Analysis of 3D Foot Shape Features in Elderly with Hallux Valgus Using Multi-Dimensional Scaling Method

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Abstract

Foot shape data were collected from 489 Japanese elderly subjects aged 70 years or older to identify the features of normal and hallux valgus foot shapes. An INFOOT (I-Ware Laboratory Co., Ltd.), a three-dimensional scanner, was used to measure the foot shapes. The data points obtained by scanning the foot surface shapes were used to develop homologous shape models. The distance between two feet was defined as the sum of the distances between corresponding data points of the two homologous models. The distance matrix was then analyzed using the multi-dimensional scaling method (MDS) to identify the shape features. The analysis was conducted for eight groups (male/female x right/left x normal/hallux valgus) separately. A four-dimensional solution was obtained for each analysis, and each of the obtained axes was interpreted using calculated virtual shapes located at both ends of the axis. The following foot shape features were obtained: 1. foot size, 2. arch height, 3. medial/lateral shank shift, 4. calcaneus valgus/valus, 5. foot width, 6. ankle thickness, 7. dorsal arch height, 8. sphyrion height, and 9. foot abduction/adduction. A MDS analysis using normal feet and hallux valgus feet of the same foot length was also conducted. As a result, female hallux valgus group had more valus heels and lower arch height than female normal group, but some females with hallux valgus had normal arch height. No gender difference was found in the hallux valgus types, while females had lower arches than males. These results suggest that there are two types of hallux valgus in terms of foot shapes, and it is likely that they have similar deformity resulted from different mechanisms.

Keywords: hallux valgus, multi-dimensional scaling, elderly, foot shape feature, arch height

1. Introduction

It is generally believed that the habit of wearing high-heeled shoes with tapering off shape frequently causes hallux valgus [1]. However, it is reported that hallux valgus develops populations that do not have habit of wearing shoes including high-heeled shoes [2, 3, and 4]. Therefore, shoes are not the only cause of hallux valgus. It is thought that hallux valgus is related to various factors besides shoes; malalignment posture, muscle weakness, lifestyle (meal, intensity of activity, style of activity), and inheritance. It is conjectured to the mechanism of hallux valgus appearance that the deformity of foot would occur when external force to foot is beyond tolerance of joint structures. Strength of lower limb muscles may influence the gait, and gait may influence the foot deformation. In order to clarify the relationships between lower limb muscles, gait, and foot deformity, we need to describe the deformation of 3D foot shapes. Hallux valgus has been analyzed based on measurements obtained from X-ray images.

The purposes of the present study are to analyze the variation in the 3-dimensional shapes of normal and hallux valgus feet using Multidimensional Scaling analysis method (MDS) of homologous models of the foot, to identify the features of normal and hallux valgus foot shapes, and to classify the types of hallux valgus feet based on the analyses.

2. Methods

2.1. Subjects and definition of hallux valgus

Subjects were 489 healthy Japanese aged 70 years or older living in Itabashi Ward, Tokyo, who participated in the health examination “Otassha (good health)” by Tokyo Metropolitan Institute of gerontology. The subjects consist of 451 persons sampled randomly and 38 persons recruited non-randomly to increase the number of subjects. Persons who can walk to the measurement hall were chosen as subjects.

In this study, a foot with valgus angle of first metatarsal joint 15 degrees or larger was defined as hallux valgus, because it was difficult to evaluate the M1/M2 angle from the surface shape of the foot (See Figure 1). Valgus angle of first metatarsal joint (Hallux valgus angle: HVA) was calculated by software at the time of foot shape measurement. Foot shape data with deformity called cross toe (the second toe was on the first toe) were not used for the analysis. The foot shape data with missing landmarks were also excluded. Table 1 shows the number of feet used for the analysis. All analyses were conducted for males and females separately and right and left feet separately.

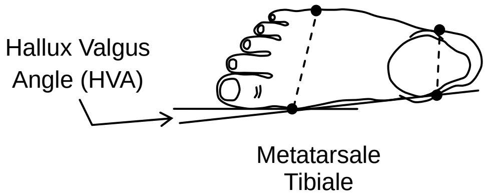

Fig. 1. Definition of angle in diagnosis of Hallux valgus.

Table 1. Number of feet used for the analysis

	Normal feet		Hallux valgus	
	Left	Right	Left	Right
Male	235	253	61	39
Female	117	117	85	82

2.2. Measurement

The foot shape was measured by a three-dimensional foot scanner, INFOOT (I-Ware Laboratory Co., Ltd.). Measurement posture was an erect standing posture with weight distributed equally on both feet. Subject gripped handrail during a scan to stabilize his/her posture. Locations of the following 10 landmarks were also measured: the most medial point of the first metatarsal head (MT: metatarsal tibiale), the most lateral point of the fifth metatarsal head (MF: metatarsal fibulare), center of the second metatarsal head, the most medial point of the navicular, the fifth metatarsal base, the most medial point of the medial malleolus, the lowest point of the medial malleolus (sphyrion), the most lateral point of the lateral malleolus, the lowest point of the lateral malleolus (sphyrion fibulare), and the lateral junction point (Figure 2). Tips of five toes were determined manually. Locations of pternion (rearmost point of the heel) and the rearmost point of the sole just below the pternion were automatically calculated.

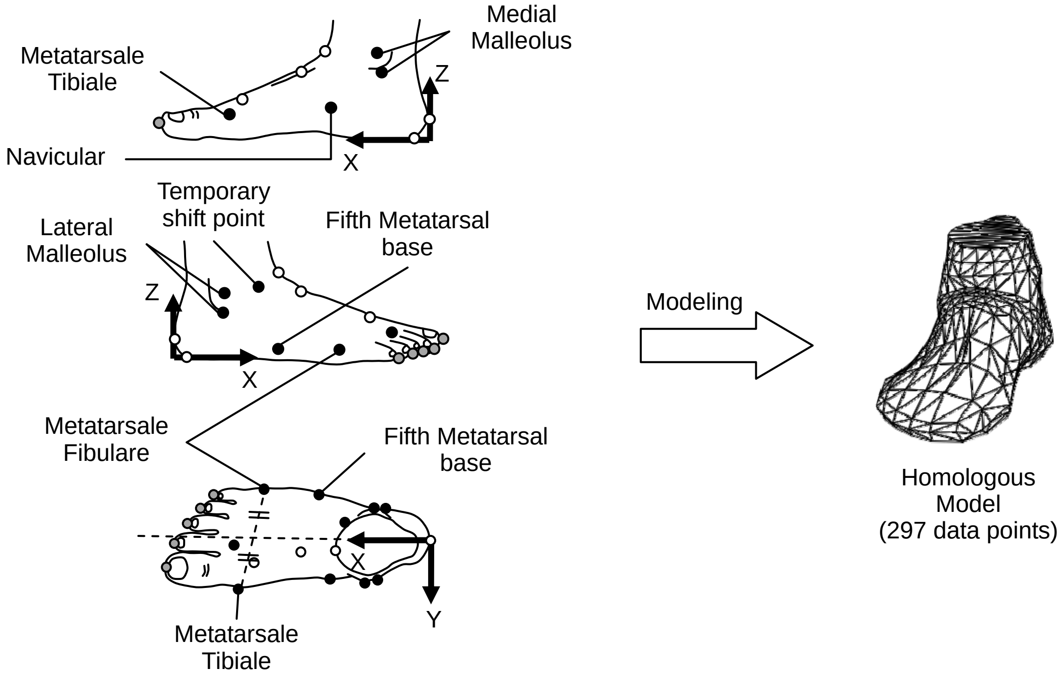

Fig. 2. Location of landmarks on the foot.
Black circles: manually determined on subjects and marker stickers were pasted;
Open circles: automatically calculated;
Gray circles: manually determined on the scanned shape.

2.3. Homologous modeling and statistical analysis of the foot shape

A homologous shape model was created for each foot by using software “Diplus” (I-Ware Laboratory Co. Ltd.). Feet of all individuals were represented by the same number of data points of the same topology by homologous modeling. A homologous shape model of the foot, in present study, consists of 297 data points, which are defined using the landmarks (see Figure 2). A foot-oriented coordinate system was defined as follows: the standing surface was the X-Y plane; the origin was the pternion projected into the standing surface; the X-axis was the line connecting the origin and the mid-point between the MT and the MF projected into the X-Y plane; The Z-axis is perpendicular to the X-Y plane; the Y-axis was the vector product from the Z-axis and the X-axis.

A distance between two homologous foot models was defined as the sum of Euclidean distances between corresponding data points. The distance was calculated for every possible pair of feet, and the distance matrix was analyzed by MDS using HBM (Human Body Statistica, Digital Human Technology Inc.) MDS is a statistical method to calculate independent variables (scales) that resolves the distance relationships between the subjects. The first scale represents the largest variance, the second scale the next largest variance, and so on. Purposes of MDS analyses were to clarify the pattern of right-left differences (males and females, and normal and hallux valgus feet separately) and quantify the difference between normal and hallux valgus feet (males and females separately.
For the analysis to examine the sex difference, only subjects with foot length >=230 mm and <240 mm were selected for both males and females. Foot length was restricted to minimize the effects of allometry: males have larger feet than females, and this may affects the difference in the shape. Similarly, only data from male subjects with foot length>= 240 mm and <250 mm and female subjects with foot length >=220 mm and <230 mm were used for the comparison of normal and hallux valgus feet. Significance of normal-hallux valgus differences and sex differences were tested using the t-test. The level of significance was chosen as $p<0.05$.

3. Results

A four-dimensional solution was calculated for each analysis. Four scales explained more than 90% of the information contained in the original distance matrix in all the analyses (R^2=0.92-0.99). Meaning of each scale was interpreted by comparing virtual shapes located at both ends of the scale.

3.1. Variation of normal foot shape

3.1.1. Female normal foot

Figure 3 shows scattergrams of normal feet of older females based on MDS scales with examples of foot shapes. Two scattergrams on the upper row are results of the left feet, and two scattergrams on the lower row are results of the right feet. Two scattergrams on the left side are based on scores of the first and the second MDS scales, and two scattergrams on the right side are based on scores of the third and the fourth MDS scales. By comparing feet located near both ends of an axis, each scale can be interpreted as follows: the first scale represents the size, the second scale contrasts the valus and valgus calcanei. The second scale of the right foot is also related to the height of sphyrion. The third scale of the left foot was related to the medial/lateral shift of the shank to calcaneus, while the third scale of the right foot contrasts feet with low and high dorsal and plantar arches. The fourth scale contrasts thin and thick minimum leg circumferences in both right and left feet.

3.1.2. Male normal foot

In results of male normal feet, scales with similar meanings with those in the analyses of female normal feet were obtained such as a scale representing the size (right and left Dim-1), a scales related to the arch height (right and left Dim-2, left Dim-3), a scale contrasting medial and lateral shift of shank to the calcaneus (right Dim-2, right Dim-3), and a scale contrasting varus and valgus calcanei (right and left Dim-3). Scales representing variations not observed in female results are also extracted: the second scale of the right foot was also related to the foot abduction/adduction, and the fourth scale of the left foot represents foot width, and the fourth scale of the right foot was related to the medial protrusion of the navicular bone.

3.2. Variation of hallux valgus foot shape

3.2.1. Female hallux valgus foot

Figure 4 shows scattergrams of hallux valgus feet of older females based on MDS scales with examples of foot shapes. Two scattergrams on the upper row are results of the left feet, and two scattergrams on the lower row are results of the right feet. Two scattergrams on the left side are based on scores of the first and the second MDS scales, and two scattergrams on the right side are based on scores of the third and the fourth MDS scales. The first scale represents the size, The second scale, for left foot, was concerned with the dorsal arch height, the ankle height, and the varus/valgus calcaneus. Here, the dorsal arch height differs from the height of the sole arch, and means height from the plantar surface to the foot dorsal. It is possible to regard the dorsal arch height as thickness of mid foot. The second scale, for right foot, was concerned with the dorsal arch height, the ankle height, and the shank medial/lateral shift. The third scale was related to the shank medial/lateral shift for left foot, to the varus/valgus calcaneus for right foot. Since it is thought that the shank medial/lateral shift cause varus/valgus calcaneus, the shank medial/lateral shift is treated almost as same as varus/valgus calcaneus. The fourth scale was concerned with the ankle anterior/posterior position for left, with the foot width for right. The ankle anterior/posterior position is influenced by ankle dorsal/plantar flexion. By ankle dorsal flexion, load is added to the foot and the foot becomes wide. Although the difference of results in MDS was between right and left feet, since two or more features are related to each other such as relation between the shank medial/lateral shift and varus/valgus calcaneus, it is thought that interpretation of foot shape features may be same between right and left foot.

3.2.2. Male hallux valgus foot

In male hallux valgus feet, first scale of both the right and left feet also represents the size. The second scale, for left foot, was related to the varus/valgus calcaneus, the ankle height, and the shank medial/lateral shift. The second scale, for right foot, was related to the dorsal arch height. The third scale was concerned with the dorsal arch height for left, with the ankle height and the shank medial/lateral shift for right. The fourth scale was concerned with the foot width and the ankle diameter for left, with the foot width for right.

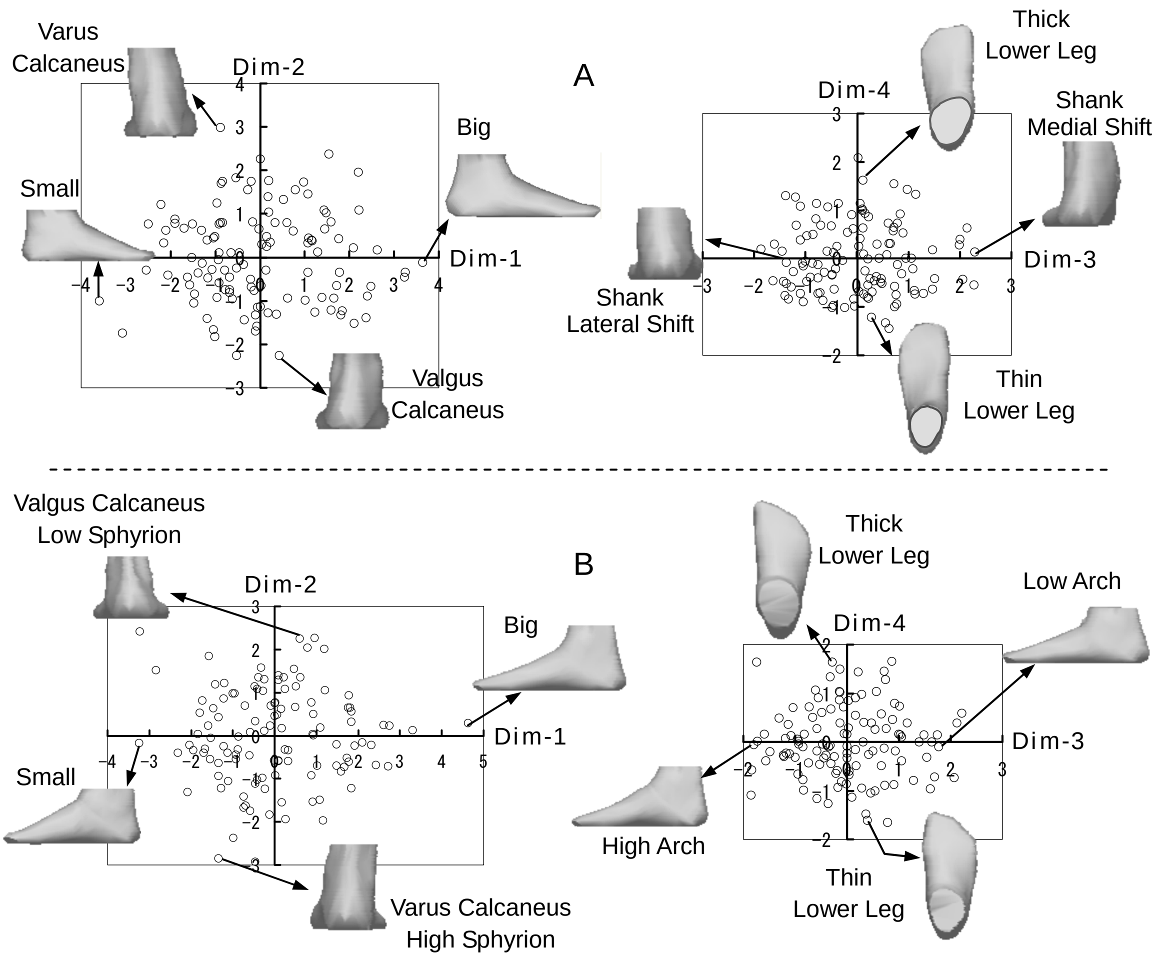

Fig. 3. Results of MDS analysis of female normal feet.
Scattergarms of feet based on MDS scores with examples.
A. Results of the left foot, B. Results of the right foot
Each Dim-1, Dim-2 is the horizontal and vertical axis in two scattergrams on left side.
Each Dim-3, Dim-4 is the horizontal and vertical axis in two scattergrams on right side.

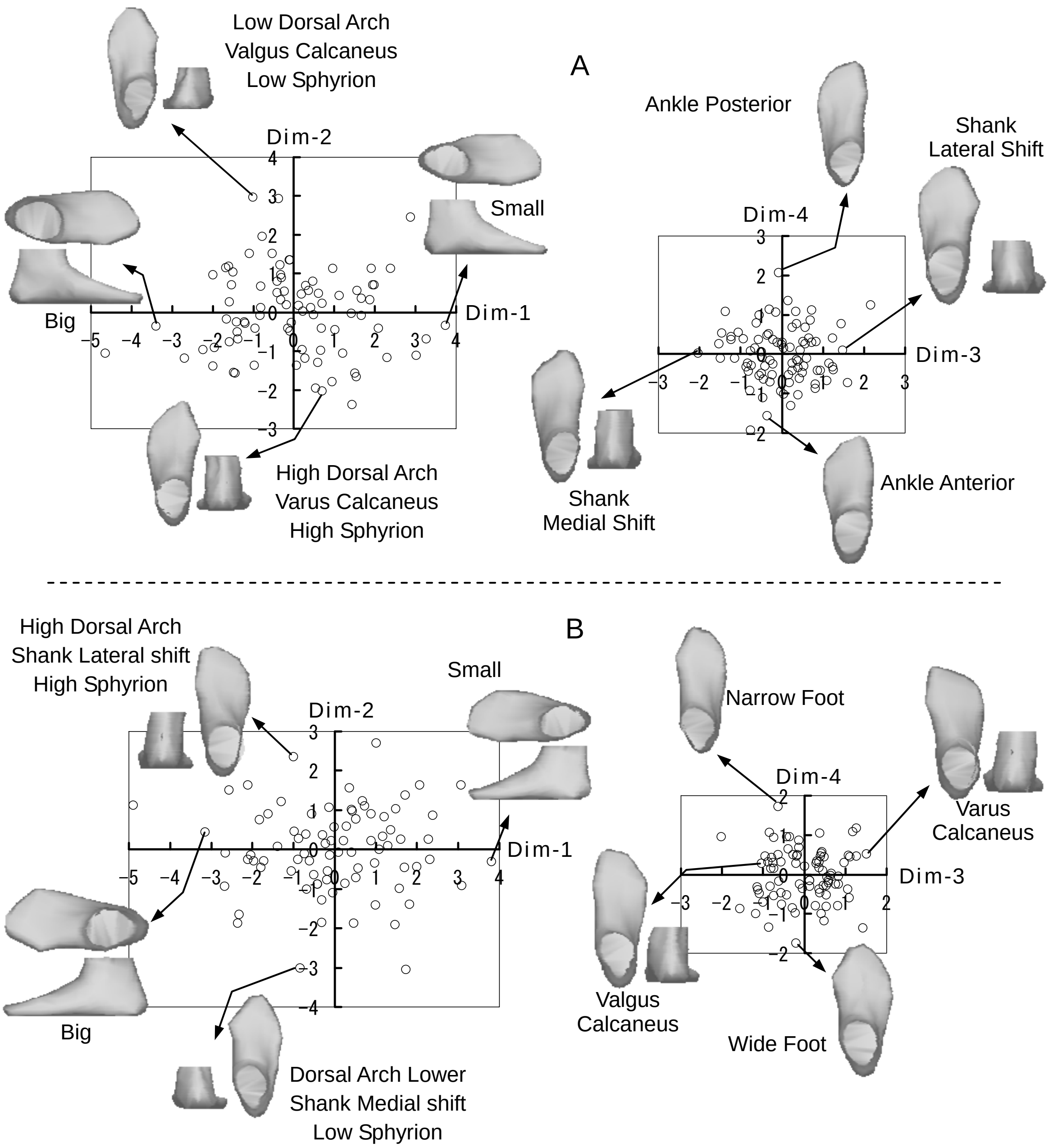

Fig. 4. Results of MDS analysis of female hallux valgus feet.
Scattergarms of feet based on MDS scores with examples.
A. Results of the left foot, B. Results of the right foot
Each Dim-1, Dim-2 is the horizontal and the vertical axis in two scattergrams on left side.
Each Dim-3, Dim-4 is the horizontal and the vertical axis in two scattergrams on right side.

3.3. Difference between the normal and hallux valgus feet

Figure 5 shows scattergram of the normal and hallux valgus feet of females base on scores of the first and second MDS scales. The first scale contrasts feet with large hallux valgus angle, low dorsal arch, valgus calcaneus, and medially shifted shank and feet with small hallux valgus angle, high dorsal arch, varus calcaneus, and laterally shifted shank in both right and left feet. The hallux valgus feet have larger scores for the first MDS scale in both right and left feet. Mean scores of the two groups were significantly different. That is, the hallux valgus group with larger scores for the first scale has lower dorsal and plantar arches, varus calcaneus, and medially shifted shank. However, distributions of the hallux valgus and normal feet overlap considerably. This means not all hallux valgus feet have low arches. The male results were very similar to female results.

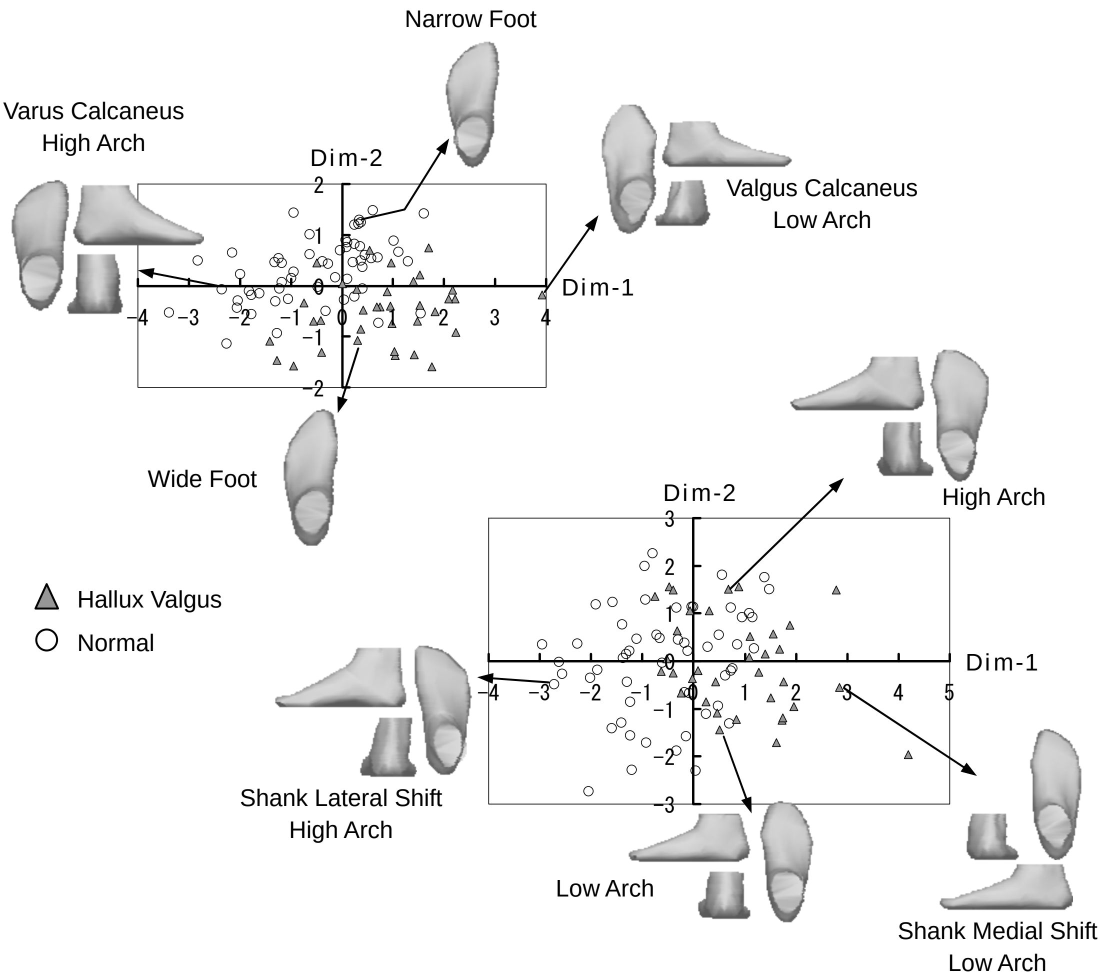

Fig. 5. Results of MDS analysis of female normal and hallux valgus feet of the same foot length. Scattergarms of feet based on MDS scores with examples. Top: results of the left feet, bottom: results of the right feet. Each Dim-1, Dim-2 is the horizontal and the vertical axis in scattergrams.

4. Discussion

4.1. Important characteristics of foot shape connected with movement pattern

The scales obtained by MDS for 3D expression of foot shape were 1. The foot size, 2. The arch height, 3. Medial/lateral shank shift, 4. The calcaneus valgus/valus, 5. The foot width, 6. The ankle thickness, 7. The dorsal arch height, 8. The sphyrion height, and 9. The foot abduction/adduction. Here, the foot abduction/adduction is defined as the whole foot being the form of inside/outside convex. See figure 6 as reference to imaging hallux valgus foot.

The foot size becomes the first scale because it has the largest variation. The size is not a main factor in the relation between a habitual movement pattern and foot deformity. Therefore, scales other than the size factor may be used to describe 3D shape and examine relationships between shape characteristics of the foot and habitual movement patterns. In order to use these 3D foot shape characteristics in diagnosis and evaluation in the medial treatment, grading or classification of each characteristic is necessary.

In medical diagnosis or treatment, important shape factors are those influencing the load on the foot during motion and thus cause deformity. It is thought that such shape factors are the varus/valgus calcaneus, the arch height, and medial/lateral shift of the shank. The present results showed that these factors have large individual variations. Author believes that these factors are related to the loading pattern on the foot during the single support phase. For instance, when the load on the right foot directed more medially during midstance phase in walking, the right calcaneus will become valgus, the arch becomes lower, and the shank shift medially. In the load laterally on the right foot, it is likely that opposite things occur. Additionally, if internal twist movement of lower limb occurs during midstance phase in walking, the calcaneus will become valgus, the arch become lower, and the shank rotate internally. Inman had described the motor chain that foot arch lowers at the same time when the shank rotates internally [5, 6]. For example, if the upper-body is twisted right, the left leg becomes an internal rotation, as described by Inman, and the left arch will decrease. In the evaluation of foot shape with hallux valgus, it is recommended for a therapist to examine the foot focusing the following three characteristics, the varus/valgus calcaneus, the arch height, and the medial/lateral shift of the shank to calcaneus.

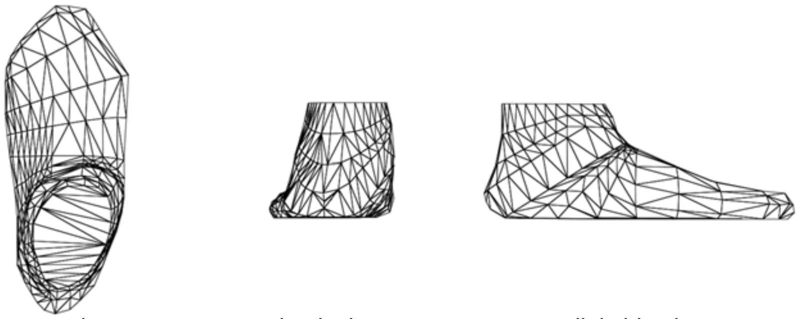

Fig. 6. Typical homologous shape model of female hallux valgus foot

4.2. Possibility of type classification of foot shape with hallux valgus

The hallux valgus foot in the older tends to have lower arch and stronger valgus calcaneus than the normal foot (See Figure 5), but some hallux valgus foot have normal arch. If there are two loading patterns on the foot during gait as described in the previous section, dividing the foot type into two is possible. Here, the hypothesis that the difference of the way of the load might decide the type of foot deformity is set up.

Figure 5 shows the possibility of appearing to the height of the arch in the difference between hallux valgus and a normal foot. Therefore, the foot shape with hallux valgus can be classified into the type1 with a low arch and the type2 with a high arch based on zero on the scale of the height of the arch.

Kim, et al. has reported on data that proves the existence of these two foot types [7]. In the data of center of pressure on foot sole with hallux valgus, there were the one type to draw trajectory from heel to ball of hallucal and the another type to draw trajectory passing from heel to second toe through lateral on sole. Here, it is thought that the former is the low arch type1, and the latter is the high arch type2. Blomgren and others also have reports that draw tracks so that hallux valgus patient's center of pressure may pass over the sole outside [8]. These reports suggest that it be appropriate to classify hallux valgus into the type of the height of the arch.

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References

1. Kato, T., Watanabe, S., (1981): “Etiology of hallux valgus in Japan”. Clinical Orthopaedics and Related Research, 157, pp.78-81.
2. Barnicot, N.A., Hardy, R.H., (1955): “The position of the hallux valgus in West Africans”, Journal of Anatomy, 89(3), pp.355-361.
3. Lam, Sim-Fook, Hodgson, A.R., (1958): “A comparison of foot forms among the non-shoe and shoe-wearing Chinese population”, Journal of Bone and Joint Surgery American, 40(5), pp.1058-1062.
4. Shine, I.B., (1965): “Incidence of hallux valgus in a partially shoe-wearing community”, British Medical Journal, 26, pp.1648-1650.
5. Inman, V.T., Ralston, H.J., Todd, F., (1981): “Human walking”, Williams & Wilkins, pp.15-21.
6. Inman, V.T., (1974): “Hallux valgus: A review of etiologic factors”, Orthopedic Clinics of North America, 5(1), pp.59-66.
7. Kim, S.H., et al., (2005): “Biomechanical measurement and analysis of moving dysfunction in person with hallux valgus”, Journal of the Society of Biomechanisms, 29(1), pp.36-46.
8. Blomgren, M., Turan, I., Agadir, M., (1991): “Gait analysis in hallux valgus”. Journal of Foot Surgery, 30(1), pp.70-71.