

Effects of Foot Arch Structure on Postural Stability

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Abstract

Background: In many human postural studies, the foot is considered to be a rigid body. The human foot is composed of the arch structure, which is characteristic in every person and deforms with aging. Foot arch structure is assumed to effect postural control; however, underlying mechanisms remain unclear. The aim of this study was to elucidate the relationship between the structure of the foot arch and postural control in the elderly.

Methods: [Protocol 1] Thirty-seven healthy subjects participated in a test to determine the relationship between midfoot plantar pressure and arch height. Midfoot plantar pressure distribution (ratio of MP) was measured using the Shoe Type Stabilometer. The arch height was measured using a three-dimensional foot scanner.

[Protocol 2] Ratio of MP and postural stability was measured in 143 elderly subjects using the Shoe Type Stabilometer. Postural stability was evaluated by center of pressure (CoP).

Results: In Protocol 1, the correlation coefficient between the ratio of MP and ratio of arch height was $r=-0.59$ for the left foot and $r=-0.54$ for the right foot. Therefore, arch height could be predicted by ratio of MP. In Protocol 2, a significant correlation was recognized between the ratio of MP and lower limb strength, CoP total length, area anterior-posterior length, and medial-lateral (ML) length.

Conclusions: The Shoe Type Stabilometer could evaluate CoP and foot arch structure. Using this device, it was found that people with a high ratio of MP, who tends to be flat-foot, displayed an increase in CoP sway. Therefore, foot arch structure contributed to postural control. Correlation between the ratio of MP and ML length, and between the ratio of MP and lower limb strength, indicated that the function of the plantar intrinsic foot muscles, which contributes to foot arch structure.

Keywords: Shoe type stabilometer; Flat-foot; displayed; Postural studies; Human foot

Introduction

The foot is a very complex and unique structure, and comprises numerous bones, ligaments and joints. The bones in human feet are arranged to form three arches. The arches are considered to play functionally significant roles by supporting body weight and reducing the impact of the body during running and walking [1,2]. During standing, the arch is thought to not only support weight but also contribute to dynamic postural control and equilibrium maintenance; however, these functions have not been fully elucidated.

Many studies have evaluated postural control using the inverted pendulum model, which considers the body as a reverse pendulum with a fulcrum at the ankle [3]. In these studies, the foot was identified as a single rigid body. Movability of the foot arch has not been considered in previous studies. Recent research has reported that foot arch deformations and body sway revealed a significant correlation during quiet standing, indicating that the arch of the foot is related to postural sway [4]. Foot structure has individual characteristic in every person and becomes deformed with aging. However, previous studies have not revealed the effects of foot characteristics on postural control. One reason for this lack of findings may be that subjects in these

studies were restricted to patients with disease or several young participants able to use large equipment (e.g. force plate, three-dimensional (3D) motion analyzer) [5,6].

To further investigate the role of the foot arch in postural control, we quantified the individual characteristics of the foot arch in many subjects using the Shoe Type Stabilometer [7] developed in this study. The aim of this study was to elucidate the effects of foot arch structure on postural control in the elderly.

Materials and Methods

Shoe type stabilometer

The Shoe Type Stabilometer [7] was used in this study (Figure 1). The device consists of a shoe insole with seven pressure-sensitive conductive rubber sensors. Sensors were located in the heel (#A), lateral midfoot (#B), lateral forefoot (#C), great toe (#D), head of the first metatarsal (#E), center of the midfoot (#F), and center of the forefoot (#G). This arrangement was based on the mechanism of postural maintenance and the anatomical structure of the foot arch. #A, #C, and #E relate to weight support, #D is a toe and #B, #F, and #G are related to the foot arch. Center of pressure (CoP) was quantified based on the pressure value from the 14 sensors and coordinates indicating a relative position of the foot. CoP waveforms measured by

the Shoe Type Stabilometer were strongly correlated with a stationary type stabilometer. The correlation coefficient of anterior-posterior (AP) sway was 0.93 and of medial-lateral (ML) sway was 0.97 during standing. Postural control is therefore able to be evaluated with this device. Additionally, the measurement device had a wireless data transmission unit (communication method: Bluetooth, distance: ~50 m, sampling frequency: 100 Hz). Therefore, this device could evaluate plantar pressure and CoP during natural standing.

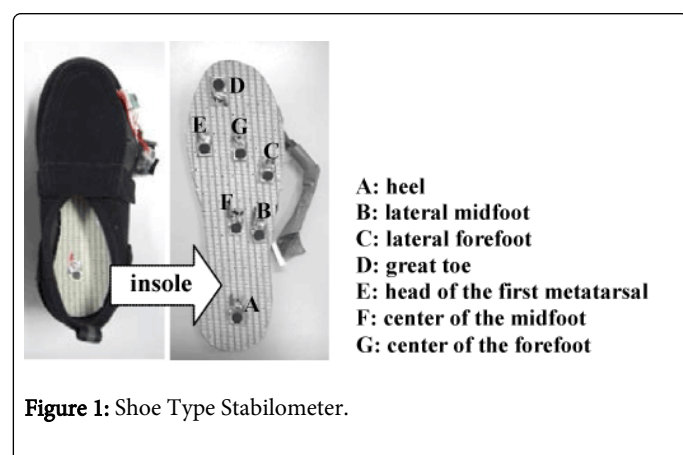


Figure 1: Shoe Type Stabilometer.

Protocol 1: Prediction of arch structure using the shoe type stabilometer

The human foot contains three strong arches; two arranged longitudinally and one transverse arch. This study focused on the longitudinal arch structure, which we hypothesized to be involved in postural control. As previously explained, the Shoe Type Stabilometer was designed to evaluate foot arch structure. In this protocol, to quantify arch height using the Shoe Type Stabilometer, a comparison of arch height and midfoot plantar pressure distribution was conducted. The foot area was divided into big toe (#D), forefoot (#C, #E, #G), midfoot (#B, #F), and rear foot (#A) as shown in Figure 2. Midfoot pressure was calculated summing the pressure value of sensor #B and #F. The ratio of midfoot pressure (ratio of MP) was calculated by dividing midfoot pressure by the sum total of the 14 point sensor pressure values (Total Pressure). This formula is shown below. The correlation between the ratio of MP and longitudinal arch height was investigated.

$$\text{Ratio of MP [\%]} = ((\text{Midfoot pressure}) / (\text{Total Pressure})) \times 100$$

A 3D Foot Scanner (JMS2100CU, DreamGP co., Japan) was used for the measurement of the longitudinal arch height. This device measures the three dimensional geometry of foot structure using laser scanning. Longitudinal arch height was assumed as the marking position of the navicular. This position was marked by the same examiner. The longitudinal arch height was normalized to each foot length. Therefore, ratio of arch height was calculated, which divided arch height by foot length.

37 healthy people (mean age 72.8 years, standard division 6.9, range 57-85 years) participated in this study. The ratios of MP of the right and left feet were measured with the Shoe Type Stabilometer in standing position. The ratios of arch height and foot length the right and left feet were then measured using a 3D Foot Scanner in standing position. The ratio of MP was compared with the ratio of arch height.

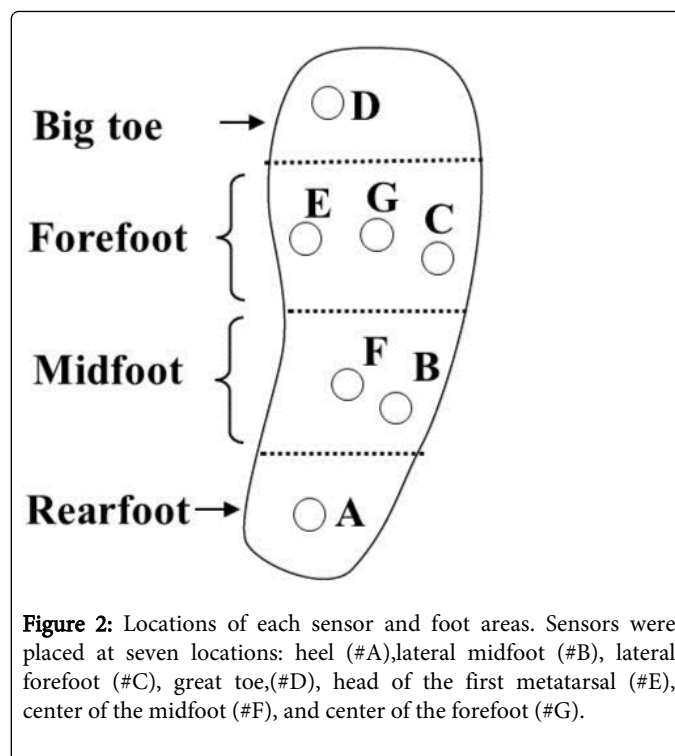


Figure 2: Locations of each sensor and foot areas. Sensors were placed at seven locations: heel (#A), lateral midfoot (#B), lateral forefoot (#C), great toe, (#D), head of the first metatarsal (#E), center of the midfoot (#F), and center of the forefoot (#G).

Protocol 2: Examination of correlating ratio of MP and postural stability

Based on results from Protocol 1, the study focused on the effect of foot arch structure on postural control. To investigate the correlation between midfoot plantar pressure, which relates to foot arch structure and postural control, 143 elderly subjects (mean age 74.8 years, standard division 5.8, range 65-90 years) participated in this study. The subjects put on the Shoe Type Stabilometer, and plantar pressure distribution was measured for 45 seconds while standing. The subjects were directed to gaze at a point 1.5 m away while measurements occurred. The distance between both feet was 12 cm at the toes and 8 cm at the heels. In addition, height, weight, and age of the subjects were noted. Lower limb muscle strength was also measured using toe gap force [8].

All subjects in this study were included if they were able to walk independently and were excluded if they had uncontrolled systemic disease and or a serious heart disease or hemiplegia from cerebrovascular that affected their walking. They were recruited through advertisements in local newspapers. The physical condition of each subject had been checked and the research was explained to all participants. Informed consent was received from the subjects before measurements were obtained.

Data analysis

All analyses were performed using SAS (JMP 8.0.1) for Windows. In Protocol 1, Pearson's correlation coefficient was used to determine the correlation between weight and ratio of MP, and between ratio of MP and the ratio of arch height. In Protocol 2, as in Protocol 1, ratio of MP (average for 45 seconds) was calculated summing the left and right ratio of MP based on plantar pressure distribution. Postural stability was evaluated by CoP sway for 45 seconds. CoP was calculated based

on the pressure value of the 14 sensors and coordinates relative to the position of the foot. The correlations between the ratio of MP and parameters (age, weight, height, toe gap force, CoP total length, area, ML length and AP length) were analyzed with Pearson's correlation coefficients. A p value less than 0.05 was considered significant for all analyses.

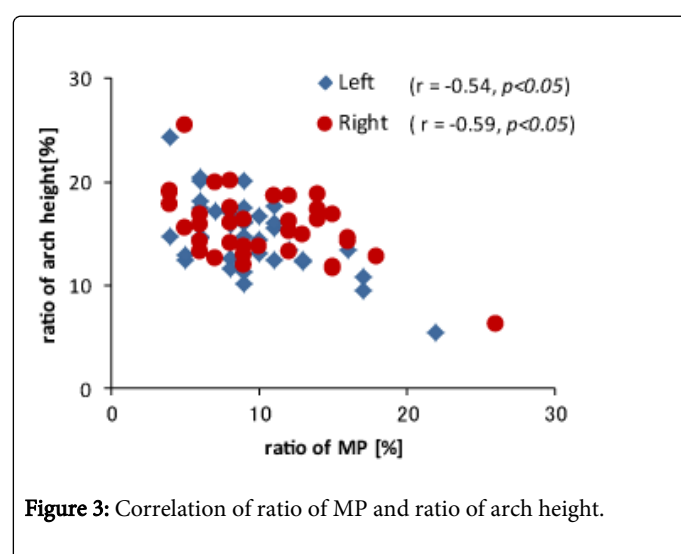
Results

Predicting arch height with the Shoe Type Stabilometer (Protocol 1)

To determine foot arch structure using the Shoe Type Stabilometer, the ratio of MP obtained from the Shoe Type Stabilometer and ratio of arch height obtained from a 3D Foot Scanner were compared. The comparative result of ratio of MP and ratio of arch height is shown in Figure 3. The vertical axis shows ratio of arch height while the horizontal axis displays the ratio of MP. The correlation coefficients between the ratio of MP and ratio of arch height were -0.59 ($p < 0.05$) for the left foot and -0.54 ($p < 0.05$) for the right foot. The correlation of weight and ratio of MP was not significant.

Correlating foot arch structure and postural stability (Protocol 2)

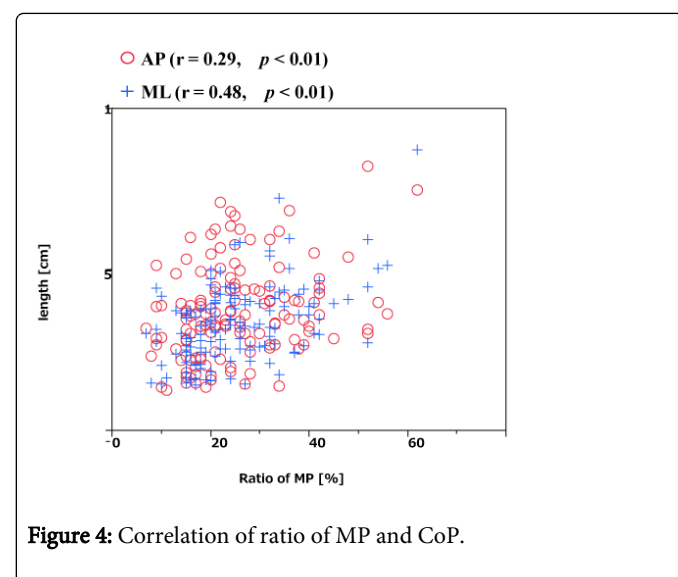
To evaluate postural control in relation to individual characteristics of the foot arch, verification experiments that used the Shoe Type Stabilometer were conducted. All 143 subjects, including frail elderly, were able to be measured using the Shoe Type Stabilometer. Table 1 shows the correlation coefficient of each parameter with ratio of MP. Correlations among the ratio of MP and age ($r = 0.19$), height ($r = -0.19$), lower limb strength ($r = -0.21$), CoP total length ($r = 0.39$), and area ($r = 0.37$) were significant. Weight had no significant relationship with ratio of MP. Correlations among the ratio of MP and AP length ($r = 0.29$), and ML length ($r = 0.48$) were significant as shown in Figure 4. ML length was highly correlated with the ratio of MP rather than AP length.



Discussion

The role of foot structure has not been clarified in research into human posture when compared with the role of the vestibular system, lower limb and visual sensation. Wright et al. [4] reported that foot arch deformations and body sway were significantly correlated during quiet standing, indicating that the arch was related to postural sway. Kelly et al. [5] have reported that there is a correlation in the change of CoP and the activity of the plantar intrinsic foot muscles. The foot arch is also believed to have a role in postural sway since the plantar intrinsic foot muscles form the foot arch. In this study, we focused on the effects of individual characteristics of foot arch structure on postural control.

To evaluate these individual characteristics, it is necessary to measure many subjects including the frail elderly. Therefore, this study used the Shoe Type Stabilometer that can measure CoP and plantar pressure in the natural standing position [6,9].



Arch structure and the Shoe type stabilometer

To determine arch height using the Shoe Type Stabilometer, the ratio of MP obtained with this device and the ratio of arch height measured with a 3D Foot Scanner were compared. The correlation coefficients between the ratio of MP and ratio of arch height were significant.

Various methods have been used to evaluate foot arch structure. These include X-rays [10], clinical measurement of navicular drop [11], foot prints and plantar pressure distribution [12,13]. X-rays are accurate; however they are expensive and require attendance at specialized facilities and carry a potential risk of radiation exposure. Evaluations of the foot arch structure using footprints and plantar pressure distribution are easy techniques, and are used by many researchers. Cavanagh et al. [12] developed the arch index (AI) that calculates the arch height from foot shape measured from a footprint. This group reported that the correlation coefficient between arch height and AI was 0.67. In the present study, plantar pressure was analyzed and revealed that the ratio of MP correlated to the ratio of arch height. Therefore, ratio of arch height could be determined using the Shoe Type Stabilometer. In addition, this device could measure

CoP and foot arch structure at the same time, and can potentially quantify human postural control, with a focus on foot structure.

Previous studies reported that foot arch structure, for example high medial longitudinal arch or low medial longitudinal arch (flat foot), related to risk of lower-limb injury [14-17]. A future clinical application of our research results would be the easy evaluation of these risks using this device. In addition, since foot problems are related to decreasing postural stability and risk of fall in the elderly, our device can also quantify these problems.

Effects on posture control by foot arch structure

To elucidate the influence of foot arch structure on postural control, subjects were measured using the Shoe Type Stabilometer. All 143 subjects, including the frail elderly, could be measured safely. Because most of the previous studies used a large scale device to investigate the role of the foot arch on postural control, subject selection was limited. Wright et al. [4] used a linear transducer and force plate to examine the relationship between the deformation of the foot arch and CoP sway in seven subjects. Kelly et al. [5] measured body sway and muscle activity of the plantar intrinsic muscles in ten young people, using a wire electrode electromyogram and force plate. By contrast, the present study used the Shoe Type Stabilometer to evaluate postural control focusing on the individual foot arch structure and conducted measurements in over 100 subjects. Therefore, it is possible to evaluate a large and varied number of subjects. This method had not been used in previous studies. The Shoe Type Stabilometer also allowed us to apply the structure of the foot and relate it to postural control in various studies.

As shown in Table 1 and Figure 4, the correlations between the ratio of MP and CoP total length, area, AP length, and ML length were significant. These findings therefore revealed that the foot arch structure contributed to postural control. Melzer et al. [18] reported that increasing CoP total length and area decreased postural control. In the present study, we showed that increased the CoP total length may be associated with an increased ratio of MP. Therefore, in addition to previous studies, it is possible to assess body sway using foot arch structure.

In present study, lower limb muscle activity was considered to have influenced the foot arch, in turn effecting postural control while standing. It is reported that the major muscular activity while standing appears to occur in the ankle plantar flexors, and is associated with body sway [19]. The longitudinal foot arch is mainly supported by the inferior calcaneonavicular ligament, the short plantar ligament, the long plantar ligament, and the plantar aponeurosis, with auxiliary roles played by the abductor pollicis muscle, the flexor pollicis brevis, the flexor brevis, the anterior tibialis muscle, the flexor pollicis longus, and the posterior tibial muscle. Toe gap force measured in this study reflects muscle strength of the posterior tibial muscle and flexor pollicis longus that mainly support foot arch structure. Therefore, as shown in Table 1, the ratio of MP and toe strength showed a significant correlation. In addition, a previous study reported that the muscle activity of the abductor pollicis is especially associated with CoP ML sway [5]. As shown in Figure 4, we found that ML length was highly correlated with the ratio of MP rather than AP length. This observation may be a reflection of function of the abductor pollicis muscle that support foot arch structure and associate with lateral sway. Therefore, this study demonstrated effects of foot structure based on musculoskeletal system on human postural control.

Criteria	r	p
Age	0.19	<0.05
Height	-0.19	<0.05
Weight	0.10	N/A
Toe gap force	-0.21	<0.05
Total length	0.39	<0.05
Area	0.37	<0.05

Table 1: Correlation of Parameters with ratio of MP.

Conclusion

In many studies into human postural control, the foot arch structure was considered as a rigid body. The present study focused on the role of the foot and evaluated the effects of the foot arch structure on postural control using the Shoe Type Stabilometer. The following findings were obtained.

1. A significant correlation was shown between ratio of MP obtained by the Shoe Type Stabilometer and the ratio of arch height. Predicting foot arch height may be possible using this device.
2. People with a high ratio of MP, who tends to be flat-foot, were found to have an increase in CoP sway. Therefore, the foot arch structure contributed to postural control.
3. Correlation between the ratio of MP and ML length, and between the ratio of MP and lower limb strength, indicated that the function of the plantar intrinsic foot muscles, which contributes to the structure of the foot arch.

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