Development of a quantitative measurement system for three-dimensional analysis of foot morphology using a smartphone*

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***Abstract*— Existing techniques for measuring foot morphology are invasive or cumbersome. A new technique was developed using a smartphone, which can measure foot morphology to within 1 mm. This is shown to be applicable to the prediction of hallux valgus, which allows for early intervention.**

I. Introduction

Human feet consist of 26 bones connected by muscles and ligaments. The arch of the foot has three fundamental functions: support, shock absorption, and weight bearing. Bone structure and muscle function are the most important factors for achieving these functions. The bone structure of the foot forms during childhood and develops its final configuration as the body matures.

Factors that affect bone development include genetics [1], body weight [2], footwear such as shoes [3,4], and injury. One variation in foot shape is called flat feet [5]; however, a unified understanding of the condition has not yet been established. Some researchers have reported that it has no correlation with obesity and body weight.

Many studies have shown that the incidence of flat feet among children decreases with age and that the medial longitudinal arch (MLA) develops naturally with age. It has been established that the MLA is developed at the age of nine [6].

Flat or high arch feet have been examined. Evaluations of foot configuration include measurements of the footprint and the height of the navicular bone as well as x-ray imaging [7], which are utilized with Clarke's angle and the Denis method [8]. These measurements are affected by the standing posture of the subject. Moreover, most of the analysis is handled manually, which is a cause of incorrect measurements and is cumbersome.

The purpose of such a foot analysis is not to identify the existence of flat or high arch feet, but to measure features of the bone structure and to evaluate their development. Currently, feet are divided into three groups: flat, normal, and high arch feet; however, there is no absolute standard method for the evaluation of feet in clinical settings [9].

In this study, we developed a 3D foot morphology measurement system to quantitatively measure the features in the foot bone structure in a simple and convenient manner. Here, we discuss the precision of the developed system and consider the parameters of the feet with a focus on hallux valgus in children. The etiology of hallux valgus deformities is complex. Besides intrinsic factors, which include heredity factors [10], the first metatarsal length [11] and hypermobility of the metarsophalangeal joint, extrinsic factors are also involved.

The results of this study will aid in the early prediction of such conditions, enabling early intervention and improvements to quality of life.

II. Development of The three-dimensional foot morphology measurement system

X-ray and laser systems are used to evaluate the bone structure of feet. The x-ray method is invasive, and the margin of error may be large depending on the imaging angle. The laser method allows us to evaluate the exterior of feet with high precision, but it is expensive, heavy, has a high risk of failure, and measurements may be affected by dirt or foot size.

In this study, we used a smartphone to quantitatively measure the bone structure of feet in a simple and convenient manner. We made this choice because smartphones are ubiquitous, there is no device lag, and it is cost effective.

The system creates a 3D replica of the exterior of a subject's foot by recording a video of its perimeter using a smartphone; the surface features can then be extracted and tracked automatically using the analysis software. Video data are analyzed by placing them on a cloud system, so there is no need to download software to a smartphone. Analysis is possible as long as the foot is filmed continuously, even if the camera shakes when filming by hand. The video data are divided into still image data. The, the system creates a three-dimensional wireframe model by tracking features using the structure from motion (SfM) for the still image data. The system renders colors as additional information.

In the developed analysis system, it is possible to perform floor surface deletion, and analyze the feature amount extraction of the foot part, and the distance of the designated position semi-automatically. The video is saved and analyzed in the cloud. This means that participants do not have to

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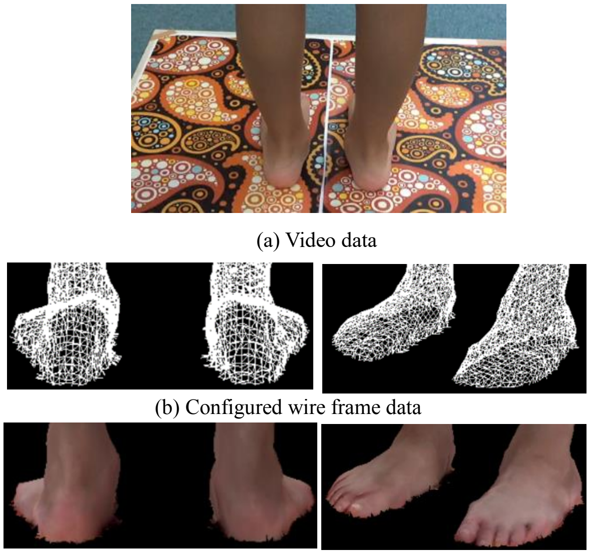


(a) Video data

(b) Configured wire frame data

(c) Rendered wire frame data

Figure 1. Results obtained from 3D foot measurement system

download an app to their smartphone and there is no burden on their device as a result of the data analysis.

Fig. 1 shows a portion of the analysis and the video recorded using a smartphone. The system was configured to evaluate the highest point of the instep (instep height: IH), highest point of the metatarsal bones (forefoot arch thickness: FAT), foot length, first metatarsal bone head-heel-second toe angle (FHS angle), second toe-instep-heel angle, pronation, and supination angles of the heels.

III. Methods

A. Verification of system accuracy

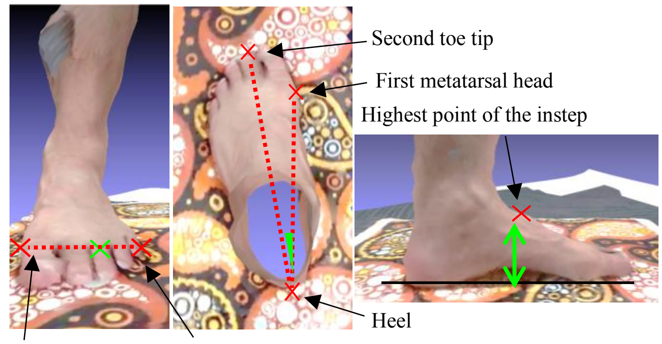
To inspect the precision of the system, three 5-mm stickers were applied to the feet of 20 subjects at the highest point of the instep, medial malleolus, and lateral malleolus. The size measured by the system was then compared to the true value. The precision analysis was not affected by age or sex because the same marker was used for all the subjects.

This study was approved following an ethical evaluation by Tokyo Healthcare University. The content of the study was explained to the guardians of the children and their school, and signed consent was then obtained.

B. Extraction experiment of feature quantity of foot structure

The subjects included 197 elementary students aged 10 and 11. To conduct 3D foot measurements, the subject was asked to stand still with their feet apart, a distance of 18 cm between each heel and 22 cm between each hallux. One recording, 12 s long, was made for each subject.

The analytical parameters of the 3D foot measurement system were the foot height ratio, which is the IH divided by the foot length (IH ratio); the metatarsal bone height ratio, which is the FAT divided by the foot length (FAT ratio); and the FHS angle, as shown in Fig. 2. The value was standardized



(a) First metatarsal bone head- heel-second toe angle

(b) Highest point of the metatarsal

(c) Highest point of the instep

Figure 2. Analytical parameters of the 3D foot measurement system

by foot size because the height of the instep and metatarsal bones has a significant correlation with foot size. In addition, the presence of hallux valgus was visually checked. Hallux valgus is defined as a lateral deviation exceeding 15°.

IV. Results

A. Verification of system accuracy

Table I shows the results of the precision inspection of the 3D foot measurement system. On average, the stickers were found to be 4.90±0.23 mm, a 98% precision level. This means that we were able to detect the size of the markers to within 0.1 mm. Additionally, we achieved precisions of 99% for the instep and medial malleolus, and 96% for the lateral malleolus.

B. Foot structure features of the subjects

The percentage of subjects with hallux valgus on either foot was 32.3%. Table II shows the evaluation parameters of the 3D foot measurement system separated depending on the presence of hallux valgus. The IH ratio was higher in the normal group than in the group with hallux valgus, but the difference was not significant. The FAT ratio was significantly higher for the normal group and the FHS angle was significantly higher for the group with the condition.

Table III shows the correlation coefficients for the parameters obtained from the 3D foot measurements. A coefficient of 0.54 was observed for the IH and FAT ratios.

Table IV shows the results of a multiple logistic regression analysis that predicts the presence of hallux valgus. The results of the model $\chi 2$ test and each variable were significant. These were investigated through multiple logistic regression analysis by the variable increase method based on the likelihood ratio. The inspection result was $p = 0.797$ and the percentage of correct classifications was 72.6%. There were no predicted values exceeding ±3SD with respect to the measured values.

V. Discussion

A. Verification of system accuracy

Problems such as hallux valgus and flat feet cause various issues such as foot pain, osteoarthritis disorder, and increased risk of falling [12,13]. In this study, we developed a measurement system that uses a smartphone to measure the features of the feet quantitatively and in a convenient manner. To inspect the precision level of the system, 5-mm markers

TABLE I. VERIFICATION OF SYSTEM ACCURACY

	Instep (mm)	Medial malleolus (mm)	Lateral malleolus (mm)
Average	4.94	4.95	4.81
SD	0.13	0.19	0.32

TABLE II. MEASUREMENT RESULT BASED ON PRESENCE OR ABSENCE OF HALLUX VALGUS

	Normal group	Hallux valgus group	p value 95% CI
IH ratio (%)	27.2	26.6	P = 0.08 0 to 0.01
FAT ratio (%)	14.8	14.2	P = 0.01, 0.012 to 0.091
FHS angle (degrees)	13.8	14.4	P < 0.01, −1.01 to −0.31

TABLE III. CORRELATION COEFFICIENT OF PARAMETERS OF FOOT 3D MEASUREMENT

	IH ratio	FAT ratio	FHS angle
IH ratio	1	0.54**	−0.07
FAT ratio	0.54**	1	0.23**
FHS angle	−0.07	0.23**	1

** p<0.01

TABLE IV. RESULTS OF MULTIPLE LOGISTIC REGRESSION ANALYSIS ON HALLUX VALGUS

		FAT ratio	FHS angle	Constant
	Partial regression coefficient	−52.672	0.684	−2.769
	Significance probability, p	0	0	0.254
	Odds ratio	0	1.982	-
Confidence interval of odds ratio	Lower limit	0	1.446	-
	Upper limit	0	2.718	-

Model χ2 test: p<0.01

Percentage of correct classifications: 72.6%

were applied to the subjects' feet and the system measured their sizes. The average recoded size was 4.9 mm. A precision of 0.5 mm or better was obtained, even when the standard deviation range was included. This system constructed a 3D replica of feet from a video of the foot perimeter; thus, we were concerned that the precision was lower at the inside of the feet, which is difficult to capture. Therefore, a marker was applied in the medial malleolus. The results showed that the precision was equivalent to that of the instep, which was less than 0.4 mm. In contrast, the precision for the lateral malleolus, which is easier to film, was lower than for other parts of the foot; the value here was approximately 0.6 mm. This is because the bone structure of the lateral malleolus projects sharply such that the marker applied at the peak is curved. Therefore, when the liner distance was measured on the 3D structure the output value was low.

The height and angle are the parameters of the feet feature points; however, they are easily affected by the posture of the subject. For example, the flexible structure of the foot means that they are affected by the weight of the body when in the standing position compared with its absence in the sitting position. The navicular bone moves by several millimeters depending on the presence or absence of load. Measurements using 3D video analysis or lasers can be carried out with a precision of 1 mm or better, and the same precision was achieved with this system. We believe that it is possible to estimate the risk of hallux valgus and to evaluate the development of children's feet from a static viewpoint and that it is also possible to carry out inspections, including the presence or absence of a load, from the dynamic viewpoint.

The system captured the parameters of the foot features with high precision.

B. Foot structure features of the subjects

We focused on hallux valgus as an example of a change in the bone structure of a child's foot. Hallux valgus is defined as a state where the hallux is bent toward the second toe by 15° or more. Causes include loss of the anterior transverse arch due to weakened muscles, pronation of the metatarsus (flattened foot), and widened angles of the hallux due to the flexibility of the hallux thenar.

A previous study showed 23% pooled prevalence for Hallux valgus in adults aged 18–65 years, and 35% in people aged over 65 years. Prevalence increased with age and was higher in females compared with males [14]. The percentage of subjects with hallux valgus on either foot was 32.3%. It was inferred that the prevalence rate of hallux valgus was higher in children than in elderly people.

With this system, we tried to evaluate the IH and FAT ratios as indices of the MLA and forefoot arch, respectively, in addition to the FHS angle as an index of the hallux angle. The results show that the IH ratio was lower for the group with hallux valgus than for the normal group; however, the difference was not significant. The anatomical development of the foot increases at approximately age 10 owing to the increase in muscle strength, functional improvement of ligaments, and progression of ossification and other anatomical changes [15]. It is necessary to investigate the effects of foot pressure distribution because flattening of the

MLA, such as the pronation of the metatarsus, is a risk factor for hallux valgus.

We found that the FAT ratio was lower and the hallux angle was wider among the hallux valgus group compared with the normal group. It is understood that the FAT ratio becomes higher during the development process along with the MLA. However, the hallux thenar cannot bear the load (center of pressure) and from biomechanics we know that the muscle function supporting the hallux thenar is loosened owing to the influence of the flattening forefoot. Thus, the load is applied to the inner portion of the hallux when a person kicks out their step. Therefore, we can assume that the bone structure changes, the heel angle becomes wider, and the formation of hallux valgus progresses as a result. Thus, children whose FAT ratio is decreasing and whose FHS angle is increasing can be classified as at risk of hallux valgus from the viewpoint of the mechanism of hallux valgus occurrence.

C. Correlation coefficient of measurements and prediction of hallux valgus

Table III shows the correlation between the three measured parameters. There was a correlation between the IH and FAT ratios and there was a slight correlation between the FAT ratio and the FHS angle.

Both the IH and FAT ratios reflect the arch structures of the foot [16]. This means its development is related to these factors. The peroneus longus is related to the MLA and the transverse head adductor pollicis muscle is related to the forefoot arch. Kinematic parameters such as intorsion and extorsion of the fibular tarsal bone, flexibility of the metatarsus, and movable nature of the toes, as well as environmental parameters such as shoes, affect the features of foot arches. Therefore, the correlation between the IH ratio (MLA) and FAT ratio (forefoot arch) was found to be 0.5.

The FAT ratio, which is highly related to hallux valgus, was adopted for the multiple logistic analysis owing to the significant correlation between the IH and FAT ratios. Hence, a result that was significant for prediction when combined with the FHS angle was obtained. The distinction accuracy ratio was 72.6% in this model and we assume that the precision level may be improved by adding other anatomical and kinetic parameters.

VI. Conclusions

In this study, we developed a 3D foot measurement system that uses a smartphone to measure the bone structure of the foot quantitatively and conveniently. We used this to conduct a precision inspection and risk prediction for hallux valgus. The results were sufficiently precise to allow this technique to be used to evaluate a child's risk of hallux valgus. This approach will allow for early interventions that could improve quality of life.

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