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Effect of Load Change on Foot Arch in Different Positions—Assessment of Foot Arch Using a Motion Analysis System and a Caliper —Goniometer System—

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Abstract. [Purpose] The purpose of this study was to analyze the effect of load change on the foot arch in different foot positions using a Vicon motion analysis system and clinical assessment using a goniometer and calipers. The reliabilities of the measurements taken by the Vicon motion analysis system and clinical assessment were analyzed. [Subjects and Methods] The study (24.8 ± 2.1 years). Two methods were used to measure the foot arch: (1) Vicon motion analysis and (2) a goniometer and calipers. Measurements were taken bilaterally in six different positions: standing on both feet, standing on one leg, cuff raise, medial weight shift, lateral weight shift, and toe dorsiflexion. [Results] The heights of the medial longitudinal, lateral longitudinal, and transverse arches in dynamic positions were significantly greater than that in the static standing position. The results of the Vicon motion analysis system correlated highly with those of measurements obtained via clinical assessment only in the static position. [Conclusion] When the foot and ankle joints were in dynamic and unstable positions, the arches were higher than those in the static position because of the windlass mechanism. Simultaneous assessment of all three foot arches in various positions is needed for effective evaluation.
Key words: Foot Arch, Weight shift, Reliability of clinical assessment

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INTRODUCTION

The sole mainly has contact with the ground and supports body weight during standing or walking[1)]. Moreover, it adjusts to changes in ground condition. The foot arch takes on the role of distribution of the foot load. In general, during erect standing, the talus supports 50% of the full body weight, and the calcaneus and forefoot support 25%, respectively[2)].

The foot arch is represented by three parameters: the medial longitudinal arch (MLA), the lateral longitudinal arch (LLA), and the transverse arches (TA). The MLA is composed of the calcaneus, the talus, the navicular, the medial cuneiform bone, and the first metatarsal bone, and the top is the navicular. The LLA is composed of the calcaneus, the cuboid bone, and the fifth metatarsal bone, and the top is the calcaneocuboid joint. The TA is composed of the first metatarsal bone head of the fifth metatarsal bone head, and the top is the second head of metatarsal bone.

As MLA has abundant retractility as compared with the other arches, it is one of the most important arch positions. The main role of MLA is to support the human body during walking. It can compensate for an unstable ground surface by absorbing shock due to overloading. The structural support of the MLA consists of bone, joint capsule, and ligament, while the functional support is provided by the muscle[3)]. The LLA is related to the foot alignment[2)]. LLA is tighter than MLA, because LLA transmits the activity of the triceps surae muscle to the foot[4, 5)]. Two TA's exist at the position of the metatarsal bone and the forefoot. The metatarsal arch that is supported by ligaments has a strong construction[6)]. The forefoot arch becomes easily flattened by overloading. TAs are influenced by the change of load in walking and the condition of foot contact on the ground[7)].

There are many clinical assessments of MLA including the Yokokura method[8)], the Navicular Hieght Test[9, 10)], the Navicular Drop Test[10)], and the Dorsum Height Test[11)]. These tests use X-ray images and have high reliability and validity. Dorsey reported that the Dorsum Height Test and Navicular Height Test have a high reliability and validity[11)]. Ohno et al. estimated the foot arch by footprint and sole pressure. Kayano developed a device which can depict and evaluate by measuring voltage differentials at various foot

Fig. 1. Measurement positions
1) static standing on both feet (SBF), 2) standing on one leg (SOL), 3) cuff raise (CR), 4) medial weight shift (MWS), 5) lateral weight shift (LWS) and 6) toe dorsiflexion (TD).

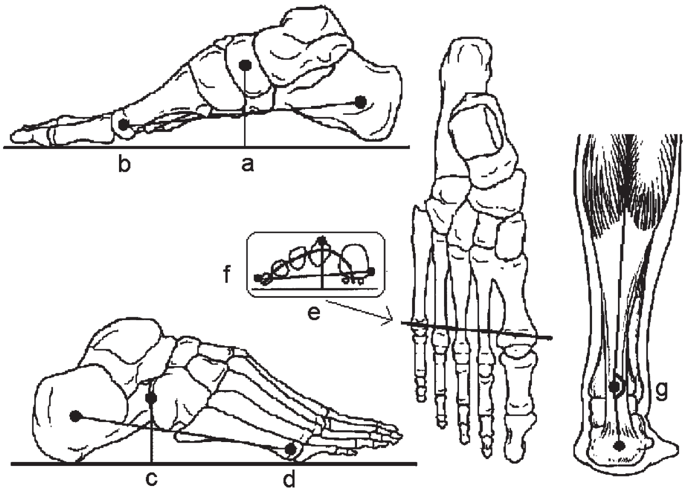

Fig. 2. Analysis parameters
a) the height of the navicular position, b) the distance between the head of the first metatarsal bone and medial calcaneus, c) the height of the calcaneocuboid joint, d) the distance between the head of the fifth metatarsal bone and lateral calcaneus, e) the maximal height of the head of the second metatarsal bone, f) the distance between the head of the first metatarsal bone and head of the fifth metatarsal bone, g) the eversion angle

points.

LLA is measured as the maximal height of the calcaneocuboid joint. The TA is measured as an Axial Sesamodial Projection by X rays[12], the Cobey method[13], and a method which puts expanding electric rubber on the dorsum of the foot corresponding to the TA and measures the expansion rate[6]. However, these clinical evaluations of the arch are mainly used as a static measurement of MLA as observed in an X-ray[14]. Although disorders of MLA are few, complex disorders in arches, such as foot deformities may occur. For example, hallux valgus sometimes accompanies talipes planuses, talipes valgus, or bench plastic which is caused by a decrease in height of the transverse arch.

The purpose of this study was to analyze the influence of change of the foot load in different positions on the foot arch using motion analysis and calipers. Moreover, the reliability of clinical assessment of the foot arch was studied.

SUBJECTS AND METHODS

The study subjects were 12 males (24.8 ± 2.1 years) with no history of auditory or vestibular disease. Subjects with a

Table 1. Body characteristics

	Subjects (n=12) Mean ± S.D.	
a) Age and morphological character		
Age (years)	24.8 ± 2.1	
Height (cm)	173.3 ± 5.5	
Weight (kg)	66.9 ± 10.8	
BMI	19.3 ± 2.9	
	Rt	Lt
Length of upper limb (cm)	55.0 ± 2.6	54.6 ± 2.5
Trochantomalleolus distance (cm)	80.8 ± 3.8	81.5 ± 3.0
Spinomalleolus distance (cm)	89.5 ± 3.9	89.0 ± 3.6
Foot length (cm)	23.9 ± 1.3	23.8 ± 1.3
Foot width (cm)	9.2 ± 0.6	9.1 ± 0.7
b) Range of motion (°)	Rt	Lt
Hip Jt Flexion	129.2 ± 11.0	126.3 ± 9.8
Extension	20.4 ± 4.0	18.3 ± 6.2
Abduction	36.3 ± 8.6	37.9 ± 8.4
Knee Jt Flexion	145.4 ± 10.3	142.9 ± 9.2
Extension	0	0
Ankle Jt Plantarflexion	51.3 ± 7.5	50.8 ± 16.4
Dorsiflexion	19.2 ± 6.7	19.2 ± 7.6
Great toe (MTP) Flexion	33.8 ± 8.0	31.7 ± 9.1
Extension	80.8 ± 15.1	81.3 ± 9.6
c) Muscle strength (Nm)	Rt	Lt
Hip Jt Flexion	272.3 ± 40.3	271.7 ± 46.7
Extension	210.5 ± 74.4	212.4 ± 48.4
Abduction	230.3 ± 52.8	228.3 ± 42.0
Adduction	240.3 ± 39.0	217.5 ± 46.0
Knee Jt Flexion	267.7 ± 125.4	245.9 ± 103.0
Extension	310.0 ± 53.7	308.5 ± 58.0
Ankle Jt Plantarflexion	408.9 ± 124.1	395.0 ± 104.0
D orsiflexion	213.4 ± 47.5	203.2 ± 38.1
Great toe (MTP) Flexion	69.3 ± 29.9	70.5 ± 24.9
Extension	54.3 ± 21.2	63.6 ± 26.1

chronic (orthopedic or neurological) or psychiatric disease were excluded. Informed consent was obtained from all subjects prior to data collection. This study was approved by the Research Committee of Sapporo Medical University.

For all subjects, body characteristics were measured and the dominant foot was determined. Range of motion (ROM) of lower limbs was measured using methods established by the Japanese Orthopedic Association and the Japanese Association of Rehabilitation Medicine[15]. Muscle strength of lower limbs was measured using a portable dynamometer (MICROFET2, Hoggan Health Industries, Draper, Utah) using the Bohannon method[16].

Measurements of the foot arch were taken bilaterally with the subjects standing in six different positions (Fig. 1): erect static standing on both feet (SBF); standing on one leg, on the dominant foot (SOL); standing with maximum plantar flexion with the weight supported by the toes and heads of the metatarsal bones (CR); standing with a load on the medial side of the sole (medial weight shift: MWS); standing with a load on the lateral side of the sole (lateral weight shift: LWS); and standing on both feet with maximum toe dorsiflexion (TD).

The Vicon 512 motion analysis system (Oxford Metrics, Oxford, UK) was used to quantitatively measure the arches. Reflective markers of 8 mm in diameter were used. The sampling rate was 120 Hz. Markers were placed on the navicular, head of the first metatarsal bone, medial side of the calcaneus, calcaneocuboid joint, head of the fifth metatarsal bone, lateral side of the calcaneus, head of the second metatarsal bone, heel, center of the gastrocnemius muscle, and Achilles tendon. All subjects wore T-shirts and shorts for the experiment and were barefoot to allow marker placement on the skin surface. They were instructed to place their arms in front of their chest and stand erect without any inclination of the trunk. For the experiment, the subjects were asked to stand in the six positions at random and hold

Table 2. Foot arch measurements

		Vicon (n=12)	Gonio & calipers (n=12)	c orrelation
		Mean ±S.D.	Mean ±S.D.	coefficient
SBF	%H-MLA (%)	19.3 ± 3.0	19.2 ± 2.9	0.771**
	LLA	20.2 ± 2.2	22.7 ± 3.2	0.874**
	TA	12.8 ± 1.5	13.5 ± 1.1	0.734**
	%L- MLA	65.6 ± 4.6	63.8 ± 2.7	0.644*
	LLA	59.7 ± 3.2	55.9 ± 2.8	0.362
	TA	42.9 ± 4.2	42.6 ± 4.2	0.986**
	Eversion angle	11.5 ± 6.5	7.0 ± 4.0	0.744**
SOL	%H-MLA	20.5 ± 3.1	19.9 ± 3.3	0.759**
	LLA	18.9 ± 2.1	21.3 ± 2.4	0.749**
	TA	12.7 ± 1.5	13.0 ± 1.0	0.266
	%L- MLA	65.2 ± 4.7	63.7 ± 3.3	0.542
	LLA	59.6 ± 3.1	55.4 ± 2.3	0.386
	TA	43.1 ± 4.4	43.0 ± 4.6	0.965**
	Eversion angle	10.9 ± 5.3	10.6 ± 4.8	0.727**
CR	%H-MLA	23.9 ± 2.5	24.2 ± 3.7	0.393
	LLA	22.7 ± 1.8	25.4 ± 3.1	0.748**
	TA	17.5 ± 1.9	14.1 ± 3.4	0.707*
	%L- MLA	61.2 ± 4.3	59.8 ± 2.8	0.677*
	LLA	57.8 ± 3.3	54.5 ± 2.9	0.303
	TA	40.6 ± 4.0	40.3 ± 4.2	0.909**
	Eversion angle	6.0 ± 26.5	3.1 ± 9.5	0.850**
MWA	%H-MLA	17.9 ± 2.8	18.8 ± 2.5	0.685*
	LLA	21.3 ± 2.0	24.0 ± 2.1	0.716*
	TA	13.2 ± 1.5	14.2 ± 2.3	0.203
	%L- MLA	66.3 ± 4.6	64.0 ± 3.0	0.467
	LLA	58.9 ± 3.2	55.1 ± 2.6	0.43
	TA	41.9 ± 4.3	41.6 ± 4.4	0.944**
	Eversion angle	12.7 ± 5.4	9.9 ± 4.8	0.098
LWS	%H-MLA	22.3 ± 2.6	23.4 ± 2.6	0.769**
	LLA	19.4 ± 2.3	22.1 ± 2.7	0.698
	TA	13.5 ± 1.7	14.3 ± 1.3	0.175
	%L- MLA	64.2 ± 4.6	62.2 ± 3.1	0.763**
	LLA	60.1 ± 3.2	56.2 ± 3.0	0.412
	TA	42.2 ± 4.3	41.2 ± 4.6	0.867**
	Eversion angle	5.9 ± 9.3	1.7 ± 4.3	0.500
TD	%H-MLA	21.9 ± 2.5	22.1 ± 2.4	0.512
	LLA	20.9 ± 2.0	23.7 ± 2.0	0.759**
	TA	16.0 ± 1.5	15.5 ± 1.2	0.623*
	%L- MLA	63.7 ± 4.7	62.7 ± 3.8	0.818**
	LLA	58.7 ± 3.3	55.4 ± 2.8	0.377
	TA	39.8 ± 4.7	41.2 ± 4.6	0.972**
	Eversion angle	9.3 ± 6.0	4.8 ± 6.4	0.575

*: Significant difference $p<0.05$. **: Significant difference $p<0.01$

each position for 20 seconds. The mean measurement value obtained at 10 seconds was used for calculation. After taking measurements, arch parameters and eversion angles were calculated on a computer (Fig. 2)

For the clinical assessment, a caliper was used to measure six parameters of the foot arches. The parameters measured were %height and %length of the medial longitudinal arch (%H-MLA, %L-MLA), lateral longitudinal arch (%H-LLA, %L-LLA), and transverse arch (% H-TA, % L-TA). Seal markers were attached to the skin at 10 sites on the lower

Table 3. Comparison of arch parameters between the SBF position and the other five different positions for the Vicon motion system

	SBF	Others§
%height of MLA (%)	19.3 ± 3.0	20.5 ± 3.1
		23.9 ± 2.5 **
		17.9 ± 2.8
		22.3 ± 2.6 *
		21.9 ± 2.5
%height of LLA	20.2 ± 2.2	18.9 ± 2.1
		22.7 ± 1.8 *
		21.3 ± 2.0
		19.4 ± 2.3
		20.9 ± 2.0
%height of TA	12.8 ± 1.5	12.7 ± 1.5
		17.5 ± 1.9 **
		13.2 ± 1.5
		13.5 ± 1.7
		16.0 ± 1.5 **
%length of MLA	65.6 ± 4.6	65.2 ± 4.7
		61.2 ± 4.3
		66.3 ± 4.6
		64.2 ± 4.6
		63.7 ± 4.7
%length of LLA	59.7 ± 3.2	59.6 ± 3.1
		57.8 ± 3.3
		58.9 ± 3.2
		60.1 ± 3.2
		58.7 ± 3.3
%length of TA	42.9 ± 4.2	43.1 ± 4.4
		40.6 ± 4.0
		41.9 ± 4.3
		42.2 ± 4.3
		39.8 ± 4.7
Eversion angle	11.5 ± 6.5	10.9 ± 5.3
		6.0 ± 26.5
		12.7 ± 5.4
		5.9 ± 9.3
		9.3 ± 6.0

§:SOL, CR, MWS, LWS, and TD in order from top. *: Significant difference p<0.05. **: Significant difference p<0.01

Table 4. Comparison of arch parameters between the SBF position and the other five different positions for goniometer and vernier calipers

	SBF	Others§
%height of MLA (%)	17.6 ± 6.5	19.9 ± 3.3
		24.2 ± 3.7 **
		18.8 ± 2.5
		23.4 ± 2.6 **
		22.1 ± 2.4
%height of LLA	22.7 ± 3.2	21.3 ± 2.4
		25.4 ± 3.1
		24.0 ± 2.1
		22.1 ± 2.7
		23.7 ± 2.0
%height of TA	13.5 ± 1.1	13.0 ± 1.0
		14.1 ± 3.4
		14.2 ± 2.3
		14.3 ± 1.3
		23.7 ± 2.0
%length of MLA	63.8 ± 2.7	63.7 ± 3.3
		59.8 ± 2.8 *
		64.0 ± 3.0
		62.2 ± 3.1
		62.7 ± 3.8
%length of LLA	55.9 ± 2.8	55.4 ± 2.3
		54.5 ± 2.9
		55.1 ± 2.6
		56.2 ± 3.0
		55.4 ± 2.8
%length of TA	42.6 ± 4.2	43.0 ± 4.6
		40.3 ± 4.2
		41.6 ± 4.4
		41.2 ± 4.6
		41.2 ± 4.6
Eversion angle	7.0 ± 6.5	10.6 ± 4.8
		3.1 ± 9.5
		9.9 ± 4.8
		1.7 ± 4.3
		4.8 ± 6.4

§:SOL, CR, MWS, LWS, and TD in order from top. *: Significant difference p<0.05 **: Significant difference p<0.01

leg. Markers were placed at the same sites used for Vicon motion analysis. All data were normalized to the foot length of each subject. The eversion angle was measured using a goniometer.

The reliability of the measurements obtained with Vicon motion analysis and clinical assessment was analyzed. The SBF and MWS positions in three subjects were randomly chosen. Each position was repeated five times. Intra-rater reliability was examined with intraclass correlation coefficients [ICCs (1, 1)]. SPSS (11.5 J) was used for statistical analysis.

The seven parameters measured in the SBF position were compared with those in the other five positions by one-way ANOVA, a post-hoc test, and a non-parametric test. A significance level of 0.05 was chosen. Pearson's correlation coefficient was determined for measurements obtained using motion analysis and clinical assessment.

RESULTS

Table 1 shows the subjects' body characteristics. All subjects were right-limb dominant. No significant differ-

Table 5. Correlation of % height of MLA with the other parameters

		Vicon	Gonio & calipers
SBF	vs % height of LLA	0.368	0.537
	vs % height of TA	0.230	0.544
	vs % length of MLA	–0.230	0.142
	vs % length of LLA	0.180	0.574
	vs % length of TA	0.246	0.390
	vs eversion angle	–0.082	–0.141
SOL	vs % height of LLA	0.451	0.232
	vs % height of TA	0.339	0.202
	vs % length of MLA	0.089	0.204
	vs % length of LLA	0.199	0.563
	vs % length of TA	0.330	0.270
	vs eversion angle	–0.017	–0.322
CR	vs % height of LLA	0.309	0.438
	vs % height of TA	–0.449	0.104
	vs % length of MLA	0.121	0.357
	vs % length of LLA	0.162	0.456
	vs % length of TA	0.111	0.145
	vs eversion angle	–0.125	–0.113
MWS	vs % height of LLA	0.306	0.506
	vs % height of TA	–0.018	0.127
	vs % length of MLA	–0.226	0.187
	vs % length of LLA	0.016	0.383
	vs % length of TA	0.132	0.242
	vs eversion angle	–0.155	0.503
LWS	vs % height of LLA	0.318	0.183
	vs % height of TA	0.209	–0.046
	vs % length of MLA	–0.021	0.120
	vs % length of LLA	0.322	0.583
	vs % length of TA	0.082	0.138
	vs eversion angle	–0.153	–0.134
TD	vs % height of LLA	0.501	0.111
	vs % height of TA	–0.114	0.285
	vs % length of MLA	0.200	–0.082
	vs % length of LLA	0.146	0.528
	vs % length of TA	0.193	0.229
	vs eversion angle	0.140	–0.003

ences in height and weight were found when compared with the standard averages of Japanese body characteristics[17]. Therefore, the subjects' characteristics were within the normal range of values. Moreover, all ROM values were within the normal range except for hip joint abduction[18]. There were no significant differences between the right and left sides of the lower and upper extremities, ROM and muscle strengths.

Tables 2 and 3 show the results of the foot arch measurements recorded by the Vicon motion analysis system. In the SBF position, %H-MLA was 19.3% ± 3.0, %H-LLA was 20.2% ± 2.2, %H-TA was 12.8% ± 1.5, %L-MLA was 65.6% ± 4.6, %L-LLA was 59.7% ± 3.2, %L-TA was 42.9% ± 4.2, and the eversion angle was 11.5° ± 6.5. For %H-MLA, the measurements in the CR (23.9% ± 2.5) and LWS positions (22.3% ± 2.6) were significantly greater than those in the SBF position ($p<0.001$ and $p<0.05$, respectively). For %H-LLA, the measurement in the CR position (22.7% ± 1.8) was significantly greater than that in the SBF position ($p<0.05$). For %H-MLA, the measurements in the CR (17.5% ± 1.9) and TD positions (16.0% ± 1.5) were significantly greater than those in the SBF position ($p<0.0005$ and $p<0.001$, respectively). No significant differences were found in the data for %L-MLA, %L-LLA, %-TA, and the eversion angle.

Tables 2 and 4 show the results of foot arch measurements taken using the goniometer and calipers. In the SBF position, %H-MLA was 17.6% ± 6.5, %H-LLA was 22.7% ± 3.2, %H-TA was 13.5% ± 1.1, %L-MLA was 63.8% ± 2.7, %L-LLA was 55.9% ± 2.8, %L-TA was 42.6% ± 4.2, and the eversion angle was 7.0° ± 4.0. For %H-MLA, the measurements in the CR (24.2% ± 3.7) and LWS positions (23.4% ± 2.6) were significantly greater than those in the SBF position ($p<0.0005$ and $p<0.01$, respectively). For %L-MLA, the measurement in the CR position (59.8% ± 2.8) was significantly greater than that in the SBF position ($p<0.05$). No significant differences were found in the data for %H-TA, %L-LLA, %L-TA, and the eversion angle.

Table 2 shows the correlation between the two methods used in this study. Although measurements obtained using the two methods showed poor correlation for %L-LLA, %H-TA, and the eversion angle ($0.098< r<0.303$), the other four positions demonstrated a high correlation ($r>0.600$). Table 5 shows the correlation between %H-MLA and the other six parameters. MLA did not always show a significant correlation to the six parameters.

ICCs of both the Vicon motion analysis system and the caliper–goniometer system were 0.99, demonstrating high reliability.

DISCUSSION

In this study, the heights of MLA (H-MLA), LLA (H-LLA), and TA (H-TA) in dynamic positions were significantly greater than those in the static SBF position. In the CR position, H-MLA increased because of increased contraction of the plantar flexors (the windlass mechanism). Similarly, in the LWS position, H-MLA increased because the navicular may have been elevated by inversion of the ankle joint following increased contraction of the tibialis posterior. Hoshino et al. reported that in their study, LLA data recorded while walking was influenced by a compromised windlass mechanism during the toe-off period[5]. The CR position is the same as the foot position in the toe-off period. One hypothesis explaining the increase in H-TA is that when the toe flexors and plantar aponeurosis are extended, the H-TA increases in conjunction with the shortening of LLA and MLA. Moreover, the plantar interosseous and adductor hallucis may contract more than the other toe muscles (abductor hallucis, dorsal interossei, extensor hallucis, flexor hallucis, and abductor digiti minimi)[4].

The Vicon motion analysis system and the caliper–

goniometer system showed a high correlation for many parameters, except those measured in the MWS, LWS, and CR positions, which showed a poor correlation. One reason for this poor correlation is that these three positions represent unstable dynamic positions at the ankle joint. Therefore, the data were inconsistent in these dynamic positions, resulting in low reliability.

General clinical assessment of foot arch and alignment focuses on measuring the height of MLA. However, in this study, we found that the height of MLA alone may not be a reliable indicator of any pathology of foot arches and joint alignment in the lower leg (foot and ankle joints). Thus, simultaneous assessment of heights of all three foot arches in various positions may provide more effective results and may be more beneficial for improving a subject's activities of daily living.

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