lower leg was now exorotated maximally. The sole of the foot rested with the lateral side on the bottom of the cage. The forefoot was left free and was not pronated, but moved with the hindfoot in supination.

Position 3: "complete supination with metatarsal pronation twist"

The tarsal position as for position 2. The forefoot was pronated by gentle wringing and by exerting finger pressure on the dorsal side of the head of the first metatarsal.

We constructed a standard system for three directional photography of the tarsus, with the pins in situ,

affording an anterior view, a lateral view and an axial view.

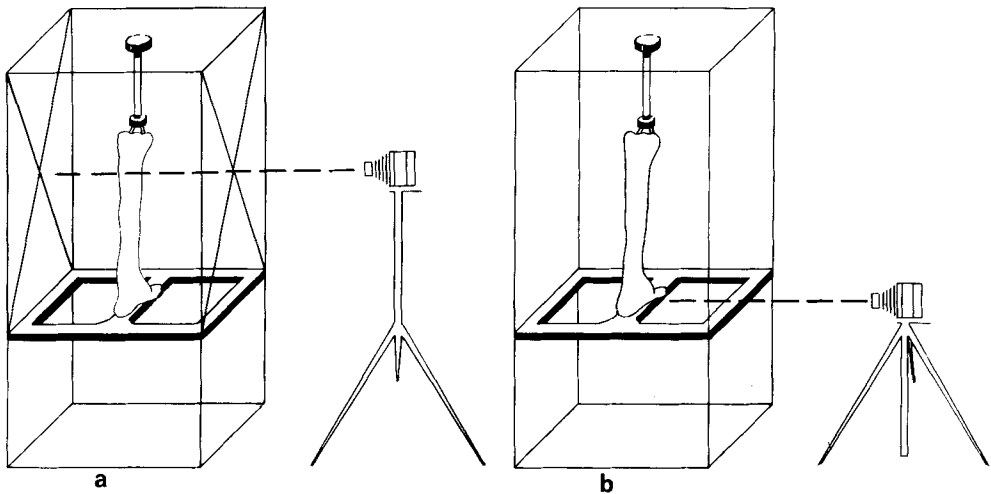


fig.6 (see text)

For the two horizontal views, anterior and lateral, the cage was set as follows: -

In the front and back sides of the cage a diagonal wire cross was made. The camera was set up in such a way that the middle of the photographic plate coincided with the projection of the two points of intersection of the wire crosses (fig.6a). Thereafter, the camera was lowered until the optical axis skimmed over the bottom plate. The bottom was now projected as a line which passed through the middle point of the photographic plate (fig.6b).

For the anterior view it was of no consequence whether the foot was photographed from the ventral side or from the dorsal side. In the side view, the medial side of the foot faced the camera. For the axial view the cage was laid on its side. The position of the camera was now such that the picture of the calcanean pin fell on the middle of the plate. Two series of preparations were measured. In series 1 we measured the rotations of the tarsal bones and the medial malleolus. With the exception of cadaver

nr. 338, tendon slip measurements were also performed in this series. In series 2 we measured the rotations of the tarsal bones and both malleoli. The legs were rotated externally without force and until the foot adopted the desired position.

Before starting the measurements with a newly set up preparation, it was necessary to manipulate the specimen through the various movements. The ligaments and joint capsules became flexible and the mobility increased.

During the measurements the preparation was sprinkled regularly with water since dehydration does influence joint mobility somewhat.

#### 4.1.2. Possible errors in the measurement of the rotations of the tarsal bones.

The rotations of the tarsal bones were measured from the positions of the pins in the photographs. The influence of parallax could be estimated by calculating the effect of improper positioning of the camera. Possible faults in the positioning of the apparatus include: -

- a. some rotation of the camera around a vertical axis.

The positioning of the camera in the horizontal plane is ensured by the built-in levelling gauge.

- b. displacement of the camera to right or left.
- c. rotation of the cage around a vertical axis -  
a combination of a. and b.
- d. error in the measurements of the angle in the photographs.

- a. The rotation of the camera around a vertical axis  
(fig.7).

In this case the difference between the projections of the pins on the properly-positioned plate and on an oblique plate was calculated. The pin AB was placed

in the bone in A and BDC was the angle formed by the projection of the pin on a plane parallel with the plate of the camera, when this camera was correctly positioned. The angle BDC was that which had to be measured.

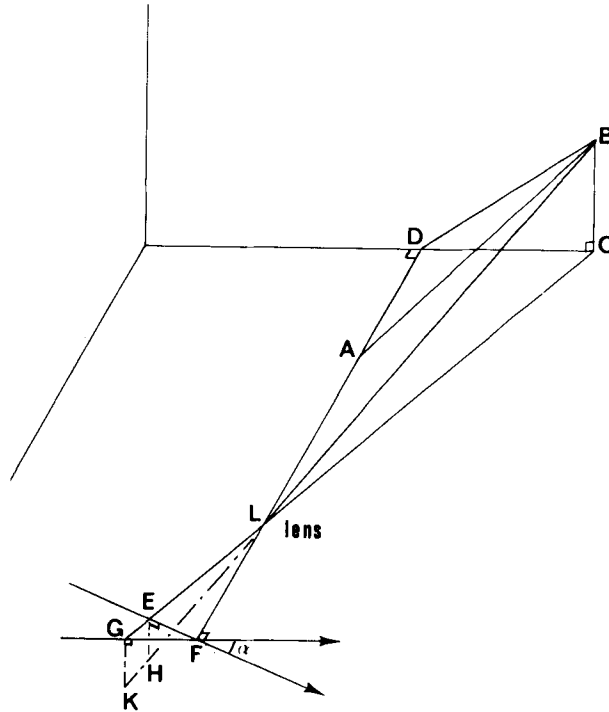


Fig.7 (see text)

From fig. 7 can be deduced that  $\angle BDC = \angle KFG$ . By improper positioning of the camera, the angle HFE will be measured instead of the angle KFG. The angle HFE is formed when the camera is rotated around the vertical by  $\alpha$  degrees.

$$\left. \begin{aligned} \tan (\angle HFE) &= \frac{BC}{CD} \cdot \cos \alpha \\ \tan (\angle BDC) &= \frac{BC}{CD} \end{aligned} \right\} \cos \alpha < \frac{\angle HFE}{\angle BDC} < 1$$

Example:  $\alpha = 7.5^\circ$      $\cos \alpha = 0.99144$   
 $\angle BDC = 10^\circ$      $\tan \angle BDC = 0.17633$   
 $\tan \angle HFE = 0.99144 \times 0.17633 = 0.17482$   
 $\angle HFE = 9^\circ 55'$

The difference is  $5'$ , thus very small. See also table IIa.

- b. Displacement of the camera to right of left (fig.8).  
 We shall see later (table III, p.76) that the pins of the navicular and cuboid, observed in the lateral view, move mainly in a vertical plane parallel to the optical axis of the camera. Beginning from the principle that the pin lies in a vertical plane, seen through the optical axis of the camera, a fault is most likely to occur when the angle between the pin and this optical axis is small and the camera is displaced horizontally and parallel to the photographic plate. The angle between the pin and the optical axis, however, is never smaller than  $45^\circ$ . Thus the maximal value of the error can be calculated assuming that the pin makes an angle of  $45^\circ$  with the optical axis. The pin AB was placed in the bone at A.

Calculation:

From fig. 8 can be deduced that the displacement of the camera ( $L_1L_2$ ) was 5 cm. (L = the position of the lens.)

Distance object (pin) - camera is  $L_1A = 150$  cm.

The length of the pin AB is 15 cm.

The angle pin/optical axis is  $\angle CAB = 45^\circ \rightarrow AC = BC$ .

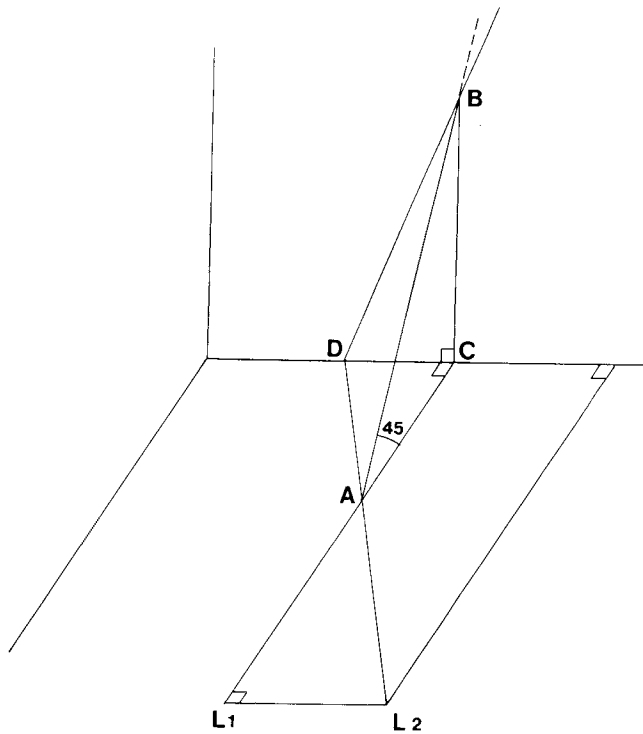


fig.8 (see text)

Required is to measure the difference between this angle and the angle resulting from displacement of the camera, viz.  $90^\circ - \angle BDC = \angle CBD$ .

$$CD = \frac{AC}{L_1 A} \cdot L_1 L_2$$

$$\tan \angle CBD = \frac{CD}{BC} = \frac{CD}{AC} = \frac{L_1 L_2}{L_1 A} = \frac{5}{150} = \frac{1}{30}$$

$$\angle CBD \approx \frac{1}{30} \text{ rad} = \frac{180}{\pi} \cdot \frac{1}{30} = \frac{6^\circ}{\pi} \approx 2^\circ \text{ (in reality it is less.)}$$

$$\angle BDC = 90^\circ - \angle CBD$$

It will be shown also (table IIIa, b, c) that the talus moves practically in a horizontal plane. In this case a displacement of the optical axis of the camera in a vertical direction will produce errors with a comparable magnitude.

Special photographs side view, position 2.

Cad.nr.368	<u>Camera in normal situation</u>	<u>Camera turned <math>7\frac{1}{2}^{\circ}</math> to left(dorsal side)</u>	<u>Camera turned <math>7\frac{1}{2}^{\circ}</math> to right(ventral side)</u>
1.Navicular	+ 6.5	+ 6	+ 6
2.Calcaneus	+ 5.5	+ 5.5	. 5.5
3.Cuboid	+ 6	+ 6	*
4.Lat.mall.	- 2	- 2.5	- 2
5.Talus	- 3	- 3	- 2
6.Med.mall.	+10.5	+10	+11

table IIa

Special photographs side view, position 2.

Cad.nr.368	<u>Camera in normal situation</u>	<u>Camera displaced 5 cm to left (dorsal side)</u>	<u>Camera displaced 5 cm to right (ventral side)</u>
1.Navicular	+ 6.5	+ 5.5	+ 5.5
2.Calcaneus	+ 5.5	+ 5.5	+ 5.5
3.Cuboid	+ 6	*	+ 6
4.Lat.mall.	- 2	- 3	- 2
5.Talus	- 3	- 3	- 3
6.Med.mall.	+10.5	+10	+10

table IIb

\* This pin could not be measured. It was hidden behind the specimen as result of rotation or displacement of the camera.

c. Rotation of the cage around a vertical axis.

This is the combination of displacement and rotation of the camera (a. + b.) and will give a fault of the same proportions as b. The influence of rotation is thus negligible.

d. Error in the measurements of the angles in the photographs.

The error in measurements of the angles in photographs

is due to the thickness of the pin ( $2\frac{1}{2}$  mm.) and the graduated arc. This error is greater than mentioned in a. and b. and may attain the same proportion as in b.

We measured also the angles of the pins after introducing both kinds of fault, viz. the rotation of the camera and the displacement of the camera. In this way we got an impression of the magnitude of the fault in our measurements. Table IIa, represents the faults introduced by a rotation of the camera and table IIb, represents the faults introduced by a displacement of the camera. In both cases the error in measurement of the angles in the photographs also influences the results.

However, the difference in the angles reproduced in tables IIa and IIb is not more than 1 degree.

#### 4.1.3. The tendon slip of the lower leg muscles during movements of the tarsus and ankle-joint.

In this part the measurements of the slip of the tendons will be described (fig.9). For this purpose stainless steel wires 0.4 mm. thick were attached to the proximal ends of the tendons and the wires were led through metal straps. Such a strap was attached to the bone at the central point of muscle origin. The wire was led across two pulleys and the tendon now tightened by hanging a weight at the other end of the wire. On the length of the wire, between the end of the tendon and the strap, a splitshot was placed as a marker. Slipping of the splitshot was prevented by glueing them to the wire. The distances between the upper side of the splitshot and the lower side of the strap were measured in the different positions with sliding compasses.

Before starting the measurements with a newly set up preparation the specimen was manipulated through the

various movements. The mobility of the preparation increased and the application of the wire at the tendon became tighter. The series of measurements were then performed. During the measurements the preparation was sprinkled regularly.

R.Fick performed similar measurements. He supported the foot with a plank and changes the position of the foot by altering this plank. He used a gin-trap to fix the lower leg (see fig.3). With our apparatus the position of the foot, resting on the sole, was changed by turning the lower leg around its long axis, or by rotating the lower leg and stabilizing the foot with a wooden block under the forefoot when the foot was dorsiflexed or with the block under the heel when the foot was plantar flexed. The measurements of Fick were performed by moving the separate joints of the tarsal chain. During our measurements of tendon slip, the joints of the ankle, tarsus and metatarsus were not blocked, in contrast with the experiments of Fick. We studied the influence of the lower leg muscles in relation to the supinatory remodelling of the foot. This movement takes place largely in the tarsus. Changes sometimes do take place in the position of the ankle and the metatarsal joints, but such changes are secondary. In our measurements we moved the whole chain. Thus the results of Fick cannot be compared simply with ours (see tables Vb and VIIb).

To compare the measurements of the different legs, a standard rotation for the lower leg from the positions 1 and 2 was introduced. The exorotation of the lower leg in position 1 was  $35^{\circ}$  and, in position 2,  $50^{\circ}$ . In some specimens the lower leg had to be rotated forcibly due to reduced mobility of the tarsalia.

In addition to the positions 0, 1, 2 and 3 we have chosen positions for imitating a balancing movement on the ball of the foot (A and B) and a position where the

foot rests on the heel (C). These positions may be described as follows: -

Position P: "plantar flexion position"

Starting position. The foot rests wholly on the forefoot, which implies that the heads of the fifth metatarsals are loaded. The heel rests on a block, 5.5 cm. in height.

Position A: "plantar flexion and pronation"

Plantar flexion of the ankle as for position P. The forefoot is pronated by elevation of the head of the fifth metatarsal by a block, 22 mm. high. The leg is rotated internally. This position was chosen to compare the tendon slip from maximal pronation with maximal supination while standing on tiptoe.

Position B: "plantar flexion and supination"

Plantar flexion of the ankle as for position P. The forefoot is now supinated by elevation of the head of the first metatarsal by a block of 32 mm., the leg in this case being rotated externally. The fixation of the foot between blocks in these positions was more stable than could be achieved by rotation of the tibia alone.

Position C: "dorsiflexion"

The ankle is in dorsiflexion. The forefoot is elevated by a block of 35 mm. The position of the forefoot qua pronation or supination is neutral. The sole of the foot makes an angle of  $60^{\circ}$  with the lower leg. Position P is the starting position.

The results of the measurements of four legs were recorded.

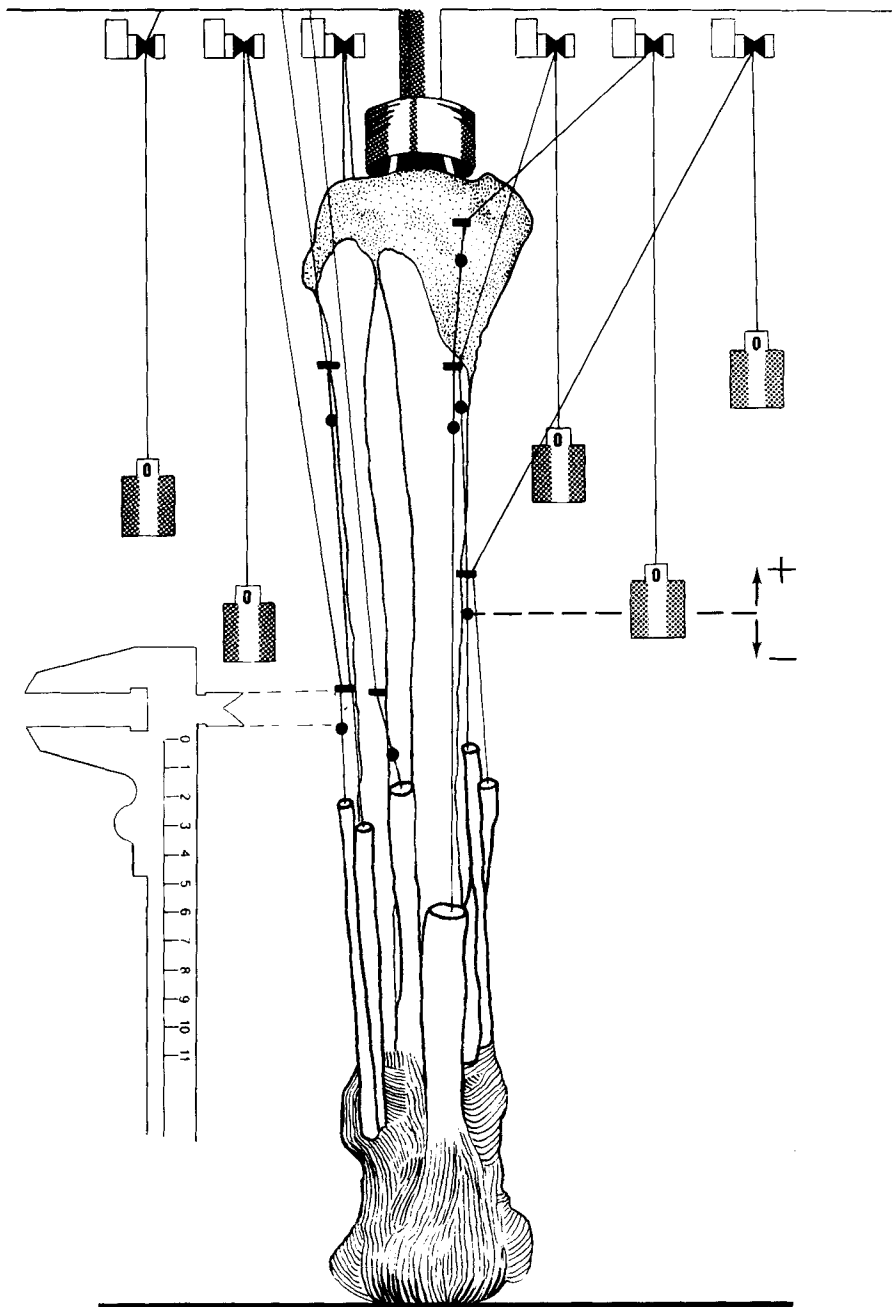


Fig.9.

Showing method of measurement of tendon slip.  
 The distance between splitshot and strap is  
 measured with sliding compasses.  
 + = upward shift of splitshot  
 - = downward shift of splitshot

The sequence of performance of a measurement was as follows: -

At first the leg was placed in the starting position (position 0). The distances between the splitshot and the strap belonging to each tendon were now measured and the results recorded. The leg was then placed in position 1 and the distances were measured again. Thereafter, the same procedure was repeated for the positions 2 and 3. In this way, every leg was measured 4 times, for the positions 0, 1, 2 and 3. The tendon slip was then calculated from the distances between the splitshot and the strap in the different positions, with regard to position 0. These distances can be negative or positive. A positive slip implies that the distance between splitshot and strap is shortened, and a negative slip implies the reverse, lengthening.

We calculated the slip of the following tendons:

- |                             |                              |
|-----------------------------|------------------------------|
| 1. tibialis posterior       | 5. peroneus longus           |
| 2. flexor digitorum longus  | 6. peroneus brevis           |
| 3. flexor hallucis longus   | 7. tibialis anterior         |
| 3. extensor hallucis longus | 8. extensor digitorum longus |
|                             | 9. achilles tendon           |

(The serial numbers of the muscles of these tendons are the same as those used for the E.M.G.measurements.)

#### 4.2. Observations on healthy experimental subjects.

##### 4.2.1. Performance of the E.M.G. experiments.

As discussed in the introduction we also made experiments in vivo. The experimental subjects performed the same movements with their feet as used in the experiments in vitro. In addition to these standard movements we introduced the clawing movement, the pronation movement, the rolling movement and walking. The subjects trained

these foot movements till they were performed correctly.

To describe the performance of the standard movements we have to define firstly the starting and end positions.

Position 0 = foot flat position - medial arch low  
(fig.10).

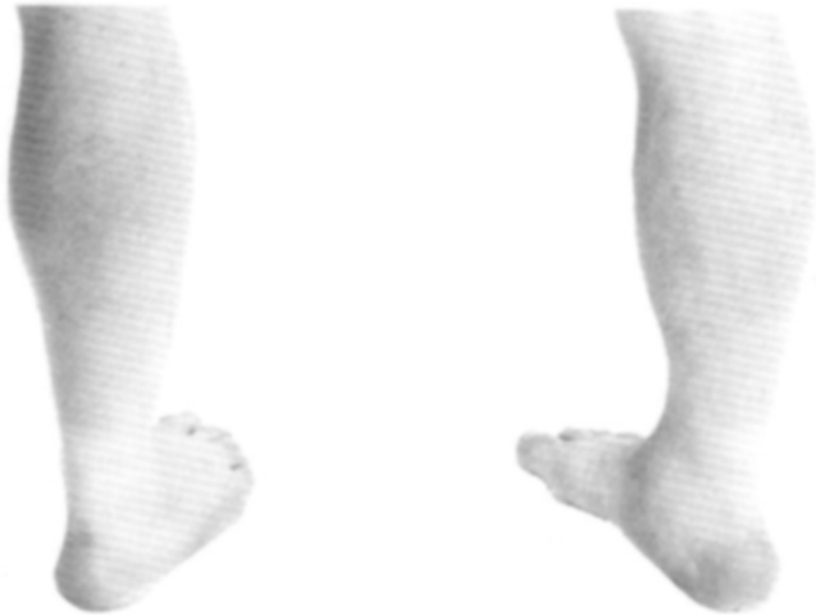


fig.10. Foot in position 0

Position + 1 = the lower leg is exorotated, the medial arch is heightened as far as possible without losing the contact of the first metatarsal head with the floor (fig.11). (This position is equivalent to position + 1 in the tendon slip experiments.)

Position 2 = maximal supinatory remodelling of the tarsus. The lower leg is maximally exorotated. There is no pronation twist of the forefoot. The foot rests on the lateral side (fig.12).

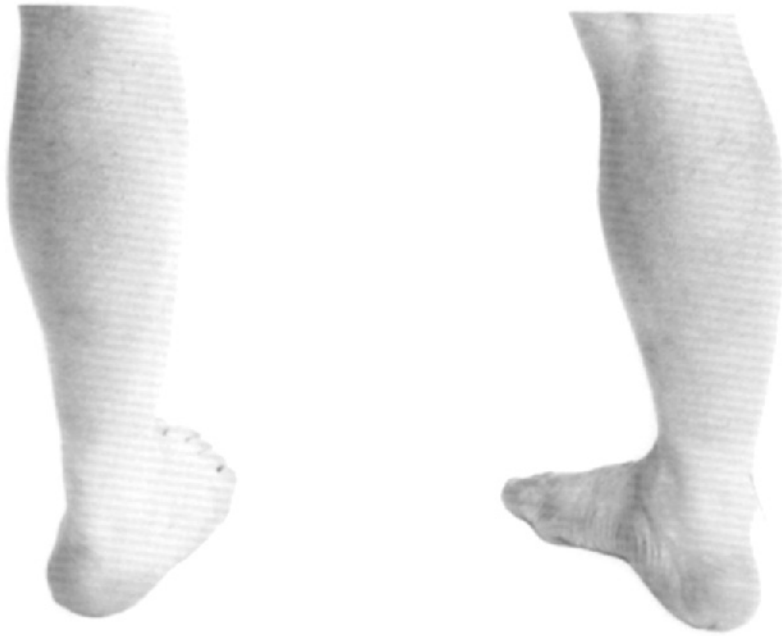


fig.11. Foot in position + 1



fig.12. Foot in position 2

Position - 1 = medial arch is as low as possible. The lateral tarso-metatarsal arch is raised and there is maximal endorotation of the lower leg (fig.13).



fig.13. Foot in position - 1

Claw position = there is another mechanism in raising of the arch. For this movement the medial and lateral arch are heightened together. The position of the tarsal chain is almost unchanged and there is no exorotation of the lower leg. To make this movement while standing upright, it is necessary to lean backwards somewhat (fig.14).



fig.14. Foot in claw position  
See also figs.25,26,27,28

There were two groups of experimental subjects. In the first group the standard movements were carried out with the examinee standing upright, using an 8-channel main amplifier, as follows: -

1. movement from position 0 to position + 1;
2. movement from position 0 to position 2;
3. movement from position 0 to clawing position;
4. walking on the *trottoir roulant*.

In the second group we used an improved 12-channel main amplifier. This group went through the following movements: -

1. "incomplete supinatory movement"
  - a. movement from position 0 to position +1; standing upright.
  - b. movement from position 0 to position +1; sitting, lower leg vertical.
  - c. movement from position 0 to position +1; sitting, lower leg vertical, but now with a weight of 1 kg. on the knee.
  
2. "complete supinatory movement"
  - a. movement from position 0 to position 2; standing upright.
  - b. movement from position 0 to position 2; sitting, lower leg vertical.
  - c. movement from position 0 to position 2; sitting, lower leg vertical, with a weight of 1 kg. on the knee.
  
3. "pronatory to supinatory movement"
  - a. movement from position 0 to -1 (3a) to position 0 to position +1 (3a'); standing upright.
  - b. movement from position 0 to -1 (3b) to position 0 to position +1 (3b'); sitting, lower leg vertical.
  - c. movement from position 0 to -1 (3c) to position 0 position +1 (3c'); sitting, lower leg vertical, with a weight of 1 kg. on the knee.
  
4. "clawing movement"
  - a. movement from position 0 to claw position; standing upright.
  - b. movement from position 0 to claw position; sitting, lower leg vertical.
  - c. movement from position 0 to claw position; sitting, lower leg vertical, with a weight of 1 kg. on the knee.

## 5. "rolling movement"

This movement is performed with the subjects standing upright. In order to describe this movement ten successive positions have been chosen. The subjects were trained to adopt these positions in time with a prescribed rhythm. In this series several positions of the other standard movements can be recognized.

step 1: the movement starts with a pronated position of the tarsus, the foot resting on the medial edge (position - 1).

step 2: the position of normal standing is reached (position 0).

step 3: the tarsus is remodelled in supination as in position + 1.

step 4: the tarsus is now tilted to the lateral side by maximal exorotation of the lower leg as for position 2.

step 5: the load is transmitted from the entire lateral edge to the front part of the edge and the heel is raised.

step 6: the foot is now extended maximally and rests on the most lateral part of the ball of the forefoot (position B, p.51).

step 7: thereafter, the forefoot is rolled medially to adopt a neutral position and the load is equally divided between all the metatarsal heads,

step 8: until by further rolling medially, the load rests on the first metatarsal heads (position A), and finally,

step 9: until it rests on the medial side of the sole in a maximal pronation of the tarsus (position - 1).

step 10: now the foot is returned to the normal standing position (position 0).

## 6. "Walking"

Walking on the *trottoir roulant*, at successive speeds of 1, 2, 4 and 5 km./h. and running at speeds of 4, 5 and 6 km./h.

In addition to these E.M.G. registrations the foot positions were photographed. We adapted for the rolling movement a podoscope, the "mirror box". This podoscope was built out of a horizontal square glass plate on which the subject placed his foot (the lower leg vertical). Below this glass the first mirror was placed, with its bright side at an angle of  $45^{\circ}$  to the glass plate. At each side of the leg on the two rear angles of the glass plate, the second and third mirrors were positioned vertically. The bright side of these mirrors faced forwards, making an angle of  $45^{\circ}$  with the sagittal plane. The vertically placed photographic plate was thus capable of seeing three sides of the lower leg and also the sole of the foot.

The photographs were made with an electronic flash apparatus as the source of light. The flash time was very short, about  $\frac{1}{100,000}$  s, and we photographed in the dark with an open shutter, the flash time thus becoming also the time of exposure. The electronic flash unit could also be used as a stroboscope, and was capable of flashing with a timed frequency. The exact time of the flash was recorded on the tape recorder via a photocell, the tape being that on which the E.M.G. also was recorded. By the inclusion of a counter in the electronic circuit it was, moreover, possible to stop the registration of the E.M.G., the light source and the camera after a preset number of flashes.

### 4.2.2. E.M.G. recordings.

The electrical signal was used for the registration of

of the muscular activity. We used wire and surface electrodes. Both types of electrode were used according to the method of Basmajian (Basmajian, 1974, chapter 2). The surface electrodes were small silver plates with a diameter of 8 mm. and had a central perforation. They were employed for observations on the superficially lying muscles. The electrodes were stuck to the skin with double adhesive plastic rings. Before the electrodes were applied to the skin, the latter was shaved. In order to reduce the resistance, thereafter, the superficial horny layer was scraped with abrasive paper. Scraping continued until the electrical resistance was reduced from more than 20 kilo-ohm to about 2 kilo-ohm. Such a resistance was necessary to reduce hum and noise to acceptable level. The input impedance of the preamplifier was 100 times greater than that of the unscraped skin. The reason for preparation of the skin therefore bears no association with this factor. Care must be taken to avoid over-scraping since this results in irritation and leaking of serous fluid, the appearance of skin potentials, and poor application of the surface electrodes.

After application of the electrodes, a portion of electrode jelly was introduced between the skin and the electrode through a hole in the disc (fig.16). For each muscle two electrodes were used. The surface electrodes were applied to the thickest part of the muscle belly in such a way that the imaginary line between these electrodes lay parallel to the working line of the muscles.

A surface electrode was used as zero (reference electrode) and was applied to the tibia as neutral part of the body. The differences in potential of one electrode relative to zero and of the other electrode relative to zero were measured.

Platinum wires, coated with lac, and of 0.1 mm. diameter, were used as wire electrodes. The coating at the tip of the wire was burned off over a distance of

2 to 3 mm. Here also, two wire electrodes were employed for each muscle. These electrodes were introduced into the thickest part of the muscle belly, with a needle of the type used for intramuscular injection. The electrodes were then threaded through the lumen and their white tips were bent at the sharp end of the needle. The needle was inserted into the muscle after intradermal anaesthesia with 2% lignocaine and on withdrawal the white ends were caught with their hooks in the muscle tissue. The wires were soldered to the input side of the preamplifier.

After introduction of the wires, the experimental subject was asked to make the exercises necessary to contract the muscle because the signal was low immediately after introduction of the electrodes but improved in height and clarity after these exercises. The wires were removed easily at the end of the experiment by pulling them out gently, during which time the experimental subject alternately strained and relaxed his muscle.

Our preamplifier (gain 25) is of the differential type. This means that signals arriving in phase on both electrodes, such as the 50 Hz disturbance of the line voltage, are eliminated. The signals from muscles in the vicinity of the muscles under investigation arrive mainly in phase and are also rejected. The remains of these signals disappear in the noise of the amplifier.

We estimated as a signal a curve with a frequency of more than 30 Hz and an amplitude in excess of 100 mV (output level). This was effectuated partly by connection in series of the high pass filter (filter 30 Hz = 30 dB) and partly by visual interpretation of the recorded signals on the U.V. paper afterwards. Thus we made a choice between signal and no signal and determined which muscles were active or inactive during a certain period in the motion.

The 12-channel preamplifier was carried in a box on

the back of the experimental subject. From this box the signal was led to the main amplifier by a cable and the signal was amplified to voltage level. After passing through the main amplifier, the signal could be projected on an oscilloscope. Finally, the information was stored on a bandrecorder and made visible with an ultra-violet recorder (fig.17).

In our first group of experiments the main amplifier had only 8 channels. For the registrations of all 12 muscles (11 lower leg muscles and one foot muscle) the latter were divided into 3 groups. Four muscles were connected to wire electrodes and this group (I) was used as a reference for the other 2 groups (II and III, see table hereunder). In this way the muscles of I and II and the muscles of I and III respectively could be recorded simultaneously.

The activity of the popliteal muscle was not recorded. The abductor hallucis was the only foot muscle investigated.

I	I
<u>wire electrodes:</u>	<u>wire electrodes:</u>
tibialis posterior	tibialis posterior
flexor digitorum	flexor digitorum
flexor hallucis	flexor hallucis
extensor hallucis	extensor hallucis
II	III
<u>surface electrodes:</u>	<u>surface electrodes:</u>
peroneus longus	lateral gastrocnemius
peroneus brevis	medial gastrocnemius
tibialis anterior	soleus
extensor digitorum	abductor hallucis



fig.15. The location of the electrodes used.

OO = surface electrodes

O = wire electrodes

t.p. = tibialis posterior  
 f.d. = flexor digitorum  
 f.h. = flexor hallucis  
 e.h. = extensor hallucis  
 p.l. = peroneus longus  
 p.b. = peroneus brevis  
 t.a. = tibialis anterior  
 e.d. = extensor digitorum  
 g.l. = gastrocnemius lateralis  
 g.m. = gastrocnemius medialis  
 s. = soleus  
 a.h. = abductor hallucis

In our second group of experiments we employed a specially built 12-channel main amplifier. Now all the 12 muscles could be recorded simultaneously.

Before commencing an experiment, we confirmed the location of the electrodes and calibrated the recording apparatus.

The localisation of the superficial muscles was identified by palpation. More problems were presented by the deeper muscles. We used anatomical specimens to find a suitable way for inserting the wire electrodes. The flexor hallucis and the flexor digitorum are palpable when tightened alternately in not unduly obese persons with well-developed muscles. The flexor of the hallux can be felt at the lateral side of the leg, just behind the edge of the fibula, at the junction of the middle and lower thirds of that bone. The peroneus brevis muscle has to be pressed aside somewhat. On the medial side at the same height, just behind the edge of the tibia, one finds the flexor digitorum muscle. With the puncture of the flexor digitorum muscle it is possible to perforate one of the posterior tibial vessels. Haemorrhage can be sufficiently annoying to necessitate introduction of another electrode. In the extensor of the hallux, the electrodes were placed by puncturing the needle in the middle of the quadrangle formed by the tibia and fibula, in the direction of the tibia. The needle made an angle of  $45^{\circ}$  with the skin and penetrated the tissues until it came into contact with the tibia. On withdrawal of the needle, the electrodes hooked the muscle tissue. The tibialis posterior muscle lies dorsal to the interosseus membrane in the upper quarter of the lower leg. Penetration of the membrane with a needle is very painful. Even after withdrawal of the needle, this pain is sufficiently annoying as to influence the walking pattern. The muscle, therefore, is penetrated behind the medial edge of the tibia just proximal to where the flexor digitorum is

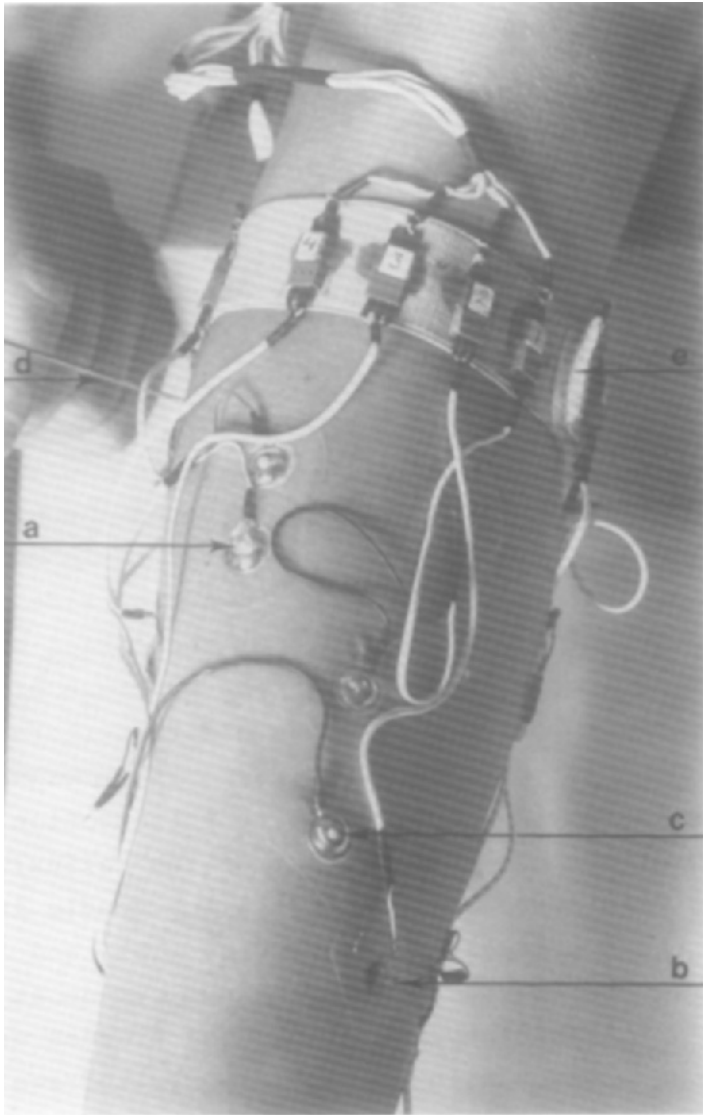


fig.16

The electrodes in situ

- a = surface electrode (white cable) with jelly. Distance between surface electrodes not less than 2 cm.
- b = wire electrodes
- c = zero electrode (black cable)
- d = needle to inject jelly between skin and surface electrode
- e = connections between electrodes and amplifier unit

palpable.

After introduction of the wire electrodes and application of the superficial electrodes, both were coupled to the input of the preamplifier and their position checked. Not only misplacing of the electrodes but also bad or wrong connections, poorly sticking electrodes, ruptured wires, and inadequate calibration could have an undesirable influence on the results.

A simple and usual test to check the localisation of the wire electrodes involves getting the subject to perform movements in which only the muscle in question participates (Long and Brown, 1964). Mann and Inman (1964) have stated that direct muscle stimulation is the method of choice. However, there are several contra arguments.

Direct muscle stimulation needs a low voltage, 5 - 20 V, and a high current, 10 - 100 mA for 1 - 5 s. Stimulation through the skin demands a higher voltage to obtain the same current intramuscularly (van Hof-van Duin, 1958). Direct stimulation, however, is only possible in the case of a curarized muscle. When the myoneural junction is intact the muscle is always stimulated via the nerve, the motor nerve being stimulated already by a current of 0.1 - 1 mA for a duration of 0.01 - 1 ms. Moreover, the current is dispersed unevenly by the tissue bordering on the nerve and muscle (van Hof-van Duin, 1958).

The current of stimulation will increase the electrode offset potential, thus making the electrode unsuitable for use as a recording electrode (Geddes and Baker, 1969). In such a case the E.M.G. response would be unreliable.

Reichman and Jonsson (1967) described a check for the proper location of intramuscular electrodes by contrast radiography with carbon dioxide. This method is considered as safe but the identification of the radiographs is difficult. The method requires radiographs from several

different projections and one cannot forecast the intramuscular distribution of the carbon dioxide.

In our experiment we invited the subjects to contract selectively a muscle performing a selected movement. We verified the muscle contraction by palpating the muscle belly or tendon. The E.M.G. patterns were assessed on the monitor. In this way we tested the location of the electrode and controlled the interference by other channels.

These selected movements were as follows: -

- Tibialis posterior - supination of the tarsus while the foot is plantar flexed. The tendon of the muscle is easy to palpate caudal to the medial malleolus.
- Flexor digitorum - plantar flexion of the toes, against resistance. The muscle belly is palpable.
- Flexor hallucis - plantar flexion of the hallux against resistance. The muscle belly is palpable.
- Extensor hallucis - dorsal flexion of the hallux, also moving with and without resistance. The tendon is visible and palpable.
- Peroneus longus - pronation of the foot with simultaneous plantar flexion of the first metatarsal. The experimental subject is asked to press the head of the first metatarsal forcibly against resistance in a plantar direction. The plantar flexion of M1 is specific for the peroneus longus.
- Peroneus brevis - pronation of the tarsus. The tendon is palpable.
- Tibialis anterior - dorsal flexion of the foot with the tarsus supinated. The E.M.G. is judged on moving against gravity and

against resistance. The tendon is visible and palpable.

Extensor digitorum - dorsal flexion of the toes, moving with and without resistance. The tendons are visible and palpable.

The muscle bellies

of the triceps surae-it is difficult to activate voluntarily the gastrocnemius lateralis, gastrocnemius medialis and soleus selectively. During plantar flexion or while standing on tip toe, these muscles are activated almost simultaneously. However, the muscles are large and anatomically easily localized and palpable. In one subject we observed that after standing for a long time the lateral head of the gastrocnemius takes over from the medial head (see pp.114 and 115).

Abductor hallucis - abduction of the hallux against resistance.

#### 4.3. Anatomical specimens and technical equipment employed during E.M.G. measurements.

##### 4.3.1. Post mortem specimens.

The measurements of the tendon slip were performed on the following specimens: -

<u>Cadaver number</u>	<u>Male/Female</u>	<u>Age (Years)</u>	<u>Left/Right</u>
344	M	61	L
284	M	65	L
355	M	59	L
355	M	59	R

To standardize these measurements, the lower leg was

exorotated  $35^{\circ}$  to attain position + 1, and  $50^{\circ}$  to attain position 2.

For the measurements of the rotations of the tarsal bones we used the following specimens: -

Series 1

<u>Cadaver number</u>	<u>Male/Female</u>	<u>Age (Years)</u>	<u>Left/Right</u>
338	M	80	L
344	M	61	L
284	M	65	L
355	M	59	R
355	M	59	L

Series 2

<u>Cadaver number</u>	<u>Male/Female</u>	<u>Age (Years)</u>	<u>Left/Right</u>
395	F	57	L
368	M	75	R
342	M	79	R
365	M	76	L
390	M	84	L

In these series the positions of the foot were realized by exorotating the lower leg without force.

The photographs were made with a Linhof technical plate glass camera, the distance between plate and object being 1.5 m. in both groups.

4.3.2. Experimental subjects for observations in vivo.

The E.M.G. studies were performed in physiotherapy students with clinically normal feet and gait.

Group 1 : 16 subjects : 10 males, aged 17 - 27 years.

6 females, aged 21 - 26 years.

Group 2 : 13 subjects : 9 males, aged 19 - 22 years.  
4 females, aged 19 - 21 years.

#### 4.3.3. Technical equipment for E.M.G. measurements.

Particulars regarding the electronic apparatus used for the E.M.G. recordings.

Surface electrodes : silver discs of 8 mm. diameter.

Wire electrodes : lac coated platinum wire of 0.1 mm. diameter.

Differential preamplifier : gain 25; input impedance  
2 x 10 Mega-ohm; noise  
0.001 mV R M S (1 Hz - 10 Hz).  
Rejection factor 100 db.

Main amplifier : in combination with preamplifier : total  
gain 100 000 with low and high pass  
filter settings. Position used 30 - 3000  
Hz ( - 3 dB).

Signal to noise ratio of the whole electrical system  
(subject and electronic equipment) 100 : 1.

Multichannel instrumentation tape recorder, type  
Thermionic: 12 working channels,  
1 voice channel,  
1 photo cell channel.

Preset Counter type H.P. 5332 B (Hewlett Packard).

2 General Radio Strobolume flash units.

1 High Speed Camera Philips / Zeiss (with Ilford F P 4  
film 15 metres long).

1 Knott monitor unit 16 channels.

1 Multichannel ultra-violet recorder S.E. Laboratories.

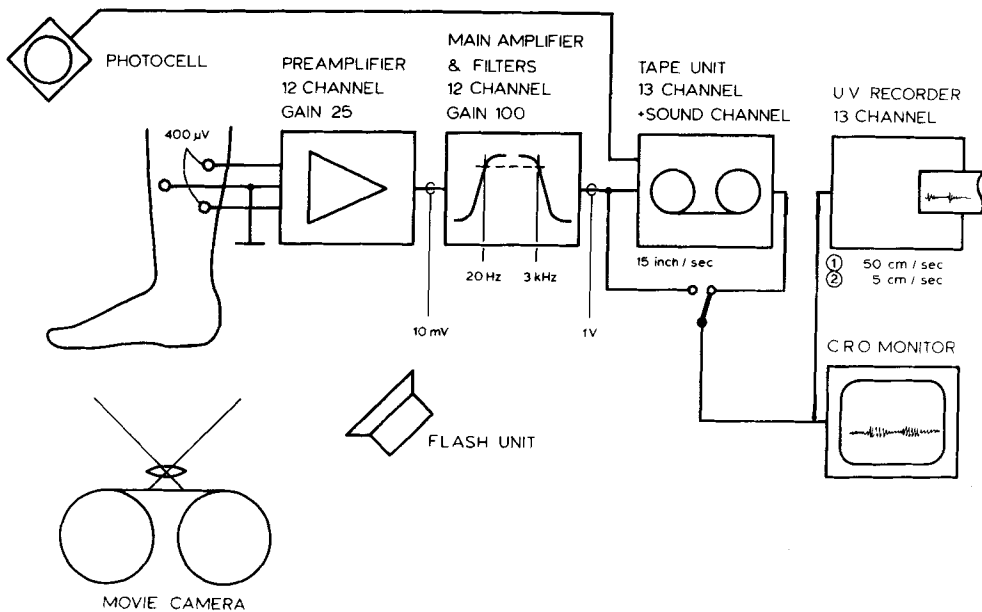


fig.17. Lay out of the amplifier unit. The electrode marked  $\perp$  is the reference electrode. The signal from the tape unit is reproduced on the U.V. recorder and monitor in the situation represented in this lay out.

*Trottoir roulant*: Marathon I (Maschinen-Schmid,  
Oberau/Loisach)  
year of manufacture: 1957  
possible speeds: 0.66 - 8 km/h.  
driven by 3 H.P. electric motor (BEN-  
Nürnberg)  
length of the *trottoir*:  $2\frac{1}{2}$  m.

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CHAPTER 5

RESULTS AND DISCUSSION

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## CHAPTER 5

### RESULTS AND DISCUSSION

#### 5.1. Anatomical observations.

##### 5.1.1. Measurements of the rotations of the tarsal bones.

In chapter 4 we have seen that the same apparatus was used for the measurements of the tendon slip as for the measurements of the tarsal rotations. To measure these rotations, pins were placed in the tarsal bones and photographs were made from three directions perpendicular to each other. We made three photographs of each position of the foot and from these the rotations were measured. Two series of legs were investigated, the only difference being that, in the second series, we also placed a pin in the medial malleolus. The rotations were expressed in degrees.

Fig. 18 is a schematic representation of the foot showing the alteration of the pins as a result of supination, in frontal or anterior view (fig.18a), side view (fig.18b), and axial view (fig. 18c).

The following tables record the mean values of the two series of measurements about the rotations of the tarsal bones (in degrees). The measurements of each specimen separately are presented in the appendix.

<u>Position</u>	<u>0 → +1</u>	<u>0 → 2</u>	<u>0 → 3</u>
Navicular	+16	+29	+27
Calcaneus	+ 8	+12	+11
Cuboid	+14	+23	+22
Lat.mall.	- 2	- 4	- 4
Talus	0	+ 1	0
Med.mall.	- 3	- 5	- 5

Table IIIa. Anterior view.

<u>Position</u>	<u>0 → +1</u>	<u>0 → 2</u>	<u>0 → 3</u>
Navicular	+ 1	+ 7	+ 5
Calcaneus	+ 2	+ 4	+ 4
Cuboid	+ 1	+ 6	+ 5
Lat.mall.	+ 1	+ 1	+ 1
Talus	+ 1	+ 1	+ 1
Med.mall.	+ 1	+ 2	+ 2

Table IIIb. Side view.

<u>Position</u>	<u>0 → +1</u>	<u>0 → 2</u>	<u>0 → 3</u>
Navicular	0	0	0
Calcaneus	+10	+16	+16
Cuboid	+ 1	0	+ 1
Lat.mall.	+25	+38	+38
Talus	+23	+33	+34
Med.mall.	+27	+38	+38

Table IIIc. Axial view.

table III

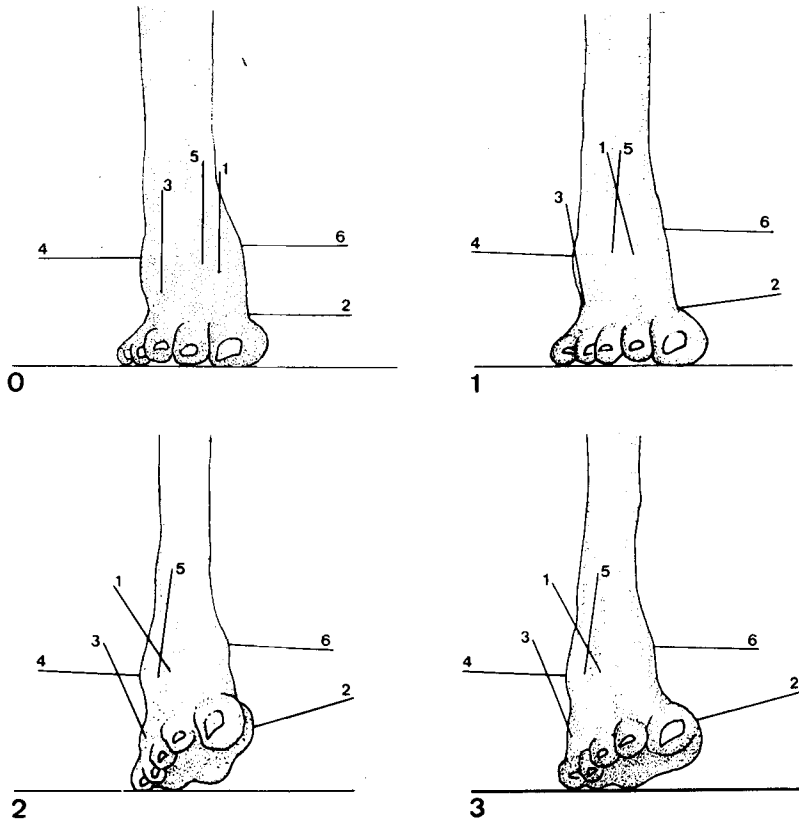


fig.18a. Anterior view.

Schematic representation of the foot, showing alteration of the direction of the pins as result of supination.

0 = starting position

1 = position + 1, 2 = position 2, 3 = position 3.

1 = navicular

4 = lateral malleolus

2 = calcaneus

5 = talus

3 = cuboid

6 = medial malleolus

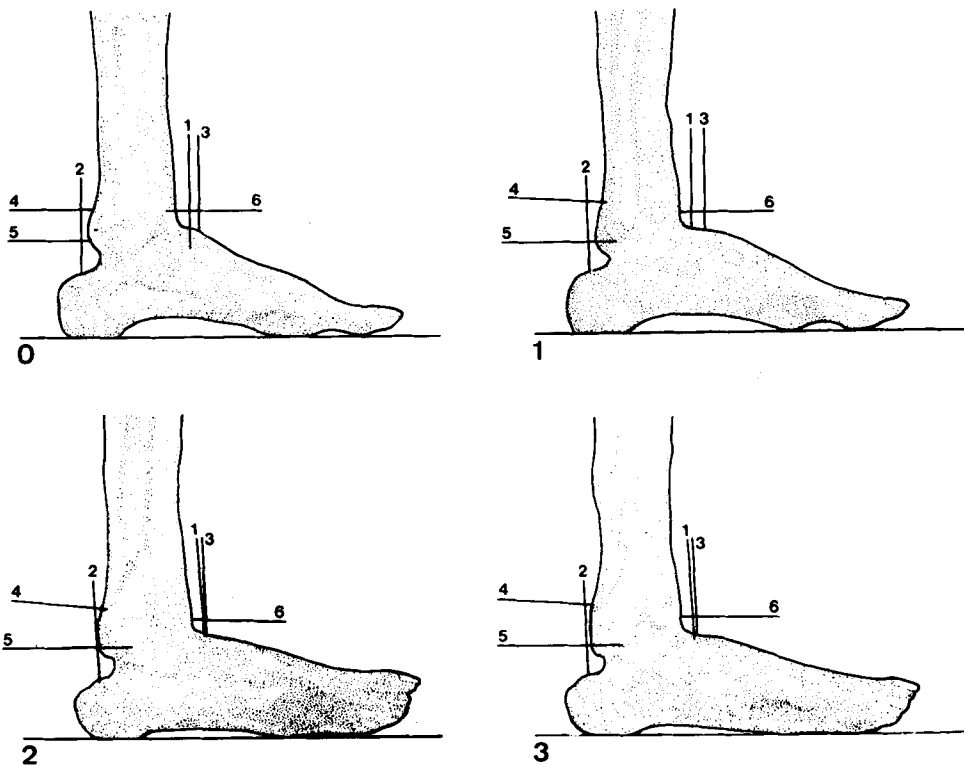


fig.18b. Side view.

Schematic representation of the foot, showing alteration of the direction of the pins as result of supination.

0 = starting position

1 = position + 1, 2 = position 2, 3 = position 3.

1 = navicular

4 = lateral malleolus

2 = calcaneus

5 = talus

3 = cuboid

6 = medial malleolus

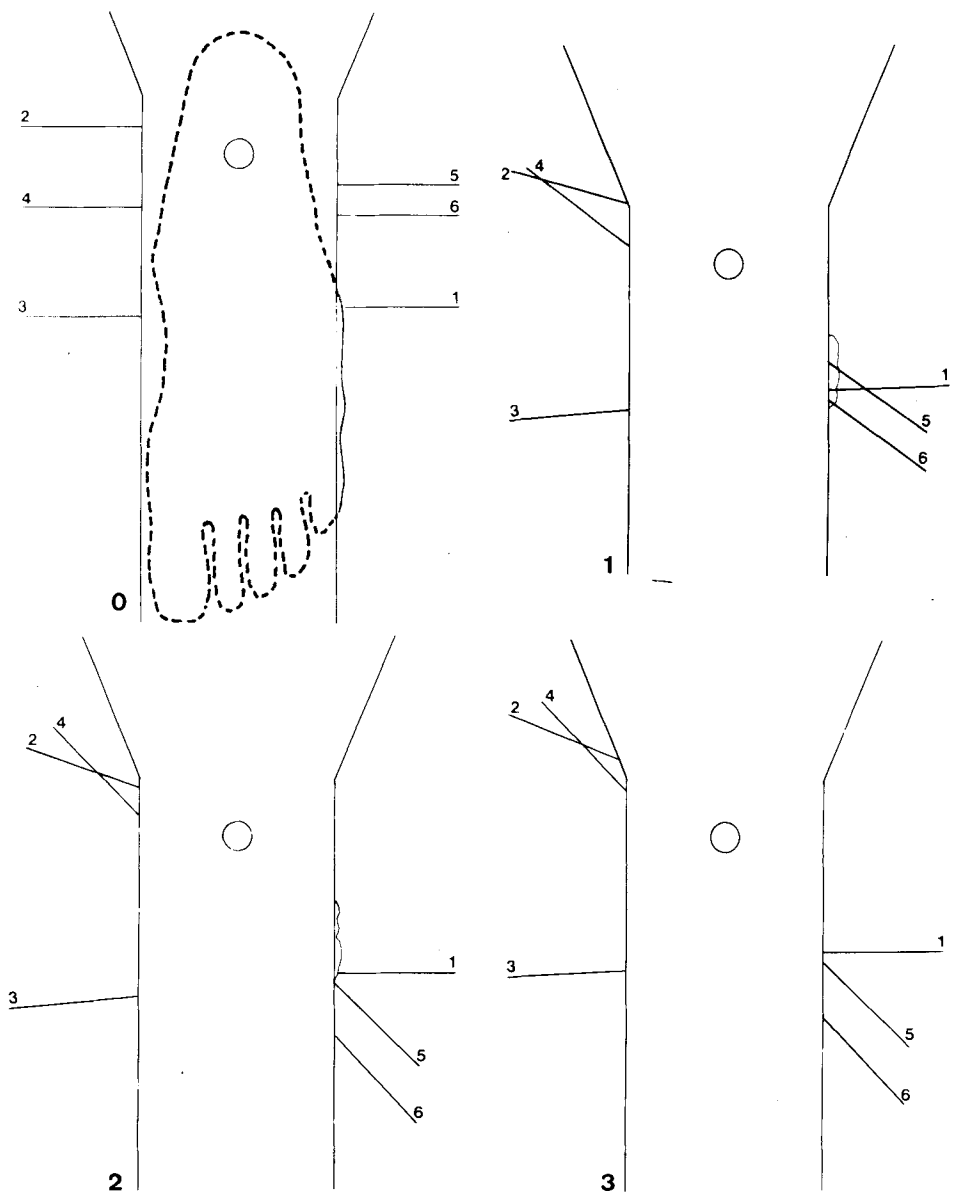


fig.18c. Axial view.

Schematic representation of the foot showing alteration of the direction of the pins as result of supination.

0 = starting position

1 = position + 1, 2 = position 2, 3 = position 3.

- |               |                       |
|---------------|-----------------------|
| 1 = navicular | 4 = lateral malleolus |
| 2 = calcaneus | 5 = talus             |
| 3 = cuboid    | 6 = medial malleolus  |

In contrast with the investigations of Fick, Duchenne and Wright, who used in their experiments the unloaded hanging or lying foot, our measurements were performed with the foot in a loaded position. The points of support of the foot are the tuber calcanei, part of the lateral edge of the foot and the metatarsal heads.

In this study of the tarsal movements we fixed the calcaneal point of support in such a way that the calcaneus could not slide sideways but only tilt.

With reference to the three projections portrayed in the photographs (fig.18a, 18b, 18c), it can be seen that the excursion of the tarsal bones during supination is greatest when travelling from position 0 to position + 1. The transition from position 2 to position 3 affects mainly the metatarsal bones and the effect upon the tarsal chain is less.

The principal movement of the navicular and cuboid in supination is in a frontal plane and there is only a slight deviation from this plane (fig.18b and 18c), as seen in the side and axial views (tables IIIb, IIIc). In the tables IIIa, IIIb, IIIc we see how the rotations of the ankle mortise - together with the talus - are visible mainly in the axial view with only slight deviations in the frontal and side views. So these rotations occur in a horizontal plane. The rotations of the ankle mortise in the horizontal plane are transmitted into rotations of the navicular and cuboid bones in the frontal plane. Translation of the rotational movement from the lower leg to the navicular and cuboid results in a reduction in rotation by some  $10^{\circ}$  of these two bones: the result is a supinatory remodelling of the tarsus.

In the axial view there is a slight difference of  $2^{\circ}$  to  $5^{\circ}$  between the excursions of the tibia (medial malleolus). This may be due to play existing between the tibia and fibula and between the ankle mortise and the trochlea of the talus, the latter being rotated by the horizontal-

ly running fibres of the talocrural ligaments. There is also some play ( $2^{\circ}$  to  $5^{\circ}$ ) between the mortise and talus in the frontal view. This mobility may be the result of some laxity of the vertical fibres of the ankle ligaments. The calcaneus tilts in a lateral direction (assuming a varus position, fig.20) some  $8^{\circ}$  in position + 1,  $12^{\circ}$  in position 2 and  $11^{\circ}$  in position 3 (table IIIa). It can be seen from the same table that this supinatory tilt of the calcaneus is accompanied by a far greater supinatory rotation of the navicular ( $16^{\circ}$  in position + 1 and  $29^{\circ}$  in position 2) and cuboid ( $14^{\circ}$  in position + 1 and  $23^{\circ}$  in position 2). The rotations of the navicular in position 2 is combined with a shift of this bone in a cranial direction and a heightening of the medial arch. This movement is in accordance with the positive slip of the tibialis anterior muscles and the negative slip of the peroneals (table Va).

It must be kept in mind that the lateral collateral fibres of the ankle-joint will be taut as soon as the loaded foot is supinated (positions + 1 and 2) and the vertical chain of bones, formed by the tibia - talus - calcaneus, bends outwards. The supinatory rotation of the cuboid and navicular, as measured by the pins with reference to the cage, has about twice the value of the calcaneal tilt.

In the axial view in position 2 there is an exorotation of the talus of  $33^{\circ}$  and of the navicular of  $0^{\circ}$ . Thus there is an endorotation of the navicular with respect to the talar head of  $33^{\circ}$ . This latter shift explains the bending of the subtalar foot plate, and is also in accordance with the shortening (= positive slip of the tendon) of the tibialis posterior muscle (table Va). The shortening of the flexor digitorum muscle is less; this could be explained by a more lateral position of the tendon and, therefore, a shorter distance of this tendon to the momentary axis. It is possible that

tibialis anterior functions more as an arch raiser than tibialis posterior and flexor digitorum whose principal function is to tighten the medial arch and whose action in raising the arch is only secondary.

In table VIIa is shown the positive slip of the tibialis anterior (34 mm.) and the negative slip of the tibialis posterior tendon (3 mm.) in dorsiflexion of the foot (position C). These are caused by differences in the position of these tendons with respect to the axis of the ankle-joint. During the movements  $0 \rightarrow +1$  and  $0 \rightarrow 2$  the dorsiflexion due to tibialis anterior will be much greater than the plantar flexion due to tibialis posterior.

The recorded rotations of talus and navicular give an impression of the movement of these bones relative to each other. This can be related to the difference in shape of the articular surfaces between the calcaneus and cuboid and the talus and navicular. The talo-navicular joint, almost a ball and socket type of joint, permits more rotatory movement than other types of joint. We do not imply, however, that the talar head can be considered as a pure spherical ball. For this reason it is somewhat misleading to speak of a mid-tarsal joint with the suggestion of an uniform motion occurring in the complex joint. Moreover, these quantitative data illustrate the correlated motions in the kinematic chain of the tarsal bones. Finally, it should be noted that some movement exists also between navicular and cuboid. The difference in rotation between the navicular and cuboid is position + 1 ( $2^{\circ}$ ) and in position 2 ( $6^{\circ}$ ).

The calcaneus rotates also in a lateral direction (abduction) through  $10^{\circ}$  in position + 1 and through  $16^{\circ}$  in positions 2 and 3 (table IIIc, axial view). This causes bending outwards of the lateral edge of the foot (fig.19). The talus exorotates through  $33^{\circ}$  during the movement  $0 \rightarrow 2$ . The endorotation of the calcaneus with

respect to the talus is about  $17^{\circ}$ . Moreover, a slight dorsiflexion of the calcaneus in position + 1 ( $2^{\circ}$ ), increasing to  $4^{\circ}$  in position 2, can be ascertained (table IIIb, side view). This may be recognized in the arch raising effect of the supinatory movement. We admit, however, that there is also a slight dorsiflexion of the talus ( $1^{\circ}$  to  $3^{\circ}$ ) in most cases and that it is impossible to differentiate between these motions as components of talocrural or talo-calcaneal movement.

It can be seen from the movement of the ankle-mortise together with the talus on the one hand and the movement of the navicular and the cuboid on the other hand, how the rotations of the lower leg are transmitted to the foot. During this transmission the calcaneus adopts intermediary positions as can be observed from the movements of the heel in the supinated living foot with exorotated leg. One important effect of the movement is lateral shift of the body's centre of gravity. While standing on one leg, balance is maintained by lateral or medial displacement of the centre of gravity.

One is reminded that movements of the elements in a kinematic chain, relative to each other, remain the same, regardless of the input link. Differences in the description of the movements of the tarsus due to variation in the reference links are to be expected according to whether the foot is free-hanging, the calcaneus is fixed or the foot adopts the position employed in our experiment. Formerly, tarsal movements were described in the free-hanging foot with the lower leg fixed and the talus was considered to be a fixed point. The movements of the heel are supination and adduction, both of which are not only adopted but also amplified by the forefoot. In the case of a fixed calcaneus, the talus, together with the leg, will execute a movement which is the exact reverse of that of the heel as described above: the forefoot will

still make supination and adduction movements but of lesser degree due to the immobility of the calcaneus.

The situation in our experiment is rather complex: due to the absence of a reference link, the movements are here referred to spatial coördinates. Furthermore some components of the combination of movements, as formerly described, can now be discarded since abduction of the forefoot alone is not possible, this movement having been achieved by abduction of the calcaneus; the talus and lower leg joined in this abduction (exorotation). One remarkable result of this movement was rotation of the navicular and cuboid in an almost entirely frontal plane. one consequence of supinatory arch-raising, therefore, is some upward shift of the tibia (see table IV).

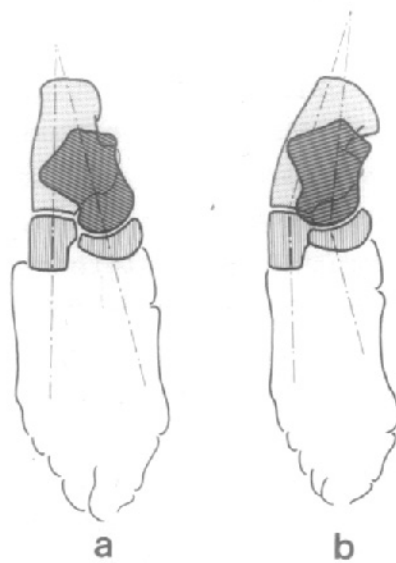


fig.19. a = position 0; b = position 2.

The dotted lines in fig.19b show the kink in the medial and lateral arches in position 2. This is no indication of the real rotation of the tarsal bones.

Translation in a proximal  
direction of tibiaplateau

Cad.nr. 390	position 1	4 mm	
	position 2	4 mm	
	position 3	4 mm	
Cad.nr. 342	position 1	1 mm	
	position 2	1 mm	*
	position 3	1 mm	
Cad.nr. 395	position 1	0 mm	
	position 2	0 mm	*
	position 3	0 mm	
Cad.nr. 365	position 1	3 mm	
	position 2	5 mm	
	position 3	5 mm	
Cad.nr. 368	position 1	2 mm	
	position 2	3 mm	
	position 3	3 mm	

table IV. This table demonstrates the upward shift of the tibia as result of supination.

\* According to table XX these feet appeared to be not particularly stiff. We have no explanation for the absence of a shift.

The results of our measurements illustrate the combined motion of the tarsal mechanism. We have also indicated the fact that in our experiments the transition to position 3 has little effect upon the positions of the tarsal bones. It is mainly the metatarsus which is affected in this positional change. When in a maximal supination of the foot (position 2) the forefoot is pronated (position 3), there is only a slight influence on the position of the navicular and cuboid but the positions of talus and calcaneus remain unchanged. So there

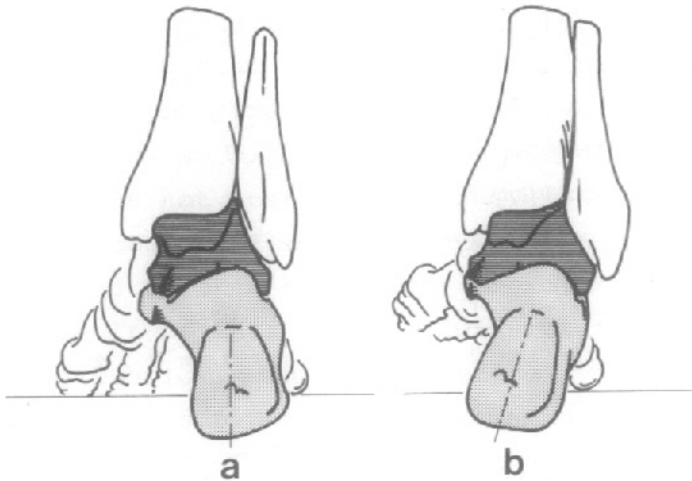


fig.20. See text. a = position 0; b = position 2

is a small independent mobility in the mid-tarsal joint. In our opinion this is not in contradiction with the concept of a closed kinematic chain with constrained motion; the tarsal chain has joints in which ligaments play an important steering role with respect to the prescribed motion pattern. The guiding function of the ligaments is no doubt influenced to considerable degree by their tension. This tension for the plantar ligaments in the positions 0 and + 1 with full sole contact, will differ from that in positions 2 and 3 with the foot resting only on its lateral edge. This problem will be discussed further in chapter 5.3.2.4 when dealing with the so-called clawing movement.

The effect of pronation of the forefoot after maximal supination upon the position of the metatarsal bones can also be seen from the measurements of the tendon slip comparing the positions 2 and 3. There is an apparent difference for the tendons of peroneus longus and tibialis anterior in these positions: the peroneus longus

muscle shortening (positive slip) and the tibialis anterior muscle lengthening when the forefoot changes from position 2 to position 3. The peroneus longus inserts at the plantar side of the first metatarsal and the tibialis anterior at the medial side of the first cuneiform bone and base of the first metatarsal.

We now leave the discussion of the rotations of the tarsal bones to examine the results of the tendon slip measurements.

#### 5.1.2. Tendon slip.

##### Calculation of the average tendon slip of the four legs.

The measurements were performed 4 times for each leg. The average values in mm. of the tendon slip of each leg with a decimal of  $\geq 0.5$  mm. are rounded off upwards, and values with a decimal of  $\leq 0.4$  mm. are rounded off downwards.

From these rounded off values for each leg the average values of all the legs were calculated (table V). The measurements of each leg apart are recorded in the appendix (tables XXI, XXII and XXIII).

The average range of tendon slip of each leg (results of positions + 1, 2 and 3 taken together) was 1.1 mm. (table XXIb), 1.6 mm. (table XXIIa), and 1.7 mm. (tables XXIIc and XXIIId). The average range of the four legs together regarding the positions + 1, 2 and 3 was 1.5 mm. and 2 mm. concerning the positions A, B and C. This error is independent of the length of the tendon slip.

In the tables XXIIa, b, c and d (the positions + 1, 2 and 3), and XXIIIa, b, c and d (the positions A, B and C) we see positive and negative values. A positive slip implies that the distance between splitshot and strap shortens. A negative slip implies the reverse, lengthening (fig.9, p.52).

The tendons with the + sign (tibialis posterior and

flexor digitorum) shift in the same direction going from the positions 0 to 3 in this special movement. For this supination movement they are synergists (supinators).

The tendons with the - sign (peroneal muscles) shift also in the same direction but opposite to the directions of the supinators. These peroneal muscles (pronators) are the antagonists of the supinators. We also see an antagonistic shift in the tendons of tibialis anterior and extensor digitorum. These values are therefore an indication of muscle function and they will be compared with the results of the E.M.G. investigations in chapter 5.2.

Our findings are in agreement with the results of the tendon slip during supination as found by Fick (table Vb). The differences are noted in the table. The experimental assembly employed by Fick, however, was not quite the same as ours (see p.50).

5.1.2.1. Tendon slips in movement from position 0 → + 1, 0 → 2, 0 → 3.

The following table records the average tendon slip of 4 legs in mm. (cad.nr.344, 284, 355 right, 355 left).

<u>Position</u>	<u>0 → +1</u>	<u>0 → 2</u>	<u>0 → 3</u>
Tib.post.	+16	+21	+21
Flex.dig.	+10	+15	+15
Flex.hall.	+ 4	+ 6	+ 7
Ext.hall.	- 1	+ 2	- 2
Per.long.	-12	-24	-20
Per.brev.	-16	-24	-24
Tib.ant.	+ 3	+ 8	+ 5
Ext.dig.	- 5	- 9	-10
Achilles tendon	- 3	- 5	- 4

table Va. Average tendon slip of 4 legs in mm.

## Tabelle XII.

### Mittelwerte aus Präparat I—III.

Supinatoren:		Pronatoren:	
1. Tibialis posticus	21,5 (+21)	1. Peroneus longus	24,5 (-24)
2. Flexor digit. comm. 1.	19,3 (+15)	2. „ brevis	22,8 (-24)
3. Soleus fibularis	13,0 (- 5)	3. „ tertius	22,6 -
4. Flexor hallucis	12,2 (+ 6)	4. Extens. digit. comm. 1.	19,4 (- 9)
5. Soleus tibialis	11,5 (- 5)	5. „ hallucis long.	9,0 (+ 2)
6. Gastrocnemius	10,8 (- 5)		
7. Tibialis anticus	0,8 (+ 8)		

table Vb. Measurements obtained by Fick. Shortening in mm. Average tendon slip of three preparations calculated with respect to the tarsus. The ankle-joint was locked.

In brackets the results of our measurements concerning the 0 → 2 movement. The supinators were indicated + and the pronators - (see section 4.1.3.).

In our measurements the triceps surae works as a pronator and not as a supinator. The tibialis anterior and extensor digitorum show a remarkable difference in tendon slip in the measurements of Fick compared with our measurements.

Although the range between maximum and minimum values may sometimes be fairly great when compared with the associated tendon slip, it is nevertheless a surprising finding that these ranges seldom overlap each other, as far as the transition from position 1 to position 2 is concerned. The same is also true for the extensor hallucis, peroneus longus and tibialis anterior in moving from position 2 to position 3 (see table XXI). A detailed discussion of the various muscles now follows.

#### Tibialis posterior and flexor digitorum.

In an anatomical study of the situation and insertion of the tendons in their relation to the tarsal joint, one gets already some impression of their functions. By studying the slip of these tendons and comparing them with the findings of the other tendons, we see how the flexor digitorum and tibialis posterior are synergists.

However, the shortening of the flexor digitorum is less than that of tibialis posterior.

#### Flexor hallucis.

This muscle has a synergistic function with tibialis posterior and flexor digitorum during the tarsal movement up to position 1. The tendon slip is, however, slight.

#### Extensor hallucis.

The influence of this muscle on the movement in positions + 1 and 2 is uncertain. There is a lengthening of the muscle on pronation of the forefoot (2 → 3).

#### Peroneus longus.

The slip of this tendon is of the same quality in all legs, being 11 to 14 mm. in position 0 → + 1. In position 0 → 2 the slip is 21 to 25 mm. in all the preparations examined. With regard to tibialis posterior the findings are virtually the same, but the sign negative. In the position 2 → 3 we see the influence of the forefoot pronation. The slip of the peroneus brevis remains almost unchanged (+ 1 mm.). The peroneus longus tendon lengthens by + 2 to + 7 mm. This finding can be reconciled with our knowledge of the insertion of the peroneus longus at the base of the first metatarsal.

#### Peroneus brevis.

A remarkable fact that emerges from our measurements is the fact that for this tendon the value as far as position 0 → + 1 for every leg lies somewhat higher than the value for the tendons of the peroneus longus and the tibialis posterior, namely 14 to 17 mm. This difference can be considered as the result of a combination of supination of the tarsus and plantar flexion of the first metatarsal as a component of the arch raising motion during 0 → + 1. The latter component has a positive influence upon the peroneus longus but none in the case of the peroneus brevis. In position 0 → 2 the values

for the peronei longus and brevis are equal. In position 2 → 3 we see no effect of pronation on the tendon slip of the peroneus brevis.

Tibialis posterior and flexor digitorum together have the peroneal muscles as their antagonists. We get the impression that these four muscles control the mechanism of the tarsus.

#### Tibialis anterior.

The tendon slip up to position 0 → + 1 is only slight, namely 1 to 4 mm. In position 0 → 2 we measured a positive slip of 5 to 9 mm. This slip in position + 1 → 2 is 4 to 6 mm, and we suppose that the muscle has now adopted a more important function. The insertion of the tendon distal to the talo-navicular joint is reflected in the lengthening ( 1 to 3 mm.) of the muscle in position 2 → 3. For the pronatory movement of the forefoot we have to consider not only the function of the peroneus longus but also that of the tibialis anterior.

#### Extensor digitorum.

Contrary to expectation, this muscle lengthens in position 0 → + 1 from 4 to 8 mm. This lengthening increases still more in position 1 → 2. One may call this muscle the antagonist of the tibialis anterior in the movement necessary for supinatory tarsal remodelling. The tendons of these muscles obviously lie one on either side of the momentary axes of the talo-calcaneal and calcaneo-cuboid joints. Both tendons lie ventral to the ankle-joint. During dorsiflexion in the ankle they are synergists (table XXIII). In the results of the E.M.G. investigations we will see how tibialis anterior and extensor digitorum are both active during supination.

#### Achilles tendon.

The results differ considerably from leg to leg: the reason lies in the location of the strap. The achilles tendon is the tendon of three muscles, each having its own

origin. It is, therefore, impossible to determine an average place of origin. Depending on how laterally the strap is placed, the mean value of the tendon slip is subject to variation, viz. the more laterally it is placed, the greater the negative slip.

The influence of the tarsal position on the tendon slip is slight for the three legs. The negative slip of the tendon in one of them is greater: the location of the strap is the probable reason. The mobility of the tarsal joints is not more than in the other legs, as can be seen from the tables of rotations of the tarsal bones (see appendix table XX).

The achilles tendon shows a negative slip in supination (table Va) viz. a pronator effect. There is, however, activity of the medial component of the triceps surae muscles, the soleus, during the supinatory movement of the experimental subjects (table VIII) and of the lateral component of the triceps, lateral head gastrocnemius, during pronation. This activity would appear to anticipate the shortly to be described E.M.G. result.

We cannot read a functional difference in the three components of the triceps surae out of the tendon slip measurements. But the experimental subjects do show a selective activity of the medial and lateral components during pro- and supination.

#### 5.1.2.2. Tendon slip in movement from position P → A, P → B. (the balancing on the forefoot).

Besides the supinatory remodelling of the tarsus as described earlier, we were interested in the use of the lower leg muscles in relation to balancing on the forefoot. We designated the standard positions of this movement P, A and B (see p.51) for the description of these positions).

From table VI concerning the average tendon slip of

P → A and P → B can be ascertained that the movement P → A is a more restricted movement than P → B. There now follows a discussion of tendon slip during the balancing movement with the subject standing on the fore-foot and moving from pronation to supination. In a later section (section 5.3.3.) further discussion will show that the movement P → A forms part of the rolling movement.

The following table records the average tendon slip of 4 legs in mm. (cad.nr. 344, 284, 355 right, 355 left). The measurements of each specimen separately are recorded in the appendix.

<u>Position</u>	<u>P → A</u>	<u>P → B</u>
Tib.post.	- 1	+13
Flex.dig.	- 1	+ 9
Flex.hall.	0	+ 4
Ext.hall.	0	+ 1
Per.long.	+ 2	-17
Per.brev.	+ 2	-15
Tib.ant.	- 1	+ 9
Ext.dig.	+ 2	- 7
Achilles tendon	- 1	- 3

table VI. Average tendon slip of 4 legs in mm.

#### Tibialis posterior and flexor digitorum.

The slip of both tendons is quite the same. They are synergists. The flexor hallucis is also a synergist but its influence is less. A shortening of 4 mm. was recorded for flexor hallucis in A → B (table VI).

#### Extensor hallucis.

In the movement A → B the slip of this tendon is only slight.

### Peroneus longus and brevis.

These muscles are antagonists of the tibialis posterior and the flexor digitorum. The slip of these muscles is significantly greater than that measured for the positions 0 → + 1 and 0 → 2.

### Tibialis anterior and extensor digitorum.

For this movement these muscles are antagonists.

### Achilles tendon.

With regard to this tendon, there is only a slight difference between the findings in position P → A and P → B. One of the specimens is again an exception in this part of the investigation (cad.nr.344). During the measurements in the positions + 1 and 2 with the strap located more laterally we had a similar experience. We may be allowed to conclude that the lateral head of the gastrocnemius has a selective function during the performance of this movement.

### 5.1.2.3. Tendon slip in movement from position P → C.

The starting position for this movement is position P. The foot is dorsiflexed 30° at the ankle-joint.

<u>Position</u>	<u>P → C</u>
Tib.post.	- 8
Flex.dig.	-11
Flex.hall.	-17
Ext.hall.	+27
Per.long.	-12
Per.brev.	- 7
Tib.ant.	+34
Ext.dig.	+24
Achilles tendon	-37

table VIIa. Average tendon slip of the 4 legs in mm.

Table VIIa records the average tendon slip of the 4 legs in mm. (cad.nrs. 344, 284, 355 right, 355 left). The results for each specimen separately are recorded in the appendix.

#### Tabelle IV.

##### Mittelwerte aus Präparat I—III.

##### Beuger:

1. Ext. digit. comm. long.	36,1 mm	Verkürzung	(24)
2. „ hallucis long.	33,6 „	„	(27)
3. Tibialis anticus	32,5 „	„	(34)
4. Peroneus tertius	30,4 „	„	

##### Strecker:

1. Soleus caput fibul.	45,7 mm	Verkürzung	
2. „ „ tibiale	43,7 „	„	(37)
3. Flexor hallucis long.	21,3 „	„	(17)
4. Flexor digit. comm. long.	13,2 mm	Verkürzung	(11)
5. Peron. longus	12,8 „	„	(12)
6. Tibialis posticus	7,7 „	„	( 8)
7. Peroneus brevis	6,7 „	„	( 7)

table VIIb. Measurements obtained by Fick. Shortening in mm. Average tendon slip of three preparations calculated with respect to the ankle.

Beuger = Flexors; Strecker = Extensors.

In brackets the results of our measurements concerning the P → C movement. The values of the extensor digitorum comm. and extensor hallucis longus are also dependent on the position of the toes.

Peroneus longus and peroneus brevis,  
tibialis posterior, flexor digitorum and flexor hallucis.

All these muscles are now synergists. Each of them has relatively little contribution in the plantar movement, because their lever arms are shorter and the cross-section of their muscle bellies are smaller than those

of the triceps surae muscles. Only when their activity is coordinated can they contribute to the strength of plantar flexion.

#### Achilles tendon.

The function of the triceps surae as a plantar flexor is evident. The average slip in relation to position P gives an impression of its importance.

#### Tibialis anterior, extensor digitorum and extensor hallucis.

These muscles are the most important antagonists of the triceps surae. The extensor digitorum, tibialis anterior and extensor hallucis can now be considered as synergists.

### 5.2. Summary and conclusions concerning the sections 5.1.1, 5.1.2.1, 5.1.2.2, 5.1.2.3.

The tarsus of the ten lower leg preparations on which the rotations of the tarsal bones were measured, show the typical supinatory movement during exorotation of the lower leg.

The rotations of every tarsal bone in supination in all the preparations are the same both in direction and in magnitude. The positions of these bones are hardly influenced by forefoot pronation. The remodelling of the tarsus during maximal supination is explained by the magnitude and the direction of rotation of the tarsal bones as follows: -

- During supination the talus exorotates  $33^{\circ}$  in the horizontal plane and the navicular endorotates  $33^{\circ}$  with respect to the talus. By these movements the subtalar plate is shortened on the medial side and, therefore, bent. (The rotations are the mean values of ten preparations.)
- The navicular ( $29^{\circ}$ ) and the cuboid ( $23^{\circ}$ ) rotate in a

lateral direction in a frontal plane; by this movement the medial arch is raised.

- The calcaneus supinates ( $12^{\circ}$ ) and exorotates ( $16^{\circ}$ ). As a result of this movement the lateral edge of the foot bends outwards.

- During supination there is an upward shift of the tibia. See table IV.

During pronation of a supinated foot the tarsal bones move in the reverse direction; the bending of the subtalar plate, the heightening of the medial arch and the bending outwards of the lateral edge of the foot are abolished. This remodelling of the foot during pro- and supination is recognizable also in vivo (Huson, 1961).

The tarsal movements in the experimental apparatus for the measurements of tarsal rotations and tendon slips were performed by rotation of the lower leg and so also of the talus. The talus functions as the input link. The movements of the tarsus can also be performed by contraction of one or more muscles which attack the tarsus. Another link of the kinematic chain functions then as input link.

It appears from the measurements of the tendon slip that during supination considerable shift in a positive direction of the tibialis posterior (21 mm.) and flexor digitorum (15 mm.) occurs, and in a lesser degree also of the tibialis anterior (8 mm.) and flexor hallucis (6 mm.).

There is a considerable shift too - but in the opposite direction - of peroneus longus (24 mm.) and brevis (24 mm.) and to a lesser extent of the extensor digitorum (9 mm.) and achilles tendon (3 mm.). Pronation of the forefoot has a shortening effect on the peroneus longus muscle and a lengthening effect on the tibialis anterior. (The mean values of 4 preparations are placed in brackets.)

During supination of the foot in plantar flexion (P → B) the tendon slips are in the same direction but of a lesser extent than during supination with the foot in neutral position with respect to the ankle (movements 0 → + 1 and 0 → 2).

During dorsal flexion of the foot the positive shift of tibialis anterior, extensor hallucis and extensor digitorum and the negative shift of the achilles tendon and flexor hallucis are considerable. The negative shifts of tibialis posterior, flexor digitorum and the peroneals are less.

How can these tendon slips be explained from the remodelling of the tarsus?

- The contraction of the tibialis posterior gives a bending of the subtalar plate caused by insertion of its tendon at the navicular and the direction of traction. At the same time the ankle mortise is exorotated by the push of the tendon which runs behind the medial malleolus. In the experimental set-up the foot is in the loaded position thus rendering plantar flexion impossible. The tendon slip in dorsal flexion of the foot (P → C) is less, as can be seen in table VIIa. During supination of the foot in plantar flexion there is a large positive shift of the tibialis posterior tendon (P → B, table VI).

- The flexor digitorum exorotates the ankle mortise by the push of the tendon which also runs behind the medial malleolus.

- The tibialis anterior, which runs ventral to the mortise, is inserted into the first cuneiform bone. This muscle heightens the medial arch during contraction.

The supinated foot pronates to the starting position by the influence of gravity. The supinators, tibialis posterior, flexor digitorum and tibialis anterior, have

to be relaxed and the mortise is allowed to endorotate.

The foot can pronate (movement  $0 \rightarrow - 1$ ) by muscle action of the pronators, peroneus longus, brevis and extensor digitorum.

The peroneus brevis tendon is attached to the base of metatarsal V and goes through the retinaculum of the peronei at the calcaneus. The contracting muscle moves the supinated calcaneus to the starting position. The tendon runs dorsal to the lateral malleolus and thus there is also an endorotating effect on the mortise.

The peroneus longus muscle functions partly in the same way as the peroneus brevis. The peroneus longus tendon goes under the forefoot and attaches to the base of metatarsal I. In the measurements of the tendon slip we see during pronation of the forefoot with a fixed lower leg a positive slip of the peroneus longus tendon only. This muscle can abolish the bending of the foot plate and brings the supinated forefoot into pronation.

Peroneus longus and brevis can be regarded as primary pronators.

### 5.3. E.M.G. Studies.

There were two groups of experimental subjects. The movements performed by group 1 and discussed in this chapter are  $0 \rightarrow + 1$ ,  $0 \rightarrow 2$ , and the clawing movement (each of the movements was performed by 16 subjects).

The movements performed by group 2 and discussed in this chapter are  $0 \rightarrow + 1$  (13 subjects),  $0 \rightarrow 2$  (13 subjects),  $0 \rightarrow - 1$  (13 subjects), the clawing movement (13 subjects), the rolling movement (12 subjects), walking (11 subjects) and running (5 subjects).

#### 5.3.1. Data reduction of the E.M.G.

Data reduction of the E.M.G. recording is necessary for evaluation purposes. The signals obtained have to

be distinguished for deflections due to interference and be reproducible on paper for evaluation; see section 4.2.2.

We noted from this recording whether a muscle was active or not during a given movement. The number of times the movements were performed by the subjects varied from 4 to 12. This number was dependent on whether or not the recording was subjected to technical interference.

We calculated for every subject the frequency of muscle activity in the total series of movements. This frequency of activity was expressed as a percentage for every subjects (see p.101). From these percentages we arranged frequency tables which displayed an activity pattern in such a way as to give an impression regarding the importance of a given muscle during a given movement. These tables were used in the appreciation of the E.M.G. recording of the standard movements ( $0 \rightarrow + 1$ ,  $0 \rightarrow 2$ ,  $0 \rightarrow - 1$  and the clawing movement).

It was impossible to construct frequency tables for the rolling and walking movements. The rolling and walking movements are complicated movements and the change from one step or phase to the other is a gradual one. The rolling movement was performed five times in every subject. We selected the most constant combination for the diagram.

The activity during the whole movement for each muscle and each subject was expressed graphically in a block diagram. It has to be borne in mind that the interpretation of the recordings was subjective.

For the walking movement, that part of the E.M.G. recording which represented activity was lined out. Blocks were formed with these outlines and the interpretation was thus rendered easier. In these outlines typical phases of the walking cycle were indicated by vertical lines, as for example, heel-strike after the

swing phase, and the moment at which the foot sole contacts the floor.

### 5.3.2. Review of the frequency tables relating to the standard movements.

Data obtained from the standard movements were used to construct the frequency tables.

These frequency tables expressed the activity of individual muscles as a percentage of the total number of movements performed.

For example, we have 4 subjects (nrs. 1, 2, 3 and 4). The movement is performed 4 to 12 times.

In subject 1. muscle A is active in 6 of the 10 movements performed, that is in 60%.

In subject 2. muscle A is active none of the 8 movements performed, that is in 0%.

In subject 3. muscle A is active in 4 of the 5 movements performed, that is in 80%.

In subject 4. muscle A is active in 12 of the 12 movements performed, that is in 100%.

The average percentage of all the subjects is, therefore,  $\frac{1}{4} \times (60\% + 0\% + 80\% + 100\%) = 60\%$ . This is the frequency percentage. In this way we calculated the frequency percentages of all the muscles for the several movements.

We suppose that muscles with an activity in a high percentage have an essential function in the performance of the movement. The muscles which were active in at least 70% of the movement were called "essential" and the muscles which participated in 40% to 69% of the movement "auxiliary". However, in some cases an essential muscle is not used in a particular movement. We must pay attention to the combination in which essential or auxiliary muscles are used in these unusual cases. We shall see that muscles often operate in couples. The case in which both muscles of a couple remain

inactive is still more rare: such a situation can be evolved by using alternative input links (chapter 1, p. 7). Since supinatory remodelling of the foot and exorotation of the leg are coupled, the first motion could be induced by exorotators acting below the knee or hip-joint.

5.3.2.1. The incomplete supinatory movement  
(0 → + 1 movement).

In this movement the medial arch is raised without lateral tilt of the forefoot. The sole and the lateral edge of the foot, together with all the metatarsal heads rest on the ground. The shape of the sole is curved in the form of a comma, increasing the medial concavity and thus shortening the foot.

In the following table we express as a percentage the number of times an individual muscle was active. The essential muscles in italics and the auxiliaries are marked with an asterisk.

We expressed as a percentage the number of times an individual muscle was active from the total number of times the movement was performed by all subjects together.

This total number of movements performed (100%) is 48 for group 1, and 393 for group 2. The subjects of group 2 performed the 0 → + 1 movement in two different ways, namely, as a solitary movement (0 → + 1), and as a part of a movement (0 → -1 → 0 → +1). This latter movement started with the foot in pronation (position - 1).

The movement 0 → + 1 is performed standing in group 1. The results are given in column 1 of table VIII. The movements 0 → + 1 and 0 → - 1 → 0 → + 1 are performed standing, sitting, and sitting with a loaded knee in group 2. The results of the 0 → + 1 movement in group 2

are given in columns 1a (standing), 1b (sitting) and 1c (sitting with loaded knee). The results of the  $0 \rightarrow +1$  movement as part of the  $0 \rightarrow -1 \rightarrow 0 \rightarrow +1$  movement are given in 3a' (standing), 3b' (sitting), and 3c' (sitting with loaded knee).

The column of the average values (1a, 1b, 1c, 3a', 3b', 3c') indicates that the muscles essential for this movement are tibialis posterior and flexor digitorum. The extensor hallucis, tibialis anterior, extensor digitorum, soleus and abductor hallucis muscles can be qualified as auxiliary. Within group 2 activity of tibialis posterior and of flexor digitorum occurs more frequently in 1a than in 1b and 1c and also greater in 3a' than in 3b' and 3c'. It is possible that this difference may be due to the influence of the body weight while standing, as the movement must be performed against gravity.

As already stated the tibia shifts in an upward direction during supinatory remodelling of the tarsus (table IV). The experience gained in group 1, not only in investigating the movements, but also in standardizing the apparatus, resulted in more accurate data when we came to examine group 2. From group 2 three tables were obtained relating to the  $0 \rightarrow +1$  movement; three further tables were obtained from movements of which the  $0 \rightarrow +1$  movement was a part. When the frequency tables 3a', 3b', 3c' are compared with 1a, 1b, 1c it can be seen that the difference between auxiliary and essential muscles is accentuated. This may be the result of starting the movement from a pronated position (-1).

Only one column was obtained from group 1, namely 1; when compared with the column 1a a difference is evident in the values obtained for several of the muscles. The percentages in column 1 of the peroneus brevis and the abductor hallucis are high. We suppose that the subjects in group 2 were better prepared in the performance of

the 0 → + 1 motion with exorotation of the lower leg than the subjects of group 2.

	Group 1			Group 2			Average (1a, 1b, 1c, 3a', 3b', 3c')
Series:	1	1a	1b	1c	3a'	3b'	3c'
Number of subjects:	16	13	13	13	13	13	13
Number of movements:	48	68	79	89	51	51	55
Muscle:	%	%	%	%	%	%	%
tib.post.	91*	71*	60	61	83*	73*	79*
fl.dig.	78*	74*	69	72*	96*	85*	88*
fl.hall.	66	48	23	14	27	12	30
ext.hall.	34	45	48	30	47	58	62
per.long.	51	51	18	16	14	27	40
per.brev.	75*	58	35	33	16	16	40
tib.ant.	59	75*	64	60	58	61	78*
ext.dig.	69	74*	60	51	69	73*	68
lat.gast.	44	17	14	30	15	15	21
med.gast.	25	21	14	26	15	19	43
soleus	31	55	55	66	53	31	45
abd.hall.	88*	55	59	26	58	36	60

table VIII. Frequency table. The frequency of individual muscular activity in the several series of experiments during the 0 → +1 movement is expressed as a percentage. (See fig. 21 for a diagrammatic representation of the column of the average percentages.) For explanation of 1, 1a, 1b, 1c, 3a', 3b', 3c', see text p.103.

In addition to the percentages in the columns 1a, 1b, 1c and 3a', 3b', 3c', we were interested in the specificity of the essential muscles. The percentages in which these muscles were used either alone or in combination (see tables IXa, IXb, X and XI), were calculated for these same movements.

The distinction between essentials and auxiliaries was based on the average percentage of the last column in

table VIII.

In the tables IXa and IXb the percentages of combinations of active muscles during the 0 → + 1 movement are noted.

	1a	1b	1c	Average value in % (1a - 1c)
	%	%	%	
Tib.post. without flex.dig.	12	12	9	11
Flex.dig. without tib.post.	15	21	20	19
Tib.post. + flex.dig. together	59	48	52	53
Neither	14	19	19	17

table IXa. See text p. 105 and 106

	3a'	3b'	3c'	Average value in % (3a' - 3c')
	%	%	%	
Tib.post. without flex.dig.	4	10	5	6
Flex.dig. without tib.post.	17	22	14	18
Tib.post. + flex.dig. together	79	63	74	72
Neither	0	5	7	4

table IXb. See text p. 105 and 106

We compared the average values in table IXa with those in table IXb. From these calculations one observes that supination preceded by pronation (table IXb) leads to a greater degree of specificity in muscle function. The combination of tibialis posterior and flexor digitorum had a specific function in the supinatory movement and from table IXb it can be seen that in only 4% neither muscle was employed.

From tables IXa and IXb it appears that in 17% and 4% respectively (average value 10%) neither of the specific supinators is used during supination. This would seem a high percentage but since supination of the foot and exorotation of the leg are linked to each other functionally, we should

remember that the foot during standing can be supinated by exorotation of the whole leg at the hip-joint. While sitting the lower leg can be rotated at the knee-joint by action of the medial and lateral hamstrings. It is also possible to supinate the foot while sitting or standing when the lower leg is moved in a lateral direction, thus tilting the foot in supination. For the performance of any particular movement it would appear that different parts of the kinematic chain may assume the function of the input link. Regarded in this way, the above mentioned figure of 10% may be considered a surprisingly low one! As our experiments progressed it became increasingly clear that instruction of the subject in the performance of the movements was of paramount importance.

The specificity of the pretibial muscles during the  $0 \rightarrow +1$  movement (1a) was calculated in the same manner as for the supinators. The results of these calculations are recorded in table Xa. It should be borne in mind that these percentages are independent of supinator activity.

Tibialis anterior without extensor digitorum	14%
Extensor digitorum without tibialis anterior	10%
Tibialis anterior and extensor digitorum together	63%
None of these muscles	13%

table Xa. Calculation of the specificity of the pretibials during the movement  $0 \rightarrow +1$  (column 1a).

Comparing table Xa with table IXa we observe no difference between the pretibials and supinators during the movement  $0 \rightarrow +1$ . The essential rôle of the pretibials during maximal supination (the movement  $0 \rightarrow 2$ ) is recorded in table XIII.

Reference to table Xb shows the percentages in which essential muscles (tibialis posterior and flexor digi-

torum) were combined with two important auxiliary muscles (tibialis anterior and extensor digitorum) during standing (movement 0 → + 1). The soleus, the abductor hallucis and extensor hallucis, also auxiliaries according to the last column of table VIII, were left out of consideration in this calculation.

	%
Tibialis posterior + tibialis anterior	11
Flexor digitorum + tibialis anterior + extensor digitorum	13
Flexor digitorum + tibialis posterior + tibialis anterior	2
Flexor digitorum + tibialis posterior + extensor digitorum	3
Fl.digitorum + tib.posterior + tib.anterior + ext.digitorum	43
Extensor digitorum alone	7
Extensor digitorum + tibialis anterior (pretibials)	7
Tibialis anterior alone	0
Flexor digitorum alone	2
Flexor digitorum + tibialis posterior (supinators)	11
Two supinators + 1 pretibial	5%
The two supinators together with two pretibials	43%
Pretibials alone, no supinators	14%
One supinator and 1 or 2 pretibials	24%
Supinators alone, no pretibials	13%

table Xb. Calculation of the specificity of the combinations of supinators and pretibials during the movement 0 → +1 whilst standing (column 1a).

In table Xb we see how the activity of one or two supinators alone or one or two pretibials alone is almost equal, 13% and 14% respectively. This is in agreement with column 1a of table VIII. In this latter table the pretibials are essentials. In instances where one or two pretibials were active, the abductor hallucis also appeared to be active. When there is no activity of a supinator the abductor hallucis shortens the medial arch and functions as a supinator.

	1a	1b	1c
	%	%	%
Only supinators used	14	27	24
Combination of 1 or 2 supinators + 1 or 2 pretibials	72	53	57
Only pretibials used	14	16	11
No supinators and no pretibials used	0	3	8

table XI. Calculation of the specificity of the combination of supinators and pretibials. As illustrated examples of the  $0 \rightarrow +1$  movement we have selected columns 1a (standing), 1b (sitting), and 1c (sitting with a loaded knee).

During standing the  $0 \rightarrow +1$  movement was performed in 14% without using the supinators (table XI, column 1a), possible evidence of involvement of the exorotators of the hip-joint.

In table XI the combination of one or two supinators with one or two pretibials is 72% in column 1a (movement performed standing) and 53% in column 1b (movement performed sitting). The supinators only are used in a higher percentage in 1b than in 1a. We suppose that the pretibials are used during standing more as stabilizers than as supinators.

During sitting a higher percentage of movements are performed without concomitant use of the supinators and pretibials (columns 1b, 1c) than during standing. We may suppose this to be a result of supporting action of the hamstrings.

Finally, some remarks with regard to the other auxiliaries. The high frequency of recorded activity of the abductor hallucis in the E.M.G. recordings is logical in its function of shortening the base of the medial arch. The activity of one of the calf muscles may be necessary in order to compensate for the dorsal flexion of the foot effected by tibialis anterior and extensor digitorum. In this movement ( $0 \rightarrow +1$ ) we noted a dominant activity of the soleus.

We now return to the tendon slip measurements for a

comparison of the average values of the 0 → + 1 movement (table XII) with the frequency tables.

Tibialis posterior	+ 16 mm	Peroneus longus	- 16 mm
Flexor digitorum	+ 10 mm	Peroneus brevis	- 12 mm
Flexor hallucis	+ 4 mm	Tibialis anterior	+ 3 mm
Extensor hallucis	- 1 mm	Extensor digitorum	- 6 mm
		Achilles tendon	- 3 mm

table XII. Average tendon slip in 4 legs. Movement from position 0 → +1.

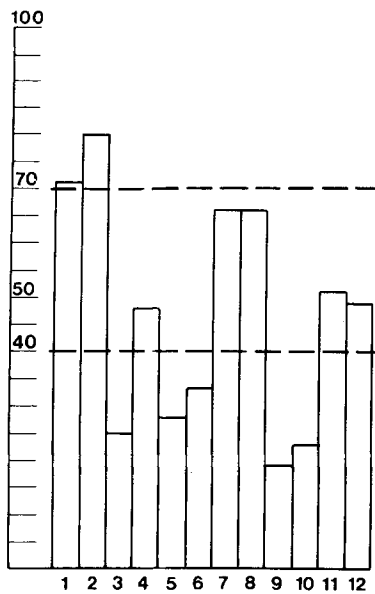


fig.21. Diagrammatic expression of the average values recorded in frequency table VIII.

- |                        |                        |
|------------------------|------------------------|
| 1 = tibialis posterior | 5 = peroneus longus    |
| 2 = flexor digitorum   | 6 = peroneus brevis    |
| 3 = flexor hallucis    | 7 = tibialis anterior  |
| 4 = extensor hallucis  | 8 = extensor digitorum |
|                        | 9 = lat.gastrocnemius  |
|                        | 10 = med.gastrocnemius |
|                        | 11 = soleus            |
|                        | 12 = abductor hallucis |

From table XII we observe that the muscles tibialis posterior, flexor digitorum, flexor hallucis and tibialis anterior shorten during the 0 → + 1 movement. The tibialis posterior and flexor digitorum in this table seem to function also as essential muscles. Concerning the importance of tibialis anterior and extensor digitorum, as observed in table VIII, we regard the extensor digitorum as stabilizing the toes in extension instead of clawing. The tibialis anterior and extensor digitorum collaborate in the stabilization of the lower leg and foot.

#### 5.3.2.2. The complete supinatory movement (0 → 2 movement).

In this movement there is maximal exorotation of the lower leg and talus and, therefore, a maximal supination of the tarsus and forefoot. The foot is now tilted laterally and resting on its lateral edge.

When we compare the data of the groups 1 and 2 we see the tibialis posterior, flexor digitorum, tibialis anterior and extensor digitorum as the essential muscles. In group 2 the extensor hallucis is also essential in function. The difference between the two groups is slight, presumably because the movement is simpler, more easily defined, and well-known from every-day life. The soleus functions again in an auxiliary capacity and compensates for the pull in dorsiflexion of tibialis anterior, extensor digitorum and extensor hallucis. The muscle also lends support to supination.

In this movement, too, we can compare the average value of the frequency tables with the results of the tendon slip measurements and so with the conclusions in section 5.2.

Again tibialis anterior and extensor digitorum together are active during this maximal supination. The

tendon slip measurements suggest an antagonistic function of these two muscles with respect to each other (table XIV).

Series:	2	2a	2b	2c	Average (2a-2c)
Number of subjects:	13	13	13	13	
Number of movements:	48	104	88	102	294
Muscle:	%	%	%	%	%
tib.post.	100*	67	70*	90*	76*
fl.dig.	78*	62	69	82*	71*
fl.hall.	20	24	27	43	31
ext.hall.	55	79*	70*	79*	76*
per.long.	42	29	33	43	35
per.brev.	26	29	16	29	25
tib.ant.	82*	100*	99*	98*	99*
ext.dig.	90*	100*	99*	91*	97*
lat.gast.	16	41	25	25	30
med.gast.	29	33	27	33	31
soleus	64	75*	65	68	69
abd.hall.	39	25	34	27	29

table XIII. Frequency table. Results (again expressed as percentages) obtained during the performance of the 0 → 2 movement. Pretibials are essentials!

2, 2a : movement performed standing;

2b : movement performed sitting;

2c : movement performed sitting with loaded knee.

In the table the essentials are marked with an asterisk and the auxiliaries are in italics. See fig. 22 for a diagrammatic representation of column 2a - 2c.

The extensor hallucis is active in a strikingly high percentage in contrast with the percentage for the flexor hallucis muscle. The hallux was dorsiflexed and in this way the subjects did their best to show that they supinated their feet maximally. The extensor hallucis muscle cannot be considered as an essential muscle for the 0 → 2 movement.

The frequency of the abductor hallucis is very low. The medial edge of the foot is lifted from the floor but the concavity of the medial arch is not exaggerated by straining the abductor hallucis muscle.

	<u>Average value tendon slip in mm</u> <u>0 → 2 movement</u>
Muscle: tibialis posterior	+ 21
flexor digitorum	+ 15
flexor hallucis	+ 6
extensor hallucis	+ 2
peroneus longus	- 24
peroneus brevis	- 24
tibialis anterior	+ 8
extensor digitorum	- 9
achilles tendon	- 5

table XIV.

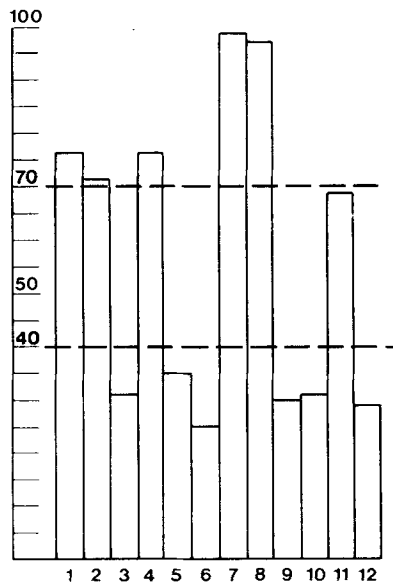


fig.22. Diagram displaying the average values as a percentage of frequency table XIII, column 2a - 2c (movement 0 → 2).

- |                    |                   |                        |
|--------------------|-------------------|------------------------|
| 1 = tib.posterior  | 5 = per.longus    | 9 = lat.gastrocnemius  |
| 2 = flex.digitorum | 6 = per.brevis    | 10 = med.gastrocnemius |
| 3 = flex.hallucis  | 7 = tib.anterior  | 11 = soleus            |
| 4 = ext.hallucis   | 8 = ext.digitorum | 12 = abd.hallucis      |

5.3.2.3. The pronation movement (0 → - 1 movement)  
as a part of the movement 0 → - 1 → 0 → + 1.

For the performance of this movement the lower leg is endorotated and the lateral edge of the foot elevated. We find the data in the columns 3a, 3b and 3c of the frequency table XV. These data are compared with the tendon slip values of the 0 → + 1 movement, for which reason the tendon slip measurements are recorded thereunder.

Series:	Group 2			Average (3a - 3c)
	3a	3b	3c	
Number of subjects:	13	13	13	
Number of movements:	51	51	55	157
Muscle: tib.post.	0	0	19	6
fl.dig.	0	0	25	8
fl.hall.	<i>50</i>	<i>58</i>	<i>54</i>	<i>54</i>
ext.hall.	<i>52</i>	<i>60</i>	<i>45</i>	<i>53</i>
per.long.	94*	80*	86*	87*
per.brev.	75*	81*	81*	79*
tib.ant.	36	47	50	44
ext.dig.	97*	74*	77*	83*
lat.gast.	50	30	23	34
med.gast.	10	3	9	7
soleus	30	0	16	15
abd.hall.	77*	68	68	71*

table XV. Frequency table. Results (again expressed as percentages) obtained during the performance of the 0 → -1 movement.  
 3a : movement performed standing;  
 3b : movement performed sitting;  
 3c : movement performed sitting with loaded knee.  
 In the table the essentials are marked with an asterisk and the auxiliaries in italics. See fig. 23 for a diagrammatic representation of column 3a - 3c.

	<u>Average value tendon slip in mm</u>
	<u>0 → + 1 movement</u>
Muscle: tibialis posterior	+ 16
flexor digitorum	+ 10
flexor hallucis	+ 4
extensor hallucis	- 1
peroneus longus	- 12
peroneus brevis	- 16
tibialis anterior	+ 3
extensor digitorum	- 6
achilles tendon	- 3

table XVI

In the pronation movement (table XV) there is no activity of the tibialis posterior and the flexor digitorum muscles. It is clear that tibialis posterior and flexor digitorum are not prime movers nor do they play a prominent rôle as stabilizers in the pronation movement. The peroneus longus, peroneus brevis, extensor digitorum are essential muscles and also synergists. The abductor hallucis opposes the arch-lowering effect of pronation. Is this a reflex action (Basmajian and Stecko, 1963)? The flexor and extensor hallucis are in equilibrium with each other.

In the supination movement (0 → + 1, table VIII) we noted a dominant activity of the soleus, whereas in the pronation movement (0 → - 1, table XV), we observed that the lateral gastrocnemius is used. The calf muscle is principally a plantar flexor. In addition the lateral head supports pronation whereas the soleus supports supination. This apparent functional difference between the parts of the triceps was denied by Duchenne.

In our investigations it appeared that most subjects preferred to use the medial head of the gastrocnemius during standing. In one subject we observed that after

standing for a longer time the lateral head of the gastrocnemius takes over from the medial head. In this instance fatigue would appear to be an important factor.

The data of table XV compared with the column featuring the tendon slip measurements of the  $0 \rightarrow +1$  movement, table XVI, unveil an identical pattern in the  $+1 \rightarrow 0$  movement. The movement  $+1 \rightarrow 0$  however, is not the reverse of movement  $0 \rightarrow -1$ . From the frequency tables concerning the  $0 \rightarrow -1$  movement and the table of the tendon slip concerning the  $+1 \rightarrow 0$  movement, we conclude that the peroneus longus and brevis muscles can be regarded as primary pronators.

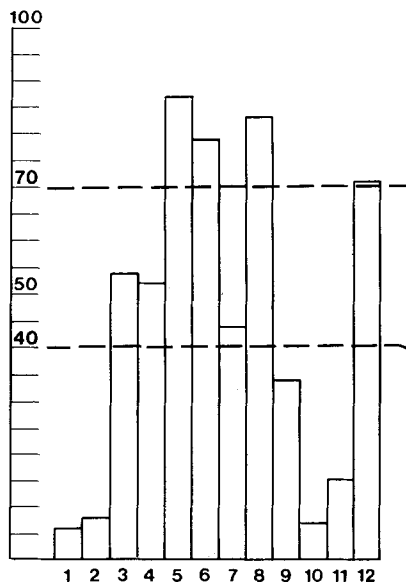


fig.23. Diagram displaying as a percentage the average values of frequency table XV, column 3a - 3c (movement  $0 \rightarrow -1$ ).

- |                    |                   |                        |
|--------------------|-------------------|------------------------|
| 1 = tib.posterior  | 5 = per.longus    | 9 = lat.gastrocnemius  |
| 2 = flex.digitorum | 6 = per.brevis    | 10 = med.gastrocnemius |
| 3 = flex.hallucis  | 7 = tib.anterior  | 11 = soleus            |
| 4 = ext. hallucis  | 8 = ext.digitorum | 12 = abd.hallucis      |

#### 5.3.2.4. The clawing movement.

In this movement both arches, the medial and lateral, become higher. There is an isolated but restricted movement in the Chopart joint and in the tarsometatarsal joints: the calcaneus is elevated. There is no exorotation of the lower limb and talus and no supinatory remodelling of the tarsus (see figs. 24, 25, 26, 27). This clawing movement could only be performed with the subject leaning backwards. Doing this, the line of gravity passes through the heel and the tension in the plantar ligaments will be decreased (see also Hicks p.32). Thus the tarsal kinematic chain is more or less unlocked so that some additional movement in the Chopart joint is now possible apart from the supinatory movement so typical for this kinematic chain. The head of the talus is lifted somewhat out of its wedge position between the navicular socket and the anterior feet of the sustentaculum tali.

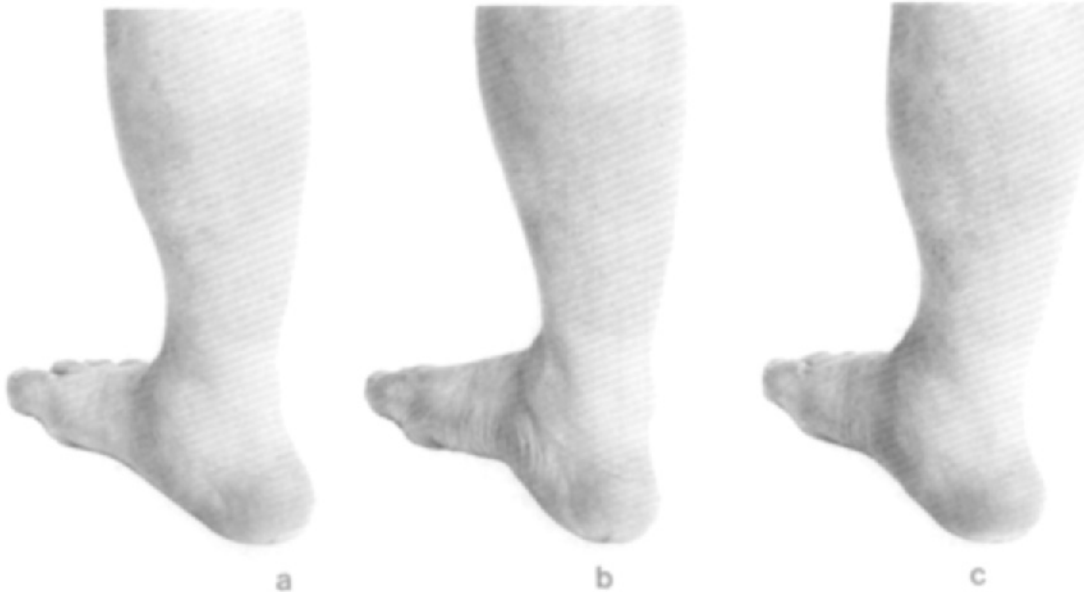


fig.24. a = foot in normal standing  
b = foot in position +1, heightening of the medial arch with exorotation of the lower leg  
c = foot in clawing position, heightening of medial and lateral arch. No exorotation of the lower leg.

To gain a better insight into the movements of the tarsal bones performing the clawing movement and the 0 → + 1 movement, radiograms of the foot were made, figs. 25, 26 and 27. In the radiogram of fig. 26 we see that the medial and the lateral arch are raised during clawing. There is a slight rotation of the ankle mortise as can be concluded from the position of the fibula with respect to the tibia. The sinus tarsi is slightly widened, the foot is shortened and there is some upward shift of the tibia. There is also an elevation of the talar head with respect to the navicular socket, in contrast with position + 1.

Fig. 27 represents the + 1 position. The medial arch is raised by tilting the forefoot in a lateral direction as can be seen from the position of metatarsal V. From the position of the fibula with respect to the tibia and from the radiogram of the talar head in fig. 27, it will be clear that the exorotation of the ankle mortise and the talus is greater than during clawing. The foot is shortened and the upward shift of the tibia is greater than during clawing.



fig.25. Radiogram of the foot in position 0



fig.26. Radiogram of the foot in claw position.



fig.27. Radiogram of the foot in position + 1.

The data pertaining to group 1 are to be found in column 3. The data relating to group 2 appear in the columns 4a, 4b and 4c (table XVII). Column 4c comprises data obtained from movements while sitting with loaded knee (1 kg). From the tables 4a, 4b and 4c we observe the importance of the peroneus brevis, tibialis anterior and extensor digitorum (tables XVII and XVIII). These three muscles are the essentials for raising the medial and lateral arches simultaneously. Moreover, the pretibials are active during standing to prevent falling backwards. For the clawing movement the abductor hallucis, by reason of its tension, shortens the base of the medial arch. This is especially the case during standing. During clawing the percentages for tibialis posterior and flexor digitorum are considerably lower than when the medial arch is raised by the supinatory movement. This would appear to illustrate once again that the combined action of these two muscles has a specific function in supination of the tarsus.

In order to gain further insight into the specificity of the muscles employed, the frequencies of combinations of active muscles were calculated in a manner similar to that used for examination of the 0 → + 1 movement.

In table XVIII is reflected that pronators, supinators and pretibials commonly work in combination to perform the clawing movement.

Combined action involving the flexor digitorum is particularly common (table XVII). We suppose that the flexor digitorum shortens the base of the medial and lateral edges of the foot; supination of the tarsus and exorotation of the lower leg, however, are prevented by the peroneus brevis muscles. In the absence of supinator activity, the clawing movement is commonly performed by the pronators and pretibials together.

Series:	Group 1		Group 2		Average (4a - 4c)
	3	4a	4b	4c	
Number of subjects:	16	13	13	13	
Number of movements:	48	78	76	74	228
Muscle:	%	%	%	%	%
tib.post.	<i>51</i>	<i>42</i>	28	<i>40</i>	30
fl.dig.	<i>64</i>	<i>52</i>	35	<i>58</i>	<i>48</i>
fl.hall.	93*	38	40	19	32
ext.hall.	88*	<i>69</i>	<i>67</i>	<i>68</i>	<i>68</i>
per.long.	<i>69</i>	<i>60</i>	36	<i>46</i>	<i>47</i>
per.brev.	<i>64</i>	86*	71*	<i>58</i>	71*
tib.ant.	86*	85*	79*	85*	83*
ext.dig.	78*	85*	<i>62</i>	73*	73*
lat.gast.	21	27	15	15	19
med.gast.	21	9	15	11	12
soleus	28	<i>67</i>	<i>49</i>	<i>66</i>	<i>57</i>
abd.hall.	81*	74*	<i>41</i>	<i>45</i>	<i>53</i>

table XVII. Frequency table. Activity of individual muscles during clawing movement expressed as percentage of total muscular involvement.

3, 4a : movement performed standing

4b : movement performed sitting

4c : movement performed sitting with loaded knee

In the table the essentials are marked with an asterisk and the auxiliaries in italics. See fig. 28 for a diagrammatic representation of column 4a - 4c.

	4a	4b	4c
	%	%	%
Pronators + supinators + pretibials (abd.hall.excl.)	44	43	43
Pronators + pretibials	36	35	27
Pronators + supinators (abd.hall.excl.)	4	0	0
Pretibials + supinators (abd.hall.excl.)	7	6	12
Pretibials alone	4	8	16
Pronators alone	0	0	0
Supinators alone (abd.hall.excl.)	0	5	0

table XVIII. This table represents the combination of muscles used in the clawing motion. We considered the whole group as active when one or two muscles of that group showed activity. Muscle were also considered as being active when they functioned during part of a movement.

Supinators = tibialis posterior + flexor digitorum

Pronators = peroneus longus - peroneus brevis

Pretibials = tibialis anterior + extensor digitorum

4a, 4b, 4c = see table XVII.

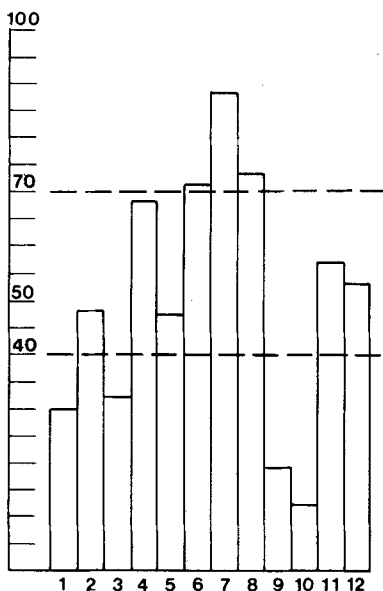


fig.28. Diagram displaying the average values as a percentage of the frequency table XVII, columns 4a - 4c (clawing movement).

1 = tib.posterior

5 = per.longus

9 = lat.gastrocnemius

2 = flex.digitorum

6 = per.brevis

10 = med.gastrocnemius

3 = flex.hallucis

7 = tib.anterior

11 = soleus

4 = ext.hallucis

8 = ext.digitorum

12 = abd.hallucis

### 5.3.3. The rolling movement.

The rolling movement is represented diagrammatically in fig. 29a - 29 l, each of which relates to one single muscle and records the tracings obtained from 12 different subjects. The E.M.G. signals obtained during performance of the rolling movement by subject 3 were not recorded on tape due to a technical hitch. The vertical lines indicate the ten steps of the rolling movement.

The rolling movement is a smooth motion in which the foot passes through the following steps (see also section 4.2.1).

- step 1 - pronation position (position - 1),
- step 2 - starting position (position 0),
- step 3 - first step of supination (position + 1),
- step 4 - maximal supination (position 2),
- step 5 - transmission of the load to the front part of the lateral edge, with raising of the heel,
- step 6 - maximal extension of the foot; load rests on the lateral part of the forefoot (position B),
- step 7 - load rests on the forefoot,
- step 8 - load rests on the medial part of the forefoot (position A),
- step 9 - foot sinks back on the floor until it rests on the medial edge (position - 1),
- step 10 - starting position (position 0).

During performance of the rolling movement we pass through the pronation position (- 1) in steps 1 and 9; the foot is also pronated whilst standing on the forefoot in steps 6, 7 and 8. In section 5.3.2.3 the muscle pattern for the pronation movement was recorded. Essential activity of the pronators (the peroneus longus and brevis) and the extensor digitorum were described. This same pattern is recognizable in the corresponding steps of the rolling movement. There is again supporting

activity of flexor and extensor hallucis and of the abductor hallucis. In step 1 (position - 1) the foot rests on the medial edge of the tuber calcanei and on the first metatarsal head. In step 8 (position A) the foot rests only on the first metatarsal head. The activity of the abductor hallucis, however, is less evident in step 8. This muscle is obviously active in step 1 in preventing lowering of the medial arch; in step 8 however there is no lowering of the medial arch under influence of the body weight since the foot rests on the medial part of the forefoot and also since the peroneus longus has a supporting function. There is a remarkable resemblance between the activities of the tibialis anterior and the extensor hallucis. In a number of subjects it was noted that both were active during pronation. We suppose that the tibialis anterior muscle acts as a stabilizer in position - 1, equivalent to steps 1 and 9.

In step 3 the supination position (+ 1) is attained and once again we identify the tibialis posterior and flexor digitorum as the essential muscles. There is less support from tibialis anterior and extensor digitorum. In agreement with the findings of the tendon slip measurements and the frequency tables of position + 1, there is no activity of peroneus longus and brevis.

In step 4, corresponding to position 2, we note the activity of tibialis posterior, flexor digitorum and extensor hallucis. There is more activity of the tibialis anterior and the extensor digitorum than in step 3, and no activity of the peroneals. The increase in activity of the tibialis anterior and the extensor digitorum is also in accordance with the findings in the frequency table concerning the 0 → 2 movement.

Elftman (1939) pointed out that muscles function during the release and reception of energy. In this way a muscle can generate a motion but can also brake a

motion. The braking function of muscle was observed also in our experiments. The flexor digitorum muscle is frequently active during the 0 → + 1 movement and this activity commences somewhat earlier than that of the tibialis posterior. The flexor digitorum muscle seems to function more as a prime mover than the tibialis posterior during the 0 → + 1 movement (steps 3 and 4). During steps 6 and 9, the activity of flexor digitorum ends somewhat earlier than that of tibialis posterior. This latter muscle now functions more as a brake than flexor digitorum (figs. 29a and 29b).

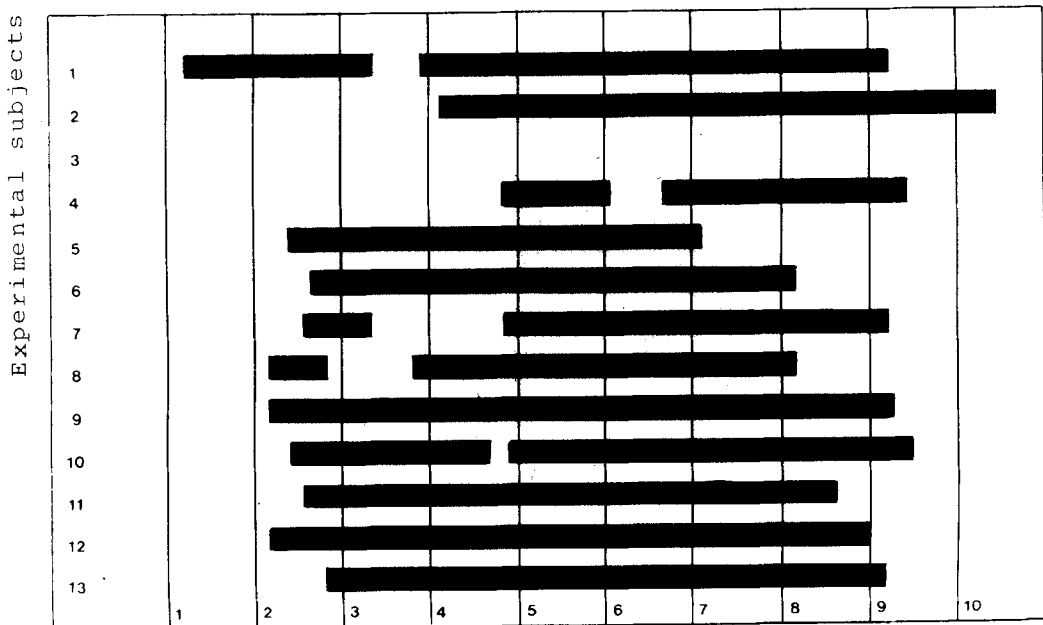
During rising and standing on tiptoe (steps 5 to 6) body weight is transmitted through the lateral edge of the foot to the lateral part of the forefoot, and one observes the activity of all the muscles whose tendons are related to the dorsal aspect of the ankle-joint (table VIIa). Peroneus longus and peroneus brevis are supported by the extensor digitorum in rolling the forefoot medially (steps 6 to 8). When the ankle is in plantar flexion this pronation movement of the tarsus is controlled to some degree by tibialis posterior and extensor digitorum (compare with tendon slip table VI, p.93, but travelling from positions B to A). This activity of the tibialis posterior can be explained by the fact that the muscle no longer functions as a prime mover, but as a stabilizer of the tarsus which brakes and controls pronation. The tarsus is less stable whilst standing on the forefoot than in the normal upright position, in which the sole makes full contact with the floor. During steps 9 and 10 the foot sinks back onto the floor and rests on its medial edge. The tarsus is pronated, and the peroneals and the extensor digitorum function as stabilizers of the tarsus.

The lateral gastrocnemius, the medial gastrocnemius and the soleus are broadly similar in activity. Their function during plantar flexion is obvious. The lateral

gastrocnemius muscle is active during pronation, especially in step 1. The activity of this muscle ends later than that of the medial gastrocnemius.

The soleus muscle is more actively involved during supination. The activity of the lateral gastrocnemius muscle during pronation and of the soleus muscle during supination agrees also with the results of the standard movements.

Diagrammatic representation of the rolling movement. Each diagram represents the activity of one muscle in all of the 13 subjects who performed the rolling movement in ten successive steps.



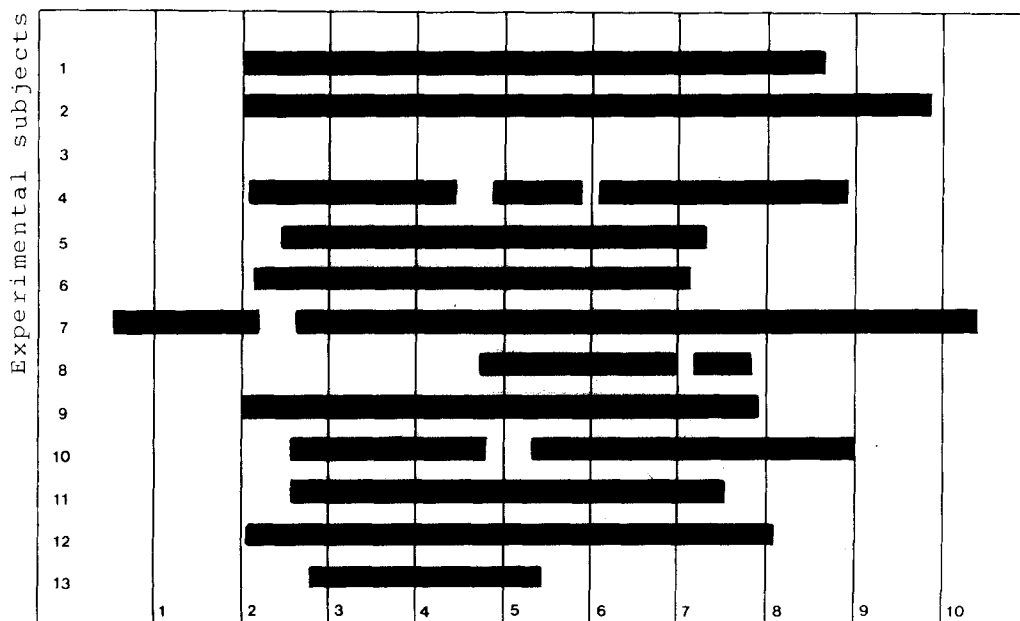
Ten steps of the rolling movement

Fig.29a. Tibialis posterior muscle. No recording in the case of subject 3 (see text).  
 step 1. position -1, the foot is in pronation, no signal.  
 step 2. position 0, foot flat position, no signal.  
 step 3. position +1, first step in supinatory movement, signal in most subjects.  
 step 4. position 2, maximal supination, signal in most subjects.

step 5. foot rests on metatarsal V, there is some plantar flexion. The activity increases. Prime mover.

steps 6, 7, 8. the foot is in plantar flexion and rolls over from the head of metatarsal V to that of metatarsal I. The pronation movement is controlled partly by the tibialis posterior. The muscle functions as a brake.

steps 9 and 10. the foot sinks back onto the floor and rests on its medial edge. In step 9 the muscle functions as a brake and there is activity. In step 10, the normal foot flat position is adopted.



Ten steps of the rolling movement

fig.29b. Flexor digitorum muscle. No recording in the case of subject 3.  
 The graphs are almost the same as those obtained from tibialis posterior. The function of this muscle seems more that of a prime mover.  
 Compare this figure with 29a.



Ten steps of the rolling movement

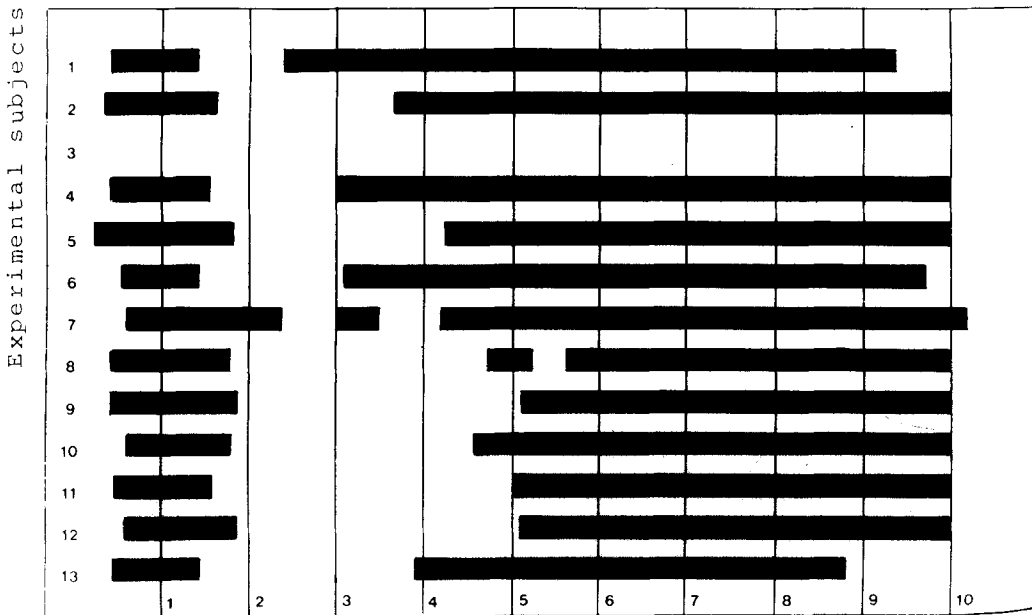
fig.29c. Flexor hallucis muscle.

Five subjects were not recorded due to a fault in the main amplifier (nos. 3, 8, 9, 10 and 12). The flexor hallucis is very active in position -1 (steps 1 and 9). During position -1 the foot rests on the medial arch. The flexor hallucis also prevents a lowering of the medial arch. The diagram can be compared with that of the abductor hallucis. From steps 2 to 8 the picture resembles that of the first two muscles.



Ten steps of the rolling movement

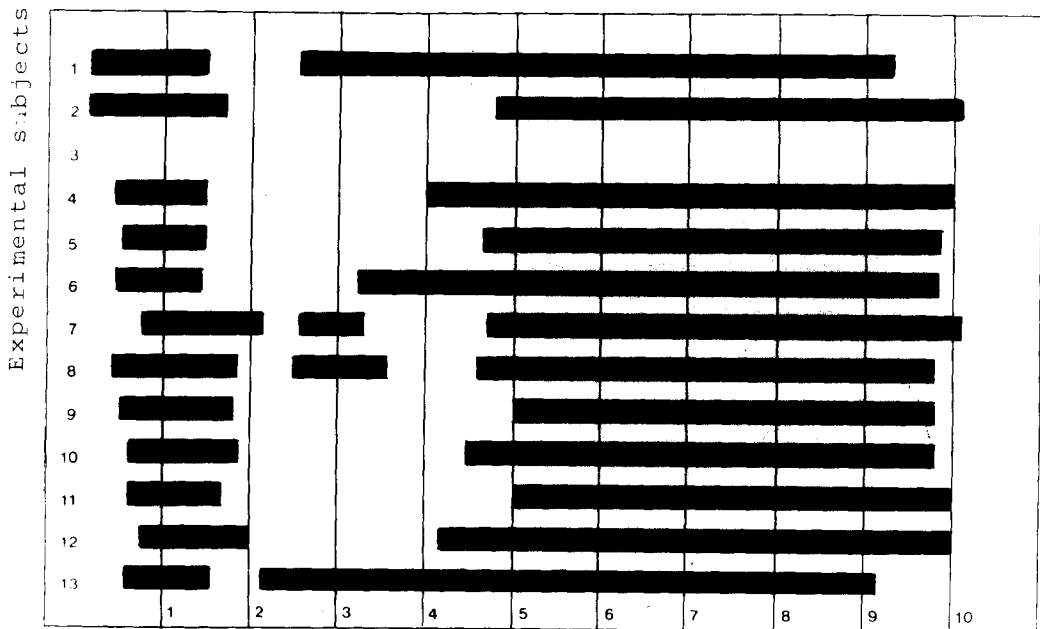
fig.29d. Extensor hallucis muscle. No recording in subjects 3 and 13. There is some activity of this muscle during pronation in step 1 and much more in steps 9 and 10. Compare this diagram with that of the tibialis anterior.



Ten steps of the rolling movement

fig.29e. Peroneus longus muscle.

fig.29e. Peroneus longus muscle. No recording in the case of subject 3. Text see under fig. 29f.



Ten steps of the rolling movement

fig.29f. Peroneus brevis muscle. No recording in the case of subject 3.

fig.29e and fig.29f. There is a remarkable resemblance of activity between peroneus longus and peroneus brevis, namely maximal function during pronation (step 1 and steps 6 - 8). They act synergistically with the plantar flexors (steps 5 - 6). Function is more that of a prime mover than of a brake. During steps 9 - 10 the tarsus is stabilized in pronation by the peroneals and by extensor digitorum.



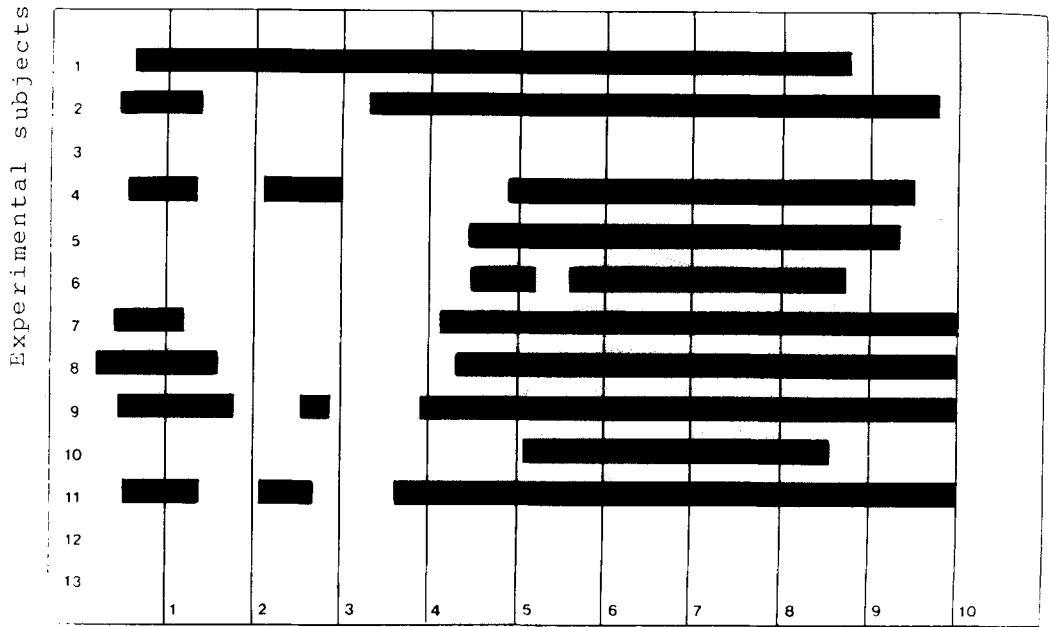
Ten steps of the rolling movement

fig.29g. Tibialis anterior muscle. No recording of subject 3. There is a remarkable resemblance with the activity of extensor hallucis muscle. In a number of subjects it is noted that some activity exists during pronation, (stabilizer during position -1?). As may be seen from the frequency table the muscle has an auxiliary function. During supination (steps 3, 4) activity is in keeping with the frequency tables (table XV, 0 → -1 movement, steps 1 and 9, and table XIII, 0 → 2 movement, step 4). This muscle can function as a prime mover and as a brake or stabilizer.



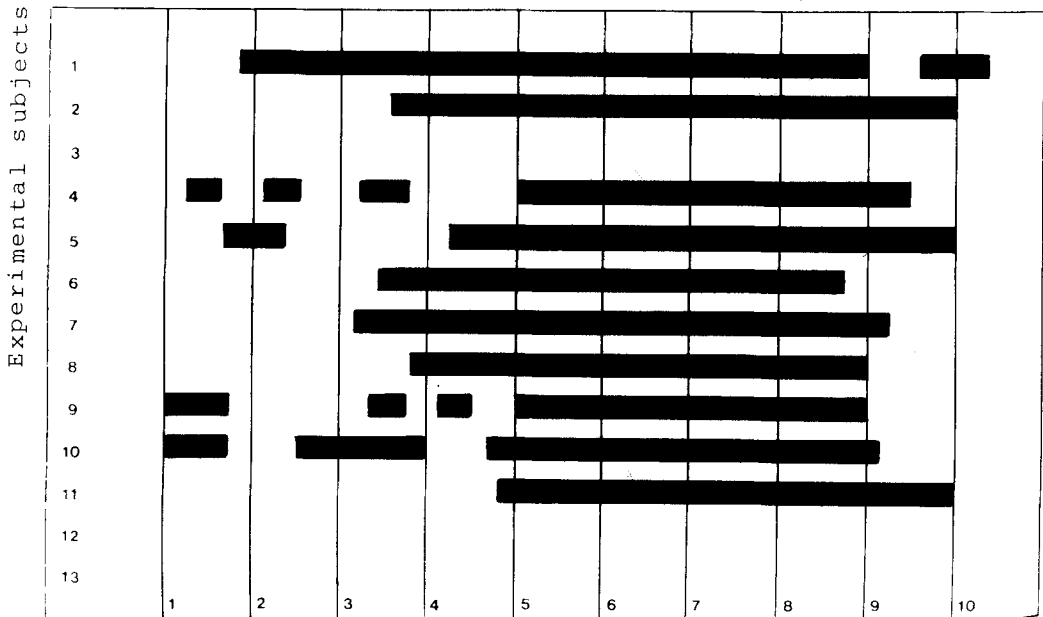
Ten steps of the rolling movement

fig.29h. Extensor digitorum muscle. No recording of subject 3. This graph resembles those of the peronei, the only difference being that the activity of extensor digitorum starts earlier (in steps 3, 4) in the phase of supination. This agrees closely with the results of the frequency tables. Compare table XV of the movement  $0 \rightarrow -1$ , with steps 1 and 9, and table XIII of the movement  $0 \rightarrow 2$ , with step 4. The muscle is essential in the pronation movement, steps 1 and 9, auxiliary in supination  $0 \rightarrow +1$ , (step 3), but essential also in the supination movement  $0 \rightarrow 2$ , (step 4).



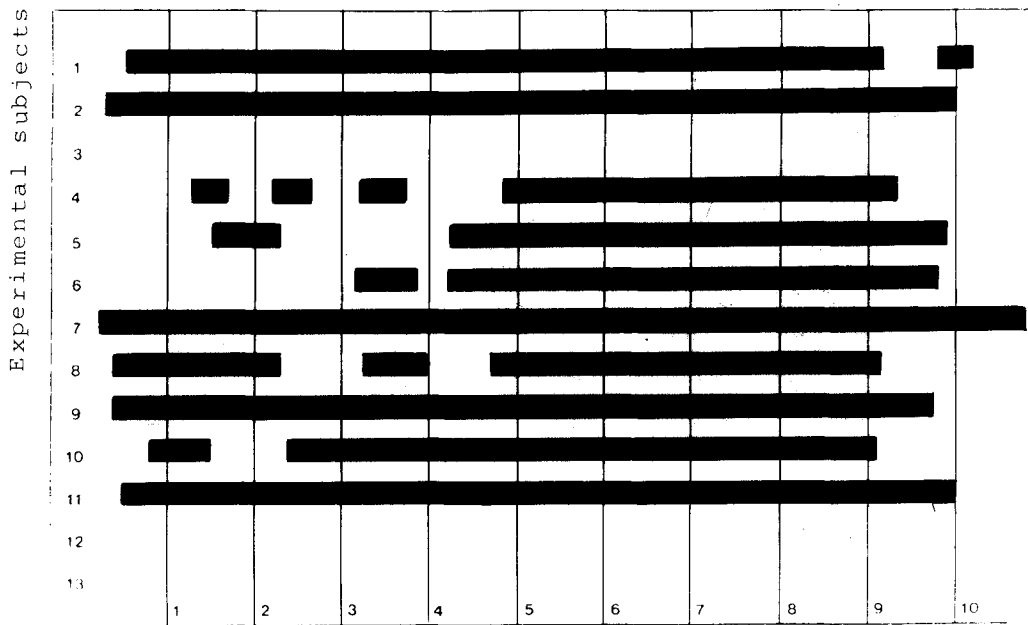
Ten steps of the rolling movement

fig.29i. Lateral gastrocnemius. See figs. 30j and 30k.  
No recording from three subjects (3, 12 and 13).



Ten steps of the rolling movement

fig.29j. Medial gastrocnemius. No recording from three subjects  
(3, 12 and 13).



Ten steps of the rolling movement

fig.29k. Soleus. No recording of three subjects (3, 12 and 13).

figs.29i, 29j, 29k. The muscles lateral gastrocnemius, medial gastrocnemius and soleus are broadly similar in activity. Their function during plantar flexion is obvious. Lateral gastrocnemius is active in pronation, especially in step 1. Soleus is more actively involved during supination.



Ten steps of the rolling movement

fig.291. Abductor hallucis muscle.

No recording from three subjects (3, 12 and 13). This muscle is obviously active in step 1 in preventing lowering of the medial arch.

#### 5.3.4. The E.M.G. pattern during walking.

We recorded in 11 subjects (nos.2 to 12 inclusive) the E.M.G. during walking at a speed of 1, 2, 4 and 5 km/h, and in 5 subjects (nos. 2 to 6) during running at 4, 5 and 6 km/h.

The following walking and running movements were recorded.

Walking: 1 km/h. - 5 steps - 2 subjects

2 km/h. - 26 steps - 8 subjects

4 km/h. - 35 steps - 8 subjects

5 km/h. - 8 steps - 2 subjects

Running: 4 km/h. - 3 steps - 1 subject

5 km/h. - 14 steps - 2 subjects

6 km/h. - 13 steps - 3 subjects

For the analysis of the E.M.G. patterns of the twelve muscles we used ultra-violet recordings with paper speeds of 5 cm/s and 50 cm/s respectively. The recordings with a paper speed of 5 cm/s (figs. 30 and 31) afford an insight into the entire pattern of the contracting muscles whereas tracings with a speed of 50 cm/s display the details of these patterns (fig.33). In section 5.3.4.1 the recordings with a paper speed of 5 cm/s, during walking at 2 and 4 km/h., are discussed. In section 5.3.4.2 the recordings with a paper speed of 50 cm/s, during walking (1, 2, 4 and 5 km/h.) and running (4, 5 and 6 km/h.) are discussed.

As usual we recognize during the walking motion a stance- and a swing-phase. The E.M.G. pattern is more regular during walking at 4 km/h. than at 2 km/h. During walking at low speeds it is possible that more reflexes are required to maintain balance.

The walking movement was filmed with help of a stroboscope at 30 pictures/s. The flashes of the stroboscope were correlated with the myographic records with help of a photocell. The subjects in our experiments walked in their own cadence. A description will be given of the common pattern of sway- and stance-phase with the deviations of this pattern in several subjects. Figs. 30 and 31 are examples of the pattern in one subject.

Whilst standing the following three events in time may be described:

1. heel strike or heel contact (h.s.),
2. foot flat = the first event of the first sole contact (f.f.), including the toes, and
3. the moment of toe-off left or right foot (t.o.l. or t.o.r.).

These events may be discerned from the photographic film (30 pictures per second). The three phases are more

easily recognizable at the slower walking pace (2 km/h.) than at the faster (4 km/h.).

For purposes of analysis of the E.M.G. recordings some form of data reduction is required and, for this reason, the outlines of the recordings of muscle activity were traced on transparent paper. The transparencies of the several subjects could then be compared with each other and the general pattern elicited.

The Californian Advisory Committee on Artificial Limbs (1953) employed an alternative method of registration. They made electromyographic summary curves for each muscle in several subjects. The subject walked on a level floor in a cadence of 95 steps per minute. The phasic activity of the action potentials was correlated to the placement of the feet by electrical contacts on the heel and hallux of each subject. These contacts initiated a signal on a channel separate from the myographic records. They summarized the integrated curves of all the subjects in one recording. In this way one curve represented the summarized E.M.G. activity of several subjects.

#### 5.3.4.1. Recordings with a paper speed of 5 cm/s.

(walking movement at speeds 2 and 4 km/h.)

The account hereunder is restricted to a description of the sway- and stance-phases. It appears that the muscles can be divided into two groups, pretibials with a characteristic pattern in the sway- or swing-phase and the others with a variable pattern in the same phase. During the stance-phase the opposite situation exists in which the dorsiflexors are more variable in their activity than the non-dorsiflexors. We shall discuss these phases consecutively.

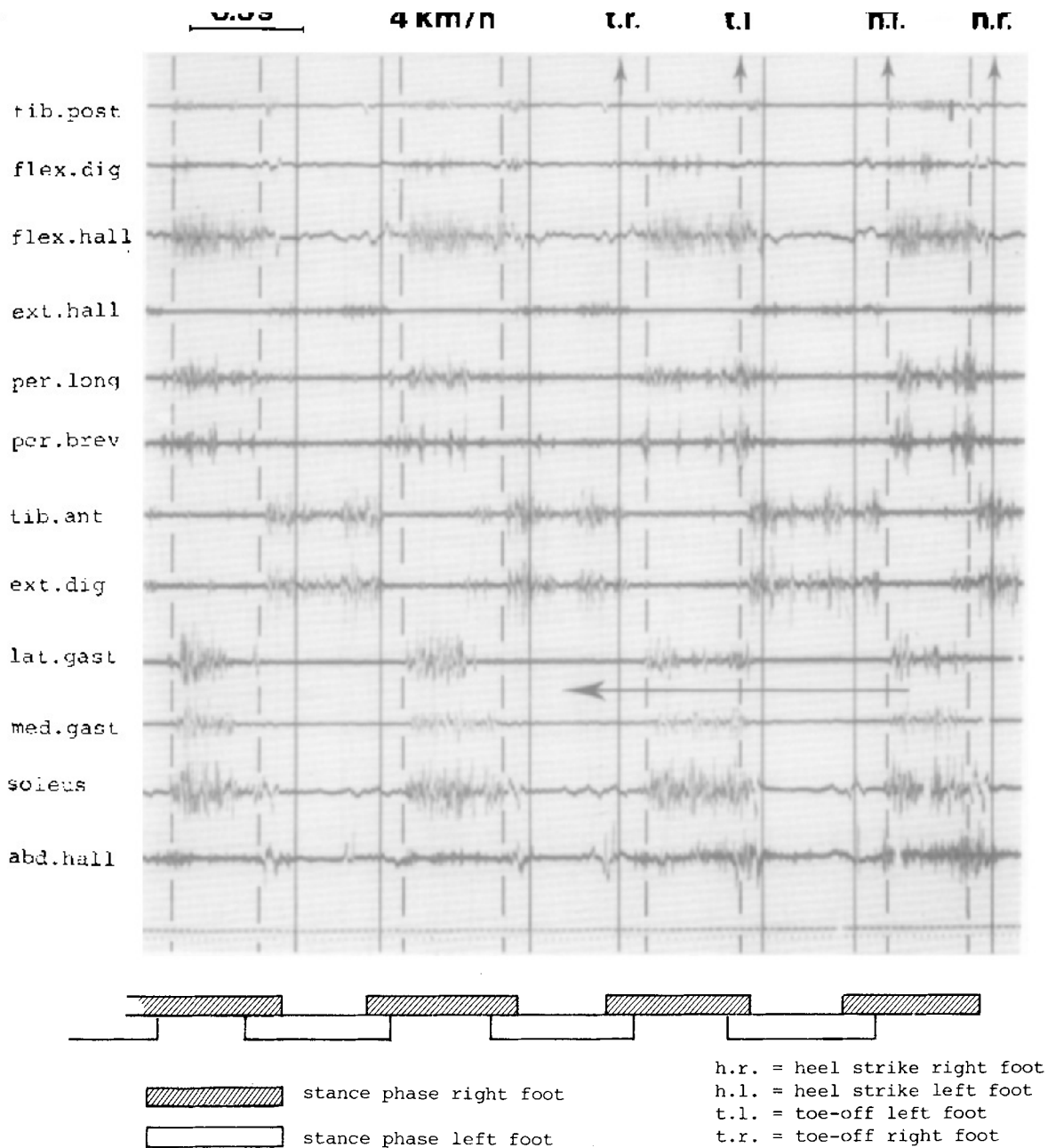


fig.30. Subject 7.

Myographic recordings from the 12 muscles of the right leg during walking at a pace of 4 km/h. The tracing is read from right to left. The broad space between two vertical lines represents the stance phase of the right leg. The narrow space between two such vertical lines represents the swing-phase. The dotted vertical lines display the stance- and swing-phases of the opposite leg. Paper recording speed 5 cm/s.

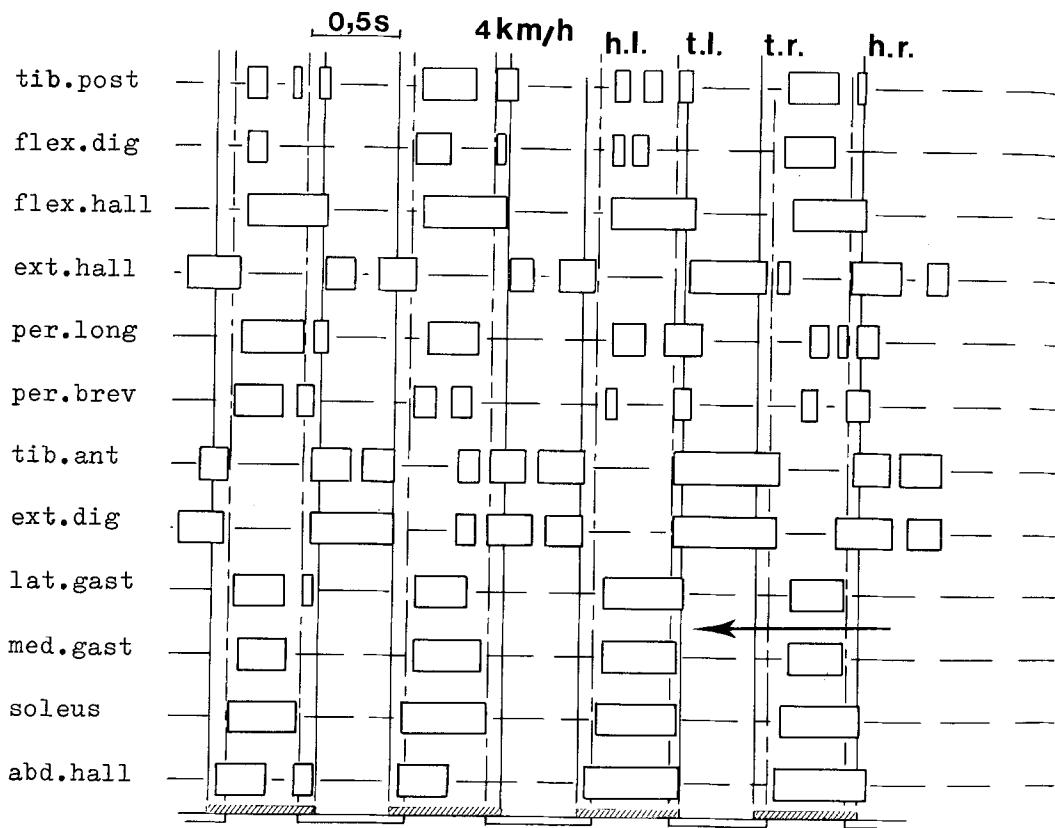


fig.31. Subject 7.

Myographic recordings from fig. 30 reproduced as outline drawings. The tracing is read from right to left.

## The sway-phase.

### Pretibials.

2 km/h.

The activity of the pretibial muscles, viz. the tibialis anterior, the extensor digitorum and the extensor hallucis is now observed in the sway-phase. Their function, to prevent the foot touching the floor, will be obvious. The activity commences or increases before toe-off, about 60 ms. after the plantar flexors end their activity, and ends after heel-strike. A continuous band of activity of the pretibial muscles is not always discernible. Halfway through the sway-phase, 9 subjects showed a dip in the amplitude or a short period of non-activity in the recordings of one or more of the pretibials. Only 2 subjects (nos. 11 and 12) showed continuous activity at speeds of 2 km/h. of all the pretibials.

4 km/h.

Here again, a dip of one or more of the pretibials halfway through the sway-phase was noted. Four subjects (nos. 5, 10, 11 and 12) showed a continuous activity of all the pretibials at a walking speed of 4 km/h.

The Advisory Committee on Artificial Limbs (1953) reported a dip in mid-swing of tibialis anterior, extensor digitorum and extensor hallucis. Sheffield, Gersten and Mastellone (1956), Battye (1966) and Joseph (1965) made the same observations on the tibialis anterior muscles. Our observations agree with these reports. Basmajian (1974) describes also a brief period of electrical silence of the tibialis anterior muscle at mid-swing. He explains this from his motion films which show the foot everting (pronating) at the end of "acceleration" (push-off) and remaining pronated through mid-swing. The

evertors (pronators) are active and, following the concept of reciprocal inhibition, the invertors (supinators) are inhibited.

In this investigation there was no indication of such a relation between pronators and supinators.

We measured in our photographs the flexion angle of the knee- and ankle-joints at mid-swing (the moment at which the foot of the sway leg passes the leg in stance), because we supposed that the short period of inactivity of the pretibials was related to these angles. When the knee of the swinging leg is flexed still more, the foot may adopt further plantar flexion without touching the floor. Flexion of the knee and dorsiflexion of the ankle were studied, not only in subjects displaying a continuous band of activity, but also in subjects showing a discontinuous band: no difference was discernible between the two groups.

The tibialis posterior, flexor digitorum, flexor hallucis, peroneals and triceps surae muscles: the muscles without dorsiflexion function.

2 and 4 km/h.

These muscles have a variable pattern of activity in the swing phase.

In the subjects 3, 6, 8, 9, 11 and 12 activity of the flexor muscles and abductor hallucis muscle was observed also in the sway-phase.

Subjects 3, 6, 9 and 12: 2 km/h and 4 km/h.: these subjects showed how the tibialis posterior or flexor digitorum started its activity shortly before heel-strike. However, this phenomenon was not recognized at all walking cycles.

Subject 8: 2 km/h.: the tibialis posterior and flexor digitorum muscles started their activity shortly before heel-strike. There was activity of the flexor hallucis

in early sway, of the peroneal muscles in the second half of the sway-phase, and of the abductor hallucis muscle in the late sway-phase.

Subject 8: 4 km/h.: only activity of the abductor hallucis could be detected during late sway.

Subject 11: 2 km/h.: this subject showed mid-sway activity of the flexor digitorum and late-sway activity of the abductor hallucis.

Subject 11: 4 km/h.: at this speed the subject showed late-sway activity of the peroneus longus, peroneus brevis and gastrocnemius medialis muscle. There was a mid- and late-swing activity of the soleus; the abductor hallucis was active throughout almost the entire sway-phase.

#### The stance-phase.

2 and 4 km/h.

#### Pretibials.

These muscles have a variable pattern of activity in stance. For this reason the pretibial muscles are not pure sway-phase muscles. The pretibials showed an increase in activity shortly before and after heel-strike. All the subjects, except 6 and 8, showed full stance activity of the extensor digitorum at both speeds. In subjects 6 and 8 there is only sway activity of the tibialis anterior muscle.

Subjects 5, 11 and 12 showed activity of the extensor hallucis, mainly in the first half of the stance-phase at a speed of 4 km/h.

Subjects 4, 7 and 8 had active tibialis anterior muscles in mid-stance at a speed of 2 km/h. and the subjects 5, 7 and 12 at a speed of 4 km/h.

The tibialis posterior, flexor digitorum, flexor hallucis, peroneals and the triceps surae muscles: muscles without dorsi-flexion activity.

These muscles are predominantly active in this phase, showing a more regular pattern. The electrical activity increased at mid-stance and ended at the moment or after the moment of heel-strike of the left foot in all subjects, but before the moment of push-off, right foot. We regard as push-off the moment when the ball of the forefoot is lifted. (The moment of heel-strike left foot is the beginning of the bipedal phase.) The increase in activity of the plantar flexors corresponds with the progression of the foot towards push-off. It should be borne in mind that the subject is not walking on the floor but on a *trottoir roulant*; the push-off may, therefore, be less forceful than normal.

Berntsen and Visser (1969) reported a difference in recorded muscle activity of the rectus femoris between walking on the floor and walking on a *trottoir roulant*. While walking on the floor, there was stance-phase activity from just before heel-strike until the moment when the heel was lifted and the foot was resting on the forefoot. Walking on a *trottoir roulant*, the muscle was active from the end of the sway-phase till mid-stance and became active again at end-stance. This latter period of activity continued into the first third of the sway-phase. Thus there would appear to be a difference between the E.M.G. recordings during walking on a *trottoir roulant* and during walking on the floor.

In order to ensure that mechanical differences play no part between walking on the floor and walking on the *trottoir roulant* it is essential that the mass presented by the *trottoir roulant* is sufficiently great (van Ingen Schenau, 1978) and that the *trottoir roulant* itself moves at a constant speed. In our series of experiments the subjects did have an obvious influence on the speed of

the *trottoir roulant*. This factor, in turn, had to be taken into consideration in determining the presence or absence of push-off. The E.M.G. may be further influenced by proprioceptive impulses and visual stimuli.

The termination of electrical activity before push-off and much earlier than expected may be in agreement with the fact that electrical activity always precedes muscle contraction: there is normally a delay between the initiation of an electrical signal and the moment of mechanical muscle activity. We have no exact information regarding a delay between the end of electrical activity and the completion of contraction. The maximal muscle strength is reached about 30 ms. after commencing maximal electrical activity (Katz, 1974). According to Katz, muscle strength decreases by 50% about 30 ms. after ending maximal electrical activity. From our recordings can be seen how the activity of the triceps muscles ends about 30 ms. before push-off.

In our recordings during walking the plantar flexor activity ends at the moment at which the heel is just lifted from the floor. During running (7 km/h.), however, we observed how all the plantar flexors end their activity at the moment of push-off (foot rests on the ball of the forefoot). The muscle strength necessary for push-off in this instance, should have been considerably greater. Eberhart, Inman and Bresler, using the force plate (Human limbs and their substitutes, 1954) showed that push-off is given by the ball of the foot (however, the subjects in their experiments did not walk on the *trottoir roulant*).

Close (1973) differentiates sharply between swing- and stance-phase muscles. In tendon transposition operations he advises against the use of a swing-phase muscle as a stance-phase muscle. His analysis of the results of transposition, nevertheless, lent no strong support for this opinion. We, like van der Straaten

(1972), have been unable to confirm this claim regarding functional difference. From our observations we conclude that pure sway-phase muscles and pure stance-phase muscles probably do not exist.

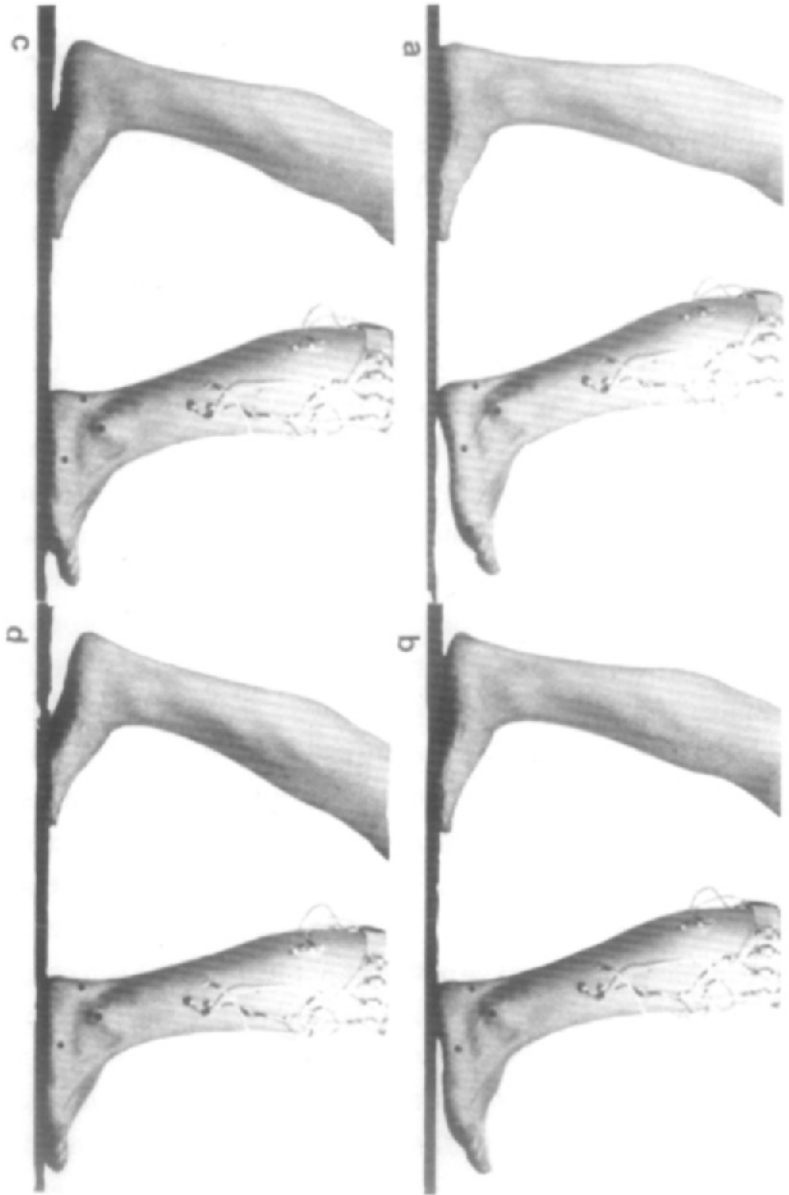


Fig.32 a, b, c, d (walking at 2 km/h.)

Serial photographs demonstrating the adoption of supination of the foot during heel-strike. In 32 d the foot has attained the foot flat position. In this position we see the foot from the lateral side. The angle formed by the extensor digitorum tendons on the dorsum of the foot is more acute.

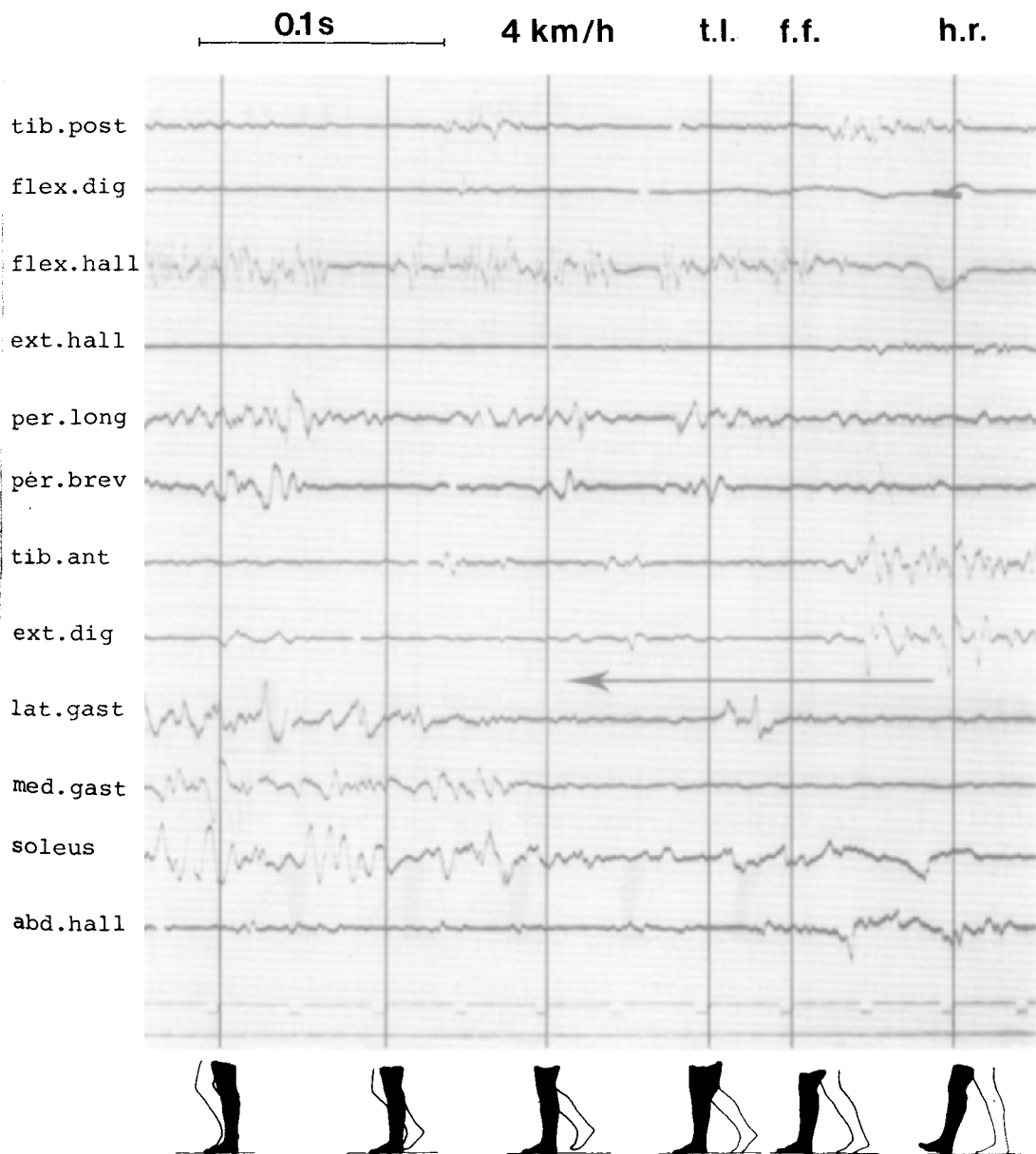


fig.33. Subject 7.

Myographic recordings from the twelve muscles of the right leg during walking at a pace of 4 km/h. Paper recording speed 50 cm/s. Read from right to left. The moments of heel strike (h.r.) and foot flat (f.f.) are indicated. t.l. = toe-off left foot.

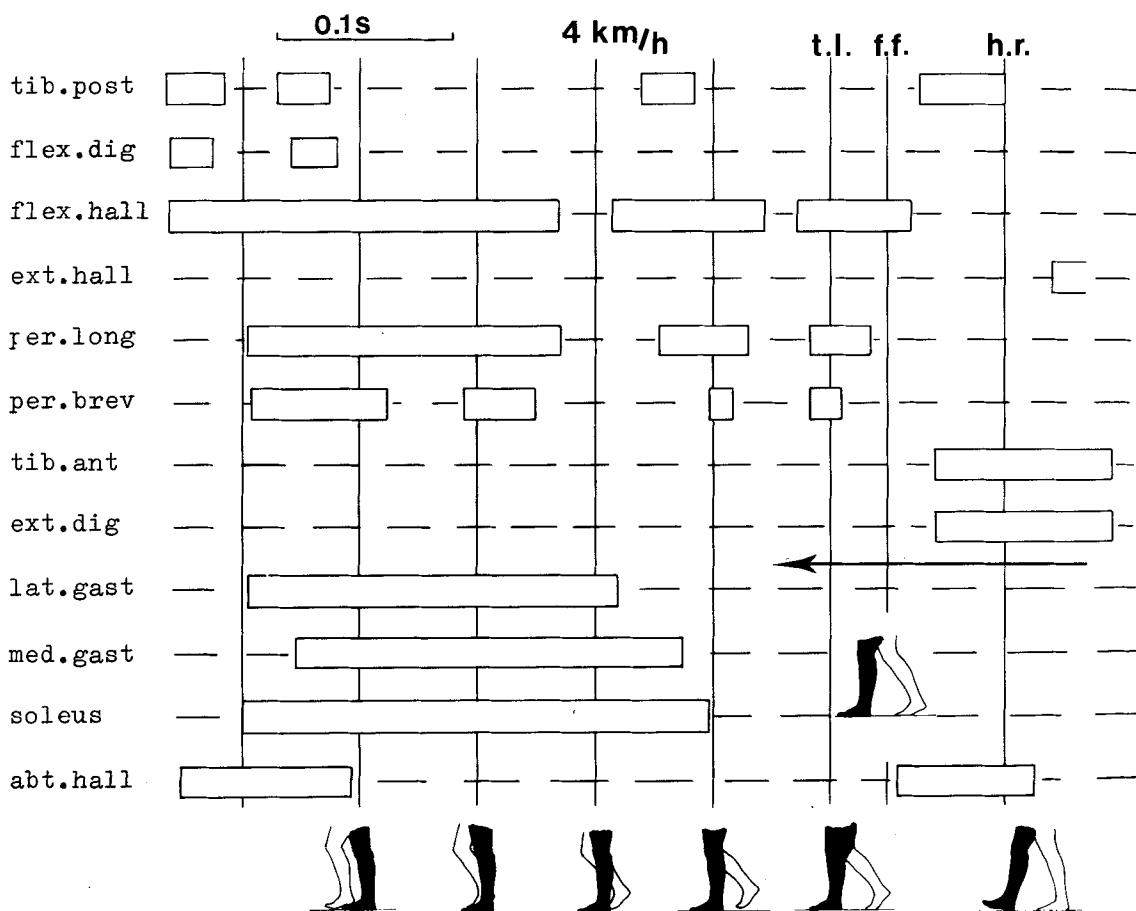


fig.34. Subject 7.

Myographic recordings from fig.33 reproduced as outline drawing.

#### 5.3.4.2. Recordings with a paper speed of 50 cm/s.

A description in detail. (walking at speeds of 1, 2, 4 and 5 km/h., and running at speeds of 4, 5 and 6 km/h.)

In the photographs of the filmed recordings (30 cycles/s.) of the walking movement we see how the foot is dorsiflexed and slightly supinated at the end of the swing-phase. At heel-strike the tarsus and forefoot are in a supinatory position (fig.32). After heel-strike the foot plantar flexes and the sole contacts the floor with the lateral edge; thereafter, the foot is pronated and the foot sole makes maximal contact with the floor. This means that at heel-strike the lower leg is in an exorotated position with respect to the foot. Eberhart, Inman and Bresler (1954) determined with the help of pin studies that the tibia endorotates about  $10^{\circ}$  after heel-strike during slow walking on the level. At fast level walking, this rotation increases considerably and, according to these writers, is related to the movements of the tarsal bones in a complicated way. Huson (1961) investigated and described the way in which these rotations of the lower leg are related to the tarsal movements and we measured in a simple way the extent of the rotations of the tarsal bones.

In the E.M.G. registrations with high paper speed we designated heel-strike right foot (the foot of the conducted leg), foot flat right foot and toe-off left foot (end of bipedal phase, see figs. 33 and 34). From the photographs we see in most cases how the moment of foot flat of the right foot lies between the moments heel-strike right foot, and toe-off left foot, in the bipedal phase. However, some subjects place their foot in an almost neutral position on the floor and there is only a very short delay between heel-strike and foot flat right foot. In other subjects, the moment foot flat

coincides with, or even follows, toe-off left foot. This makes a difference in the E.M.G.

The recordings from our walking subjects were studied and a general pattern of muscle activity was derived.

The general pattern of the myogram shows commencement of activity of the tibialis posterior, the flexor digitorum and the flexor hallucis shortly after heel-strike. It is also possible that the activity commences a short time before heel-strike. At heel-strike or a short time before, there is an increase of activity of tibialis anterior, extensor digitorum and to a lesser degree of extensor hallucis. What is the explanation for this pattern?

We learned from the measurements of the tendon slip to what extent tibialis posterior, flexor digitorum, tibialis anterior and extensor digitorum shortened or lengthened in certain tarsal movements. The findings of these measurements are comparable with the patterns of the E.M.G. investigations of the standard supinatory movement. These latter patterns are also to be found in the E.M.G. tracings during walking. The walking movement therefore has to be broken up into a series of successive and partly simultaneous motions which are comparable with the standard movements. During walking, the first movement of the foot after heel-strike is plantar flexion from the dorsiflexion supination position until the lateral edge of the sole makes contact with the floor. Thereafter the foot pronates until the foot makes full contact with the floor - the foot flat position (see fig.32).

The pretibials and supinators are active during the movement of the foot from dorsiflexion and supination to foot flat.

During this period of activity the muscles are lengthened and break the movement of the foot. Therefore, we can expect a contraction pattern similar to the one

which generates the movement. For this reason we are interested in the first part of the stance-phase.

Before heel-strike and in the first part of foot movement after heel-strike we see from the pretibials how the amplitude of the recording of tibialis anterior and extensor digitorum increases. The activity of the extensor hallucis is less from heel-strike to foot flat. Tibialis anterior and extensor digitorum are obviously more essential as brakes of plantar flexion in this part of the movement.

In the second part of the movement tibialis posterior, flexor digitorum and flexor hallucis participate in the pattern of active muscles as brakes of pronation movement. Before foot flat the pretibials decrease or discontinue their activity, whilst the supinators increase their activity. After foot flat there occurs a variable activity of the pretibials, supinators and pronators. The participation of flexor hallucis in combination with the peroneals is worthy of note (figs. 33 and 35). It is obvious that the foot becomes adapted to the floor and that the tarsus becomes stabilized to adopt a weight-bearing function during standing, especially in the monopodal part of this phase.

Between heel-strike right foot and foot flat right foot we see occasionally the simultaneous start of the sural musculature. The calf muscles increase their activity at mid-stance, shortly before toe-off left foot at walking speeds of 2 km/h. During walking at 4 km/h. activity of the calf muscles commences after toe-off left foot. The activity of the plantar flexors (calf muscles, peroneals, tibialis posterior, flexor digitorum and flexor hallucis) stops after the heel of the conducted leg is lifted (heel-off right foot). We do not see a push-off phenomenon in our recordings, probably due to the fact that the subjects walked on a *trottoir roulant*.

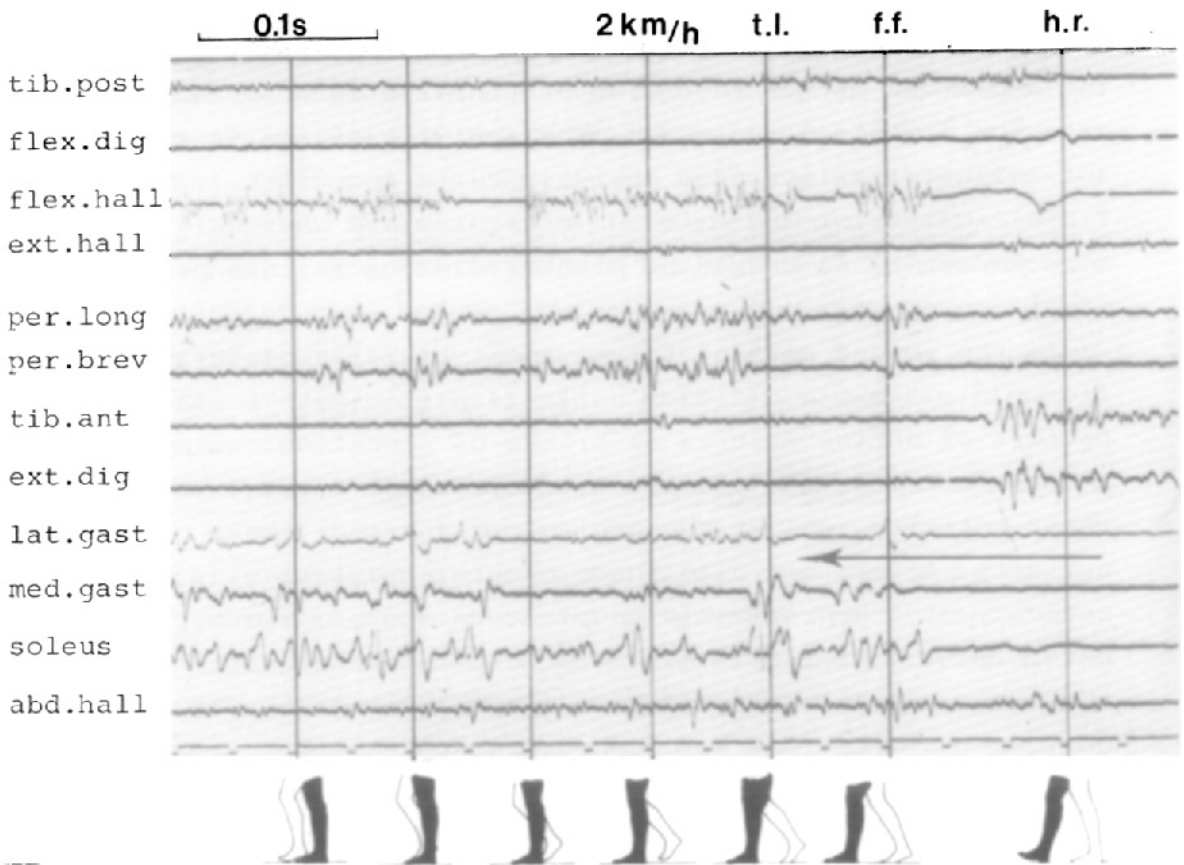


fig.35. Subject 7.

Myographic recordings from the twelve muscles of the right leg during walking at a pace of 2 km/h. Paper recording speed 50 cm/s. Read from right to left. The moments of heel-strike (h.r.) and foot flat (f.f.) are indicated. t.l. = toe-off left foot.

During running (4, 5 and 6 km/h.), however, not the pretibials but the calf muscles and supinators are active in braking the movement of the foot from plantar-

flexion-supination to foot flat (fig.36). The lateral part of the ball of the foot now makes its first contact with the floor (fig.37).

The difference between the above described general E.M.G. pattern and the E.M.G. patterns of the individual subjects are detailed hereunder, employing the following abbreviations: -

h.r. = heel-strike right foot

f.f.r. = foot flat position right foot

t.o.r. = toe-off right foot

h.o.r. = heel-off right foot

#### Subject 2.

No tracing at 2 km/h. due to technical hitch; no recording on bandrecorder.

1 tracing at 4 km/h. Walking, 5 steps, 2 complete steps with photoregistration, 60 photographs, starting point at t.o.r. 3 complete steps without photographs.

No activity of the flexor digitorum muscle.

Swing-phase: activity of the pretibials. During mid-sway in 4 of the 5 cases a dip in the activity of the pretibials. There is some activity of low voltage and low frequency of the peroneals.

Stance-phase: pattern as described earlier in general review. Activity of the abductor hallucis, similar to tibialis posterior.

1 tracing at 5 km/h. Running. 10 steps recorded, 2½ steps with photoregistration, 60 photographs.

There is no moment of heel-strike. The foot is placed directly with the lateral edge on the floor in supination and pronates until foot flat in 30 ms.

Swing-phase: activity of pretibials. In mid-swing their activity is increased instead of a dip. There is also some activity of the peroneals. Activity of the calf muscles starts in late swing.

Stance-phase: burst of activity of tibialis posterior, flexor digitorum, flexor hallucis, abductor hallucis and increase of activity of the calf muscles in the period from lateral edge sole contact till foot flat. At f.f. short burst of activity of the peronei, extensor digitorum and tibialis posterior. The activity of the calf muscles stops at heel-off right foot. Are these muscles used only to brake the movement and not to give the push-off? The patterns are almost the same in all steps during running.

Subject 3.

1 tracing at 2 km/h. Walking.  $2\frac{1}{2}$  steps with photoregistration, 120 photographs.

Swing-phase: a dip in the activity of the pretibials.

Stance-phase: pattern as described in general review, activity of abductor hallucis, parallel with tibialis posterior. Calf muscles, peroneals, tibialis posterior, flexor digitorum and flexor hallucis stop their activity when the ball of the foot is lifted. No push-off?

Tracing at 4 km/h. not recorded.

1 tracing at 5 km/h. Running. 4 steps, 2 steps with photoregistration, 60 photographs. Lateral part of the foot first contacts the floor.

Swing-phase: after mid-swing the activity of the pretibials stops. In the last  $\frac{1}{4}$  part of swing, activity of tibialis posterior, extensor digitorum and calf muscles begins. The foot is brought into position in contact the floor. After contact a short period (30 ms.) of no muscle activity; this falls within the bipedal phase.

Stance-phase: at foot flat (monopedal) bursts of tibialis posterior, flexor digitorum, flexor hallucis, peroneals, extensor digitorum and calf muscles. Activity of calf muscles, peroneals, tibialis posterior, flexor digitorum and flexor hallucis stops at the moment at which the ball of the foot is raised. A real push-off?

Subject 4.

1 tracing at 2 km/h. Walking.  $2\frac{1}{2}$  steps, 2 steps with photoregistration, 120 photographs.

Swing-phase: there is a dip in mid-swing of the pretibials.

Stance-phase: tibialis posterior in active a short time before f.f., not at h.r. No activity of the flexor digitorum in early stance. Pattern after f.f. as described in general review. The calf muscles, peroneals and tibialis posterior, flexor digitorum, flexor hallucis and abductor hallucis stop their activities at h.o.r.

1 tracing at 4 km/h. Running. 3 steps, 2 steps with photoregistration, 60 photographs.

Swing-phase: constructed of 2 phases. In the first half of swing there is activity of the pretibials. At mid-swing 30 ms. electrical silence of all recorded muscles. Second half of swing, activity of pretibials and calf muscles and the foot is positioned in plantar flexion and supination.

Stance-phase: the lateral part of the ball of the foot contacts the floor first. At this moment activity of the pretibials, calf muscles and also of the tibialis posterior and flexor digitorum. From lateral sole contact till foot flat, only activity of tibialis posterior and flexor hallucis. After f.f. full activity of tibialis posterior, flexor hallucis and start of activity of the peroneals, extensor digitorum and calf muscles. The activity of all these muscles increases until the foot rests on the ball. In this recording we can discern at stance three consecutive phases: a braking, a stabilizing and a push-off phase. The push-off phase starts after mid-stance.

1 tracing at 6 km/h. Running. 4 steps,  $2\frac{1}{2}$  steps with photoregistration, 60 photographs.

1 extra tracing at 1 km/h. Walking. 3 steps with photoregistration, 120 photographs.

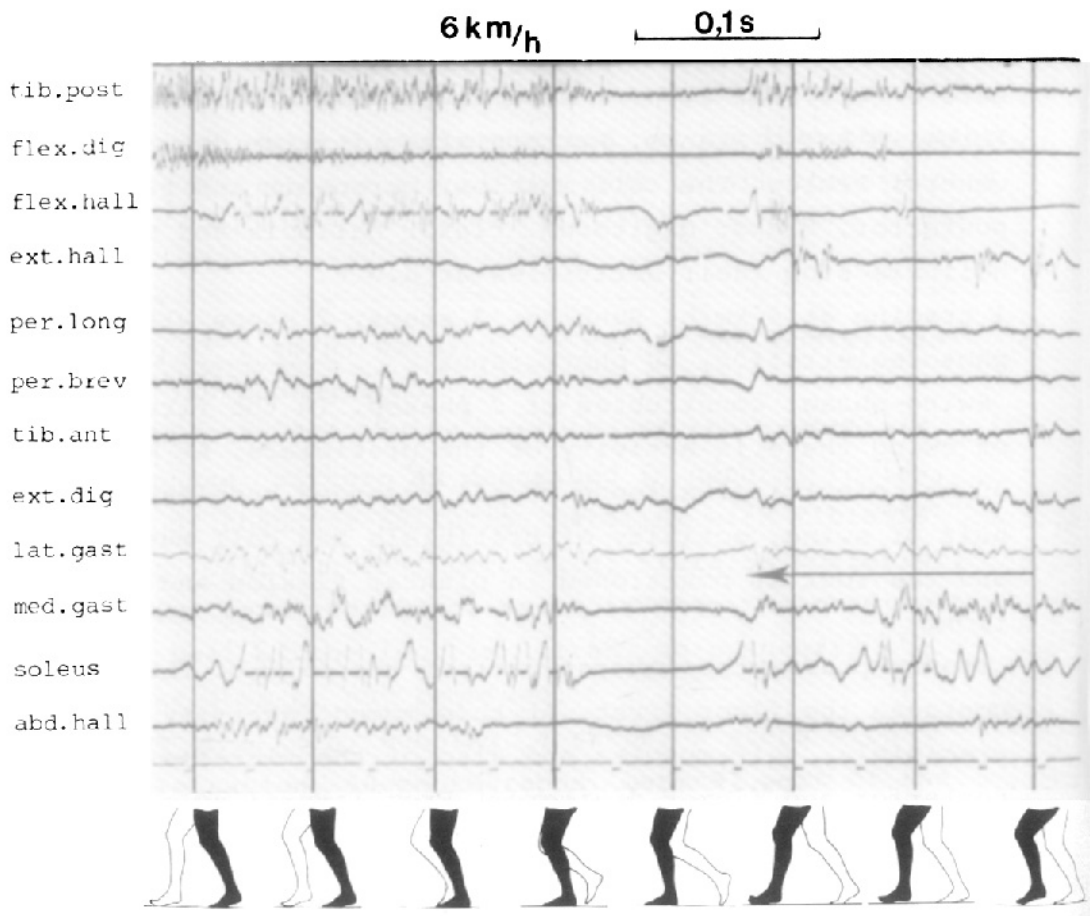


fig. 36. Subject 4 (running at 6 km/h.).

The calf muscles and supinators are active in braking the movement of the foot from plantar-flexion-supination to foot flat.



fig.37 a, b, c (running at 6 km/h.).

The lateral part of the ball of the foot now makes its first contact with the floor.

Recordings on lower voltage. Pattern as described above for 2 km/h.

Subject 5.

1 tracing at 2 km/h. Walking. 2 steps with photoregistration, 60 photographs.

Swing-phase: dip at mid-swing of the pretibials.

Stance-phase: flexor digitorum active in pronation phase, after h.r. and less activity of tibialis posterior in this part. Further E.M.G. pattern as described in general review.

1 tracing at 4 km/h. Walking. 3 steps, 2 steps with photoregistration, 60 photographs.

Swing-phase: a dip at mid-swing of the pretibials.

Stance-phase: flexor digitorum active as a brake in pronation phase. No pattern can be recognized as stabilization phenomenon. Further E.M.G. pattern as described in general review.

1 tracing at 5 km/h. Walking. 3 steps. 2 steps with photoregistration, 60 photographs.

1 tracing at 6 km/h. Running. 2 steps with photoregistration, 60 photographs.

Pattern as described in subject 4, running 5 km/h.

Subject 6.

1 tracing at 2 km/h. Walking. 2 steps with photoregistration, 60 photographs.

Swing-phase: the pretibials are active. There is a dip at mid-swing.

Stance-phase: the tibialis posterior is active at heel-strike, the flexor digitorum not. No activity of tibialis posterior and flexor digitorum between f.f. and mid-stance. There are only some activity bursts of the flexor hallucis and the abductor hallucis muscles. At mid-stance, just before t.o.l. some short bursts of tibialis posterior, flexor digitorum, tibialis anterior and extensor digitorum (stabilization?) and just after t.o.l., some

burst of activity of flexor hallucis, peroneus longus, peroneus brevis, extensor digitorum, calf muscles and abductor hallucis. In the second half of the monopodal phase there is activity of the calf muscles, together with tibialis posterior, flexor digitorum and peroneus brevis.

1 tracing at 4 km/h. Walking. 2 steps recorded with photoregistration, 60 photographs.

Swing-phase: activity of pretibials, a dip at mid-swing.

Stance-phase: between h.r. and f.f. pattern as described in general review. Between f.f. and mid-stance no activity of tibialis posterior and flexor digitorum. Activity of the other muscles as described in general review.

1 tracing at 5 km/h. Walking. 3 steps, 2 steps recorded with and 1 step without photoregistration, 60 photographs. Recordings of higher voltage than recorded at 4 km/h. Pattern clearer than that at a lower speed.

Swing-phase: activity of the pretibials with a dip at mid-swing.

Stance-phase: t.o.l. and f.f. in the same moment. At t.o.l. activity of tibialis posterior, flexor hallucis, peroneus longus, and start of activity of the calf muscles, which may be considered as a stabilization pattern.

1 tracing at 6 km/h. Running. 7 steps, 5 steps recorded with photoregistration, 120 photographs.

Swing-phase: activity of the pretibials. After mid-swing start of activity of the calf muscles, in anticipation of their brake function?

Stance-phase: the foot contacts the floor with the lateral edge. At this moment start of activity of the calf muscles. The activity of the pretibials has just stopped. The peroneus longus starts at f.f. (stabilization?). Calf muscles stop their function when the right foot rests on the forefoot. We did not consider this to be a

push-off. There is no clear differentiation in braking phase, stabilizing phase and push-off phase.

1 extra recording at 1 km/h. Walking. 2 steps with photoregistration, 120 photographs. This speed was recorded to observe the stance-phase. We expected at this very slow speed more stabilization reactions because we had already observed a more regular pattern during walking 4 km/h. than at walking 2 km/h.

Swing-phase: pattern as described in general review.

Stance-phase: no stabilization phenomenon at f.f. but it does exist at mid-stance. After t.o.l. period of activity of tibialis posterior, flexor digitorum, flexor hallucis, peroneus longus, calf muscles and abductor hallucis.

Stabilization reaction? At h.l. cessation of activity of gastrocnemius medialis and lateralis, not of flexor hallucis, soleus or abductor hallucis. These muscles stop their activity when the ball of the foot is lifted. We estimated this as a push-off. At this speed we observed no more patterns which could be discerned as stabilization phenomena than at speeds of 2 and 4 km/h.

#### Subject 7.

3 tracings at 2 km/h. Walking.

1st tracing - 2 steps with photoregistration, 120 photographs. The muscles are active as described in general review.

2nd tracing - 2 steps with photoregistration, 120 photographs. Flexor digitorum is not active before end of stance. Pattern of the other muscles as described in general review.

3rd tracing - 3 steps, no photographs. Pattern as before.

1 tracing at 4 km/h. Walking. 8 steps, 5 steps recorded with photoregistration, 120 photographs. Voltages of the signals higher than in the recordings of 2 km/h.

Swing-phase: activity of pretibials, a dip at mid-swing. Some activity of peroneals just before heel-strike.

Stance-phase: after f.f. activity burst of peroneals together with flexor hallucis, flexor digitorum till mid-stance. After mid-stance there is less activity of the peroneals.

Subject 8.

1st tracing at 2 km/h. Walking. 2 steps,  $1\frac{1}{2}$  steps recorded with photoregistration, 60 photographs. No recording of the flexor hallucis.

Swing-phase: at mid-swing a period with increased activity of the pretibials. Before and after mid-swing period of muscle "silence".

Stance-phase: pattern as described in general review.  
2nd tracing at 2 km/h. Walking. 2 steps,  $1\frac{1}{2}$  steps with photoregistration, 60 photographs.

Swing-phase: pattern as described above with exception of tibialis posterior. This muscle shows some bursts shortly before h.r.

Stance-phase: pattern as described above. All muscles except the peroneus brevis stop at h.o.r. The peroneus brevis stops at t.o.r.

2nd tracing at 4 km/h. Walking. 2 steps with photoregistration, 60 photographs. Pattern as described above.

Subject 9.

1 tracing at 2 km/h. Walking.  $2\frac{1}{2}$  steps, 2 steps with photoregistration, 60 photographs. No recording of flexor hallucis due to bad connection between electrodes and amplifier.

Swing-phase: activity of extensor digitorum is less during whole swing-phase. At mid-swing a dip in activity of the muscles extensor hallucis, tibialis anterior and extensor digitorum, but a burst of the peroneals.

Stance-phase: there was an obvious difference in three phases, h.r. → f.f., f.f. → mid-stance, mid-stance → toe-off.

Phase h.r. → f.f. After heel-strike: extensor hallucis and tibialis anterior show increase of activity. Little burst of flexor digitorum, peroneus longus and soleus. Phase foot flat → mid-stance. From just after f.f. till mid-stance little bursts of the peroneus longus and abductor hallucis.

Phase mid-stance → toe-off. Just after mid-stance some activity burst of tibialis posterior and commencement of the activity of flexor digitorum, peroneus longus and soleus.

At mid-swing left foot also start of gastrocnemius medialis and lateralis. All muscles cease their activities at heel-off right foot. No push-off.

1 tracing at 4 km/h. Walking. 6 steps, 2 steps with photoregistration, 60 photographs. No recording of flexor hallucis due to bad connection. The recordings of the other muscles have higher amplitudes.

Swing-phase: start of activity of extensor hallucis and tibialis anterior at t.o.r. Muscle "silence" at mid-swing. After mid-swing, activity of the pretibials and commencement of the peroneals. The pretibials and peroneus brevis discontinue and the activity of peroneus longus is decreased shortly before h.r. There is no real moment of h.r. The foot was placed on the floor with almost the entire lateral edge in contact. At f.f. commencement of flexor digitorum and increase of activity of peroneus longus.

Stance-phase: there are now no bursts as observed at 2 km/h. but the activities are more continuous. At heel-off right foot all muscles except the peroneus longus discontinue their activity. The peroneus longus ceases at toe-off.

#### Subject 10.

1 tracing at 2 km/h. Walking. 2 steps with photoregistration, 60 photographs. No recording of the flexor hallucis.

Swing-phase: activity of the pretibials. Short period of "silence" at mid-swing.

Stance-phase: period of h.r. till f.f. short. In this period synchronous bursts of activity of pretibials together with tibialis posterior and flexor digitorum. Just after f.f. bursts of peroneals and extensor digitorum, together with tibialis posterior, soleus and abductor hallucis. In the continuation of the bipedal part of the stance-phase (till t.o.l.) muscle "silence". At t.o.l. commencement of continuous activity of the calf muscles, peroneals, extensor digitorum, and burstlike activity of the tibialis posterior, flexor digitorum and the abductor hallucis. Cessation of activity of all the muscles at heel-off right foot. No push-off.

1 tracing at 4 km/h. Walking. 4 steps, 2 steps with photoregistration, 60 photographs. No recording of the flexor hallucis. The potentials are higher. Pattern during swing- and stance-phase as described in tracing at 2 km/h.

Subject 11.

1 tracing at 2 km/h. Walking. 4 steps, 1½ steps with photoregistration, 60 photographs. No recordings of the flexor hallucis muscle.

Swing-phase: activity of the pretibials without a dip at mid-swing.

Stance-phase: the foot is put down almost in f.f. position. No increase of activity of the pretibials when the foot contacts the floor, but bursts of activity of tibialis posterior and peroneals (stabilization?). There is full activity of the abductor hallucis at this time. Further pattern as described earlier in general review.

1 tracing at 4 km/h. Walking. 3 steps, 1½ steps with photoregistration, 60 photographs. No recording of the flexor hallucis muscle.

Swing-phase: less activity of tibialis anterior and

extensor digitorum. Full activity of extensor hallucis, during swing some little burst of tibialis posterior, flexor digitorum and abductor hallucis.

Stance-phase: between h.r. and f.f. full activity of tibialis posterior, flexor digitorum, tibialis anterior and extensor digitorum. At f.f. (f.f. and t.o.l. coincide in time!) start of full activity of the peroneals and abductor hallucis, and of less activity of extensor hallucis and extensor digitorum. The tibialis posterior is also active. Further pattern as described in general review.

Subject 12.

1 tracing at 2 km/h. Walking. 2 steps, 1½ steps with photoregistration, 60 photographs.

Swing-phase: no dip of the pretibials at mid-swing.

Stance-phase: pattern as described earlier in general review.

1 tracing at 4 km/h. Walking. 4 steps, 2 steps with photoregistration, 60 photographs.

Swing-phase: no dip of the pretibials at mid-swing. At mid-swing there is a burst of activity of the gastrocnemius medialis muscle.

Stance-phase: in the first step activity of tibialis posterior is noted before heel-strike and again directly after the foot contacts the floor.

In the second step, period h.r. till f.f. is short. The foot contacts the floor almost in f.f. position. In the first step we see tibialis posterior activity before h.r. and directly after the moment the foot contacts the floor the activity of pretibials and tibialis posterior ceases and the peroneals and flexor hallucis commence their activity. In the second step there is no activity at h.r. of the tibialis posterior before the moment at which the foot contacts the floor. Activity of tibialis posterior, flexor digitorum and the pretibials commences

immediately thereafter. At this moment there is only activity of the pretibials.

At this juncture it would seem appropriate to compare our results with the conclusions of the Advisory Committee on Artificial Limbs (1953).

The latter committee reports that:

- the extensor digitorum longus has an early stance-phase activity and a principal swing-phase activity.
- the patterns of extensor hallucis and tibialis anterior conform to that of the extensor digitorum muscle.
- the tibialis posterior and flexor digitorum muscles are acting synchronously. There is no activity of these muscles at heel-strike, only some mid-stance activity which increases progressively up to the end of the stance-phase. Only little difference exists between the patterns of the calf muscles, the tibialis posterior, flexor digitorum and peroneus longus muscles. The flexor hallucis and the peroneus brevis lack mid-stance activity. The end-stance activity of these muscles is similar to the activity of the calf muscles.

The subjects walked on a level surface.

In our observations there is no exclusive swing-phase activity of any muscle.

- the patterns of the extensor hallucis and tibialis anterior muscles are similar to that of the extensor digitorum at swing, not at stance!
- the tibialis posterior and the flexor digitorum muscles are acting mostly synchronously. In contrast with the A.C.A.L. we found activity of these muscles at heel-strike. There is a basic difference between the activities of these muscles and of the calf muscles. Our subjects walked on a *trottoir roulant*.

Certain aspects of the E.M.G. tracings are sufficiently remarkable as to merit mention here. Some subjects

display a short period of non-activity of their lower leg muscles in the bipedal part at the beginning and at the end of the stance-phase. It is possible that they stabilize the closed kinematic chain of the pelvis, legs and floor with the muscular stabilization of the hip-joints and knees (Huson, 1973). This phenomenon was seen in several subjects and was of 20 - 30 ms. duration (table XIX). We saw in our experiments that it is possible to stand upright with the legs somewhat exorotated and the knees somewhat bent without activity of the lower leg muscles.

Another phenomenon observed was the occurrence of short periods of activity in muscles synchronous with or alternating with similar short periods of activity in other muscles. Such a synchronism was noted concerning four groups of muscles. These groups consisted of:

in group 1: (deep flexors): tibialis posterior, flexor digitorum and flexor hallucis.

group 2: (peronei): the peroneus longus and brevis.

group 3: (extensors): tibialis anterior and extensor digitorum.

group 4: (superficial flexors): the muscles of the triceps surae.

Occasionally, we gained the impression that the activity of groups 1 and 2 alternated, and so thought that this activity might be due to reflexes attempting to maintain balance. But the reflex time is about 20 to 40 ms. (the conducting time of a short reflex, the H. reflex, is 20 ms.), and the time elapsing between the alternating bursts, measured in our E.M.G. recordings, is less. An alternative reason for this phenomenon must therefore be sought.

Graham Brown (1911) demonstrated that rhythmic contractions of leg muscles, similar to those that occur during walking, could be indicated following transsection of the spinal cord even in animals in which all input from

subject	speed km/h.	begin stance	end stance	total number of steps recorded
2	4	0	0	5
3	2	0	2	2
4	2	0	1	2
	4	0	2	3
5	2	0	0	2
	4	0	1	2
6	1	1	1	2
	2	0	1	2
	4	0	0	2
7	2	0	0	14
	4	0	1	5
8	2	0	4	4
	4	1	1	4
9	2	1	3	4
	4	0	0	4
10	2	1	1	2
	4	0	2	3
11	2	0	0	3
	4	0	0	2
12	2	0	2	4
	4	0	1	3

table XIX. Subjects with a short period (more than 30 ms.) of non-activity of their lower leg muscles in the bipedal part of the beginning and at the end of the stance-phase.

sensory nerves in the leg had been eliminated. He proposed that mechanisms located entirely within the spinal cord are responsible for generating the basic rhythm for stepping in each leg. The existence of central rhythm generation for each leg does not mean that sensory input is unimportant in the patterning of motor activity. In fact sensory input is essential for the animal to be able to adapt its stepping movements promptly to compensate for irregularities in the terrain on which it is

walking.

According to Grillner (1975), it seems clear that reflexes in the cat have two quite different functions in controlling the step cycle of a single leg. The first is to switch the motor-programme from one phase to the other (that is, to initiate the swing-phase or to initiate the stance-phase), and the second is to modify the motor output within a single phase. This reflex compensation takes a significant amount of time and could function effectively only in a cat that is walking rather slowly. Forssberg, Grillner and Rossignol (1977) demonstrated in the cat a predictable correcting movement when the forward movement of the limb is disturbed during locomotion as a result of meeting an unforeseen obstacle. The correcting movement is fast and depends upon the point in the step cycle at which it occurs. The reflex pathways are apparently organized in the spinal cord. The knee flexor is activated first (approximately 10 ms.), followed by the ankle and hip flexors (10 ms. and 20 ms. later respectively).

The higher centres also play a rôle in the control of walking (Pearson, 1976). An important function, particularly in animals and birds, is to modulate the basic walking motor-programme in response to sensory inputs from receptors in the head (eye and vestibular apparatus). Pearson supposes the existence in man of a comparable mechanism. When walking quickly or running the eye plays an important part in checking the position (e.g. slope) and condition (even, uneven, rough, bumpy) of the floor. It may be recalled how difficult it is to cross an unknown field in darkness and to avoid stumbling over unseen objects. The foot has to be lifted higher from the ground in swing and placed carefully in stance. The quality of the floor is sensed gingerly with the foot sole before loading the foot. To do so, reflex mechanisms are invoked. However, since these reflex systems operate comparatively slowly,

walking at speed under these circumstances is impossible.

5.3.5. Summary and conclusions concerning the measurements in vivo and suggestions regarding clinical application.

5.3.5.1. Measurements in vivo.

In this section a summary with conclusions of the measurements in vivo will be given.

The results concerning the tendon slip measurements are correlated to the measurements in vivo. We commence therefore by summarizing briefly the conclusions arrived from the tendon slip measurements.

The typical tarsal remodelling, supination, can be recognized not only in vivo but also in the anatomical preparations. The loaded foot supinates during exorotation of the lower leg and pronates during endorotation.

During supination or pronation of the foot there is a shift in positive or negative direction of the tendons of the lower leg muscles. The importance of the lower leg muscles in relation to the tarsal movements can be evaluated from the shift of these tendons.

The tibialis posterior and flexor digitorum are the important supinators (considerable shift in a positive direction during supination).

The tibialis anterior lifts the medial arch and is, therefore, a supinator; additionally, this muscle functions as a dorsal flexor. Peroneus longus and brevis are important pronators (considerable shift in a negative direction during supination).

The extensor digitorum is a pronator of the forefoot and so of the tarsus. The muscle is also an important dorsal flexor.

Plantar flexion is a secondary function only of tibialis posterior, flexor digitorum and the peroneals.

The triceps is principally a plantar flexor with a slight pronatory function.

The conclusions of the tests in vitro should be correlated with the findings of the investigations in vivo.

E.M.G. recordings were made of the lower leg muscles of several subjects.

The number of time the individual muscles were active in making a movement was expressed as a percentage. From these percentages tables were formed. The muscles which were active in at least 70% were called arbitrarily "essential". The muscles which participated in 40% to 69% of the movements were called "auxiliary".

These subjects made the same supinatory movements with their feet as performed in the experiments in vitro (movement 0  $\rightarrow$  + 1 and 0  $\rightarrow$  2).

#### 0 $\rightarrow$ + 1 movement.

The column of the average values of the 0  $\rightarrow$  + 1 movement indicates that the tibialis posterior and the flexor digitorum are essential muscles for the 0  $\rightarrow$  + 1 movement. This is in agreement with the conclusions regarding the measurements in vitro of tibialis posterior and flexor digitorum as important supinators. The extensor hallucis, tibialis anterior, extensor digitorum, soleus and abductor hallucis muscles were qualified as auxiliaries. (Tibialis anterior and extensor digitorum are borderline cases, with auxiliary and essential properties, having a frequency percentage of 66%.)

The extensor digitorum was regarded as stabilizing the toes in extension. We suppose in a way similar to that of stabilization of the finger. The stabilization of the arch formed by the phalanges of the finger during the pincet grip is not possible without help of the extensor digitorum muscle (Spoor, 1978). The tibialis anterior and the extensor digitorum collaborate in the stabilizing of

the tarsus. The frequency of recorded activity of the abductor hallucis is logical in its function of shortening the base of the medial arch. There is a dominant activity of the soleus in supination.

In pronation (movement 0 → -1) the gastrocnemius lateralis was used.

0 → 2 movement, maximal supination.

In this movement tibialis posterior, the flexor digitorum, tibialis anterior and the extensor digitorum were essential muscles. The soleus also lends support to supination. Tibialis anterior and the extensor digitorum show a maximal activity in their function as stabilizers. The tendon slip measurements suggest an antagonistic function of tibialis anterior and extensor digitorum. Tibialis anterior and extensor digitorum collaborate again in stabilizing the tarsus.

The tibialis posterior and flexor digitorum are in combination specific for the supination of the tarsus.

Clawing movement.

In addition to the supinatory movements, clawing movement was introduced. In this clawing movement both arches, medial and lateral, became higher. There is no exorotation of the lower limb and talus and no supinatory remodelling of the tarsus. The percentage for tibialis posterior is 30% and for flexor digitorum 48%.

There is an isolated but restricted movement in Chopart and in the tarsometatarsal joints; the calcaneus is elevated.

Three muscles are essential for heightening the medial and lateral arches together, namely, tibialis anterior, extensor digitorum and the peroneus brevis. Percentage of the flexor digitorum is 48% (stabilizing the toes?).

0 → - 1 movement, pronation.

During this movement the lower leg is endorotated and

the lateral edge of the foot is elevated.

The peroneus longus, peroneus brevis, the extensor digitorum and abductor hallucis are essential muscles. In the column featuring the tendon slip measurements of the 0 → + 1 movement we find these muscles with a negative slip.

The typical E.M.G. pattern during pronation or supination is also recognized when supination and pronation are the components of a movement; for example, during the rolling movement and during walking.

#### The walking movement.

In the sway phase, in the recordings with a paper speed of 5 cm/s, pure sway- and pure stance-phase muscles were not discernible. During sway-phase the tibialis anterior, the extensor digitorum and extensor hallucis prevent the foot touching the floor. Halfway through the sway-phase there was a dip in the amplitude or a short period of non-activity in the recordings of one or more of these muscles.

Other workers observed also this dip. The tibialis posterior, flexor digitorum, flexor hallucis, peroneals and triceps surae muscles, have a variable pattern of activity in the swing-phase.

In stance, the pretibial muscles show a variable pattern of activity. In most cases there is full stance activity of the extensor digitorum. The tibialis posterior, flexor digitorum, flexor hallucis, peroneals and the triceps surae muscles are predominantly active in stance, showing a more regular pattern.

The moment of push-off does not correspond with an increase of activity of the plantar flexor. The subjects, however, were not walking on the floor but on a *trottoir roulant*. The push-off may, therefore, be less forceful than normal.

In myograms recorded with a paper speed of 50 cm/s

further insight into the muscle pattern was obtained.

At heel-strike, or a short time before, there is a higher percentage of activity of extensor hallucis, tibialis anterior and a lower percentage of extensor digitorum. In most cases there is a start of activity of tibialis posterior, flexor digitorum and flexor hallucis shortly after heel-strike.

Shortly after heel-strike there is activity of supinators and dorsiflexors. These muscles are active during the movement of the foot from dorsiflexion and supination to foot flat against the effect of gravity and velocity of the body. The foot now functions as a brake and the muscles are lengthened during this period of activity.

After foot flat there appears a notable but variable activity of extensor digitorum together with the peroneals (pronators) and supinators. Obviously the foot has now become adapted to the floor and the tarsus sufficiently stabilized to accept weight-bearing in stance, especially in the monopodal part of this phase.

During running the calf muscles and the supinators are active in braking the movement of the foot from plantar-flexion-supination to foot flat. The lateral part of the ball of the foot now makes its first contact with the floor.

We suppose the existence in man of a central rhythm generation for each leg comparable with the mechanism of the cat. This autonomous system is programmed by the higher centres, the eye and vestibular apparatus.

#### 5.3.5.2. Suggestions regarding clinical application.

The importance of the tarsal mechanism with its steering muscles for normal function of the foot will be evident. A tarsus with diminished function due to stiffness, arthrosis or a bar between the tarsal bones, influences steplength and stepfrequency. In many cases

walking on an uneven floor or jumping from even a small height is painful. We all observe this in our patients. Where it is possible, we have to save the tarsal function. So, in the case of a calcaneo-navicular bar, it is better to resect the bar in children under the age of fourteen years rather than to perform an arthrodesis (Cowell, 1970).

The pes cavus is a foot with an elevated medial arch, a supinatory remodelled tarsus, and the heel inverted, comparable with position + 1. We asked our patients with pes cavus to stand on the lateral edges of their feet. Further supination of the feet, however, was in fact difficult, and often the patients really could not lift the medial edge of the forefoot, as in position 2. During normal walking such patients are unable to stabilize the tarsus adequately. Consequently the ankle may be easily sprained. In the surgical treatment of pes cavus it is better to spare the tarsal joints. The tarsal function is more essential than the cosmetic appearance of the foot.

Surgical treatment is aimed at reshaping the foot in order to adopt the 0 position. This may be achieved in one of two alternative ways, -

1. by converting the position of the tarsal bones into the 0 position by release of ligaments or tendon lengthening.

Procedure: release of the plantar fascia and Z-plasty of the achilles tendon.

2. by changing the shape of the bones, tendon lengthening, and release of the ligaments. In this way the form of the foot is remodelled to position 0.

Procedure: release of the plantar fascia and

- a. Z-plasty of the achilles tendon,
- b. lateral wedge resection of the tuber calcanei to compensate the supination position of the tuber,

c. wedge osteotomy distal to the tarsal joints. This osteotomy compensates for the height of the arch and the tarsal mechanism remains unaffected.

When the arthrodesis is necessary in a painful tarsus with arthrosis, it is better to perform a triple rather than a double arthrodesis. In a double arthrodesis (talo-calcaneus) the kinematic chain of tarsal bones is locked. However, some (abnormal) mobility may persist in the joint of Chopart, without exorotation of the talus (see X-ray photographs regarding the clawing movement), possibly giving rise to complaint.

Holscher (1965), however, found good results in double arthrodesis after calcaneal fractures even with osteoarthrititis in the joint of Chopart.

Many authors have described the pathogenesis and treatment of congenital clubfoot. As a result of their findings on anatomical dissections, Ponseti and Campos (1972), asserted that there are no primary anatomical abnormalities in this condition preventing redression by manipulations and plaster. Studying their descriptions, it appears that the position of the clubfoot is comparable with a free hanging foot in extreme supinatory remodelling. This position can be produced by extreme contraction of the supinators. Following this concept, all the components of clubfoot, namely,

supination of the heel,  
adduction of the forefoot,  
equinus, and

the appearance of excessive internal torsion of the tibia (according to Kite, 1964) are all manifestations of one basic deformity.

Deformity of bones and of soft tissues is adaptive in nature. It is essential, therefore, that conservative treatment should be instituted as soon as possible following delivery of the child. Furthermore, this

therapy should embrace simultaneously all the various elements of the malformation (Ponseti and Campos, 1972).

Our study lent insight into the synergistic function of the tibialis posterior and flexor digitorum with respect to the supinatory movement of the tarsus. However, supination is also possible by action of one of these muscles and these muscles can replace each other in normal walking. For this reason, the tibialis posterior muscle can be transferred to the dorsal side of the foot in cases of dropfoot without loss of active supinatory function.

A further method of tendon transfer is that of replacement of the lateral ligament of the ankle in old cases of rupture with instability of the ankle-joint by the peroneus brevis tendon. Two methods of surgical repair are described, namely, those of Evans and of Watson Jones (cited by Campbell's Operative Orthopaedics, 1963). In both surgical procedures the fibulo-calcaneal ligaments are replaced by the peroneus brevis tendon, in such a way that the newly formed ligament crosses perpendicular to the original. Exorotation of the talus with respect to the calcaneus is thus obviated and the kinematic chain of the tarsus becomes locked. After this operation the tarsal movements are reduced and walking on an uneven floor is difficult. In cases of recurrent dislocation, repair of the fibulo-calcaneal ligaments themselves is a preferable procedure (Blanchet, 1975, Staples, 1975).

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## SUMMARY

This study was designed to obtain more information regarding the function of the lower leg muscles in relation to the movements of the tarsus. Until now, no quantitative data have appeared in the literature concerning the movements of the tarsal bones; we began therefore, with an investigation of these latter movements.

In the functional-anatomical part of this study bone ligament preparations of lower leg and foot were mounted in the loaded position in an apparatus, which we called the cage. In this manner a combination of supination of the foot with exorotation of the lower leg or of pronation of the foot with endorotation of the lower leg could be studied.

Firstly, the rotations of the tarsal bones during supination were measured. For this purpose pins were placed in the tarsal bones of ten preparations and four consecutive, well-defined and reproducible positions of the tarsus were photographed from the frontal view, the side view and the axial view. The rotations in the three planes of projection were measured from the photographs.

Thereafter the tendon slip of the lower leg muscles during movement of the tarsus was measured in four of these preparations from the same positions mentioned above.

The starting position in the measurement of the rotations and tendon slip is that of the loaded foot in a functional position, the medial arch adopting the lowest position possible with maximal contact between the foot sole and the base of the cage. In addition, the tendon slips were measured when the foot was moved from the

starting position, mentioned above, in dorsiflexion. Moreover, the tendon slips were measured in pronation and supination when the foot was plantar flexed and rested on the forefoot.

It appears that, during maximal supination of the tarsus, the navicular rotates  $29^{\circ}$  and the cuboid  $23^{\circ}$  in a supinatory fashion in a more or less frontal plane. The mobility of the navicular with respect to the cuboid is slight. The talus exorotates  $33^{\circ}$  in a more or less horizontal plane. The navicular endorotates  $33^{\circ}$  in the same plane with respect to the talus. The calcaneus supinates  $12^{\circ}$  and exorotates through  $16^{\circ}$ .

It appears from these measurements that the movements of the bones in the tarsus during supination are considerable. The remodelling of the tarsus can be explained from these findings.

The position of the tarsal bones is influenced minimally during pronation of the forefoot when the tarsus is supinated and the lower leg is fixed in exorotation. There are no essential differences in the rotations of tarsal bones in supination in all the preparations. The results of the measurements of the tarsal bones support the conclusions of Huson, that the tarsus forms a kinematic chain with constrained motion.

It appears from the measurements of the tendon slip during supination that considerable shift in positive direction of the tibialis posterior (21 mm.) occurs and in a lesser degree also of the tibialis anterior (8 mm.) and of the flexor hallucis (6 mm.). (positive direction = direction of traction of the active muscle.)

There is a considerable shift too - but in the opposite direction - of the peroneus longus (24 mm.) and the achilles tendon (3 mm.). Pronation of the forefoot with a supinated tarsus and the lower leg fixed in exorotation, influences the peroneus longus tendon only. (The mean values of 4 preparations at maximal supination

are given in brackets.)

During supination of the foot in plantar flexion the tendon slips are in the same direction but less in degree than during supination with the foot in a neutral position with respect to the lower leg.

We suppose that the muscles which have a considerable tendon slip in a given movement in vitro also have an important function in vivo during the same movement. Muscles which do not shorten during specific movement can function as, for instance, stabilizers. Tibialis posterior and flexor digitorum are supposed to be essential supinators; peroneus longus and brevis are supposed to be essential pronators.

We have, therefore, to correlate the experiments in vitro with the findings of the investigations in vivo. E.M.G. recordings were made of the eleven lower leg muscles and of one foot muscle in two groups of experimental subjects. These subjects made with their feet the same supinatory movements as performed in the experiments in vitro. We calculated and expressed as a percentage how frequently a muscle was active during a number of given movements. Tibialis posterior and flexor digitorum are both active during supination in a high frequency.

In addition to the supinatory movements, a so-called clawing movement was introduced. In this clawing movement both arches, medial and lateral, became higher. There is no exorotation of the lower limb and talus. Three muscles are active in a high frequency during simultaneous raising of the medial and lateral arches, namely, tibialis anterior, extensor digitorum and the peroneus brevis.

During pronation, the peroneus longus, peroneus brevis, the extensor digitorum and the abductor hallucis are the essential muscles. The typical E.M.G. patterns during pronation or supination are also recognizable when supination and pronation are the components of a movement, for example during the rolling movement and during

walking. To analyse the E.M.G. recordings during walking the subject was filmed. A regular pattern of active and inactive muscles is discernible in the U.V. recordings with a low paper speed (5 cm/s) during the stance- and sway-phases. In the myograms recorded with a paper speed of 50 cm/s further insight into the muscle patterns was obtained.

The transition of sway- into stance-phase is composed of several well discernible positions. The foot is in slight dorsiflexion and supination at the end of the sway-phase and this is the position of the foot at heel-strike. After heel-strike, the foot plantar flexes and the sole contacts the floor with the lateral edge; thereafter the foot is pronated and the sole makes maximal contact with the floor. Shortly after heel-strike, there is also activity of the dorsiflexors and supinators. These muscles are active against the effect of gravity and velocity of the body. After foot-flat there appears a remarkable activity of the extensor digitorum, together with the pronators and supinators. It is now obvious that the foot is stabilized sufficiently to bear weight.

In the last chapter, clinical applications of our investigation are suggested.

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## SAMENVATTING

Het doel van deze studie is meer informatie te verkrijgen omtrent de functie van de lange onderbeenspieren in relatie tot bewegingen van de tarsus. Omdat tot nu toe bovendien geen quantitative gegevens beschikbaar waren omtrent de bewegingen van de tarsale beenstukken werd begonnen met een analyse in deze zin.

Voor het functioneel-anatomisch deel van het onderzoek zijn skeletbandenpreparaten van onderbeen en voet opgesteld in belaste positie in een kooiconstructie. In deze opstelling kan de voet supineren respectievelijk proneren als het onderbeen wordt geëxoroteerd respectievelijk geëndoroteerd, zonder dat de voetzool het contact met de onderlaag verliest en zonder dat deze de roterende beweging volgt.

Allereerst zijn nu de rotaties van de tarsalia gemeten bij het supineren van de tarsus. Daartoe werden in de tarsalia van 10 preparaten pennen gestoken, en zijn er foto's gemaakt van een aantal posities uit de supinatiebeweging van de tarsus, vanuit voorachterwaartse, zijdelingse en axiale richting. De posities zijn zodanig gekozen dat zij zowel bij het anatomisch preparaat als in vivo goed zijn te definiëren en te reproduceren. De rotaties in de 3 projectievlakken werden daarna uit deze foto's afgelezen.

Vervolgens werden bij 4 van deze preparaten de peesverschuivingen gemeten van de lange onderbeenspieren. Voor deze metingen werd gebruik gemaakt van dezelfde posities als die, welke gebruikt werden bij het meten van de rotaties van de tarsalia. De uitgangsstand voor de metingen van rotaties en peesverschuivingen is de

stand van de belaste voet in functionele stand, waarbij een maximaal contact tussen voetzool en onderlaag bestaat.

Bovendien werden de peesverschuivingen gemeten als de voet vanuit de bovenbeschreven uitgangsstand in dorsaal-flexie werd gebracht. Ook werden de peesverschuivingen gemeten bij pro- en supinatie van de tarsus met de voet in plantairflexie steunend op de voorvoet.

Het blijkt dat bij maximale supinatie van de voet het naviculare  $29^{\circ}$  en het cuboid  $23^{\circ}$  in supinatoire zin roteren in een min of meer frontaal vlak. De beweging van het naviculare ten opzichte van het cuboid is gering. De talus exoroteert  $33^{\circ}$  in een min of meer horizontaal vlak. In ditzelfde vlak endoroteert dus het naviculare  $33^{\circ}$  ten opzichte van de talus. De calcaneus supineert  $12^{\circ}$  en exoroteert  $16^{\circ}$  (de vermelde rotaties zijn gemiddelde waarden van 10 preparaten). Uit deze metingen blijkt dat er aanzienlijke verschuivingen van de beenstukken in de tarsus plaatsvinden bij supinatie. De vormveranderingen van het achterste deel van de voetwortel kunnen hierdoor worden verklaard.

De positie van de tarsale beenstukken wordt nauwelijks beïnvloed door proneren van de voorvoet als de tarsus is gesupineerd, terwijl het onderbeen in exorotatie is gefixeerd. De rotaties van de tarsalia van de preparaten onderling vertonen geen essentiële verschillen in grootte en in richting. Deze resultaten ondersteunen de conclusie van Huson dat de tarsus beweegt volgens het mechanisme van een kinematische keten met een omschreven bewegingspatroon.

Uit de metingen van de peeslengteveranderingen blijkt dat er bij de maximale supinatie een aanzienlijke verschuiving in positieve richting (positieve richting = richting die overeenkomt met de trekrichting van de spier bij verkorting) optreedt van de tibialis posterior (21 mm), de flexor digitorum longus (15 mm) en, in

mindere mate, ook van de tibialis anterior (8 mm) en de flexor hallucis longus (6 mm). Er is eveneens een aanzienlijke verschuiving, maar in de tegenovergestelde richting, van de peroneus longus (24 mm) en brevis (24 mm) en, in mindere mate, van de extensor digitorum longus (9 mm) en de achillespees (3 mm). Proneren van de voorvoet bij gesupineerde tarsus en een in exorotatie gefixeerd onderbeen veroorzaakt alleen verschuiving van de peroneus longus pees. De tussen haakjes geplaatste waarden zijn de gemiddelden van 4 preparaten. Supineren van de voet in plantairflexie veroorzaakt verschuivingen van de pezen in dezelfde richting echter in mindere mate dan supineren met de voet in neutrale stand ten opzichte van het onderbeen.

Wij veronderstellen nu, dat spieren die tijdens een beweging een aanzienlijke lengteverandering ondergaan ook een belangrijke rol zullen spelen bij het uitvoeren van deze beweging in vivo, ook al kunnen spieren die niet van lengte veranderen uiteraard op andere wijze een rol spelen, bijvoorbeeld als stabilisatoren. Zo bezien zullen tibialis posterior en flexor digitorum belangrijke supinatoren moeten zijn; peroneus longus en brevis kunnen dan verondersteld worden belangrijke pronatoren te zijn.

De conclusies van de onderzoeken in vitro werden in verband gebracht met de bevindingen in vivo. Hiertoe werden bij 2 groepen proefpersonen E.M.G. afleidingen gemaakt van 11 onderbeenspieren en van één voetspier. Deze proefpersonen maakten dezelfde supinatie bewegingen met hun voeten als die, welke in vitro werden onderzocht. De tibialis posterior en de flexor digitorum longus blijken beide zeer frequent gebruikt te worden bij het supineren van de tarsus.

Er werd ook een zogenaamde klauwbeweging onderzocht. Bij deze beweging worden zowel de mediale als de laterale voetboog verhoogd, evenwel zonder het been te roteren.

De tibialis anterior, de extensor digitorum longus en de peroneus brevis blijken overwegend actief. De supinatoren worden in dit geval aanzienlijk minder frequent gebruikt.

Bij de pronatiebeweging treden de peronei, de extensor digitorum longus en de abductor hallucis op de voorgrond.

De typische E.M.G. patronen bij supinatie en pronatie zijn ook herkenbaar als deze bewegingen het onderdeel vormen van gecompliceerde bewegingen zoals de rolbeweging en het lopen. Voor de analyse van het E.M.G. bij het lopen werd de loopbeweging gefilmd.

Een regelmatig patroon van actieve en niet actieve spieren is te herkennen op de E.M.G. registraties met een lage papiersnelheid (5 cm/s) gedurende de stand- en de zwaai-fase. Het blijkt dat er geen exclusieve zwaai-fase en standfase spieren zijn. Op de registraties met hoge papiersnelheid (50 cm/s) wordt meer inzicht verkregen in de opeenvolgende onderdelen van de loopbeweging.

De overgang van zwaai- naar standfase kan worden beschreven als opgebouwd uit een aantal goed herkenbare standen. De voet staat aan het einde van de zwaai-fase in lichte dorsaalflexie en supinatie, en in deze stand wordt de hiel op de grond geplaatst. De voetzool rolt daarna over de laterale rand naar voren en proneert. Het neerkomen van de voet wordt bij hielcontact afgeremd door de dorsaalflexoren en de supinatoren. Dit veroorzaakt een specifiek activiteitspatroon. Zo zijn bij het neerzetten van de hiel de dorsaalflexoren en de supinatoren actief totdat de voetzool volledig contact maakt met de onderlaag. Hierna zijn de supinatoren en pronatoren samen actief, waardoor de voet wordt gestabiliseerd.

In het laatste hoofdstuk worden aan aantal suggesties gedaan ten aanzien van klinische toepassing.

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## REFERENCES

- Advisory Committee on Artificial Limbs (1953). The pattern of muscular activity in the lower extremity during walking. National Research Council, Prosthetics Devices Research Project, Institute of Engineering Research, University of California (Berkeley). Series 11, Issue 25, September 1953.
- Basmajian, J.V. and Bentson, J.W. (1954). An electromyographic study of certain muscles of the leg and foot in standing position. *Surgery, Gynaecol. and Obst.* 98, pp. 662 - 666.
- Basmajian, J.V. and Stecko, G. (1963). The role of muscles in arch support of the foot. *Journal of Bone and Joint Surgery*, 45A, pp. 1184 - 1190.
- Basmajian, J.V. (1974). *Muscle alive: their functions revealed by Electromyography*. The Williams and Wilkins Company, Baltimore, p. 139.
- Battye, C.K. and Joseph, J. (1966). An investigation by telemetering of the activity of some muscles in walking. *Medical and Biological Engineering*, 4, pp. 125 - 135.
- Berndtsen, H.M. en Visser, H. (1969). *Ned.Tijdschrift voor Geneeskunde*, 113, nr. 22, pp. 1004 - 1005.
- Blanchet, A. (1975). La reflection capuloligamentaire dans les instabilité chronique de la tibio-tarsienne. *Revue de Chirurgie orthopaedique*, 61 supp.II, pp. 175 - 176.
- Brown, T.G. (1911). The intrinsic factor in the act of progression in the mammal. *Proc.Roy.Soc., London, Ser.B* 84, pp. 308 - 319.
- Campbell's Operative Orthopaedics (1971). ed. Crenshaw, A.H. The C.V. Mosby Company, vol.1, pp. 945 - 947.
- Close, J.R. and Inman, V.T. (1953). The action of the subtalar joint, Report to the Advisory Committee on Artificial Limbs, National Research Council, Series II, no.24.
- Close, J.R. and Todd, F.N. (1959). The phasic activity of the lower extremity and the effect of tendon transfer. *Journal of Bone and Joint Surgery*, 41<sup>a</sup>, pp. 189 - 208.
- Close, J.R. (1973). *Motor function in the lower extremity: Analysis by electronic instrumentation*. Springfield, Charles C.Thomas.
- Cowell, H.R. (1970). Extensor brevis arthroplasty. *Journal of Bone and Joint Surgery*, 52<sup>a</sup>, p. 820.
- Duchenne, G.B. (1967). *Physiologie des mouvements*. Translated by E.B. Kaplan (1949). Philadelphia and London, W.B. Saunders Company.

- Eberhart, H.D., Inman, V.T., Bresler, B. (1954). The principal elements in human locomotion, in human limbs and their substitutes. Edited by P.E. Klopsteg, P.D.Wilson. Inc. New York, Mc Graw-Hill Book Company, chapter 15, pp. 437 - 471.
- Elftman, H. (1939). The function of muscles in locomotion. *A.J. Physiol.* pp. 357 - 366.
- Elftman, H. (1960). The transverse tarsal joint and its control. *Clinical Orthopaedics*, 16, pp. 41 - 46.
- Elftman, H. (1966). Biomechanics of muscle (with particular application to studies of gait). An instructional course lecture. *Journal of Bone and Joint Surgery*, 1966<sup>A</sup>, vol. 48<sup>a</sup>, pp.363 - 377.
- Fick, A. (1885). *Medizinische Physik*, 3 Aufl. Published by Fr.Vieweg & Sohn, Braunschweig, p. 97.
- Fick, R. (1892). Ueber die Arbeitsleistung der auf die Fussgelenke wirkenden Muskeln. Festschrift, Herrn Geheimrat Albert von Koeliken zur Feier seiner 50-jährigen mediz. Doktorsjubiläums, gewidmet von den anatom. Institut der Universität Würzburg, Leipzig, W.Engelmann.
- Fick, R. (1911). *Handbuch der Anatomie und Mechanie der Gelenke*, D.1, I - III. Bardelebeus *Handbuch der Anatomie*.
- Forsberg, S., Grillner, S., Rossignol, S. (1977). Phasic gain control of reflexes from the dorsum of the paw during spinal locomotion. *Brain Research*, 132, pp. 121 - 139.
- Geddes, L.A., Baker, L.E., Moore, A.G. (1969). *Med. & Biol. Engin.* Pergamon Press, vol. 7, pp. 49 - 56.
- Gray, E.W. and Basmajian, E.C. (1968). Electromyography and cinematography of leg and foot ("normal" and flat) during walking. *Anatomical Rec.* 161, pp. 1 - 161.
- Gray's Anatomy (1973). Editors R.Warwick and P.L.Williams. Published by Longman, Edingburgh, 35th edition.
- Grillner, S. (1975). Locomotion in vertebrates: central mechanisms and reflex interaction. *Physiological Reviews*, vol.55, nr.2, 75, pp. 247 - 304.
- Henke, W. (1855). Die Bewegungen des Fusses am Sprungbein. *Zeitschrift für rat. Med. Neue Folge*, 7, pp. 225 - 234.
- Hicks, J.H. (1953). The mechanics of the foot, I. The joints. *Journal of Anatomy*, London, 87, pp. 345 - 357.
- Hicks, J.H. (1954). The mechanics of the foot, II. The plantar aponeurosis and the arch. *Journal of Anatomy*, London, 88, pp. 25 - 31.
- Hicks, J.H. (1955). The mechanics of the foot, III. The foot as a support. *Acta Anatomica*, Basel, 25, pp. 34 - 45.
- Hicks, J.H. (1956). The mechanics of the foot, IV. The action of the muscles on the foot in standing. *Acta Anatomica*, Basel, 27, pp. 180 - 192.

- Hicks, J.H. (1963). The three weight-bearing mechanisms of the foot. In biomechanical studies of the muskulo-skeletal system, edited by F.G.Evans, Springfield, III, Charles C.Thomas, pp.161 - 191.
- Hof-van Duin, J. van (1958). Analysis of adynamia in adrenocortical insufficiency. Thesis, University of Leiden.
- Holscher, A.A. (1965). Primaire en secundaire arthrodese bij fracturen van de calcaneus. Thesis, University of Leiden, A.M.L.Koenders.
- Huson, A. (1961). Een ontleedkundig-functioneel anatomisch onderzoek van de voetwortel (an anatomical and functional study of the tarsus). Thesis, University of Leiden, Luctor et Emergo.
- Huson, A. (1973). La chain cinematique fermée. Bulletin de l'Association des Anatomistes, vol. 57, numéro 159.
- Ingen Schenau, G.J. van (1978). Personal communication.
- International S.F.T.R. method of measuring and recording joint motion (1975). Edited by O.A.Russe and J.J.Gerhardt. Hans Huber Publishers, Bern, Stuttgart, Vienna.
- Jones, R.L. (1941). The human foot. An experimental study of its mechanics, and the rol of its muscles and ligaments in the support of the arch. American Journal of Anatomy, 68, pp. 1 - 39.
- Jones, R.L. (1945). The functional significance of the declination of the axis of the subtalar joint. Anatomical Record, 93, pp. 151 - 159.
- Katz, B. (1974). Nerv, Muskel and Synapse. Georg Thieme Verlag, Stuttgart, p.142.
- Kite, J.H. (1964). The clubfoot. Green and Stratton, New York, London, pp. 107 - 110.
- Langelaan, E.J. van, Spoor, C.W. and Huson, A. (1974). A kinematical analysis of the tarsal joints. From the proceedings of the Anatomical Society of Great Britain and Ireland, 4, 5 and 6. Journal of Anatomy, 117, p. 650.
- Levens, A.S., Inman, V.T. and Blosser, R.A. (1948). Journal of Bone and Joint Surgery, 30A, pp. 859 - 872.
- Long, C. and Brown, M.E. (1964). Electromyographic kinesology of the hand: muscles moving the long finger. Journal of Bone and Joint Surgery, 46A, pp. 1683 - 1706.
- Lovett, R.W. and Cotton, F.J. (1898). Medical Journal, 139, pp. 101 - 107.
- Mann, R. and Inman, V.T. (1964). Phasic activity of Intrinsic Muscles of the foot. Journal of Bone and Joint Surgery, 46A, pp. 469 - 481.
- Manter, J.T. (1941). Movements of the subtalar and transverse tarsal joints. Anatomical Record, pp. 397 - 410.

- Mitchell, G.P. and Gibson, J.M.C. (1967). Excision of the calcaneo-navicular bar for painful spasmodic flat foot. *Journal of Bone and Joint Surgery*, 49B, 281.
- Pearson, K. (1976). The control of walking. *Scientific American*, 235, pp. 72 - 87.
- Pearson, K.G., Fournier, C.R. and Wong, R.K. (1973). Nervous control of walking in the cockroach in control of posture and locomotion. Edited by R.B.Stein, K.G.Pearson, R.S.Smith and J.B.Redford. Plenum Press, New York - London, pp. 495 - 514.
- Ponseti, I.V. and Campos, J. (1972). Observations on pathogenesis and treatment of congenital clubfoot. *Clinical Orthopaedics and Related Research*, nr. 84, pp. 49 - 60.
- Reichmann, S. and Jonsson, B. (1967). Contrast radiography with carbon dioxide of the location of intramuscular E.M.G. electrodes. *Electromyography*, vol. 7, pp. 103 - 124.
- Scherb, R. (1952). Kinetisch-diagnostische Analyse von Gehstörungen. *Technik und Resultate der Myokinesigraphie*. Ferdinand Enkle Verlag, Stuttgart. Beilageheft zur Zeitschrift für Orthopädie, 82.
- Sheffield, F.J., Gersten, J.W. and Mastellone, A.F. (1956). Electromyographic study of the muscles of the foot in normal walking. *American Journal of Phys.Med.*, 35, pp. 224 - 236.
- Spoor, C.W. (1978). Personal communication.
- Staples, O.S. (1975). Ruptures of the fibular collateral ligaments of the ankle. *Journal of Bone and Joint Surgery*, 57A, pp. 101 - 107.
- Straaten, J.H.M. van der (1972). De activiteit van de spieren rond het kniegewricht tijdens het lopen op een trottoir roulant. Thesis, University of Rotterdam.
- Wiles, P. (1934). *The Lancet*, 127, pp. 1089 - 1094.
- Wilson, D.H. (1966). Insect walking. *Annual Review of Entomology*, vol. 11, pp. 103 - 122.
- Wright, W.G. (1962). *Muscle Function*. Hafner Publishing Company, New York, pp. 83 - 133.

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APPENDIX

Tables concerning measurements in anatomical specimens.

In this appendix are presented the average rotation of the tarsal bones and average tendon slip of each specimen separately.

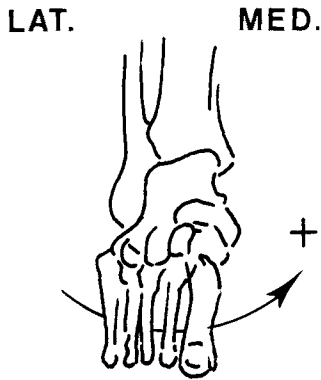


fig.38a. Anterior view. The arrow marks the + direction of the rotations as used in the tables hereunder.

Group 1

<u>Position</u>	<u>0 → +1</u>					<u>0 → 2</u>				
	<u>Cad.nr.</u>	<u>338</u>	<u>344</u>	<u>284</u>	<u>L</u> <u>355</u>	<u>R</u> <u>355</u>	<u>338</u>	<u>344</u>	<u>284</u>	<u>L</u> <u>355</u>
Navicular	+16	+16	+13	+12	+13	+41	+27	+24	+28	+25
Calcaneus	+10	+10	+ 5	+ 2	+ 5	+18	+12	+ 6	+ 8	+ 9
Cuboid	+13	+15	+12	+10	+14	+33	+22	+18	+25	+26
Lat.Mall.	- 2	- 2	0	- 1	- 1	- 3	- 3	- 4	- 2	- 2
Talus	+ 3	+ 3	+ 2	- 1	+ 3	+ 7	0	+ 8	- 1	+ 8

<u>Position</u>	<u>0 → 3</u>				
<u>Cad.nr.</u>	<u>338</u>	<u>344</u>	<u>284</u>	<u>L</u> <u>355</u>	<u>R</u> <u>355</u>
Navicular	+41	+24	+23	+27	+25
Calcaneus	+16	+12	+ 5	+ 8	+ 9
Cuboid	+31	+22	+17	+24	+24
Lat.Mall.	- 4	- 2	- 4	- 2	- 1
Talus	+ 7	0	+ 7	- 2	+ 8

table XXa. Anterior view (fig.38a)

Group 2

<u>Position</u>	<u>0 → +1</u>					<u>0 → 2</u>				
	<u>Cad.nr.</u>	<u>395</u>	<u>368</u>	<u>342</u>	<u>365</u>	<u>390</u>	<u>395</u>	<u>368</u>	<u>342</u>	<u>365</u>
Navicular	+17	+16	+18	+18	+25	+31	+22	+27	+31	+32
Calcaneus	+ 5	+ 8	+12	+10	+10	+12	+10	+15	+16	+12
Cuboid	+11	+14	+15	+16	+19	+21	+18	+22	+24	+23
Lat.Mall.	- 4	- 4	- 4	+ 1	- 5	- 9	- 5	- 6	+ 1	- 7
Talus	- 7	- 4	0	0	- 3	- 8	- 5	0	+ 1	- 3
Med.Mall.	- 5	- 3	- 4	+ 1	- 5	- 8	- 5	- 6	+ 1	- 7

<u>Position</u>	<u>0 → 3</u>				
<u>Cad.nr.</u>	<u>395</u>	<u>368</u>	<u>342</u>	<u>365</u>	<u>390</u>
Navicular	+30	+20	+25	+29	+29
Calcaneus	+12	+ 9	+15	+16	+12
Cuboid	+21	+17	+21	+23	+22
Lat.Mall.	- 9	- 5	- 5	+ 1	- 7
Talus	- 8	- 6	+ 1	0	- 3
Med.Mall.	- 8	- 5	- 6	+ 1	- 7

table XXa. Anterior view (fig.38a)

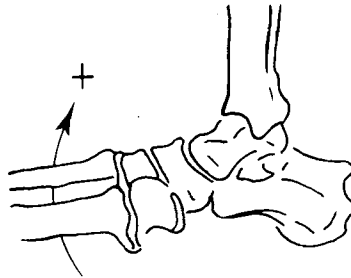


fig.38b. Side view. The arrow marks the + direction of the rotations as used in the tables.

Group 1

<u>Position</u>	<u>0 → +1</u>					<u>0 → 2</u>				
				L	R				L	R
<u>Cad.nr.</u>	<u>338</u>	<u>344</u>	<u>284</u>	<u>355</u>	<u>355</u>	<u>338</u>	<u>344</u>	<u>284</u>	<u>355</u>	<u>355</u>
Navicular	0	- 1	+ 4	0	0	+ 8	+ 6	+12	+12	+ 2
Calcaneus	+ 1	+ 3	+ 1	+ 3	+ 2	+ 4	+ 8	+ 4	+ 3	+ 4
Cuboid	+ 4	0	- 2	- 1	0	+ 6	+ 5	+ 7	+ 6	+ 2
Lat.Mall.	+ 4	- 1	0	- 1	+ 1	+ 5	- 2	0	- 4	+ 2
Talus	+ 1	- 2	0	- 2	- 2	+ 6	+ 3	+ 2	- 2	- 5

<u>Position</u>	<u>0 → 3</u>				
				L	R
<u>Cad.nr.</u>	<u>338</u>	<u>344</u>	<u>284</u>	<u>355</u>	<u>355</u>
Navicular	+ 6	+ 2	+11	+10	+ 1
Calcaneus	+ 4	+ 8	+ 3	+ 3	+ 4
Cuboid	+ 8	+ 2	+ 6	+ 5	+ 2
Lat.Mall.	+ 4	- 2	+ 1	- 4	+ 2
Talus	+ 5	+ 3	+ 1	- 3	- 4

Group 2

<u>Position</u>	<u>0 → +1</u>					<u>0 → 2</u>				
<u>Cad.nr.</u>	<u>395</u>	<u>368</u>	<u>342</u>	<u>365</u>	<u>390</u>	<u>395</u>	<u>368</u>	<u>342</u>	<u>365</u>	<u>390</u>
Navicular	+ 6	- 1	+ 5	- 3	+ 1	+10	+ 3	+ 9	0	+ 6
Calcaneus	- 2	- 1	+ 4	+ 4	+ 1	- 4	+ 1	+ 5	+ 7	+ 3
Cuboid	+ 2	+ 2	+ 5	+ 2	+ 1	+ 6	+ 4	+ 8	+ 8	+ 4
Lat.Mall.	+ 2	- 2	- 2	+ 3	+ 2	+ 2	- 3	- 1	+ 6	+ 5
Talus	- 2	+ 4	+ 4	+ 4	+ 4	- 3	+ 6	+ 4	0	+ 3
Med.Mall.	+ 5	- 2	- 2	+ 1	+ 1	+ 6	- 4	- 2	+ 6	+ 3

table XXb. Side view (fig.38b)

<u>Position</u>	<u>0 → 3</u>				
	<u>Cad.nr.</u>	<u>395</u>	<u>368</u>	<u>342</u>	<u>365</u>
Navicular	+ 8	0	+ 6	- 3	+ 4
Calcaneus	- 4	+ 1	+ 5	+ 7	+ 3
Cuboid	+ 5	+ 3	+ 7	+ 8	+ 4
Lat.Mall.	+ 2	- 3	- 1	+ 7	+ 6
Talus	- 1	+ 5	+ 3	0	+ 3
Med.Mall.	+ 5	- 3	- 1	+ 7	+ 3

table XXb. Side view (fig.38b)

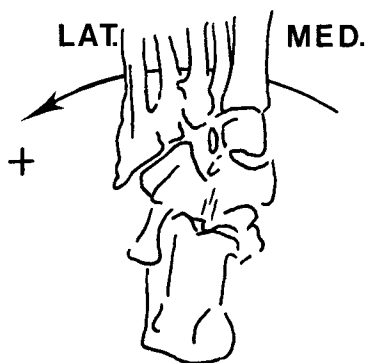


fig.38c. Axial view. The arrow marks the + direction of the rotations as used in the tables.

Group 1

<u>Position</u>	<u>0 → +1</u>					<u>0 → 2</u>				
	<u>Cad.nr.</u>	<u>338</u>	<u>344</u>	<u>284</u>	<u>L</u>	<u>R</u>	<u>338</u>	<u>344</u>	<u>284</u>	<u>L</u>
Navicular	+ 2	- 1	+ 1	+ 1	+ 1	0	- 2	+ 3	+ 3	0
Calcaneus	+ 8	+ 8	+ 8	+10	+12	+23	+ 9	+13	+24	+17
Cuboid	+ 4	0	+ 2	0	0	+ 2	- 2	+ 5	0	+ 1
Lat.Mall.	+17	+20	+21	+23	+33	+44	+26	+27	+48	+44
Talus	+17	+18	+20	+19	+23	+43	+25	+20	+43	+27

table XXc. Axial view (fig.38c)

<u>Position</u>	<u>0 → 3</u>				
				L	R
<u>Cad.nr.</u>	<u>338</u>	<u>344</u>	<u>284</u>	<u>355</u>	<u>355</u>
Navicular	0	- 2	+ 6	+ 1	0
Calcaneus	+21	+ 9	+16	+24	+16
Cuboid	+ 1	- 2	+ 4	0	+ 1
Lat.Mall.	+42	+25	+36	+48	+44
Talus	+42	+25	+33	+43	+26

Group 2

<u>Position</u>	<u>0 → +1</u>					<u>0 → 2</u>				
<u>Cad.nr.</u>	<u>395</u>	<u>368</u>	<u>342</u>	<u>365</u>	<u>390</u>	<u>395</u>	<u>368</u>	<u>342</u>	<u>365</u>	<u>390</u>
Navicular	- 1	0	+ 3	- 1	- 3	0	- 7	+ 7	- 2	- 3
Calcaneus	+15	+12	+ 9	+ 4	+14	+19	+10	+17	+10	+19
Cuboid	+ 2	+ 3	+ 4	0	- 4	+ 3	- 3	+ 8	+ 1	- 4
Lat.Mall.	+29	+27	+28	+20	+34	+37	+30	+40	+37	+47
Talus	+28	+27	+24	+14	+36	+35	+30	+33	+31	+45
Med.Mall.	+28	+26	+29	+20	+34	+35	+28	+41	+38	+47

<u>Position</u>	<u>0 → 3</u>				
<u>Cad.nr.</u>	<u>395</u>	<u>368</u>	<u>342</u>	<u>365</u>	<u>390</u>
Navicular	0	- 6	+ 5	- 2	- 2
Calcaneus	+19	+11	+16	+10	+20
Cuboid	+ 4	- 1	+ 8	+ 1	- 3
Lat.Mall.	+37	+30	+40	+37	+46
Talus	+35	+30	+32	+31	+45
Med.Mall.	+35	+29	+41	+38	+47

table XXc. Axial view (fig. 38c)

Cadaver number 344

<u>Position</u>	<u>0 → +1</u>	<u>0 → 2</u>	<u>0 → 3</u>
Tib.post.	+14(+14.7/+13.7)	+20(+20.5/+19.7)	+20(+20.2/+19.5)
Flex.dig.	+10(+11.0/+ 9.4)	+17(+17.5/+15.9)	+17(+17.3/+16.1)
Flex.hall.	+ 4(+ 5.0/+ 4.0)	+ 6(+ 6.4/+ 5.1)	+ 7(+ 7.5/+ 6.2)
Ext.hall.	- 1(- 1.9/- 0.2)	+ 1(+ 1.3/+ 0.9)	- 1(- 1.4/- 0.5)
Per.long.	-15(-15.8/-13.6)	-24(-25.1/-23.4)	-22(-22.2/-20.9)
Per.brev.	-17(-18.2/-16.3)	-25(-25.7/-24.4)	-24(-25.2/-24.1)
Tib.ant.	+ 3(+ 3.6/+ 2.6)	+ 8(+ 9.3/+ 7.8)	+ 7(+ 7.4/+ 6.2)
Ext.dig.	- 5(- 6.0/- 4.7)	- 9(- 9.3/- 7.7)	- 9(- 9.6/- 8.2)
Achilles t.	- 6(- 7.2/- 5.8)	- 9(- 8.8/- 8.2)	- 8(- 8.1/- 7.3)

table XXIA

Average tendon slip. In brackets the maximum and minimum values in mm. The average difference between maximum and minimum is 1.6 mm.

Cadaver number 284

<u>Position</u>	<u>0 → +1</u>	<u>0 → 2</u>	<u>0 → 3</u>
Tib.post.	+13(+13.8/+12.3)	+18(+17.8/+17.5)	+18(+17.8/+17.3)
Flex.dig.	+ 9(+ 9.8/+ 8.8)	+15(+15.3/+14.6)	+15(+15.2/+14.6)
Flex.hall.	+ 4(+ 4.9/+ 3.9)	+ 6(+ 7.1/+ 5.4)	+ 7(+ 7.3/+ 5.7)
Ext.hall.	- 3(- 4.2/- 2.6)	- 2(- 3.1/- 0.7)	- 4(- 5.0/- 2.6)
Per.long.	-12(-12.5/-11.1)	-21(-21.3/-20.8)	-18(-18.1/-17.9)
Per.brev.	-15(-15.5/-13.8)	-22(-23.0/-21.3)	-21(-21.6/-20.3)
Tib.ant.	+ 1(+ 1.4/+ 0.3)	+ 5(+ 5.6/+ 4.8)	+ 3(+ 3.8/+ 2.6)
Ext.dig.	- 8(- 8.5/- 7.2)	-13(-13.9/-12.2)	-13(-13.8/-12.0)
Achilles t.	- 1(- 1.5/- 1.1)	- 2(- 2.6/- 2.1)	- 2(- 2.1/- 1.6)

table XXIB

Average tendon slip. In brackets the maximum and minimum values in mm. The average difference between maximum and minimum value is 1.1 mm.

Cadaver number 355 (left)

<u>Position</u>	<u>0 → +1</u>	<u>0 → 2</u>	<u>0 → 3</u>
Tib.post.	+20(+20.5/+18.8)	+25(+25.6/+24.1)	+25(+25.8/+23.8)
Flex.dig.	+12(+14.6/+10.0)	+14(+15.1/+13.6)	+15(+15.3/+13.8)
Flex.hall.	+ 5(+ 5.6/+ 4.4)	+ 7(+ 7.1/+ 5.8)	+ 7(+ 7.7/+ 6.8)
Ext.hall.	0(- 0.7/ 0.0)	+ 3(+ 3.0/+ 2.1)	+ 1(+ 1.4/+ 0.1)
Per.long.	-12(-13.6/-11.7)	-25(-26.6/-24.1)	-18(-20.2/-17.1)
Per.brev.	-17(-17.5/-16.0)	-25(-26.2/-23.9)	-24(-25.0/-22.2)
Tib.ant.	+ 3(+ 3.5/+ 2.6)	+ 8(+ 8.8/+ 7.8)	+ 5(+ 5.5/+ 4.1)
Ext.dig.	- 4(- 4.4/- 3.8)	- 7(- 7.3/- 5.7)	- 8(- 8.0/- 6.9)
Achilles t.	- 4(- 4.3/- 2.6)	- 5(- 6.0/- 3.7)	- 5(- 5.4/- 3.3)

table XXIC

Average tendon slip. In brackets the maximum and minimum values in mm. The average difference between maximum and minimum value is 1.7 mm.

Cadaver number 355 (right)

<u>Position</u>	<u>0 → +1</u>	<u>0 → 2</u>	<u>0 → 3</u>
Tib.post.	+16(+16.5/+14.5)	+22(+22.4/+20.6)	+22(+22.6/+20.8)
Flex.dig.	+10(+11.5/+ 9.8)	+15(+15.8/+14.0)	+15(+16.3/+14.2)
Flex.hall.	+ 4(+ 4.9/+ 3.7)	+ 6(+ 6.6/+ 5.1)	+ 6(+ 6.7/+ 5.6)
Ext.hall.	0(+ 0.7/- 1.0)	+ 2(+ 2.5/+ 0.7)	0(+ 0.6/ 0.0)
Per.long.	-11(-12.3/- 9.2)	-25(-25.6/-22.0)	-21(-23.0/-19.1)
Per.brev.	-15(-15.7/-13.4)	-25(-26.4/-23.4)	-25(-25.8/-22.8)
Tib.ant.	+ 3(+ 3.0/+ 2.2)	+ 9(+ 9.0/+ 8.3)	+ 7(+ 6.9/+ 6.7)
Ext.dig.	- 5(- 7.1/- 4.2)	- 8(- 8.6/- 6.9)	- 8(- 8.5/- 6.8)
Achilles t.	- 2(- 2.2/- 1.6)	- 3(- 3.7/- 2.2)	- 2(- 3.2/- 1.9)

table XXID

Average tendon slip. In brackets the maximum and minimum values in mm. The average difference between maximum and minimum value is 1.7 mm.

Cadaver number 344

<u>Position</u>	<u>P → A</u>	<u>P → B</u>
Tib.post.	- 1 (- 1.5/- 0.5)	+13 (+13.4/+11.7)
Flex.dig.	- 2 (- 3.2/- 0.2)	+10 (+10.9/+ 9.5)
Flex.hall.	0 (+ 0.5/- 1.3)	+ 3 (+ 3.9/+ 2.7)
Ext.hall.	- 1 (- 1.3/- 1.2)	0 (+ 1.2/- 1.2)
Per.long.	+ 2 (+ 2.7/+ 1.6)	-21 (-21.6/-18.8)
Per.brev.	+ 2 (+ 2.2/+ 0.3)	-18 (-19.3/-17.1)
Tib.ant.	- 1 (- 2.0/- 0.9)	+ 9 (+10.2/+ 7.8)
Ext.dig.	+ 1 (+ 1.8/+ 0.4)	- 8 (- 8.2/- 6.5)
Achilles t.	- 1 (+ 0.2/- 1.4)	- 9 (- 9.2/- 7.9)

table XXIIa

Average tendon slip. In brackets the maximum and minimum values in mm. The average difference between maximum and minimum value is 1.6 mm.

Cadaver numer 184

<u>Position</u>	<u>P → A</u>	<u>P → B</u>
Tib.post.	- 3 (- 4.3/- 1.3)	+ 7 (+ 7.7/+ 6.5)
Flex.dig.	- 2 (- 3.1/- 1.4)	+ 8 (+ 8.2/+ 6.7)
Flex.hall.	- 2 (- 2.8/- 1.1)	+ 2 (+ 3.7/+ 1.5)
Ext.hall.	+ 1 (+ 1.3/+ 0.2)	+ 2 (+ 2.3/+ 1.0)
Per.long.	+ 3 (+ 3.8/+ 1.7)	-12 (-12.0/.11.1)
Per.brev.	+ 3 (+ 3.5/+ 2.6)	-14 (-15.6/-12.7)
Tib.ant.	- 1 (- 1.8/- 0.3)	+ 4 (+ 4.8/+ 3.4)
Ext.dig.	+ 2 (+ 2.7/+ 1.8)	- 9 (- 9.7/- 9.0)
Achilles t.	- 1 (- 1.8/- 0.4)	- 1 (- 1.5/- 0.2)

table XXIIb

Average tendon slip. In brackets the maximum and minimum values in mm. The average difference between maximum and minimum value is 1.5 mm.

Cadaver number 355 (left)

<u>Position</u>	<u>P → A</u>		<u>P → B</u>	
Tib.post.	0	(+ 0.6/- 0.6)	+ 5	(+ 8.1/+ 4.0)
Flex.dig.	0	(+ 1.0/+ 0.1)	+ 6	(+ 7.1/+ 5.1)
Flex.hall.	+ 1	(+ 0.7/+ 0.4)	+ 3	(+ 4.4/+ 1.8)
Ext.hall.	0	(+ 0.2/- 0.8)	+ 1	(+ 2.0/- 1.0)
Per.long.	+ 1	(+ 1.4/+ 0.7)	-18	(-19.0/-16.3)
Per.brev.	+ 1	(+ 1.0/+ 0.5)	-12	(-13.2/-10.3)
Tib.ant.	- 1	(- 0.8/- 0.6)	+10	(+10.9/+10.0)
Ext.dig.	+ 1	(+ 1.6/+ 0.6)	- 5	(- 5.9/- 4.1)
Achilles t.	0	(- 0.2/ 0.0)	- 3	(- 3.2/- 2.8)

table XXIIC

Average tendon slip. In brackets the maximum and minimum values in mm. The average difference between maximum and minimum value is 1.5 mm.

Cadaver number 355 (right)

<u>Position</u>				
Tib.post.	- 1	(+ 0.3/- 2.0)	+14	(+15.0/+13.8)
Flex.dig.	- 1	( 0.0/- 1.6)	+11	(+11.5/+10.9)
Flex.hall.	+ 1	(+ 0.9/- 0.9)	+ 7	(+ 7.5/+ 6.4)
Ext.hall.	+ 1	(+ 1.1/+ 0.8)	+ 2	(+ 3.0/+ 0.3)
Per.long.	+ 3	(+ 3.5/+ 1.7)	-17	(-19.2/-15.9)
Per.brev.	+ 3	(+ 4.0/+ 1.8)	-14	(-15.2/-13.5)
Tib.ant.	0	(+ 1.7/- 1.2)	+13	(+14.3/+11.6)
Ext.dig.	+ 3	(+ 3.4/+ 1.6)	- 6	(- 7.1/- 4.3)
Achilles t.	- 2	(- 2.2/- 1.3)	- 1	(- 1.8/- 0.2)

table XXIId

Average tendon slip. In brackets the maximum and minimum values in mm. The average difference between maximum and minimum value is 1.9 mm.

Cadaver number 344

Cadaver number 284

<u>Position</u>	<u>P → C</u>		<u>P → C</u>	
Tib.post.	- 5	(- 5.8/- 4.3)	- 7	(- 8.5/- 6.5)
Flex.dig.	- 8	(- 8.6/- 6.3)	-13	(-13.8/-12.8)
Flex.hall.	-14	(-15.3/-11.7)	-23	(-23.9/-22.5)
Ext.hall.	+21	(+21.2/+21.2)	+32	(+32.7/+31.1)
Per.long.	-12	(-12.8/-10.8)	-12	(-12.4/-11.3)
Per.brev.	- 8	(- 9.9/- 7.3)	-17	(-17.4/-16.0)
Tib.ant.	+24	(+23.8/+23.3)	+36	(+37.1/+33.6)
Ext.dig.	+16	(+16.7/+15.9)	+24	(+24.5/+22.4)
Achilles t.	-32	(-33.3/-31.3)	-42	(-42.7/-41.3)

Cadaver number 355 (left)

Cadaver number 355 (right)

<u>Position</u>				
Tib.post.	-14	(-15.1/-13.1)	- 3	(- 5.5/+ 0.3)
Flex.dig.	-15	(-16.7/-13.9)	- 7	(- 8.2/- 5.3)
Flex.hall.	-19	(-20.1/-18.7)	-13	(-13.6/-12.6)
Ext.hall.	+30	(+31.1/+29.3)	+25	(+25.4/+24.8)
Per.long.	-13	(-13.3/-13.2)	-13	(-16.7/- 9.7)
Per.brev.	- 4	(- 5.9/- 2.0)	- 8	(-12.1/- 5.1)
Tib.ant.	+45	(+46.2/+43.8)	+31	(+32.6/+29.7)
Ext.dig.	+32	(+32.9/+30.0)	+24	(+24.6/+23.6)
Achilles t.	-41	(-41.0/-40.0)	-35	(-35.4/-34.3)

table XXIII

Average tendon slip. In brackets the maximum and minimum values in mm. The average difference between maximum and minimum value is:

cadaver number 344	: 1.7 mm.
cadaver number 284	: 1.7 mm.
cadaver number 355 (left)	: 2.0 mm.
cadaver number 355 (right)	: 3.3 mm.