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Development of an evaluation system for foot arch types in the elderly using foot pressure distribution data*

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Abstract— **The foot arch serves important functions related to shock absorption and the action of walking. Simple and quantitative classifications of foot arch types, such as flat feet and high arches, help to provide health support services for the elderly. To develop an evaluation system for foot arch types using foot pressure distribution data, discriminant analyses were conducted using data from healthy elderly persons. The midfoot pressure ratio was selected and discriminants were derived. For evaluating the performance of the classification method, the derived discriminants were applied to the data from the other group of healthy elderly persons. Results indicate that both sensitivity and specificity of the classified foot arch types were sufficiently high.**

I. Introduction

The foot is an important part of the human body that helps the person maintain and shift one's center of gravity. Functional limitations of the foot can cause locomotion problems and pain in the lower extremities. Because many elderly individuals have foot problems, care for the feet has become increasingly important for maintaining their quality of life.

In Japan, the elderly population has been steadily increasing, whereas the younger population has experienced constant decline. In 2009, the proportion of the elderly in society was 21.5%, and this is expected to increase to 40% by 2050 [1]. Therefore, expenditures related to health care have become a serious social issue. As a result, preventive care is of great importance in reducing the burden of health care costs.

Improvement of locomotion is an important facet of preventive care. Although fall prevention and muscle strength training have been the key planks of preventive care projects, the foot structure and its care has also been given importance.

The foot has three types of arch structure: the medial longitudinal arch (MLA), lateral longitudinal arch, and forefoot transverse arch. The MLA, in particular, serves important functions with regard to shock absorption and the action of walking.

Regarding the relationship between the foot arch type and risk of injury, several studies have been reported. Cowan et al., through a survey of 246 US Army Infantry trainees [2], found that the risk of injury among the high arch group was 2.0 times higher than that of the normal foot group, and 6.1 times higher than that of the flat foot group. Otsuka et al. reported that elderly persons with flat feet tend to get tired more easily [3]. However, the evaluation method and the agreement on the relationship between the foot type and injury risk have not been established.

The footprint technique is a simple and easy method to visualize foot shape. In previous studies, simple and quantified methods of foot arch assessment using footprints were proposed [4-6]. However, there have been conflicting results concerning the relationships between indices obtained by footprints and the foot arch structure [5,6]. An effective alternative assessment system therefore remains to be proposed.

Radiographic measurements of the distance from the navicular bone to the floor are believed to be most reliable as a clinical method for the assessment of flat feet. However, its application in preventive care or health support of the elderly is not appropriate. As an alternative method, the navicular bone–floor distance was classified by palpation. In another study, this method was combined with the radiographic measurement method [6]. However, in a non-clinical setting, the latter method is unsuitable, as accurate palpation requires specialist input.

In recent years, devices that measure the foot pressure distribution have become more popular and less expensive for both clinicians and consumers; therefore, such devices can be used for preventive care or health support in the elderly. These devices are used for the qualitative measurement of foot shape because they not only measure foot shape but also provide data pertaining to foot pressure. As a result, the clinician/consumer can obtain more precise information compared with that obtained using the simple footprint technique.

Simple and quantitative classifications of foot arch types, such as flat foot and high arch, would be helpful in preventive care and health support for the elderly. In a previous study, Cavanagh et al. aimed to evaluate foot arch types using the midfoot area [2]. Their results demonstrated that when the foot types of the subjects (i.e., flat and high arches) were classified according to the first and third quartiles, the classification was relatively consistent with that obtained by qualitative clinical analysis.

In a previous study, we applied the quartile method to healthy elderly persons [7]. The result was similar to that obtained by Cavanagh. However, the quartile method cannot easily determine the optimal generalized threshold because variations in the sampling group will have a significant effect.

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Therefore, the aim of this study is to develop a highly reliable classification method for foot arch types using discriminant analysis.

II. Biomechanical Analysis

A. Method

Initially, a field test was conducted with elderly subjects to obtain some basic data and select parameters to represent foot types.

A total of 35 healthy elderly Japanese subjects (nine males, 26 females) attended a class on care prevention in Tokyo. The male subjects had a mean age of 75.1 ± 6.9 years, mean height of 162.2 ± 5.3 cm, and mean weight of 57.4. ± 6.2 kg, while the corresponding parameters for the females were 73.1 ± 6.4 years, 152.0 ± 4.9 cm, and 49.2 ± 8.0 kg.

Ethical approval for the study was obtained from the Tokyo Healthcare University Human Ethics Committee.

A MAT-SCAN (Nitta Corporation, Tokyo, Japan) device was used to measure foot pressure distribution. The sensor matrix was distributed over 44 rows and 52 columns, with a sensor interval of 8.3 mm. Subjects were requested to stand on both feet with eyes open, keeping a distance of approximately 150 mm between their big toes. When the subject was judged as being stable in the standing position, the digital foot pressure distribution data were obtained. The sampling frequency was set to be 20 Hz. The minimum and maximum measurable pressures were 4.6 and 392.0 kPa, respectively.

In this study, the left feet of all participants were analyzed. The foot contact area, excluding the toes, was divided into three equal parts: forefoot, midfoot, and hindfoot. In the following calculation for the area of each part and the sum of the pressure exerted by each part, these values were normalized to that of the entire foot. In addition to our quantified analysis, visual assessments were also carried out with the help of foot pressure distribution imaging, which gives a colored graphical representation of the foot pressure strength. The result was confirmed by a physical therapist. The results for the two types of analysis were then compared.

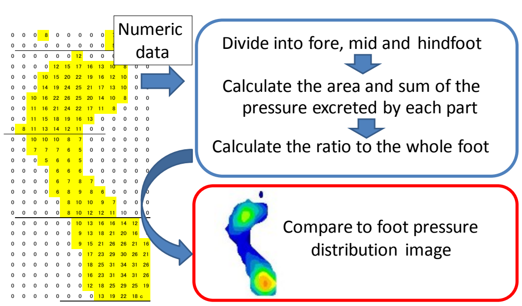


Figure 1 Processing of foot pressure distribution data.

B. Results

Typical examples of foot pressure distribution imaging are shown in Figure 2. From the visual analysis results, five subjects were categorized into the flat foot group and 14 into the high arch group. Of the six parameters, there was a correlation of the midfoot area and pressure ratios (midfoot:whole foot) in the visual analysis. The midfoot area and pressure ratios were higher in the flat foot group and lower in the high arch group (Figure 3). However, the results for other parameters did not appear to be correlated to those obtained by visual analysis (Figure 3).

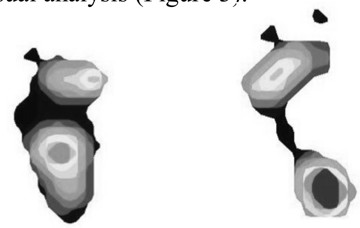
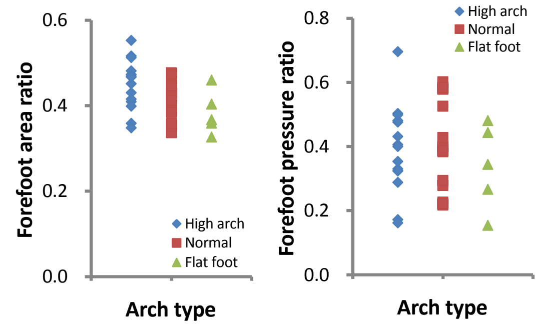
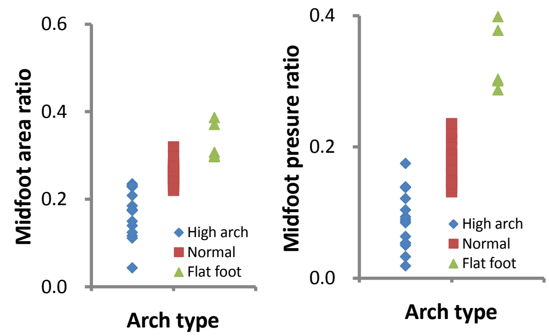


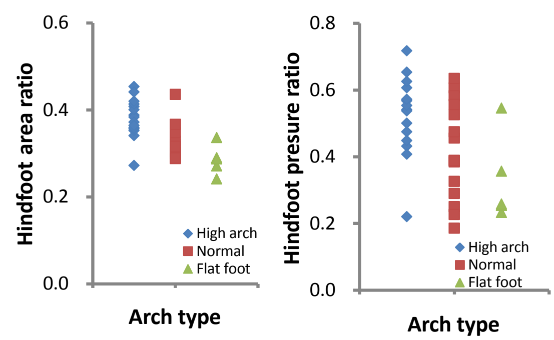
Figure 2. Foot pressure distribution images. Left, flat foot; right, high arch.



a) forefoot area ratio (left) and pressure ratio (right)



b) midfoot area ratio (left) and pressure ratio (right)



c) hindfoot area ratio (left) and pressure ratio (right)

Figure 3 Relationship between foot arch type and foot pressure parameters.

C. Discussions

With regard to the parameters derived from foot pressure distribution data, results for the midfoot tended to correspond to those of visual analysis. In terms of anatomy, the findings shown in Figure 3 were considered to be reasonable. With regard to the flat foot results, the lowering of the foot arch led to an increase in both the contact area and the pressure on the midfoot, whereas for a high arch, raising the foot arch led to a decrease in both the contact area and the pressure on the midfoot.

Therefore, we chose the midfoot area and pressure ratios as candidates for the foot pressure distribution parameters for each arch type in terms of biomechanics.

III. Discriminant Analysis

A. Method

To develop a classification method for the foot arch type using foot pressure distribution parameters, we performed a discriminant analysis. Discriminants were derived using data from the 35 healthy elderly persons obtained in the first field test.

Initially, the optimal parameter combination was discussed by calculating Akaike's Information Criterion (AIC). AIC values were calculated for all parameter combinations when the parameter number and combinations were step-wisely varied among six types of foot pressure distribution parameters. The discriminants were derived by discriminant analysis with the derived optimal parameters already set. JMP software (Version 8.0, SAS Institute) was used for the analysis.

Next, the derived formula was applied to data obtained from another healthy elderly group. The data was collected during the second field test. The subjects were 23 healthy Japanese elderly females who attended a class on care prevention in Tokyo. The mean age of the subjects was 74.9 ± 7.7 years, mean height 150.1 ± 5.3 cm, and mean weight 49.1 ± 8.6 kg. Data from studies on the left foot were analyzed.

The sensitivity and specificity of the foot arch classified by the discriminants were derived to allow the evaluation of the performance.

B. Result

The results of the AIC calculation and the minimum value were derived for the case of the midfoot pressure ratio only; the value was 11.7. Thus, the midfoot pressure ratio was selected as the optimal parameter.

The discriminants were derived by

$$\mathrm{d_{high}} = 632.3\mathrm{mfp}^2 - 109.9\mathrm{mfp} + 4.8 \quad (1)$$

$$\mathrm{d_{norm}} = 632.3\mathrm{mfp}^2 - 221.1\mathrm{mfp} + 19.3 \quad (2)$$

$$\mathrm{d_{flat}} = 632.3\mathrm{mfp}^2 - 421.4\mathrm{mfp} + 70.2 \quad (3)$$

where mfp is the midfoot pressure ratio of each subject, and d_{high}, d_{norm}, and d_{flat} are Mahalanobis' generalized distances.

For each subject data, d_{high}, d_{norm}, and d_{flat} were calculated and compared. If their minimum value was d_{high}, the subject's arch type was classified as high arch. In the same way, if the minimum was d_{flat}, the subject was classified as being flat footed, and if the minimum was d_{norm}, the subject was classified as being normal.

Table 1 shows the result of the foot arch type classification using the derived discriminants with the setting group (n = 35). Of the 15 subjects classified as high arch using visual analysis, 12 subjects were correctly classified and three subjects were classified as having a normal foot arch. On the other hand, 15 subjects with normal feet and five flat-footed subjects were correctly classified. The sensitivity and specificity of the foot arch were also shown in Table 2. The sensitivity and specificity were sufficiently high in all of the foot arch types.

Table 1 Result of the foot arch type classification by the derived discriminants with the setting group (n = 35)

	High Arch	**Normal**	**Flat foot**
Classified High arch	12	0	0
Classified Normal	3	15	0
Classified flat foot	0	0	5

Table 2 Sensitivity and specifity of the foot arch classified by the discriminants with the setting group (n = 35)

Arch Type	**Sensitivity**	**Specifity**
High Arch	0.80	1.00
Normal	1.00	0.85
Flat foot	1.00	1.00

Next, the developed classification method was applied to the other evaluation group. Table 1 shows the result of the foot arch type classification using the derived discriminants with the evaluation group (n = 23). Of the seven high arch foot subjects, five were classified correctly and two were classified as normal. Of the 13 normal arch foot subjects, 12 subjects were classified correctly, and one were classified as having flat feet. Three flat foot subjects were classified correctly. The sensitivity and specificity of the foot arch were also shown in Table 4. The sensitivity and specificity were sufficiently high in all of the foot arch types in the evaluation group.

Table 3 Result of the foot arch type classification by the derived discriminants with the evaluation group (n = 23)

	High Arch	**Normal**	**Flat foot**
Classified High arch	5	0	0
Classified Normal	2	12	0
Classified flat foot	0	1	3

Table 4 Sensitivity and specificity of the foot arch type classified by the discriminants with the evaluation group (n = 23)

Arch Type	**Sensitivity**	**Specifity**
High Arch	0.71	1.00
Normal	0.92	0.80
Flat foot	1.00	0.95

C. Discussion

The optimal parameter combination was determined by calculating the AIC value. The lowest value was for the case of the midfoot pressure ratio only, and the second one was for a combination of the midfoot area ratio and midfoot pressure ratio. The results were similar to that of the biomechanical analysis. Therefore, the midfoot pressure ratio was considered to be an optimal parameter in terms of both biomechanics and statics.

Next, the classification results obtained by the derived discriminants were sufficiently high in both setting and evaluation groups. Thus, the derived discriminants were believed to be not affected by the sampling group.

In the previous study, we indicated that the first and third quartiles may be candidates for the thresholds of the foot arch type classification [7]. Such quartiles were derived in the setting group (n = 35) of this study. We classified those having a value that is less than that of the first quartile as the high arch group, and classified those having a value that is greater than the third quartile as the flat foot group. Table 5 shows the sensitivity and specificity of the foot arch classified by the quartiles of the midfoot pressure ratio with the setting group were shown in Table 5, and those with the evaluation group (n = 23) were shown in Table 6.

Comparing the derived discriminants, the performance of the quartiles method was found to be significantly affected by the sampling group. On the other hand, the developed method was not affected by the sampling group.

Table 5 Sensitivity and specificity of the foot arch type classified by the quartiles of midfoot pressure ratio with the setting group (n = 35).

Classification parameters	Sensitivity	Specifity
High arch	0.60	1.00
Normal	0.73	1.00
Flat foot	1.00	0.87

Table 6. Sensitivity and specificity of the foot arch type classified by the quartiles of midfoot pressure ratio with the evaluation group (n = 23). Area indicates the midfoot area ratio and pressure indicates the midfoot pressure ratio.

Classification parameters	Sensitivity	Specifity
High arch	0.38	1.00
Normal	0.86	0.54
Flat foot	1.00	0.93

IV. Conclusion

To develop an evaluation system for foot arch types using foot pressure distribution data, a discriminant analysis was performed using data from healthy elderly persons. As a result, the midfoot pressure ratio was selected and discriminants were derived. To evaluate the performance of the classification method, the derived discriminants were applied to data from the other healthy, elderly group. As a result, both the sensitivity and specificity of the foot arch type were found to be adequate. Therefore, the method developed in this study was thought to be highly reliable.

The subjects used in this study were all healthy and elderly. However, more than half of them had foot arch problems, such as flat foot or high arch. Therefore, an evaluation system for foot types is considered to be very important for supporting healthy lifestyles in the elderly.

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