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Original Article

The interrelationship between three-dimensional foot mobility and bodyweight bearing

Toshihiko Sato, RPT, MS[1, 2)*], Tsutomu Fukui, RPT, PhD[2, 3)], Shinichi Kawata, PhD[1)], Kenta Nagahori, PhD[1)], Hidenobu Miyaso, PhD[1)], Zhonglian Li, MD, PhD[1)], Takuya Omotehara, PhD[1)], Masahiro Itoh, MD, PhD[1)]

1) Department of Anatomy, School of Medicine, Tokyo Medical University: 6-1-1 Shinjuku, Shinjuku-ku, Tokyo 160-8402, Japan
2) Department of Physical Therapy, Faculty of Health Science Technology, Bunkyo Gakuin University, Japan
3) Health Care Science, Graduate School, Bunkyo Gakuin University, Japan

Abstract. [Purpose] To clarify the three-dimensional nature of foot mobility and its interrelationships within the foot due to bodyweight bearing. [Participants and Methods] Data regarding left foot mobility due to body weight bearing were collected from 31 healthy adults. Foot shape differences while sitting and standing, and their interrelationship were examined. The same examiner reapplied the landmark stickers when misaligned during measurement position changes. [Results] The foot length, heel width, forefoot width, hallux valgus angle, and calcaneus eversion angle were significantly larger in the standing than in sitting position. The digitus minimus varus angle was significantly smaller in the standing than in sitting position. The medial and lateral malleoli, navicular, and dorsum of the foot were displaced medially and inferiorly; the other indices, except for the midfoot, were displaced anteriorly. The interrelationships within the foot showed a positive correlation between the calcaneus eversion angle and the medial displacement of the medial and lateral malleoli, navicular, and dorsum of the foot points. There was a negative correlation between the calcaneus eversion angle and inferior displacement of the medial malleolus, navicular, and dorsum of the foot. [Conclusion] The intra-foot coordination relationship in response to bodyweight bearing was clarified.

Key words: Foot mobility, Foot deformation, Truss mechanism

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INTRODUCTION

The truss mechanism of the foot arch contributes to shock absorption and controls body loading. Imbalances in the mobility of the medial longitudinal arch, lateral longitudinal arch, and forefoot transverse arch may affect body motion and loading. Menz[1)] and McPoil et al.[2)] recommend that the quantity and quality of foot motion be evaluated not only by arch height but also by mobility.

The truss mechanism is measured by the amount of change in foot shape in the sitting and standing positions. Navicular drop test[3)] (NDT) is an index to evaluate medial longitudinal arch mobility based on the navicular tuberosity height at the subtalar joint's neutral position. The navicular drift measurement method is also used to evaluate the medial mobility of the navicular bone[1, 4)]. However, NDT can assess the difficulty in consistently placing the subtalar joint in its neutral position using palpation[5–7)]. Foot mobility magnitude[2)] and arch stiffness index[8, 9)] have been proposed as alternatives to the NDT. The advantage of these indices is that there is no need to place the foot in the subtalar joint neutral position or to identify the navicular tuberosity necessary to perform the NDT. Recently, the mobility of the transverse arch of the forefoot[10, 11)] has also been used to evaluate forefoot height in the lower leg maximum anterior tilting position, which places a load on the forefoot.

*Corresponding author. Toshihiko Sato (E-mail: tosato@bgu.ac.jp)

However, these evaluation indices show the mobility of one part of the foot, and their interrelationships have not been examined. The foot is divided into rear, mid, and forefoot segments, and each segment adapts to the ground for shock absorption through different mobilities. In particular, the foot's mobility is considered more rigid when the calcaneus is in an inversion position and more flexible when it is in an eversion position[12–14]. The foot is displaced in three dimensions, but we have not found any reports that capture this displacement.

Against this background, the purpose of this study was to clarify the three-dimensional mobility of the rear, mid, and forefoot based on the differences in foot shape between the sitting and standing positions. We hypothesized that the mobility of the calcaneus, and base of the foot would also affect the displacement of the mid- and forefoot and clarify the interrelationship between the calcaneus eversion−inversion position and displacement of other indices.

PARTICIPANTS AND METHODS

Thirty-one healthy participants were recruited for this study (male: 15, female: 16, ages: 20.8 ± 1.0 years, height: 165.8 ± 6.9 cm, weight: 58.8 ± 7.8 kg, body mass index: 21.3 ± 1.9 kg/m^2). The study focused on the left lower limb. The participants verified that they had no history of lower extremity pain or disorders and provided informed consent to volunteer for this study. This study was approved by the Ethics Review Committees of Tokyo Medical University (T2019-0261) and Bunkyo Gakuin University (2018-0011).

In this study, foot mobility[2, 8, 9] was defined as the difference between the foot indices measured in sitting and standing positions using a 3D foot scanner (INFOOT USB scanning system, IFU-S-01, I-Ware Laboratory, Osaka, Japan). The participants were instructed to sit and relax with the hip, knee, and ankle joints bent at 90° and the feet resting on the floor. They were instructed to stand still, relax, and distribute their body weight equally over both feet (Fig. 1). Since this 3D foot scanner used landmark stickers as the measurement standard, the same examiner reapplied the stickers due to their misalignment when the measurement positions were changed. Appropriate stickers were placed on the landmarks following the manufacturer's instructions. The measurement indices were assessed on the foot surface: foot length, heel width, forefoot width, hallux valgus angle, digitus minimus varus angle, and calcaneus eversion angle (Table 1).

A computer-aided design (CAD) software (File Converter, I-Ware Laboratory) was used to output the three-dimensional coordinate data of the foot. Three points were determined on the foot surface: the heel point, the dorsum of the foot point at

Fig. 1. Foot shape measurement posture.

Table 1. Definitions of foot indices

	Foot indices	Definitions
A	Foot length (mm)	Longest straight-line distance between the heel point and the midpoint of the foot width
B	Heel width (mm)	Distance perpendicular to the foot axis from the heel point to 16% of the foot length
C	Forefoot width (mm)	Distance from MT to MF
D	Hallux valgus angle (°)	Angle between the line connecting the MT point on the foot circumference and the hallux endpoint of the heel width and the line connecting the MT and hallux
E	Digitus minimus varus angle (°)	Angle between the line connecting the MF point on the foot circumference and the digitus minimus endpoint of the heel width and the line connecting the MF and digitus minimus
F	Calcaneus eversion angle (°)	Eversion angle of the heel viewed from behind

MT: metarsal tibiale; MF: metatarsal fibulare.

50% of the foot length (dorsum of the foot), and the highest point of ball girth (forefoot). From the landmark sticker, seven points were affixed to the sticker: the innermost point of the medial malleolus point (medial malleolus), the outermost point of the lateral malleolus point (lateral malleolus), the tuberosity of the navicular point (navicular), the tuberosity of the fifth metatarsalis, the metatarsal tibiale point (MT), the metatarsal fibulare point (MF), and the head of the second metatarsal. The three-dimensional coordinates of the ten measurement indices were set with the heel point, the floor as the origin, and the foot axis aligned with the X-axis (Fig. 2).

To confirm foot mobility due to weight bearing, differences in foot indices between sitting and standing positions were assessed using the paired t-test or Wilcoxon's signed-rank-sum test, depending on the presence or absence of normality. The relationship between calcaneus eversion angle mobility and other foot mobility was analyzed using Pearson's product-rate correlation coefficient or Spearman's rank correlation coefficient. The SPSS (version 26.0, IBM Japan Ltd.; Tokyo, Japan) package was used for the statistical analysis. The data normality was assessed using the Shapiro–Wilk test and a p-value of less than 0.05 was considered statistically significant.

RESULTS

The differences in foot indices between the sitting and standing positions are shown in Tables 2 and 3. Foot length, heel width, forefoot width, hallux valgus angle, and calcaneus eversion angle were significantly larger in the standing position, and the hallux valgus angle was significantly smaller. There were no significant differences in the anteroposterior direction of the navicular, all directions of the tuberosity of the fifth metatarsalis, the medial and lateral directions of the forefoot, and the medial and lateral directions of the head of the second metatarsal. Table 4 shows the relationship between calcaneus eversion angle mobility and other foot mobility indices (indices that differed significantly between sitting and standing positions). A greater calcaneus eversion angle mobility was associated with greater medial mobility of the medial and lateral malleoli, navicular, and dorsum of the foot. In addition, a greater calcaneus eversion angle mobility was associated with less downward mobility of the medial malleolus, navicular, and dorsum of the foot and greater mobility of the lateral malleolus.

1 Heel point (mm)
2 Medial malleolus (mm)
3 Lateral malleolus (mm)
4 Navicular (mm)
5 Tuberosity of fifth metatarsalis (mm)
6 Dorsum of the foot (mm)
7 MT (mm)
8 MF (mm)
9 Forefoot (mm)
10 Second metatarsal head (mm)

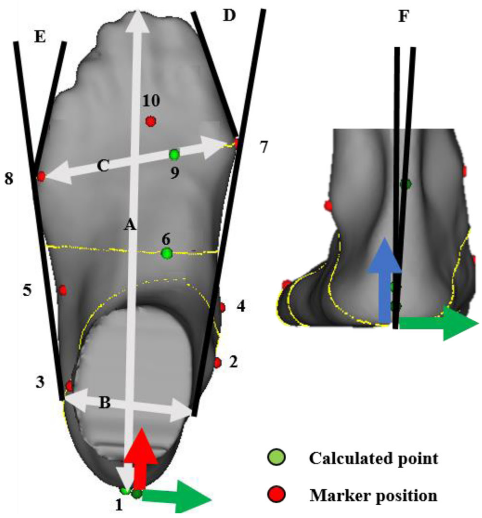

Fig. 2. Definitions of foot measurement points.
MT: metarsal tibiale; MF: metatarsal fibulare.

Table 2. Foot shape differences

Foot shapes	Sitting	Standing	Differences
A Foot length (mm)	240.7 ± 13.4	244.1 ± 13.8	3.5 ± 1.9**
B Heel width (mm)	61.8 ± 4.0	63.2 ± 4.1	1.4 ± 0.9**
C Forefoot width (mm)	95.6 ± 6.1	98.0 ± 6.5	2.3 ± 1.0**
D Hallux valgus angle (°)	10.6 ± 4.5	11.6 ± 5.4	0.9 ± 2.4*
E Digitus minimus varus angle (°)	11.3 ± 5.1	10.5 ± 5.6	0.8 ± 1.5*
F Calcaneus eversion angle (°)	0.3 ± 2.1	3.0 ± 2.0	2.7 ± 2.1**

**p<0.01, *p<0.05.

Table 3. Differences in three-dimensional foot indices

Foot indices (mm)		X (Forward +)	Y (Medial +)	Z (Down +)
1	Heel point (mm)	-	-	1.8 ± 1.1**
2	Medial malleolus (mm)	1.5 ± 2.9**	4.0 ± 2.5**	4.3 ± 1.9**
3	Lateral malleolus (mm)	3.9 ± 2.7**	2.9 ± 2.2**	3.2 ± 3.0**
4	Navicular (mm)	1.0 ± 5.3	3.3 ± 1.6**	5.6 ± 3.1**
5	Tuberosity of fifth metatarsalis (mm)	2.6 ± 10.8	4.6 ± 13.2	0.3 ± 3.1
6	Dorsum of the foot (mm)	1.8 ± 0.9**	2.4 ± 2.0**	4.7 ± 1.3**
7	MT (mm)	3.2 ± 2.9**	1.2 ± 1.3**	2.7 ± 2.7**
8	MF (mm)	0.6 ± 1.5*	−0.4 ± 1.0*	0.6 ± 1.3*
9	Forefoot (mm)	2.4 ± 2.6**	0.0 ± 4.8	2.4 ± 1.3**
10	Second metatarsal head (mm)	3.7 ± 2.9**	0.0 ± 1.8	2.9 ± 1.3*

**p<0.01, *p<0.05.
MT: metarsal tibiale; MF: metatarsal fibulare.

Table 4. Correlation coefficient (*r*) between calcaneus eversion angle mobility and other foot mobility

Foot indices			X (Forward +)	Y (Medial +)	Z (Down +)
A	Foot length (mm)	0.21	-	-	-
B	Heel width (mm)	0.27	-	-	-
C	Forefoot width (mm)	0.43*	-	-	-
D	Hallux valgus angle (°)	0.04	-	-	-
E	Digitus minimus varus angle (°)	0.26	-	-	-
1	Heel point (mm)	-	-	-	−0.32
2	Medial malleolus (mm)	-	−0.12	0.89**	−0.64**
3	Lateral malleolus (mm)	-	−0.10	0.88**	0.44*
4	Navicular (mm)	-	-	0.58**	−0.62**
5	Tuberosity of fifth metatarsalis (mm)	-	-	-	-
6	Dorsum of the foot (mm)	-	0.23	0.42*	−0.58**
7	MT (mm)	-	0.17	0.30	−0.29
8	MF (mm)	-	−0.15	−0.10	0.25
9	Forefoot (mm)	-	0.15	-	−0.25
10	Second metatarsal head (mm)	-	0.11	-	−0.27

**p<0.01, *p<0.05.
MT: metarsal tibiale; MF: metatarsal fibulare.

DISCUSSION

The difference in foot indices between the sitting and standing positions revealed three-dimensional foot mobility due to weight bearing. As in previous studies[15, 16)], foot length, heel width, and forefoot width were greater in the standing position. In addition, the three-dimensional foot indices showed greater calcaneus eversion angle[17)], other foot indices in anterior and inferior positions, and medial foot indices in the medial position[16)]. We considered that the foot indices of foot length, heel width, and forefoot width were large due to compression of the heel fat pad[18)] by weight bearing and the low foot arch. Since the calcaneus is located on the lateral side of the foot and the talus on the medial side, the load on the talonavicular joint increases due to weight bearing[15)]. The results show that the foot has increased in length, was became wider, was reduced in height, and was rotated to the medial side. In the forefoot index, the hallux, and digitus minimus angle changes were significant, but the displacements were small in both cases. Since this measurement method compares a sitting position to a standing position, we consider the displacement of the rearfoot to be measured rather than the forefoot. To evaluate forefoot deformity, it was necessary to evaluate forefoot loading[11)].

Displacement in the anterior-posterior direction was anterior for most foot indices. We believe this is because the heel point was the origin of the CAD software setup and the foot length was larger in the upright position. The medial and lateral malleoli were displaced anteriorly by approximately 1.5 mm and 3.9 mm, respectively, which may have been accompanied by displacement of the lower leg inward rotation based on their relative positions. The midfoot index showed no anteroposterior displacement. This may be because the anterior displacement due to arch lowering by loading may have been offset by the posterior displacement of the tuberosity of the navicular due to the rotation of the talonavicular joint during plantar flexion[15]. In the forefoot index, the MT and MF were displaced anteriorly by approximately 3 mm and 0.6 mm, respectively, suggesting that the displacement may have been due to the medial arch compared to the lateral arch.

The interrelationships within the foot showed a positive correlation between the calcaneus eversion angle, which is the fulcrum of rearfoot loading[15], and the medial displacement of the medial and lateral malleoli, navicular, and dorsum of the foot. On the other hand, the downward displacement of the foot due to weight bearing was thought to be due to a greater calcaneus eversion angle mobility[17]. However, based on the results of the current study, a greater calcaneus eversion angle mobility was associated with smaller downward displacement of the medial malleolus, navicular, and dorsum of the foot mobility. The displacement of the foot was influenced by the loading position, suggesting a cooperative relationship within the foot in response to weight bearing[19, 20]. In addition, since the calcaneus eversion angle[21] and NDT[3] by weight bearing are indices of foot pronation, evaluating the dominant index among the two with respect to displacement is necessary.

The changes reported were determined when the participant was standing; the changes may be different during the activity as the loads on the foot can be higher than the body weight during activity. Moreover, the participants were instructed to stand evenly on both feet, which could not be quantitatively monitored during data collection. It is considered that ground surface and foot function differ in the early-, mid- and, late stance[22]. Thus, the foot evaluation in the current study may shed more light on gait mechanics.

The foot mobility patterns observed in this study may be an indicator of musculoskeletal disorders involving by the foot. The relationship between foot mobility patterns and the overuse syndrome should be further explored and clarified in future research.

Funding and Conflict of interest

None.

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