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The Effect of Heel Height on the Anterior Transverse Arch of the Foot

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In fifteen normal female volunteers, the effect of heel height of the shoes and ground reaction forces on the medial part of the anterior transverse arch of the foot during walking were investigated.

Two electroconductive rubber sensors were used to measure the dynamic changes of the length of the anterior transverse arch during walking. On the dorsum of the foot, one of the sensors was attached in the space between the 1st and 2nd metatarsal head (medial part), and another between the 2nd and 5th metatarsal head (lateral part). The subjects were asked to walk in barefoot and with the experimental shoes of different heel heights. The peak expansion of the medial part and the ground reaction force were compared with the barefoot walking and walking with the shoes.

The point of the lateral component coinciding with time of the maximum peak of the medial part showed significant increase in amplitude when the heel was 6cmor more indicating the lateral component acting medially.

Two different types were observed in the dynamic changes of the medial part walking with shoes. One group (seven subjects) showed increase in peak expansion when the heel height was 6cm or more. Whereas in the other (eight subjects) no such change was observed.

Based on these findings, it is suggested that when the heel height is 6cm or more, the counteraction of the lateral component of ground reaction force as well as type B feet together act on the big toe to deviate laterally and as a resultant hallux valgus deformity may develop in the long run.

Key words: gait, heel height, ground reaction force, anterior transverse arch, hallux valgus.

Introduction:

In podriatic medicine hallux valgus deformity is one of the most common forefoot problem especially in female[4, 10, 11, 13, 19]. Hallux valgus often disrupts the normal continuity of the anterior transverse arch of the foot and as a result the arch is flattened[23].

The mechanism of the development of hallux valgus is still under discussion and many extrinsic and intrinsic factors have been reported as its etiology[3, 5, 20, 15]. As extrinsic factor, use of shoes, especially high heel shoes is considered to be responsible for the development of hallux valgus[2, 6, 7, 17, 18]. Schwartz et al[25] found during walking with high heel shoes the forces on the fore foot is increased, and Merrifield[26] also reported that the vertical force on the forefoot was concentrated at the 1st metatarsal head with the use of high heel shoes. Other authors also reported that by the increased above mentioned vertical load on the forefoot, the anterior transverse arch is widened[9, 27, 29] and the narrow anterior part of the shoes forces the big toe in a valgus position[24].

Other than shoes, some extrinsic factors also can influence the big toe to deviate laterally, such as tight stockings, elastic tights or forces from the ground[24, 28]. As the counteraction of ground reaction forces deviates the big toe in a valgus position in the push-off phase of the walking cycle[24], it can be considered that ground reaction forces are acting directly on the big toe as an external force. However, reports concerning with the effect of high heel and ground reaction force on the forefoot are very few. Yamaguchi[22] reported that in bare foot walking, the vertical and the lateral component of the ground reaction force have influence on the dynamic changes of the anterior transverse arch, but he has not investigated the effect of heel height in that report. Kura et al measured the circumference of the forefoot with different heel height during walking and on standing position[30]. They have reported that the circumference of the forefoot increased with the increase of heel height in standing position. In their study effect of ground reaction force was not done. Saunders et al reported that heel height has a little effect on the vertical component of ground reaction forces[16]. But the other two components nemely forward-backward and lateral component, were not mentioned. Moreover, they have not studied the effect of heel height on the anterior transverse arch.

Many works have been attempted to correlate the foot wear with the development of hallux valgus. However, in previous biomechanical studies, the parameters used were limited and the details about the effect of shoes in the mechanism of development of hallux valgus is not clear in the biomechanical point of view.

The purpose of this study is to investigate the influence of heel height of the shoes and ground reaction forces on the anterior transverse arch during walking.

Subjects and methods:

Fifteen female volunteers with foot size 23.5cm were chosen. Their average age was 24 years, ranging from 20 to 35 years with average weight of 56kg. They had no significant history of locomotor disturbance or injury.

Five pairs of experimental pumps of size 23.5cm with different heel heights of 0cm, 2cm, 4cm, 6cm and 8cm were used for this study (Figure: 1). The shapes of the heels were wide based identical in all the shoes because this study concerns with the height of the heel only. Two holes were made at the medial and lateral sides of the shoes and the edges were slit to obtain the most possible expansion of the anterior transverse arch at the level of the metatarso-phalangeal joint.

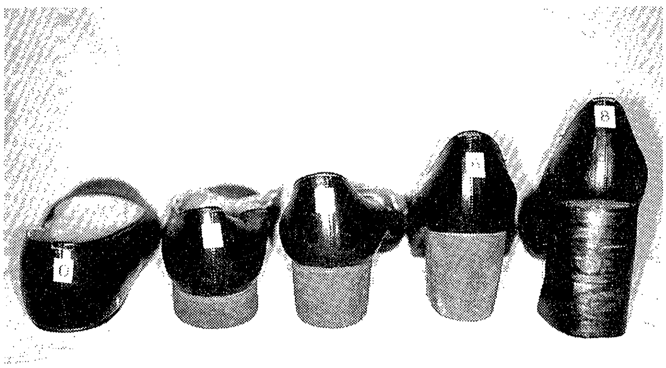


Figure:1 Experimental shoes with heel height of 0cm, 2cm, 4cm, 6cm and 8cm.

Two strips of eletroconductive rubber sensors (Elcon; Fine Rubber Institute, Saitama, Japan) were used to measure the dynamic changes of the anterior transverse arch. These rubber sensors have property of altering their electrical resistance parallelly with the change in length. Each sensor was of 30 mm in length and 5 mm in width.

To confirm the accuracy of the rubber sensor, the relationship between the expansion of the sensor and the electrical output was studied. The sensor length was increased by 1 mm at a time from 30 mm to 42 mm and then from this expanded position again the length was reduced to its original length (30 mm) by 1 mm at a time and the output of each length was measured. The relationship between the output and the stretched length of the strip showed a sigmoid curve (Figure:2). There was no difference between electrical output from the sensors in lengthening and shortening.

Kapandji[12] stated that when pressure is applied on the anterior part of the foot the anterior transverse arch of the foot widens medially and laterally keeping the second metatarsal in the middle. Also in this study the widening of the transverse arch was divided into two part, medial and lateral part. Accordingly two sensor were attached on the dorsum of the left foot; the first strip in the space between the 1st to 2nd metatarsal head which represents the medial part of the transverse arch and the second strip from the 2nd to 5th metatarsal head, which was considered as lateral part (Figure:3). This study concerns with the

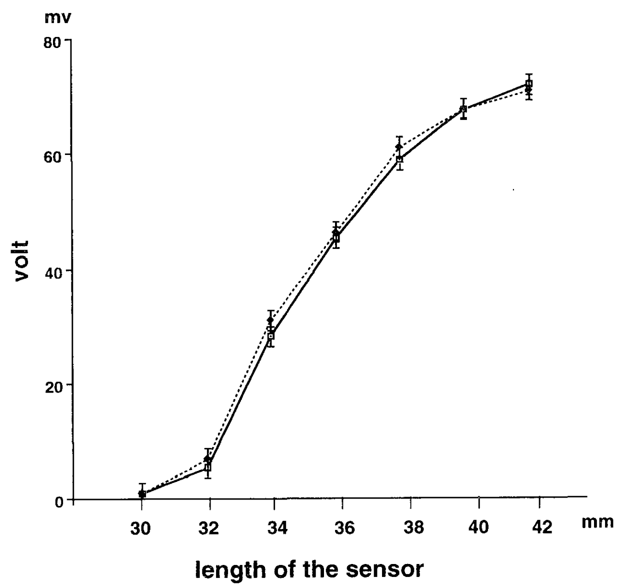


Figure:2 Relationship between the sensor's length and the electrical output. Black line: at the time of sensor lengthening. Dotted line: at the time of sensor shortening.
The relation showed as a sigmoid curve in both lengthening and shortening of the sensor.

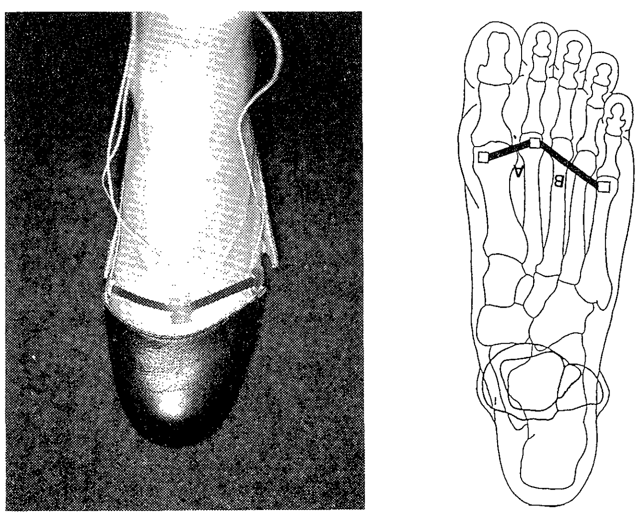


Figure:3 The electroconductive rubber sensors attached on the dorsum of the foot.
The first strip(A) was attached in the space between the 1st and 2nd metatarsal head (medial part), the second(B) between the 2nd and 5th metatarsal head (lateral part).

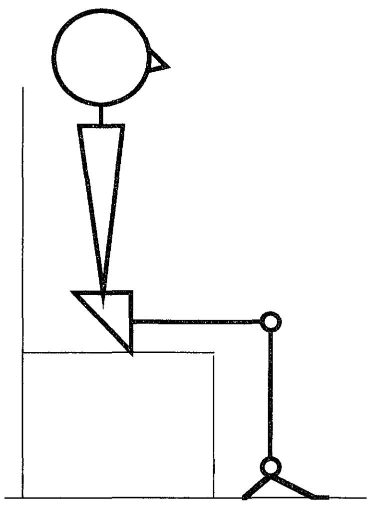


Figure:4 The zero tension of the rubber sensor was decided when the subject sat on a chair with her hip and knee joints in 90 degree flexion position and the bare foot touching the ground lightly while the sensors were attached on the dorsum of the foot.

medial part of the anterior transverse arch.

The zero tension of the rubber sensor was decided when the subject sat on a chair with her hip and knee joints in 90 degree flexion position and the bare foot touching the ground lightly while the sensors were attached on the dorsum of the foot (Figure:4).

In bare foot walking the foot switches were attached on the sole in this order the heel, head of the first metatarsal, head of the fifth metatarsal and the big toe respectively. In walking with shoes they were attached underneath the shoes in the same manner.

The subjects were asked to walk with free walking speed on a seven-meter horizontal walkway in which a 80cm×40 cm force plate (Anima Corp. Tokyo, Japan) was embedded in the center. The movement of the anterior transverse arch, the vertical, forward-backward and lateral components of the ground reaction force and foot switch signals were recorded simultaneously in fifteen times of bare foot walking and with every different heel height. Using the foot switch signals, one stride was divided into the stance phase, the double support phase and the swing phase. Dynamic changes of the medial part of the anterior transverse arch of every subject were standardized as one walking cycle (100%) by a microcomputer (PC-9801 NEC Tokyo). The amplitude of peak of expansion in the medial part (PM) and time from the left heel contact to the peak for the medial part T (M) were measured. The maximum peaks of the vertical (Z), forward-backward (X) and lateral (Y) components of the ground reaction force in the acceleration phase were also recorded. Moreover, the amplitude of the lateral component (Y') in the acceleration phase, coinciding with time PM was measured (Figure:5). The amplitudes of the ground reaction force were standardized by body weight.

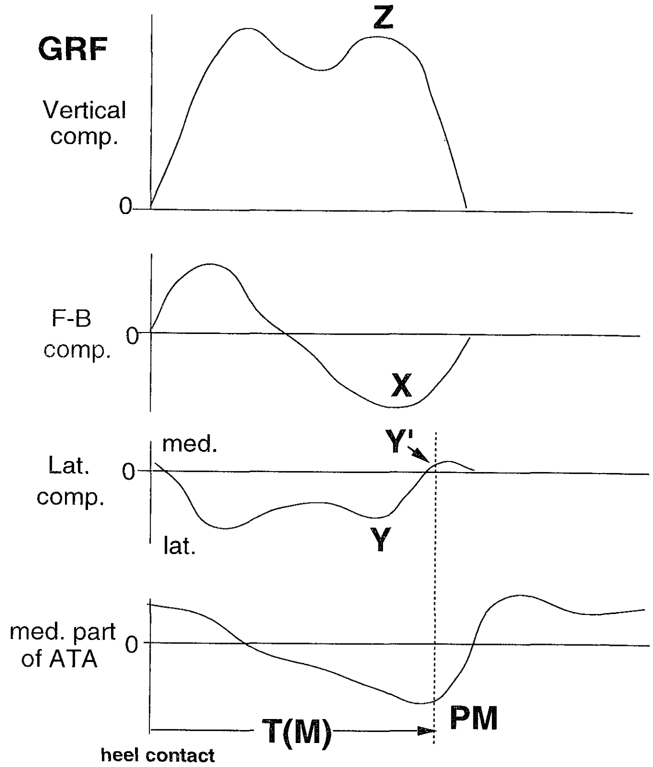


Figure:5 The measuring points of the dynamic changes of the medial part of the anterior transverse arch of the foot and the amplitudes of the three components of the ground reaction force.
PM:amplitude of peak of the medial part.
T(M):time for the medial part to reach the peak from heel contact.
Z:Peak amplitude of the vertical component in the acceleration phase.
X:Peak amplitude of the forward-backward component in the acceleration phase.
Y:Peak amplitude of the lateral component in the acceleration phase.
Y': the amplitude of the lateral component (Y') in the acceleration phase, coinciding with time of the maximum peak of the medial part of the anterior transverse arch

Results:

In barefoot walking, the medial part of the anterior transverse arch expanded rapidly. The mean PM was -0.86 mm (S.D.0.89 mm) and the T (m) was 46.9% (S.D.5.3%) of the walking cycle. In walking with 0cm heel the mean PM was -0.36 (S.D.1.3) and the mean T (M) was 57.2%. The PM of 0cm heel and the amplitude of expansion of bare foot at the coinciding time were nearly the same. (Figure:6) and the mean T (M) for 2cm, 4cm, 6cm and 8cm heel height were 59.1%, 58.5%, 58.2% and 58.7% respectively. The T (M) in walking with any shoes was significantly later than that of bare foot walking ($p<0.01$).

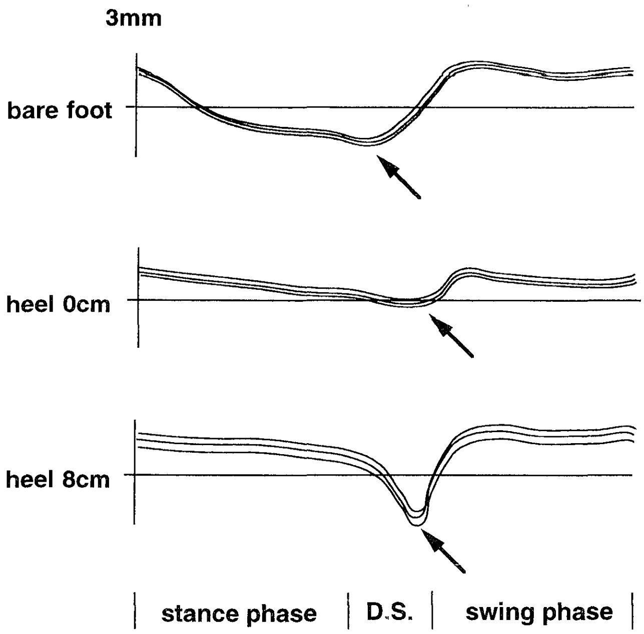


Figure:6 Delay in peak expansion with shoes compared to barefoot.
Arrows showing the time of peak expansion of the medial part T(M) of the anterior transverse arch. Delay in T(M) in walking with shoes compared to bare foot walking.
Top: bare foot walking
Middle: walking with 0cm heel.
Below: walking with 8cm heel.
D.S. Double support phase.

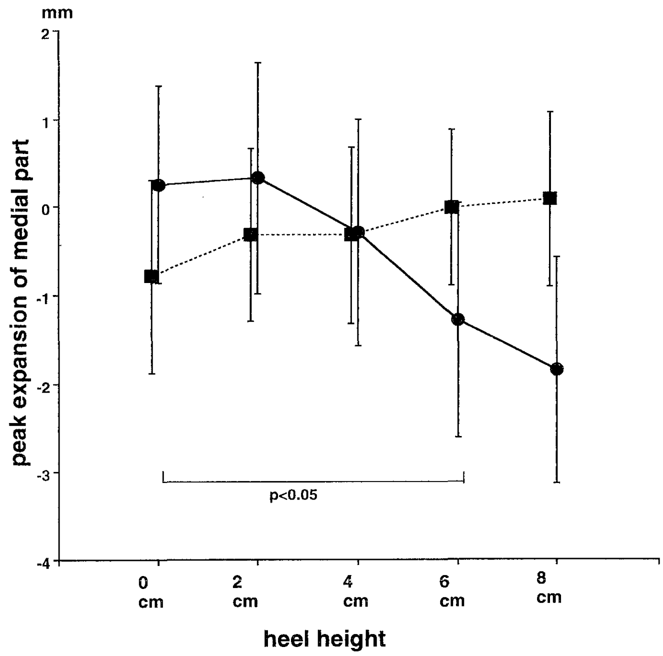


Figure:7 Mean peak expansion of the medial part with each heel height in type A and B.
Black square (■) showing the average PM with S.D. of different heel heights in type A.
Black circle (●) showing the average PM with S.D. of different heel heights in type B.
In type A, there was no significant difference with the increase of heel height. In type B, there were significant differences when the heel height was 6cm or more compared to 0cm heel ($p < 0.05$).

Table:1 Mean values of peak of the medial part in type A and B.
In type A, there was no significant difference with the increase of heel height.
In type B, there were significant differences when the heel height was 6cm or more compared to 0cm heel ($p < 0.05$).

hell height	type A	type B
0cm	−0.79±1.1	0.25±1.1
2cm	−0.32±0.9	0.33±1.3
4cm	−0.32±1.0	−0.29±1.3
6cm	−0.01±0.9	−1.28±1.3*
8cm	0.09±1.0	−1.85±1.3*

*significant difference compared to 0cm heel with p value<0.05

Eight out of fifteen subjects (53%), showed no or little change in PM with the increase of heel height. The other seven subjects (47%) showed increase in PM with the increase of heel height. The former group was classified as type A and the latter as type B. The mean values of PM for 0cm, 2cm, 4cm, 6cm and 8cm heel height in type A and type B are shown in Table 1. In type A there was no significant difference in PM with the increase of heel height ($p > 0.05$). On the contrary in type B the PM increased significantly when the heel height was 6cm or above compared to 0cm heel height ($p < 0.05$) (figure:7).

The mean values of Z, X, Y and Y'with every heel height are shown in table 2. There were no significant changes in

Table:2 Mean values of the measured points of three components of the ground reaction force.(Z, X, Y and Y').
Y' showing significant increase in amplitude with heel height of 6cm and 8cm.($p < 0.01$)

heel height	vertical(Z)	forward-backward(X)	lataeral(Y)	lateral(Y')
0cm	118±6.6	19.7±4.0	−4.67±1.0	−1.29±1.2
2cm	119±6.5	19.4±4.1	−4.58±0.9	0.19±1.2
4cm	122±6.9	21.2±3.2	−4.09±1.4	0.76±0.9
6cm	119±7.5	19.6±3.9	−4.06±1.4	1.09±0.9*
8cm	117±9.7	20.2±4.3	−3.80±1.3	1.3±1.2*

*significant difference compared to 0cm heel with p value<0.01

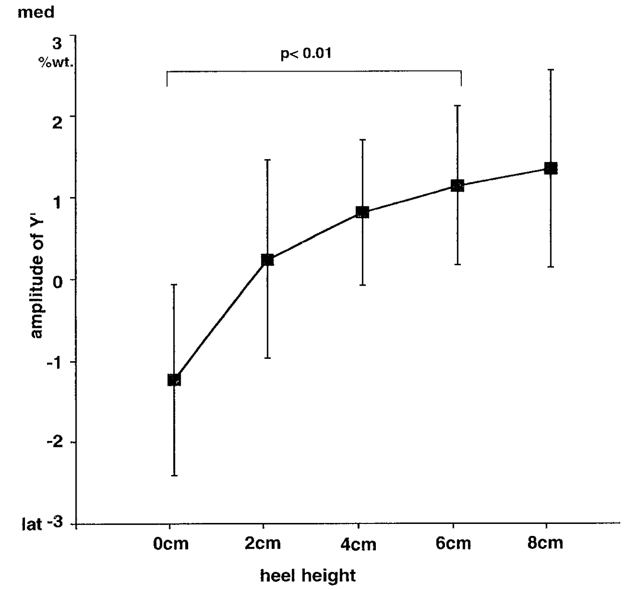
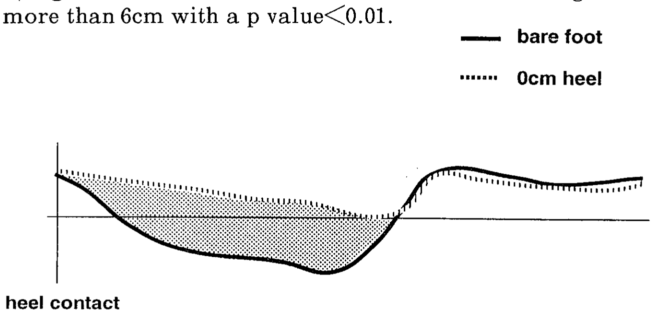


Figure:8 Mean amplitude of Y' with S.D. wearing different heels.
A significant increase was noted when the heel height was more than 6cm with a p value$<$0.01.



Fibuer:9 A superimposed pattern in one subject of the dynamic changes of the medial part during bare foot and walking with shoes of 0cm heel height. The expansion in 0cm heel height was less compared to bare foot walking. The shaded area shows the amount of less expansion.
Black line: dynamic changes of the medial part during bare foot walking. Broken line: dynamic changes of the medial part during walking with 0cm heel height.

X, Y and Z in the acceleration phase with any heel height. However Y' showed a significant increase of amplitude with the increase of the heel height. With 0cm heel Y' was acting in a lateral direction, however from 2cm heel height started acting in medial direction. A significant increase was observed when the heel height was 6cm or more compared to 0cm heel height ($p<0.01$) (Figure:8).

Discussion:

Measurement of the anterior transverse arch was very difficult because of the lack of suitable devices or equipment. However, the electroconductive rubber sensors (Elcon) used in this study made it possible. By the study of Yamaguchi[22] and also in this study, the facts showed that

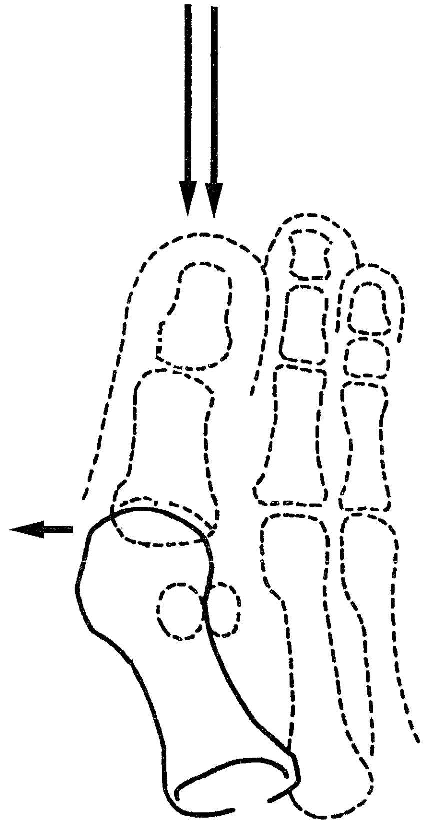


Figure:10 Schematic illustration of biomechanical action of ground on the hallux during the propulsive stage of the gait cycle.

these sensors had good correlation between the expansion and the electrical output within the range of 30 to 40mm length. Yamaguchi[22] also demonstrated a significant relation between the output from the sensors and the measured distance between metatarsal heads radiographically. This means these rubber sensors are useful to measure the dynamic changes of the anterior transverse arch during walking.

In this study only the medial part was investigated because the medial part extends from the first to second metatarsal heads which corresponds to the 1st inter-metatarsal angle. The 1st inter-metatarsal angle is a good index for hallux valgus[10].

The mean PM in bare foot walking was -0.86 and the mean T(M) was at 46.9% of the walking cycle. In walking with shoes of 0cm heel height the mean PM medial part was -0.36mm and the peak was noticed at the 57.2% of the walking cycle. A superimposed pattern in one subject of the dynamic changes of the medial part during bare foot and walking with shoes of 0cm heel height are shown in figure 9. The expansion in 0cm heel height was less compared to bare foot walking. The shaded area shows the amount of less expansion. The cause of less expansion is thought to be the constrictive effect of the shoes. However, what is the reason of delayed peak with shoes? In normal foot, the axis of the first metatarsal and the axis of the big toe forms slight valgus angle[10]. In walking with shoes the peak was observed when only the big toe was in touch with ground and the body weight was transmitted through the big toe. At that time the force is exerted on the tip of the big toe from the ground. As a result the first metatarso-phalangeal joint shifts medially. Due to this shifting the 1st metatarsal head moves medially and the medial part of the arch expands. It is thought that is the reason of peak formation with shoes (Figure 10). As a effect of that the hallux is shifted laterally.

Also in this study it was observed that with heel height of 6cm and 8cm, Y' increased significantly and the lateral component was acting medially. It can be suggested that with higher heels the counteraction force of the lateral component acts as a force to deviate the big toe in a lateral direction. Moreover, high heel shoes align the foot in plantar-flexion position and causes increased vertical loading on the metatarsal heads[14,21]. As a consequence, it is thought that the 1st inter-metatarsal angle widens more and pressure from the medial part of the shoes forces the big toe further laterally. It can be suggested that probably these three factors are acting together to force the big toe to deviate laterally. Repeated stress like these may be the factors of the incidence in hallux valgus deformity.

It has been observed that every high heel wearer does not develop hallux valgus deformity. Interestingly, in this study, two types of feet were observed; type A and type B. In type A, no significant change of the medial part was observed with the increase of heel height. However type B showed a significant increase of the peak expansion of the medial part when the heel height was 6cm or more compared to 0cm heel height. It indicates that, in type B feet, the use of 6cm and 8cm heel caused widening of the 1st inter-metatarsal angle. It has been reported that, hypermobility of the fore foot[1,3,8] and the inclination of the 1st metatarso-cuneiform joint[15] are predisposing intrinsic factors in the incidence of hallux valgus. It is assumed that these factors are responsible for the increase in peak expansion of the medial part in type B feet.

From this study it is suggested that higher heels and the lateral direction force acting on the big toe during walking are possible extrinsic factors and also some predisposing intrinsic factors contribute in the occurrence of hallux valgus deformity.

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