Analysis of foot skeletal structure by 3D foot scanner on smartphone

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ABSTRACT

Background: The influence of foot skeletal structure on hallux valgus (HV) is poorly understood, so its detailed understanding at an early stage is required for prevention. In this study, a system using a 3D foot scanner on smartphone was developed for the purpose of clarifying relationships between skeletal features and the degree of HV risk.

Methods: This system analyzes the foot skeletal structure by sending 2D video images recorded on smartphone to a computer or cloud server, where the 3D foot skeleton model is constructed by the 2D images. This system was developed to identify 10 skeletal features that are expected to be associated

20 with hallux valgus. The participants comprised 419 individuals (40–89 years), and they maintained a
21 standing pose with their toes 12 cm apart and heels 8 cm apart during the video recording. The height
22 and weight were additionally measured to calculate BMI.

23 Results: The study results showed that age-based variations in the foot skeletal features were observed
24 slightly for men whereas distinctively for women. It was observed for women that the great toe-first
25 metatarsal head-heel (GFH) angle increases with age, so it suggests that the increase of the GFH angle
26 characterizes the development of HV. The multiple regression analysis reveals that the features
27 determining the GFH angle are the second toe-heel-navicular angle and the axis of the bone distance
28 among the skeletal features related to the midfoot, and the transverse arch length and height among
29 those related to the forefoot. Their adjusted coefficients of determination were 0.52 and 0.48 for men
30 and women, respectively.

31 Conclusion: Using a 3D foot scanner on smartphone, we developed a simple method to access the
32 skeletal structure of the foot related to HV risk.

33 Trial registration: University hospital Medical Information Network- Clinical Trials (UMIN-CTR)
34 with the number: UMIN 000037694. Registration date: 20/08/2019.

35 Keywords: foot 3D scanner, smartphone, hallux valgus

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39 BACKGROUND

40 Hallux valgus (HV) is a common deformity characterized by abnormal angulation, rotation and lateral
41 deviation of the great toe at the first metatarsophalangeal joint, and it occurs widely across all age
42 groups. The prevalence for HV is 23% in adults aged 18–65 years and 35.7% in elderly people older
43 than 65 years[1], and it is also higher for women than for men (30% vs. 13%)[1].

44 It has been reported that assessing the skeletal features of the foot is effective for examining HV[2].

45 Several factors have been reported to be associated with HV, such as gender[1,3], age[1], BMI[2], first
46 metatarsal length[4,5], flatfoot[6], osteoarthritis[7,8] and footwear[9]. However, the degree to which
47 foot skeletal influences HV is poorly understood[10]. As HV is highly prevalent, understanding the
48 skeletal features of the foot at an early stage is required for prevention of HV. Quantitative analysis of
49 foot shape is important for not only clinical assessment of foot deformities[11] but also a number of
50 applications related to the ergonomic design of footwear, foot orthotics, insoles and so on.

51 There are mainly two methods for assessing the skeletal features of the foot region: laser 3D surface
52 scanners and X-ray. Laser 3D surface scanners are expensive but they are often used to create
53 custom-made shoes that are perfectly matched to the shape of the foot[11,12]. They have been used to
54 assess aspects of foot shape such as length and circumference, but no prior study has examined their
55 use for analyzing the skeletal features of the foot. On the other hand, X-ray is invasive and can be used
56 only in medical institutions. In principle, as it produces a 2D image, there is room for error in
57 measurement because of the photography angle, and furthermore the assessment process is dependent

58 on the doctor's subjectivity. Nix et al. noted that HV is not adequately defined using X-ray, and there
59 is no attempt to adjust for significant differences between groups[13].

60 Therefore, in this study, a simple 3D foot scanner system was implemented by a smart phone and a
61 remote computer. By analyzing the skeletal features of the foot measured for men and women in
62 different age groups, we suggest that some of them can be preventive indexes for the risk of HV.

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64 METHODS

65 Development of a Foot Morphology 3D Scanner on Smartphone

66 In this study, a 3D scanner system that can analyze the skeletal features of an individual's own foot
67 was developed. The key characteristic of this system is that its main hardware is a smartphone. As
68 smartphones are now widely used devices, many people will be able to use this system using the
69 devices' built-in cameras.

70 This system analyzes the skeletal features of the foot by sending 2D video images recorded on the
71 smartphone to a computer or cloud server. Thus, the system does not require particularly high
72 specifications. The video images can be recorded manually as long as the frame does not leave the foot
73 during the recording. The spatial resolution of this system is 0.5 mm in an optimal environment, and
74 the reproducibility is high[14].

75 The features of the foot region assessed in this study were the tip of the hallux, tip of the second toe,
76 inside of the first metatarsal head, navicular bone, protruding part of the calcaneus, outside of the fifth

77 metatarsal head, and talus head, all of which can be automatically detected by this system. To confirm
78 that the system can correctly detect these skeletal features, they were also identified via palpation by a
79 physical therapist who understands the skeletal construction of the foot. Good agreement was
80 confirmed in both results, so it can be considered that the developed method properly grasps the
81 skeletal features.

82 Figures 1 (a)-(d) show the definitions of foot skeletal features assessed in this study. The instep height
83 (IH) is the distance between the sole and the talus head at the highest point of the instep; the navicular
84 height (NH) is the distance between the sole and the navicular bone; and the instep (IS) angle is the
85 angle formed among the tip of the hallux, the talus head and the heel (see Fig. 1 (a)). The second toe-
86 heel-navicular (SHN) angle is the angle formed among the tip of the second toe, the navicular bone
87 and the heel (see Fig. 1 (b)). The transverse arch length (TAL) is the distance between the inside of the
88 first metatarsal head and the outside of the fifth metatarsal; the transverse arch height (TAH) is the
89 maximal distance between the sole and the line touching the upper surface of the forefoot giving the
90 TAL (see Fig. 1 (c)). The metatarsophalangeal heel (MPH) angle is the angle formed among the inside
91 of the first metatarsal head, the heel and the outside of the fifth metatarsal head; the great toe-first
92 metatarsal head-heel (GFH) angle is the angle formed among the tip of the hallux, the inside of the
93 first metatarsal head and the heel; and the axis of the bone distance (ABD) is the distance from the
94 center line between the heel and the tip of the second toe when the coordinate point of the talus head
95 is projected to the floor (see Fig. 1 (d)). In addition to these, to determine the influence of toe length,

96 the great toe-second toe ratio (GSR) is measured, which is the ratio of the distance between the tip of
97 the second toe and the heel to the one between the tip of the hallux and the heel. Consequently, the
98 10 aforementioned features are calculated by a 3D foot scanner, however, these distance-based features
99 are influenced by the foot length, in other words, the size of each parameter varies depending on the
100 size of the foot. Therefore, they were standardized by dividing each by the distance between the heel
101 and the hallux (the length of the foot) and multiplying by 100. In addition, to assess the influence of
102 personal physique, the height and weight for each individual participant were also measured to
103 calculate BMI.

104 From the above definitions of the foot skeletal features, it can be understood that the IH is an index
105 measuring the transverse arch, the SHN angle is an indicator of pronated feet, TAL and TAH are indices
106 of the lateral arch, the GFH angle is an indicator of HV, and the ABD indicates the point at which the
107 skeleton is out of alignment. Note that the HV angle, which is defined as the angle between the
108 longitudinal axis of the first metatarsal and that of the proximal phalanx [15], is clinically used to grade
109 the severity of HV, such as Mild: 15–20°, Moderate: 21–39° and Severe: $\geq 40^\circ$ [15]. In this study,
110 much attention is paid to the GFH angle as a substitute for the HV angle that can be measured only by
111 x-ray. Finally, Table 1 summarizes the 10 skeletal features.

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115 TABLE 1 THE DEFINITIONS OF FOOT SKELETAL FEATURES

Abbreviation	Meaning	Definition
IH	Instep height	Distance between the sole and the talus head at the highest point of the instep
NH	Navicular height	Distance between the sole and the navicular bone
IS	Instep angle	Angle formed among the tip of the hallux, the talus head and the heel
SHN angle	Second toe-heel-navicular angle	Angle formed among the tip of the second toe, the navicular bone and the heel
TAL	Transverse arch length	Distance between the inside of the first metatarsal head and the outside of the fifth metatarsal
TAH	Transverse arch height	Maximal distance between the sole and the line on the metatarsals giving the TAL
MPH angle	Metatarsophalangeal heel angle	Angle formed among the inside of the first metatarsal head, the heel and the outside of the fifth metatarsal head
GFH angle	Great toe-first metatarsal head-heel angle	Angle formed among the tip of the hallux, the inside of the first metatarsal head and the heel
ABD	Axis of the bone distance	Distance from the center line between the heel and the tip of the second toe when the coordinate point of the talus head is projected to the floor
GSR	Great toe-second toe ratio	Ratio of the distance between the tip of the second toe and the heel to the one between the tip of the hallux and the heel

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117 Subjects

118 Subjects were recruited through advertisements published through the public relations department
 119 of a city. All subjects, who were capable of walking without assistance, signed a consent form prior to
 120 participation, where the study design had been approved by the Ethical Review Board in Ryotokuji

121 University (Authorization number: 1909).

122 The target group was consisted of 419 people (age range, 40–89; mean age, 62.8 ± 12.4 years),
123 including 151 men (mean age, 65.6 ± 11.0 years) and 268 women (mean age, 63.8 ± 12.4 years). The
124 gender and age of the participants are shown in Table 2. The inclusion criterion was an age of 40–90
125 years, whereas the exclusion criteria were as follows: lower limb musculoskeletal disorders; inability
126 to walk independently; concomitant systemic diseases; clinical signs of joint laxity; and major lower
127 limb trauma.

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129 Measurement Methods

130 The measurements were taken using a commercially available smartphone (iPhone 6). The
131 participants maintained a standing pose with their toes 12 cm apart and their heels 8 cm apart during
132 the measurement. An individual measurer held the smartphone and recorded an approximately 12-sec
133 video images panning each subject's feet. The features of the subject's feet identified by a physical
134 therapist's palpation were noted by sticking on a 4-mm diameter marker. Note that as the measurements
135 were similar between the left and right feet, the 3D foot skeletal model only on the right foot images
136 were constructed.

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140 TABLE 2 SUBJECT CHARACTERISTICS

		Number of subjects	Age	Height (m)	Weight (kg)	BMI
Men	Total	151	65.6 ± 11.0	1.669 ± 0.058	67.1 ± 10.2	24.0 ± 3.2
	40–64 years	50	52.5 ± 7.4	1.700 ± 0.054	72.4 ± 11.1	25.1 ± 3.9
	65–74 years	70	69.1 ± 2.9	1.667 ± 0.055	65.2 ± 9.2	23.4 ± 2.8
	>75 years	31	78.6 ± 3.7	1.625 ± 0.039	62.8 ± 7.2	23.8 ± 2.6
Women	Total	268	62.8 ± 12.4	1.544 ± 0.060	55.0 ± 9.4	23.1 ± 3.7
	40–64 years	120	51.2 ± 8.1	1.572 ± 0.053	57.6 ± 10.2	23.3 ± 4.1
	65–74 years	103	69.4 ± 2.6	1.533 ± 0.044	54.1 ± 8.2	23.1 ± 3.5
	>75 years	45	78.7 ± 3.1	1.493 ± 0.069	50.1 ± 7.3	22.5 ± 3.1

141 Data are presented as the mean ± SD

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143 Statistics Analysis

144 SPSS version 24 was used for statistical analysis on the measured data. In the analysis, comparisons

145 of the feature means were performed using Student's t-test for unpaired data; statistically significant

146 differences between the feature means were assessed using one-way ANOVA with Tukey's post hoc

147 test; relationships among the features were explored using Pearson's correlation coefficient; multiple

148 linear regression was used to find features strongly associated with the GFH angle; and the p-value of

149 0.05 was considered statistically significant.

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151 RESULTS

152 Measurements of Features

153 Table 3 shows the measurements obtained using the 3D foot scanner by gender. For men, no variation
154 among age groups was observed for any features excluding GSR. For women, on the other hand,
155 variations among age groups were observed for the NH, IS angle, MPH angle, TAL, TAH and GFH
156 angle.

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168 TABLE 3 THE RESULTS OF 3D FOOT SCANNER MEASUREMENTS

	Total	40–64 years	65–74 years	>75 years	F value, p value
IH	29.2 ± 2.5	29.4 ± 2.6	28.8 ± 2.3	29.5 ± 2.9	$p = 0.39$
NH	19.5 ± 2.4	19.5 ± 2.4	19.5 ± 2.3	19.6 ± 2.6	$p = 0.98$
IS angle [degrees]	133.4 ± 5.9	133.2 ± 5.6	133.5 ± 6.1	133.5 ± 6.1	$p = 0.97$
MPH angle [degrees]	33.0 ± 1.7	32.6 ± 1.8	33.1 ± 1.8	33.1 ± 1.4	$p = 0.12$
TAL	41.2 ± 2.0	40.8 ± 2.0	41.4 ± 2.1	41.5 ± 1.7	$p = 0.22$
TAH	16.2 ± 1.3	16.1 ± 1.4	16.1 ± 1.1	16.5 ± 1.5	$p = 0.26$
GFH angle [degrees]	33.0 ± 6.1	32.6 ± 5.6	33.5 ± 6.0	32.6 ± 7.2	$p = 0.65$
SHN angle [degrees]	22.2 ± 3.0	22.5 ± 3.2	22.0 ± 2.9	22.3 ± 3.1	$p = 0.64$
ABD	4.18 ± 2.53	4.37 ± 2.57	3.99 ± 2.45	4.31 ± 2.67	$p = 0.69$
GSR	0.99 ± 0.02	1.00 ± 0.02	0.99 ± 0.02	0.99 ± 0.02	$F(2,148) = 4.21, p < 0.02$
BMI	24.0 ± 3.2	25.1 ± 3.9	23.4 ± 2.8	23.8 ± 2.6	$F(2,147) = 4.11, p < 0.02$

169 Men

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	Total	40–64 years	65–74 years	>75 years	F value, p value
IH	28.3 ± 2.5	28.4 ± 2.5	28.3 ± 2.5	27.6 ± 2.6	p = 0.17
NH	18.0 ± 2.6	18.2 ± 2.4	18.3 ± 2.5	16.9 ± 3.0	F(2,265) = 4.76, p <0.009
IS angle [degrees]	136.1 ± 5.8	135.3 ± 5.4	135.8 ± 6.1	139.0 ± 5.6	F(2,265) = 7.08, p <0.001
MPH angle [degrees]	33.6 ± 2.1	33.2 ± 2.0	33.9 ± 2.3	34.2 ± 1.6	F(2,265) = 5.82, p <0.001
TAL	42.0 ± 2.5	41.4 ± 2.3	42.3 ± 2.7	42.7 ± 2.0	F(2,265) = 5.81, p <0.003
TAH	15.9 ± 1.4	16.0 ± 1.5	16.0 ± 1.3	15.3 ± 1.3	F(2,265) = 4.48, p <0.01
GFH angle [degrees]	35.9 ± 6.6	34.5 ± 5.5	36.1 ± 6.8	39.3 ± 7.4	F(2,265) = 9.25, p <0.001
SHN angle [degrees]	23.3 ± 3.4	23.1 ± 3.4	23.3 ± 3.4	23.6 ± 3.3	p = 0.98
ABD	4.47 ± 3.05	4.46 ± 2.79	4.43 ± 3.25	4.61 ± 3.31	p = 0.95
GSR	0.99 ± 0.02	0.99 ± 0.02	0.99 ± 0.02	0.99 ± 0.02	p = 0.80
BMI	23.1 ± 3.7	23.3 ± 4.1	23.1 ± 3.5	23.1 ± 3.7	p = 0.40

176 Women

177 The data are presented as the mean ± SD

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182 TABLE4 CORRELATIONS AMONG FOOT FEATURES

		1	2	3	4	5	6	7	8	9	10	11
1	GFH angle	1										
2	ABD	0.342 **	1									
3	SHN angle	0.555 **	0.489 **	1								
4	IH	-0.2 34**	-0.3 29**	-0.1 3	1							
5	NH	-0.3 04**	-0.3 91**	-0.3 04**	0.654 **	1						
6	IS angle	0.196 *	0.095	0.201 *	-0.73 6**	-0.4 78**	1					
7	MPH angle	0.370 **	-0.0 7	0.125	0.114	0.006	0.013	1				
8	TAL	0.462 **	-0.0 5	0.161 *	0.102	-0.0 2	0.03	0.942 **	1			
9	TAH	-0.1 5	-0.1 3	-0.0 7	0.519 **	0.423 **	-0.3 72**	0.344 **	0.267 **	1		
10	GSR	0.008	0.037	-0.0 4	0.037	-0.1	0.066	-0.12	-0.1	-0.1 3	1	
11	BMI	0.109	-0.0 1	0.023	0.005	0.064	0.065	0.071	0.122	0.342 **	-0.1 80*	1

183 Men

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		1	2	3	4	5	6	7	8	9	10	11
1	GFH angle	1										
2	ABD	0.26 1**	1									
3	SHN angle	0.50 7**	0.40 4**	1								
4	IH	-0.0 38	-0.3 38**	-0.0 24	1							
5	NH	-0.1 74**	-0.3 43**	-0.2 16**	0.48 7**	1						
6	IS angle	0.15 3*	0.03 7	0.09 8	-0.6 57**	-0.3 39**	1					
7	MPH angle	0.37 9**	-0.0 55	0.18 5**	0.19 2**	0.03 7	0.12 4*	1				
8	TAL	0.50 8**	-0.0 52	0.21 3**	0.20 2**	0.02 2	0.114	0.95 3**	1			
9	TAH	-0.1 46*	-0.1 15	-0.0 44	0.37 7**	0.39 6**	-0.2 47**	0.30 4**	0.22 0**	1		
10	GSR	0.18 5**	-0.0 4	-0.0 77	-0.0 54	-0.1 17	0.22 3**	0.03 1	0.11	-0.0 21	1	
11	BMI	-0.0 03	-0.0 22	0.02 6	0.06 5	0.06 8	-0.0 21	0.16 4**	0.17 6**	0.46 1**	0.00 8	1

189 Women

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194 Correlations among Features

195 Table 4 shows the correlation coefficients among the foot skeletal features measured by the 3D foot
196 scanner. The GFH angle was correlated with the SHN angle, ABD, IS angle, MPH angle, TAL, TAH,
197 and NH, respectively, for both men and women, and additionally with the IH for men. For both men
198 and women, on the other hand, the ABD was correlated with the SHN angle, IH, and NH, respectively,
199 the NH was correlated with the TAH and IS angle, respectively, the IS angle was correlated with the
200 TAH, the MPH angle was correlated with TAL and TAH, respectively, and the TAL was correlated
201 with the TAH. For both men and women, furthermore, the BMI was correlated with the TAH.

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203 Multiple Regression Analysis for the GFH Angle

204 Table 5 shows five independent skeletal features related to the GFH angle for men and women,
205 respectively. Four of them, which are common for men and women, comprise the SHN angle, TAL,
206 TAH and ABD, and the remaining one is the BMI for men whereas the GSR for women. Concerning
207 the strength of relationship, the regulated r^2 was 0.52 for men whereas 0.51 for women. For both men
208 and women, it was implicated that the skeletal features related to the forefoot and skeletal misalignment
209 of the midfoot characterize the GFH angle.

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213 TABLE 5 RESULTS OF MULTIPLE REGRESSION ANALYSIS CONCERNING THE GFH
214 ANGLE

Variable	B	SE B	β	p value	r^2	Adjusted r^2
SHN angle	0.77	0.136	0.381	<0.001	0.536	0.52
TAL	143.02	18.558	0.467	<0.001	F for change in r^2	p value
TAH	-135.65	30.505	-0.28	<0.001	33.228	<0.001
BMI	0.26	0.114	0.14	0.02		
ABD	33.58	15.961	0.139	0.04		

215 Men

Variable	B	SE B	β	p value	r^2	Adjusted r^2
SHN angle	0.72	0.10	0.37	<0.001	0.52	0.51
TAL	1.24	0.12	0.47	<0.001	F for change in r^2	p value
TAH	-1.01	0.21	-0.22	<0.001	55.47	<0.001
ABD	0.26	0.10	0.12	0.01		
GSR	65.325	17.632	0.162	<0.001		

216 Women

217

218 DISCUSSION

219 Measurements of Features

220 In the measurement results, age-based variations in the foot features were observed slightly for men

221 whereas distinctively for women. Particularly, it is surmised for women that the lower NH and
222 increasing flatness of the foot were related to aging. However, aging did not have a great impact on
223 the SHN angle and ABD. The longitudinal arch of the foot is likely to be connected with the tibialis
224 posterior muscle, the muscle strength in the sole and the transformations in the skeletal structure
225 [16,17]. For these reasons, it is surmised that the lowering of the longitudinal arch is caused by severe
226 declines in muscle function such as impairment of the tibialis posterior muscle[18], protrusion of the
227 calcaneus[19] and pronation of the navicular bone[20] as well as the aging process. It is also surmised
228 that the IS angle increases as the thickness of foot skeletal structure decreases with ages.

229

230 Correlations among Foot Features

231 The correlation coefficient between the MPH angle and the TAL is greater than 0.94 in Table 4 for
232 both men and women, indicating a strong correlation, on the other hand, the TAL increases whereas
233 the TAH decreases with age for women in Table 3. Taking into consideration that the MPH angle and
234 TAL are skeletal features related to the width of the forefoot and the TAH is a skeletal feature related
235 to the height of the forefoot, it is surmised that flattening of the forefoot is associated with a broad foot.
236 Particularly, it is surmised for women that the GFH angle increases with age, which indicates the
237 development of HV.

238 Paying attention to the GFH angle, the skeletal features identified as being correlated with it include
239 the SHN angle and ABD, which are those related to the midfoot. As the SHN angle increases, which

240 means that the navicular bone sticks out more, the ABD also increases with the inside of the midfoot
241 deviating more inward. Therefore, this suggests that foot pronation is associated with the increase of
242 the GFH angle thus HV. This suggestion is supported by the result of a prior study[21] that the risk of
243 HV is significantly increased in persons with pronated foot function.

244 In addition, it was found that the ABD is correlated with the SNH angle ($r^2 > 0.40$), IH (which denotes
245 the health of the foot's skeletal structure) ($r^2 > 0.33$) and NH (which denotes the height of the
246 longitudinal arch) ($r^2 > 0.34$) in Table 4. This suggests that misalignment of the skeletal structure of
247 the midfoot is related to the health of feet, particularly, the formation of navicular and cuneiform bones.
248 This misalignment is considered to be influenced by both early childhood development and aging
249 process[22].

250 Furthermore, correlation between the IH and the TAH was observed for both men ($r^2 = 0.52$) and
251 women ($r^2 = 0.38$) in Table 4. The reason why the correlation is lower for women could be that the
252 transverse arch reflected by the TAH is more strongly influenced by footwear for women.

253 Finally, as for flatfeet which means the fall of the longitudinal arch, many discussions have utilized
254 footprints[23,24]. From the viewpoint of biomechanics, the main cause of flatfeet may be the influence
255 of the tibialis posterior muscle or the muscles in the sole[25]. Considering pronation, the navicular
256 bone moves directly below these muscles while causing 3D changes in various directions, such as
257 supination of the subtalar joint, pronation of the navicular bone and supination of the forefoot.
258 Therefore, assessing the 3D skeletal structure of the foot is effective for pronation, which is the very

259 benefit of the proposed system.

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261 Multiple Regression Analysis for the GFH Angle

262 It was revealed from Table 5 that dominant skeletal features determining the GFH angle are the SHN
263 angle and the ABD among those related to the midfoot whereas the TAL and the TAH among those
264 related to the forefoot for both men and women. In addition to these features, it was revealed that
265 one of the dominant features is the BMI for men whereas GSR for women. Regarding the multiple
266 regression analysis, the adjusted coefficient of determination was 0.52 for men versus 0.48 for women,
267 multicollinearity was confirmed in relation to none of the independent features, and β was large for
268 both men and women in the SHN angle and the TAL.

269 As for other features associated with HV, prior studies pointed out lower BMI and high heel use for
270 women aged 20–64 whereas higher BMI and flat feet for men[2,13]. Our results suggest that the
271 etiologic mechanisms of HV may differ between men and women. Namely, although this study
272 included neither extremely overweight nor underweight participants, it found an association of BMI
273 with HV for men, which was not strong as compared to that in the prior study[2].

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275 Overall Results

276 A prior study showed that the protrusion of the first metatarsal and the lengths of the first metatarsal
277 and the proximal phalanx of the hallux were increased in both men and women with HV as compared

278 to those in the control group[4], in other words, the first toe is a key part related to HV. On the other
279 hand, this study showed that a longer second toe was associated with a larger GFH angle, in other
280 words, the second toe was a key part related to HV. The reason of this difference may be that the length
281 of the first metatarsal was compared with that of the second metatarsal in the prior study whereas the
282 distance between the tip of the first toe and the heel was compared with that between the tip of the
283 second toe and the heel in this study. The proximal phalanx of the hallux deviates laterally towards the
284 second toe as HV develops, so the distance between the tip of the hallux and the heel gets shortened,
285 naturally resulting in the appearance of longer second toe.

286 In this study, it has been highlighted that the GFH angle as an index of HV is influenced by the flatness
287 of the forefoot and misalignment of the skeletal structure of the midfoot. In a prior study, the NH was
288 used as an index of flatfeet, which was considered to influence HV[26]. In this study, on the other hand,
289 the independent variable derived from the multiple regression analysis was not the NH but the SHN
290 angle. As the SHN angle and NH were inversely correlated (-0.3– -0.2), it is quite natural that both
291 height and position of the navicular bone can be key features for HV. The SHN angle is not on a
292 horizontal plane, so simple 2D measurement systems cannot calculate it. On the other hand, the
293 developed 3D scanner system can easily calculate the NH as well as the SHN angle, using an
294 automatically constructed 3D foot skeleton model.

295 By using a 3D foot scanner on smartphone, we have been able to implement a simple quantitative
296 method for assessing the skeletal structure of the foot. This will allow us to clarify the risk of HV.

297 LIMITATION

298 This study has several limitations. The measurement is performed from the outside of the foot, so
299 there may be some errors between the GFH angle and the HV angle measured by x-ray. In addition,
300 the measurement is performed manually, so handshake may introduce some errors in the measurement
301 data. Furthermore, the 3D foot skeleton model is constructed by 2D images, so some errors may occur
302 in the construction process.

303

304 CONCLUSION

305 In this study, a 3D foot scanning method using a smartphone was developed, and the skeletal structure
306 of the foot was analyzed. One of the main results is that dominant skeletal features for determining the
307 HV-related GFH angle are the SHN angle and ABD among those related to the midfoot whereas the
308 TAH and TAL among those related to the forefoot. Another is that age-based variations in the foot
309 skeletal features were observed slightly for men whereas distinctively for women.

310 Using a smartphone, it is possible to conduct a simple non-invasive assessment of the skeletal structure
311 of the foot at any location. This will facilitate clarification of the factors of skeletal structure
312 contributing to HV, and it is expected to improve efforts to prevent HV.

313

314 ABBREVIATIONS

315 HV: HALLUX VALGUS

316 IH: INSTEP HEIGHT

317 NH: NAVICULAR HEIGHT

318 IS ANGLE: INSTEP ANGLE

319 MPH ANGLE: METATARSO-PHALANGEAL (MP) -HEEL ANGLE

320 TAL: DISTANCE OF TRANSVERSE ARCH

321 TAH: HEIGHT OF TRANSVERSE ARCH

322 TA: TRANSVERSE ARCH

323 GFH ANGLE: GREAT TOE-FIRST METATARSAL HEAD-HEEL ANGLE

324 SHN ANGLE: SECOND TOE-HELL-NAVICULAR ANGLE

325 ABD: AXIS OF THE BONE DISTANCE

326 GSR: GREAT TOE-SECOND TOE RATIO

327

328 DECLARATIONS

329 ETHICS APPROVAL AND CONSENT TO PARTICIPATE: THE STUDY DESIGN WAS

330 APPROVED BY THE ETHICAL REVIEW BOARD AT THE RYOTOKUJI UNIVERSITY

331 (AUTHORIZATION NUMBER: 1909). PARTICIPANTS WERE PROVIDED ORAL AND

332 WRITTEN EXPLANATIONS OF THE STUDY AND PUBLICATION. ALL PARTICIPANTS

333 SIGNED A CONSENT FORM PRIOR TO THE STUDY.

334 CONSENT FOR PUBLICATION: NOT APPLICABLE

335 AVAILABILITY OF DATA AND MATERIALS: NOT APPLICABLE.

336 COMPETING INTERESTS: THE AUTHORS DECLARE THAT THEY HAVE NO COMPETING
337 INTERESTS.

338 FUNDING: THIS WORK WAS SUPPORTED BY JSPS KAKENHI, GRANT NUMBER 18H03559,
339 18K12161. THE FUNDING SOURCES HAD NO INVOLVEMENT IN STUDY DESIGN; IN THE
340 COLLECTION, ANALYSIS AND INTERPRETATION OF DATA; IN THE WRITING OF THE
341 REPORT; AND IN THE DECISION TO SUBMIT THE ARTICLE FOR PUBLICATION.

342 AUTHORS' CONTRIBUTIONS: TY AND KY PLANNED THE STUDY, ANALYZED THE DATA,
343 AND DRAFTED THE MANUSCRIPT. TY, KY, AND MS PERFORMED ALL MEASUREMENTS
344 AND CONTRIBUTED TO THE DATA ACQUISITION. TY, KY, MS, TR, MK AND SH ANALYZED
345 ALL STATISTICAL DATA AND CONTRIBUTED TO DRAFTING OF THE MANUSCRIPT. TR,
346 YT AND SH PLANNED THE STUDY, INCLUDING THE INSTRUMENTATION AND
347 CONTRIBUTED TO THE REVISION OF THE MANUSCRIPT.

348 ACKNOWLEDGEMENTS: NOT APPLICABLE.

349 AUTHORS' INFORMATION: NOT APPLICABLE.

350

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416

417 FIGURE LEGENDS

418 Figure 1. The Foot Skeletal Features

419

420 Table 1. The definitions of foot skeletal features

421

422 Table 2. Subject Characteristics

423

424 Table 3. The results of 3D foot scanner measurements

425

426 Table 4. Correlations among foot features

427

428 Table 5. Results of multiple regression analysis concerning the GFH angle