

## Dynamic Changes of the Arches of the Foot during Walking

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An original electrogoniometer was made for analyzing the dynamic changes of the anterior and medial arches of the foot during walking.

5 normal adult males were asked to fix all of the electrogoniometers and walked freely on a floor on which the MATAKE's Force Plate was fixed.

The mean patterns of the anterior and medial arches of the foot was obtained and analysed. And the entire obilities of the anterior and medial arches during walking are about 20 mm and 4 mm.

Dorsiflexion of the metatarsophalangeal joint of the foot—the windlass action—was proved to have a very closed relationship with the dynamic changes of the anterior and medial arches of the foot during walking.

### INTRODUCTION

In a normal human foot that is weight bearing, as in ordinary standing and walking which is different from the other animals, the structure and function of the foot are very important, especially when observing the use of the arch support in cases of the flat foot and the calcaneus fracture and so forth clinically.

BRUCE and WALMSLEY, in 1938, stated that the arches of the foot can be observed during the fetus period anatomically and build up rapidly after being born which held a important function during standing and walking.

For analyzing the structure and function of the arches of the foot during the static phase—standing—many researches were done from the different view points and many different results were reported such as WOOD JONE or HARRIS and BEATH (1948), J. W. SMITH, BASMAJIAN and BENTZON (1954), J. H. HICKS (1954), R. SUZUKI (1956) and K. MIYOSHI (1966). However, even J. H. HICKS (1954) said arch raising effect was seen to occur about 1cm during standing and I. A. KAPANDJI explained the

dynamic changes and the mobility of the arches of the foot in 1970, there is no any experiment which was done for analyzing the changes of the arches of the foot during dynamic walking stage.

The purpose of this paper is to try to analyze the dynamic changes of the arches of the foot during walking with our original method.

The mean patterns and mobilities of the anterior arch and the medial arch during walking were obtained and the meaning of the patterns will be analyzed and explained in the paper.

## METHOD

As shown in figure 1, we recorded the ground reaction force (G.R.F.), electric arch gauge (E.A.G.) which includes the anterior arch, the medial arch and Metatarsophalangeal Joint (MTP-Joint) of the foot, the electromyogram (E.M.G.) and the optical stick picture camera (S.P.C.) simultaneously.

### 1. G.R.F.

G.R.F. was measured with **MATAKE's** Force Plate which was reported by **MA-TAKE**<sup>4)</sup> in 1976.

### 2. E.A.G. an MTP-Joint

In order to analyze the dynamic changes of the anterior arch, the medial arch and the 1st MTP-Joint, we made an original electrogoniometer which consisted of a piece of

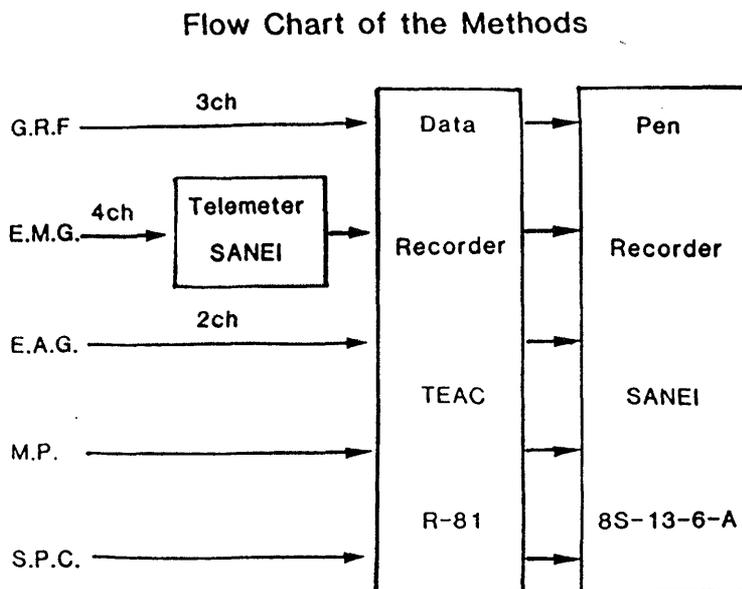


Fig. 1. G. R. F., E. M. G., E. A. G., M. P. and S. P. C. were recorded simultaneously.

thin elastic steel on which a strain gauge (KFC-2Cl-11, KYOWA) was fixed (Fig. 2).

J. KAYANO<sup>2)</sup> in 1982, stated that the mobilities of three points of the skin on the 1st metatarsal head, the calcaneus and the talo-navicular joint will have no any difference from the mobilities of these three bones during walking. The electrogoniometer shown in figure 2 were, therefore, fixed directly on the skin: the electrogoniometer A was fixed directly on the skin from the 1st metatarsal head to the 5th metatarsal head for recording the change of the anterior arch: the electrogoniometer B was fixed directly on the skin from the 1st metatarsal head to the calcaneus for recording the change of the medial arch and the electrogoniometer C was fixed directly on the skin of the 1st phalanx to the middle part of the 1st metatarsal bone for recording the change of the MTP-Joint (Fig. 3 & Fig. 4).

All of these three elastic steel on which the strain gauge was fixed was tested several times to see if there is any imperfection or disadvantage. And finally, it was found that there is a so called natural vibration for the electrogoniometer B -the medial arch- due to the shock of walking especially while heel strike and toe off. But there is no any disadvantage for the electrogoniometers A and C (the anterior arch and the MTP-Joint).

In order to cancel the natural vibration of the electrogoniometer B during walking, many kinds of the sizes and the models of the steel were tried. It was finally found that making the steel into a 2 cm round axis on which a strain gauge was fixed will be the best for recording the change of the medial arch. And the base plate using for fixing di-

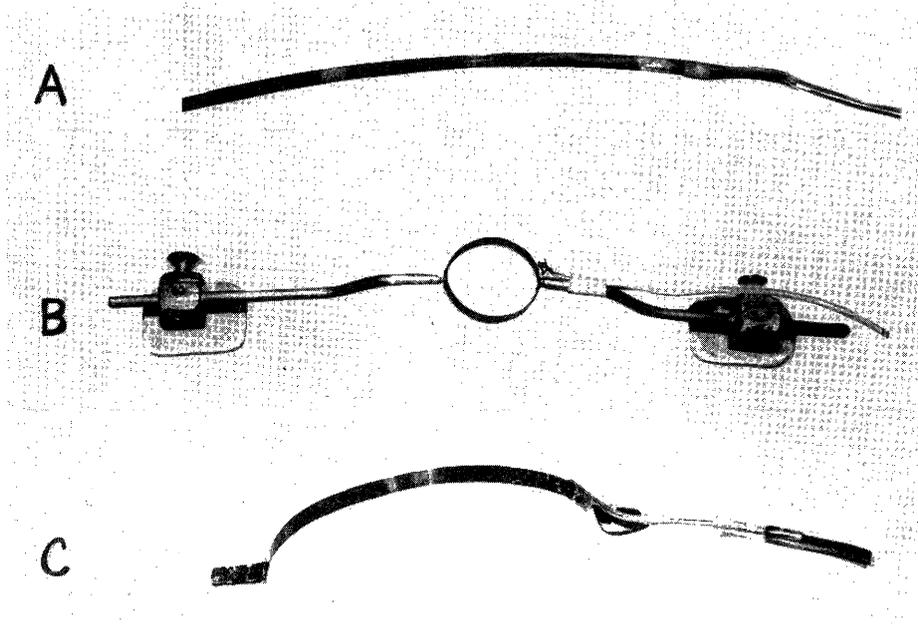


Fig. 2. The picture of the electrogoniometers A, B and C.

rectly on the skin can be rotated free from the bars which connected the 2 cm round axis steel while dorsiflexing of the MTP-Joint of the toe (Fig. 3 & Fig. 4).

Before using all of these electrogoniometers showing in figure 2 , figure 3 and figure 4 , the linearities between the changes of the calibration and the changes of the length of the electrogoniometer were confirmed.

Figure 5 shows that there is a very reliable linearity of the electrogoniometer A which was used for recording the change of the anterior arch.

The Y-axis means the length and the X-axis means the change of the calibration of the electrogoniometer. It was tried to change its length from the longest (18mm) to the shortest (0mm) and from the shortest to the longest to and fro in every 2mm for 10 times each. The change of the calibration were recorded with 95% confidence interval as shown in this figure which a reliable linearity was confirmed.

Figure 6 shows that there is a very reliable linearity of the electrogoniometer B which was used for recording the changes of the medial arch. The Y-axis means the



**Fig. 3.** The picture of the fixation of the electrogoniometer A, B and C and the surface electrode of the electromyogram.

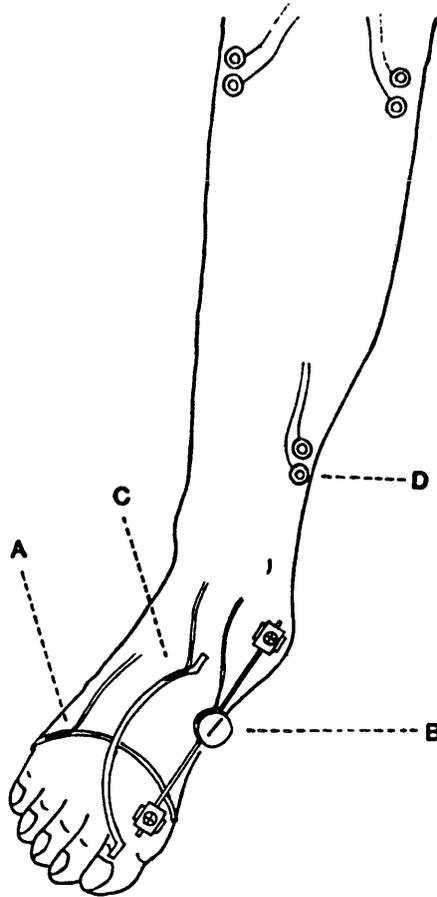


Fig. 4. Schematic picture of the fixation of the electrogoniometer A, B and C and the surface electrode of the electromyogram D.

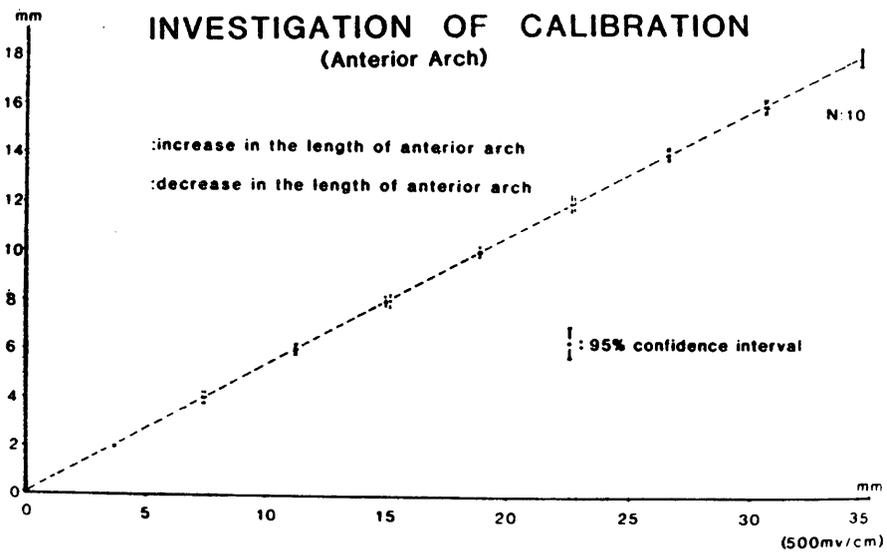


Fig. 5. A reliable linearity of the electrogoniometer A was confirmed.

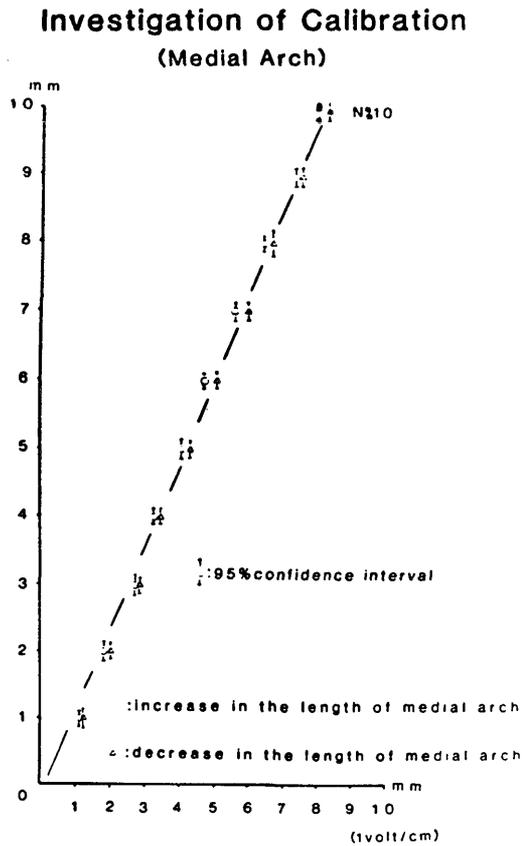


Fig. 6. A reliable linearity of the electrogoniometer B was confirmed.

length and the X-axis means the change of the calibration of the electrogoniometer B. 10 times each was tried to change its length from the longest (10mm) to the shortest (0mm) and from the shortest to the longest to and fro in every 1mm. The changes of the calibration were recorded with 95% confidence interval as shown in this figure, a reliable linearity was confirmed.

## MATERIALS

Five normal adult males aged from 25–35 (case (a) (b) (c) (d) and (e)) were used with fixing all of the electrogoniometer A, B and C and surface electrode of E.M. G. as shown in figure 3 and asked to walk 20 times each on the level walking floor freely.

## RESULTS

All of the data was calculated and pictured into a mean pattern as shown from

figure 7 to figure 18 of the case (a) (b) (c) (d) and (e) by a PC-8800 computer.

(A) The representative pattern—the result of case (a)— of the anterior and medial arch can be analyzed and explained as follow:

### (1) Anterior Arch

Figure 7 shows the mean pattern, the mobility and the standard deviation (S.D.) of the anterior arch during walking.

On the upper graph of figure 7, the Y-axis means the length of the anterior arch in which the positive value means the degree of the shortening of the arch and the negative value means the degree of the lengthening of the arch. And the value shown in Y-axis will be the exact value of the mobility of the anterior arch. The X-axis means the whole stance phase of the walking cycle which is separated in 10% each makes the whole stance phase equaled 100%.

The lower graph of figure 7 shows the change of the standard deviation (S.D.) in 15 times mobility of the anterior arch under 95% confidence interval.

The mean pattern of the anterior arch shown in figure 7 can be found as an one phase pattern with a small notch in the area of 5%, a large notch in the area of 95–100% and a flattening in the area of 40%.

Since the shortest of the anterior arch can be considered as about 4mm in the area of 95–100% and the longest can be considered as about -16mm in the area on 40–50% of the stance phase, the entire mobility of the anterior arch is about 20mm during the whole stance phase.

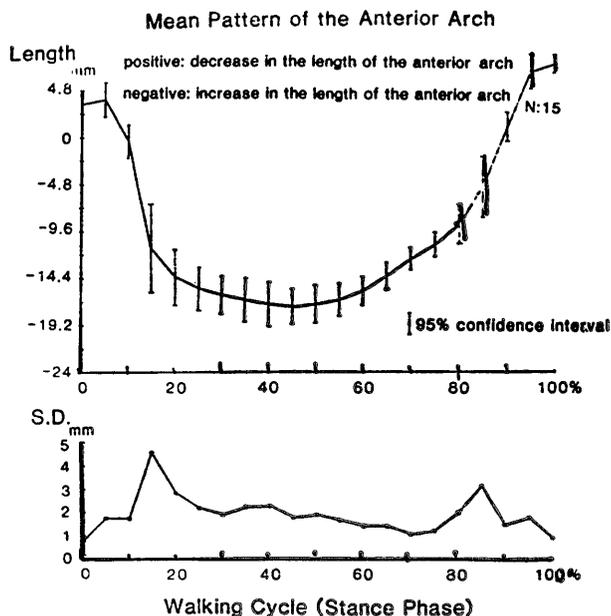


Fig. 7. A mean pattern of the anterior arch of the case (a) is an one phase pattern with two special notches in the area of 5% and 95–100%.

And all of the data will have its S.D. examined under 95% confidence interval shown in the lower graph of the figure 7.

## (2) Medial Arch

With calculating all of the data, the mean pattern of the medial arch was pictured as shown in figure 8.

The upper graph of the figure 8 shows the change of the mobility of the medial arch, the X-axis of the graph means the whole stance of the walking cycle which is separated into 10% interval makes it equaled 100% and the Y-axis of the graph means the length of the medial arch, the positive value means the degree of the shortest of the arch and the negative value means the degree of the lengthening of the arch.

The value shown in Y-axis was separated into 0.9mm interval which is the exact value of the mobility of the medial arch.

The lower graph of the figure 8 shows the standard deviation (S.D.) in 15 times mobility of the medial arch under 95% confidence interval. The X-axis means the whole stance phase of the walking cycle equaled 100% and the Y-axis means the value of the S.D.

The mean pattern of the medial arch shown in figure 8 can be found to have a two phase pattern which is different from the mean pattern of the anterior arch but with two same special notches in the area of 5% and 95% walking cycle stance phase and large flatterning in the area of 30%, a small flatterning in the area of 70-80% when the whole stance phase walking cycle equaled 100%.

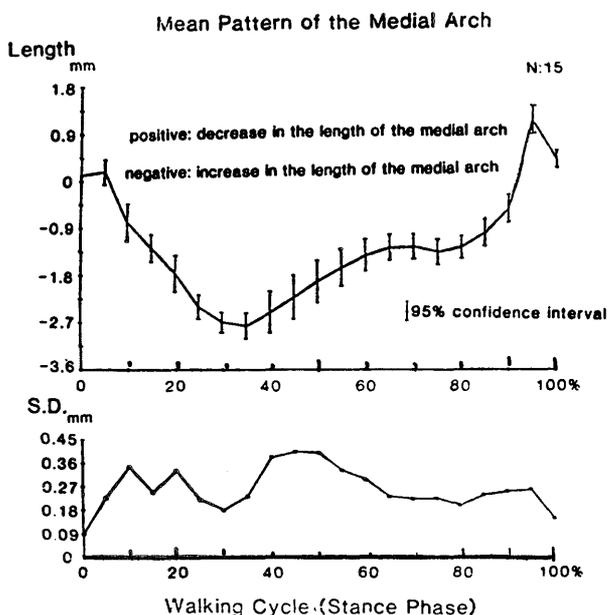


Fig. 8. A mean pattern of the medial arch of the case (a) is a two phase pattern with two same notches in the area of 5% and 95% and a large flatterning in the area of 30%, a small flatterning in the area of 80%.

Since the shortest of the medial arch can be considered as about 1mm in the area of 95% and the longest can be considered as about -3mm in the area of 30% of the stance phase, the entire mobility of the medial arch is about 4mm during the whole stance phase.

### (3) MTP-Joint

Figure 9 shows the mean pattern, the mobility and the standard deviation (S. D.) of the MTP-Joint during walking.

The upper graph of the figure 9 shows the mobility of the MTP-Joint. The X-axis of the graph means the whole stance of the walking cycle which is separated into 10% interval makes it equalled 100% and the Y-axis means the degree of the angular change of the dorsiflexion of the MTP-Joint which is the exact value of the angular change of the MTP-Joint.

The lower graph of the figure 9 shows the standard deviation (S. D.) in 15 times angular change of the MTP-Joint under 95% confidence interval.

The mean pattern of the MTP-Joint shown in figure 9 has an one phase pattern with two same notches in the area of 5% and 95% of the whole walking stance phase as in the mean patterns of the anterior and medial arch.

The maximal dorsiflexion of the MTP-Joint is about 40-50 degrees in the area of 95% and the minimal dorsiflexion of the MTP-Joint is about 10 degrees in the area of 40-50% of the whole walking stance phase.

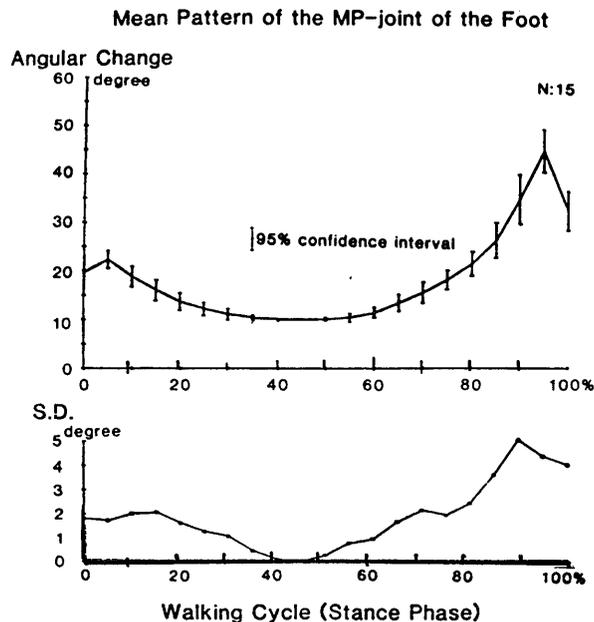


Fig. 9. A mean pattern of the MTP-Joint of the case (a) also had the two same notches in the area of 5% and 95%.

(4) **Simultaneous records of G. R. F., the angular change of the MTP-Joint, the change of the length of the E. A. G. and E. M. G.**

All of the data of the G. R. F., the angular change of the MTP-Joint, the change of the length of the E. A. G. and E. M. G. were recorded simultaneously as shown in figure 20.

According to these data, the points of heel strike and toe off can be found out clearly and the relationship between each others can be analyzed easier also.

(B) All of the other data of the anterior arch and medial arch of case (b) (c) (d) and (e) are shown in figure 10-17.

Figure 10, 12, 14, 16 are the mean patterns of the anterior arch of case (b) (c) (d) and (e). Each pattern is the same one phase pattern as the case (a) with the two same characteristic notches in the area of 5% and 95% but the flatter area are different from each others.

Figure 11, 13, 15 and 17 are the mean patterns of the medial arch of case (b) (c) (d) and (e) during walking which have the same two phase pattern with the two same characteristic notches in the area of 5% and 95% as the case (a).

(C) Figure 18 shows the 15 steps superimposed patterns of the anterior and medial arch of all of the cases (a) (b) (c) (d) and (e).

All of the patterns has also a two phase pattern of the medial arch and a one phase pattern of the anterior arch with the two same characteristic notches in the area of 5% and 95% while the whole stance phase equaled 100%.

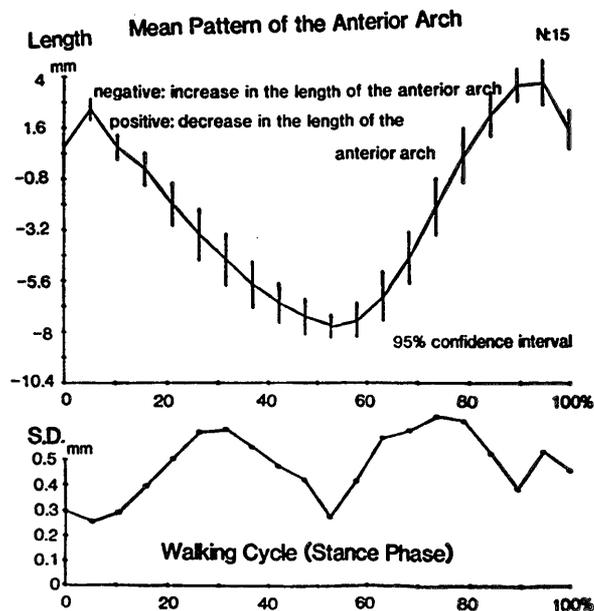


Fig. 10. A mean pattern of the anterior arch of the case (b).

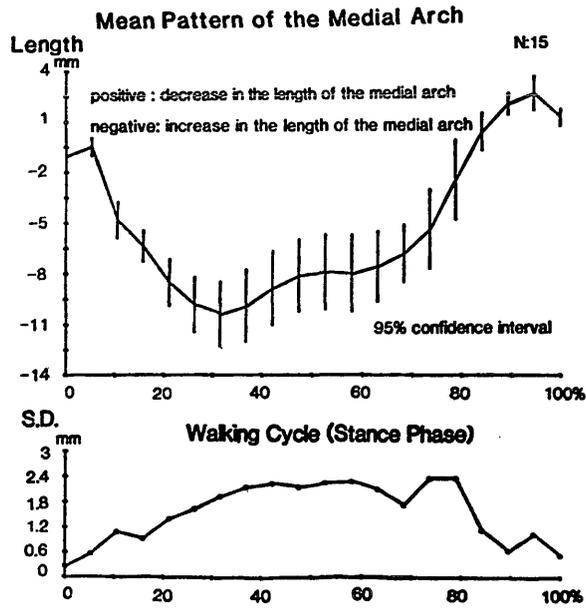


Fig. 11. A mean pattern of the medial arch of the case (b).

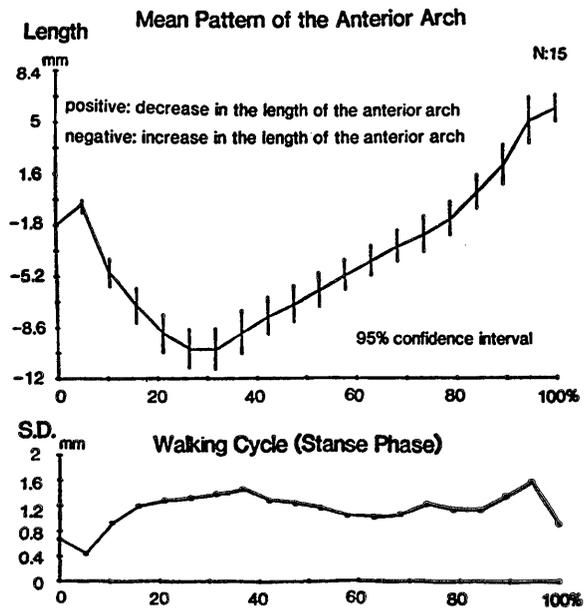


Fig. 12. A mean pattern of the anterior arch of the case (c).

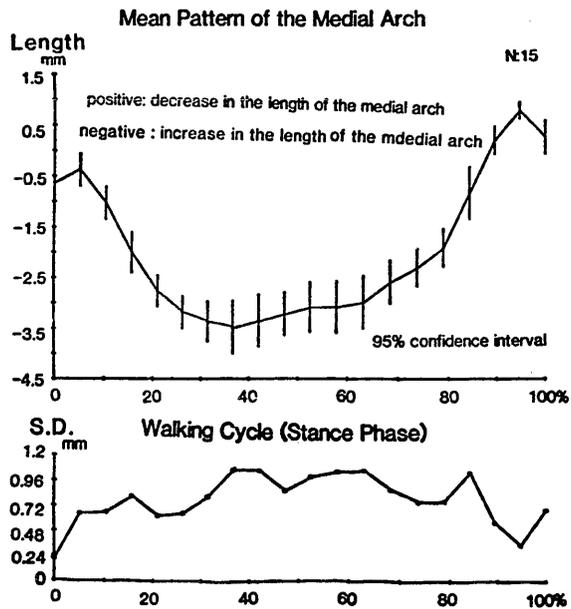


Fig. 13. A mean pattern of the medial arch of the case (c).

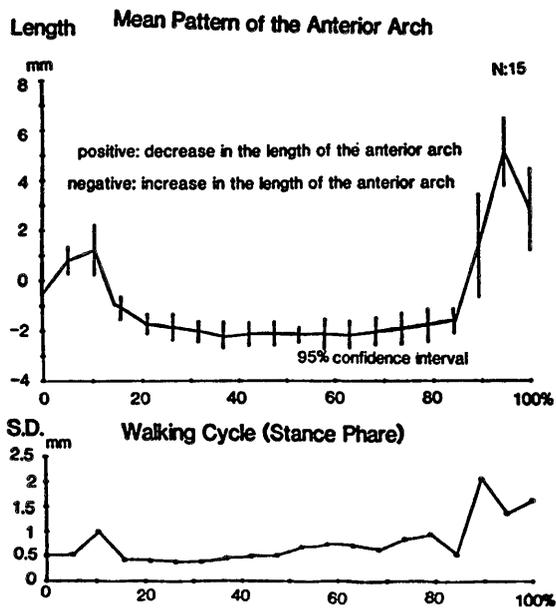


Fig. 14. A mean pattern of the anterior arch of the case (d).

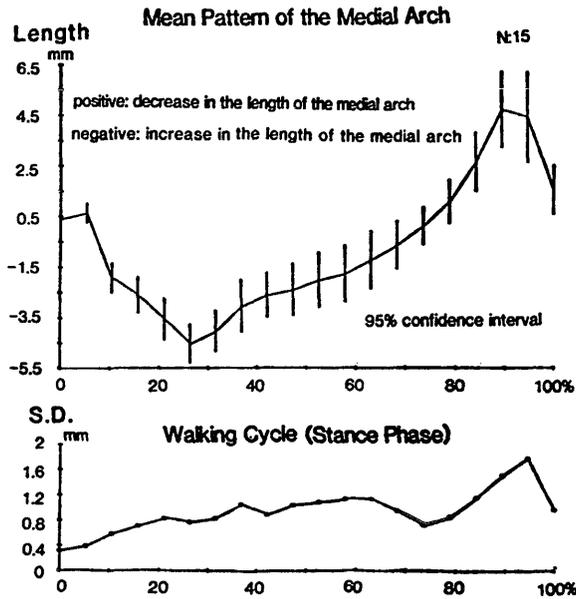


Fig. 15. A mean pattern of the medial arch of the case (d).

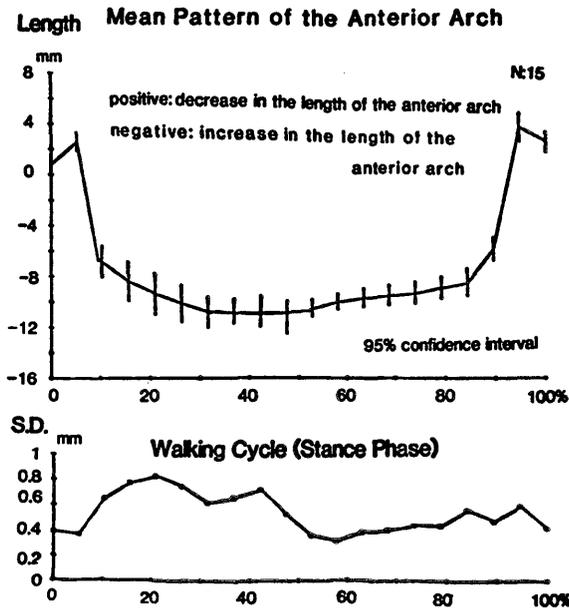


Fig. 16. A mean pattern of the anterior arch of the case (e).

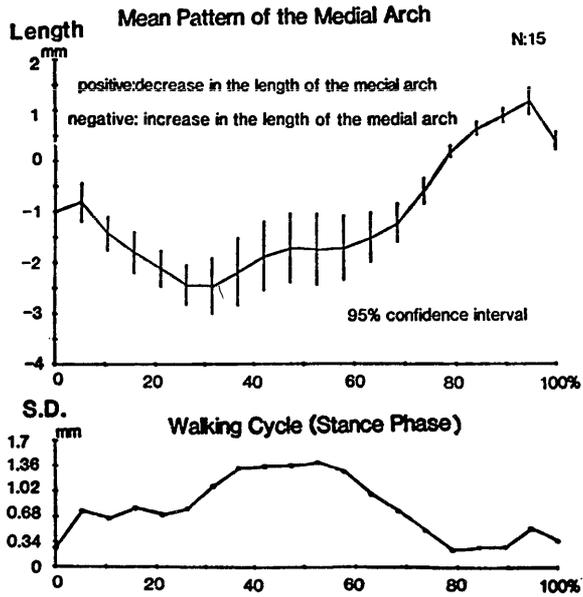


Fig. 17. A mean pattern of the medial arch of the case (e).

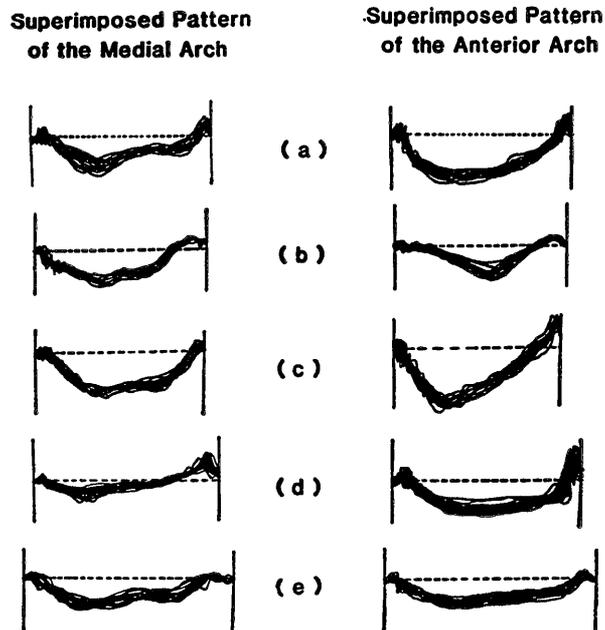


Fig. 18. The superimposed pattern of the anterior and medial arches of the cases (a), (b), (c), (d) and (e).

## DISCUSSION

The structure of the foot of human being especially the plantar vault can be said as an architectural structure consisted all the elements of the foot-joints, ligaments and muscles-into a unified system. And viewed as a whole, the plantar vault can be compared with an architectural vault with three arches: the anterior, the medial and the lateral arches.

Among the points of foot print there are three important supporting points; the point A-the head of the 1st metatarsal bone, the point B-the head of the 5th metatarsal bone, the point C-the posterior tubercles of the calcaneus, and each support point is shared by two adjacent arches. In other words, between the two anterior support points of A and B stretches the anterior arch, the points of B and C stretches the lateral arch and the points of C and A stretches the medial arch.

Here it is clear now, therefore, that all of the points we used for fixing the goniometers directly on the skin can reference these three points which explained above. And the results of the mobilities of the arches can be considered as the true reactions of the mobilities of these three points also, in other words, the mobilities of the anterior arch and the medial arch.

There are many researches concerning the role of active factors-the muscles-and the passive factors-the bones and ligaments- in arch support of the foot in the erect posture had been done and many different results were reported.

**HARRIS** and **BEATH**<sup>7)</sup>, in 1948, reported that passive supporting factor and active supporting factor are responsible for a normal arch, and plantar aponeurosis and the plantar tarsal ligaments and that the actively contracting intrinsic muscle between the aponeurosis and tarsal ligaments also play an important part.

On the contrary, **BASMAJIAN** and **BENTZEN**<sup>8)</sup>, in 1954, concluded that the tibial anterior, peroneous longus and the intrinsic muscles of the foot play no important role in the normal static support of the long arch of the foot. However, **BASMAJIAN** also stated that with a strong foot to uneven ground, and of course, to propel the body in walking and running.

In 1954, **J. W. SMITH**<sup>9)</sup> concluded that the activity was noted in the posterior cural group of muscles of the foot but the other muscle groups were inactive in the erect posture examined by means of the E.M.G..

**R. SUZUKI**<sup>10)</sup>, in 1956, stated that M. flexor hallucis longus (F.H.L.), M. Tibialis anterior (T.A.) and M. abductor hallucis contract for supporting the longitudinal arch of the foot while weight pressure loading from knee to lower leg.

In our experiment, there is nothing special finding about the relationship between the E.M.G. and the mobility of the arches of the foot during walking, but active phases of T.A., Gastrocnemus, P.L. and F.H.L. muscles are the same as the results reported by **MANN & INMAN**<sup>11)</sup> in 1964.

They stated the main intrinsic muscles—the abductor hallucis, flexor hallucis bravis,

flexor digitorum brevis and abductor digiti minimi—exert considerable flexion force on the fore part of the foot and play the principle role in the muscle stabilization of the transverse tarsal joint: that is, therefore, the main support of the arches during level walking (Fig. 19).

In figure 20, a simultaneous data of G.F.R., E.A.G., the angular change of MTP-Joint and E.M.G. (including the muscles of T.A., Gastrocnemus, P.L. and F. H.L.) are shown.

Since the same characteristic notches in the areas of 5% and 95% of the whole stance phase among the pattern of the anterior arch, the medial arch and the MTP-Joint are observed, it can be considered that there might be a closed relationship between each other.

1. The meaning of the two special notches and the relationship between the MTP-Joint, the anterior and the medial arches.

According to the period of the G.R.F. and the percentage of the stance phase, the small notch as in the area of 5% will occur in the period just after heel strike, and the large notch, as in the area of 95%, will occur in the period just before toe off.

The fact that the above three notches appear at the same time means that the mobility of the MTP-Joint exerts an important influence to the length of the arch.

F. BOJSEN-MØLLER<sup>12)</sup> in 1979 and M. FUJITA<sup>6)</sup> in 1982 already reported that dorsiflexion of the MTP-Joint occurs twice during the stance phase of walking. The first one is an active dorsiflexion, the same as the special notch in the area of 5%, starts just before heel strike and ends just after heel strike, and the second one, the same as the special notch in the area of 95%, is a passive dorsiflexion occurs after the heel off and makes maximal peak just before the toe off.

J. H. HICKS<sup>2)</sup>, in 1954, explained the importance of the mechanical effect of the attachment of the phalanx of the MTP-Joint and pointed out that plantar aponeurosis acts as a tie for the longitudinal arch of the foot. He reported that when the toe are dorsiflexed, the head of the metatarsal bone acts as a drum, and from here a pull is exerted on the plantar aponeurosis by a "windlass action" which shifted proximally towards the calcaneus and the arch was thereby made shorter and higher (Fig. 21).

Here we can now, therefore, conclude that the arches shorten twice during the whole stance: the first small notch in the area of 5% which occurs just after heel strike and twice on the second large notch in the area of 95% which occurs just before toe off. The peak of the shortening of the medial arch is caused by the windlass action of the MTP-Joint which dorsally to 40–50 degrees.

2. The meaning of the flattening of the medial arch.

The structure of the architectural vault of the human foot is a very special structure with a important function—the shock absorption—during walking.

I. A. KAPANDJI, in 1970, indicated that there are two stages of shock absorption during walking. While the sole of the foot is in whole contact with the ground, the weight of the body is fully applied to the plantar vault which is flattened. This period

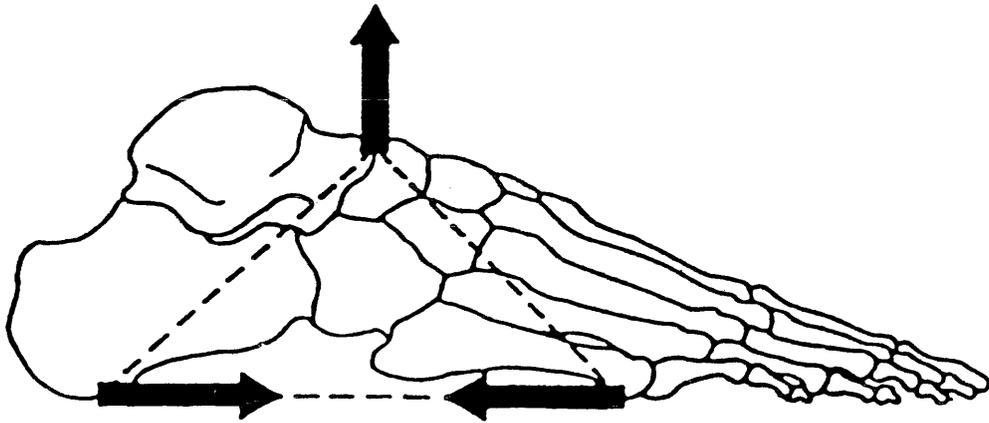


Fig. 19. Intrinsic muscles of the foot are the main contributors to the muscle support of the arch. (from J. H. Hicks)

**Simultaneous Records of  
Ground R.F. M.P. Angle E.A.G. & E.M.G.**

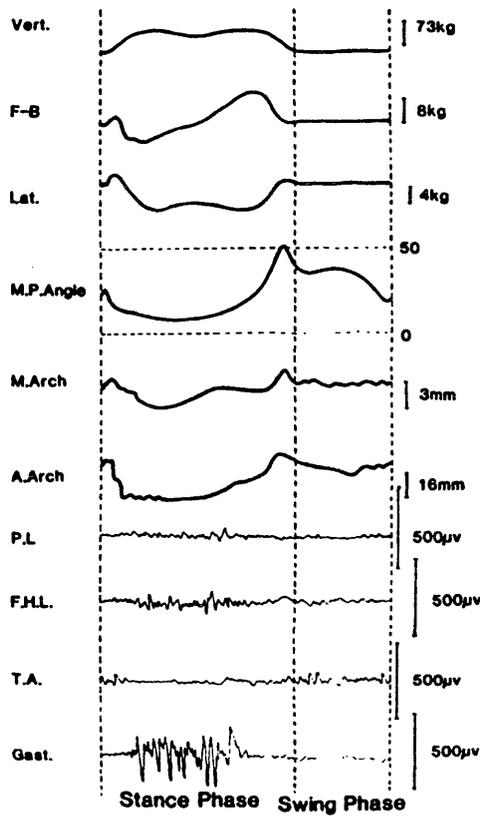


Fig. 20. A simultaneous data of the G. R. F., E. A. G., MTP-Joint and E. M. G. showing the relationship between each others.

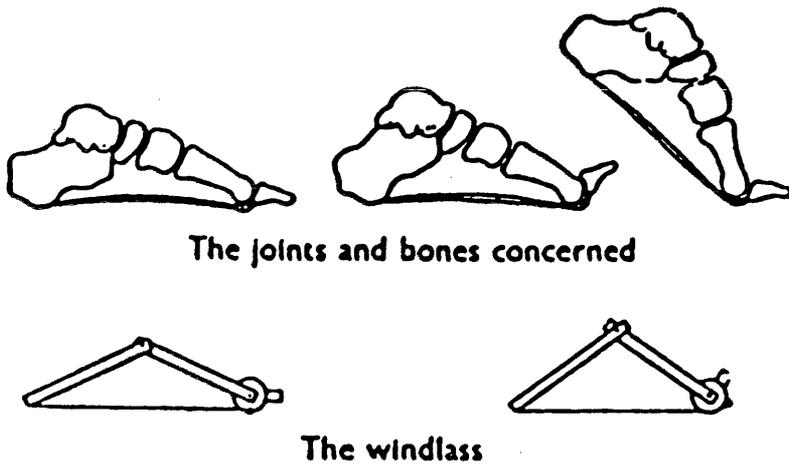


Fig. 21. When windlass action shifted proximally towards the calcaneus and the arch was thereby made shorter and higher, (from J. H. Hicks)

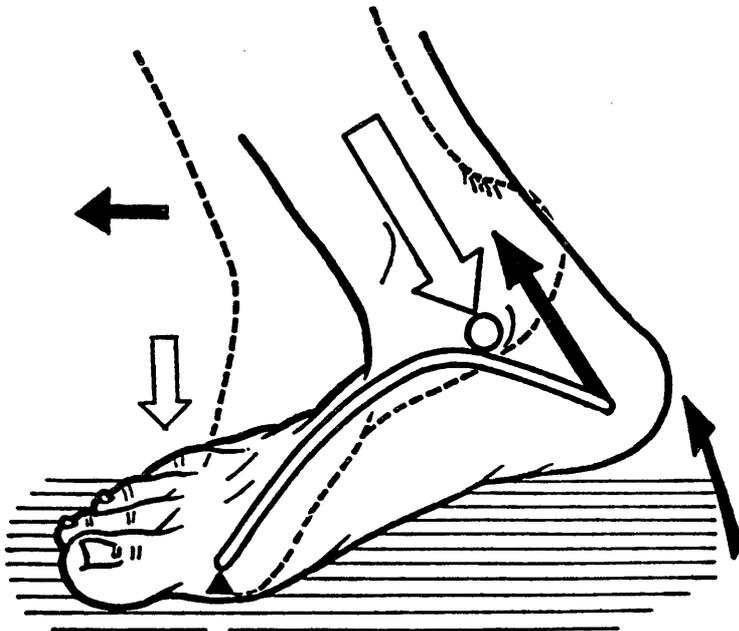


Fig. 22. The heel lifts and the body shifts forward making the body weight born on the metatarsal head. Consequently, the medial arch bended to be flat.

occurs in the area of 30% of the stance phase shown in figure 8 corresponds to the period of the foot flat. And this flattening of the vault is actively and passively checked by the sole soft tissues, —the first stage of shock absorption.

Soon after the foot-flat during walking, the weight of the body is shifted to the anterior part of the foot with heel off and the dorsiflexion of the MTP-Joint starts which makes the medial arch shorten by the windlass action.

Meanwhile, the heel is lifted by propulsion force of the crural muscles and the body weight is born on the metatarsal heads by forward shifting of the body. Consequently, a bending force acts on the medial arch and makes it flat (Fig. 22). This is the second stage of shock absorption.

### 3. The meaning of the flattening of the anterior arch

After heel off, the body is shifted to and supported on the anterior part of the foot that makes it splayed out on the ground. At the same period the anterior arch is flattened in its turn making the anterior arch the longest.

## CONCLUSION

1. Although many experiments were reported for analyzing the structure and function of the arches of the foot during the static phase, it is the first time of obtaining the dynamic changes of the arches of the foot during walking in our experiment.

2. The electrogoniometer used for recording the changes of the medial arch was made for cancelling the natural vibration.

3. The calibration of the electrogoniometers was confirmed as having a reliable linearity.

4. The mean pattern of the anterior arch is an one phase pattern with two special notches (shortening of the arch) in the areas of 5% and 95% and a flattening (elongation of the arch) in the area of 40–50% of the stance phase.

5. The mean pattern of the medial arch is a two phase pattern with the same two notches in the areas of 5% and 95% and flattening in the areas of 30% and 80% of the stance phase. And the latter notch is shorter than the former.

6. The entire mobility of the anterior arch during walking is about 20mm during the whole stance phase.

7. The entire mobility of the medial arch is about 4 mm during the whole stance phase.

8. Windlass action due to the dorsiflexion of the MTP-Joint (HICKS, 1954) which makes the shortening of the medial arch was proved during walking in this experiment.

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