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Original Article

Comparison of foot kinematics and the morphology of intrinsic musculature of the foot using a foot-type classification based on function

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Abstract. [Purpose] The purpose of this study was to investigate a correlation between the morphology of the intrinsic musculature of the foot and foot kinematics during gait using a foot type classification based on the windlass function. [Participants and Methods] We examined 67 feet of 35 healthy participants in this study. We collected three-dimensional foot kinematic data during gait from the Oxford Foot Model and assessed the morphology of the flexor digitorum brevis, abductor hallucis, adductor halluces (oblique head), and abductor digiti minimi muscles using B-mode ultrasound. Using the Foot Posture Index (six-item version), we divided static foot postures into two groups: normal arch and flatfoot. Subsequently, we compared foot kinematics and the morphology of the intrinsic musculature among the four groups using the analysis of variance with the Bonferroni test. [Results] Foot kinematics of the flatfoot-adduction type during gait significantly differed from that of the normal arch-abduction type. The abductor digiti minimi of the flatfoot-adduction type was significantly thinner than that of the normal arch-abduction type. [Conclusion] There may be some variations in flatfoot, and the flatfoot-abduction type might not be a risk factor for overuse injuries.

Key words: Flat foot, Intrinsic foot muscles, Kinematics

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INTRODUCTION

The treatment and prevention of overuse injuries of the lower extremities is important for athletes. Many risk factors, such as higher body mass index[1)], gender[2)], and altered hip function[3)], complicate the mechanics of overuse injuries. In addition, malalignment of the lower extremity is a risk factor for overuse injury (i.e. medial tibial stress syndrome, plantar fasciitis, and stress fracture of the lower extremity). Flat foot deformity is a common malalignment of the foot. Several studies have reported that flat foot with excessive pronation can cause overuse injury[1, 4)]. However, Neal et al.[5)], in a systematic review and meta-analysis, showed that while flat foot posture may be a risk factor for MTSS and patellofemoral pain, overuse injury has no relationship with flat foot. In addition, the weak relationship between flat foot and overuse injuries cannot be determined by assessment of the static foot posture during weight-bearing.

The foot addresses three important issues during locomotion. First, the loading force applied to the lower extremity at the ground is buffered by the foot arches. Second, the lower extremity and trunk is supported during the single leg stance position by the stabilizing foot. Third, forward propulsion forces are generated by the recoiled toe and the elevated foot arches. Static

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foot posture has a weak correlation with foot function[6, 7]. The windlass mechanism, proposed by Hicks (1954), states that forefoot rigidity and arch height are increased by toe extension. This posture lengthens the plantar aponeurosis and generates forward propulsion at the late stance during gait[8]. Thus, the windlass mechanism controls rigidity of the foot, and foot type can be classified by not only foot structure (flat foot), but also foot function (windlass).

Physiotherapy for flat foot deformities is important for strength training of the intrinsic muscles of the foot. McKeon proposed the foot core system, which indicates the importance of intrinsic muscles and their relation to extrinsic muscles in the development of the arch[9]. However, it is difficult to assess the function of intrinsic muscles of the foot. Recently, the intrinsic muscles of the foot were assessed in flat feet by ultrasonography[10, 11]. However, therapy that changes both the thickness and the cross sectional area of the intrinsic muscles of the foot is controversial, and the relationship of intrinsic foot musculature and kinematics of the foot during gait is unclear.

The purpose of this study was to investigate the relationship between the morphology of the intrinsic foot musculature and foot kinematics during gait using a foot type classification based on windlass function.

PARTICIPANTS AND METHODS

Sixty-seven feet of 35 normal volunteers (male/female, 19/16; age, 21.7 ± 3.3 years; height, 166.7 ± 9.6 cm; weight, 58.7 ± 8.7 kg) were examined in this study. All methods were approved by the Medical Ethics Committee of Morinomiya University of Medical Sciences (2017-002) and written consent was obtained from each participant. All participants were free from lower limb injuries since 3 months before the time of testing.

Foot kinematic data during gait were recorded using a three-dimensional motion analysis system (Vicon MX system, Oxford Metrics Ltd., Oxford, England) with 8 infrared cameras (VICON VERO) at a sampling frequency of 100 Hz and two force plates (AMTI) at a sampling frequency 1,000 Hz. Nine millimeter diameter retro-reflective skin makers were mounted according to the Oxford Foot Model and the plug-in gait[12]. A static calibration trial was recorded with the participant in a relaxed bipedal stance position that was defined as 0 degrees for calculation of segment to segment motion in the sagittal, transverse, and frontal planes. Gait kinematics during walking the 12 meter walkway at a comfortable speed were recorded in 10 trials. The mean segment to segment motion (I)–(III) for the sagittal, transverse, and frontal planes were calculated from 10 trials, where (i) is hindfoot relative to the leg, (ii) is forefoot relative to the hindfoot, and (iii) is hallux relative to the forefoot.

All data were normalized to 0–100% of the gait cycle (GC). The angle of dorsi-/plantar flexion, inversion/eversion, and abduction/adduction at heel contact (0% of the gait cycle), foot flat (19% of the GC), mid-stance (30% of the GC), and the peak angle during late stance (30–60% of the GC) were extracted. The late stance deviation, defined as the angle from the mid-stance to the peak angle of the late stance, were calculated.

The morphology of the intrinsic muscles of the foot were assessed using an B-mode ultrasound imaging system (Aplio300, Canon medical corporation, Tokyo, Japan) with a 18 MHz linear transducer (PLT-1204BT). The flexor digitorum brevis (FDB), abductor hallucis (AH), and abductor digiti minimi (ADM) muscles were measured according to the descriptions of Mickle et al[13]. For the oblique head of the adductor halluces muscle (ADHO), the transducer was aligned longitudinally along the shaft of the 1st metatarsal and the medial sesamoid bone, and the Lisfranc joint of the 1st metatarsal was captured. The transducer was rotated approximately 30 degrees laterally, aligned with the medial sesamoid bone and the second metatarsal base, and the distance from the superficial fascia to the deep fascia of the ADHO (ADHO thickness) was measured at 10 mm distal to the 2nd metatarsal base. All muscle morphology was generalized by body height because the CSA and the thickness of the intrinsic muscles showed significant correlation with body height in a pilot study.

Static foot posture (Foot Posture Index-6 item version (FPI-6)) was used to divide the feet into two groups: normal arch and flat foot. The flat foot group (35 feet) was defined as an FPI >5 points, and the normal arch group (32 feet) was defined as an FPI <5 points. Moreover, the foot groups were divided into two types (abduction and adduction) by assessment of horizontal forefoot movement during the recoil phase.

Distributions of feet in the four groups were assessed using χ^2 independence test. And difference general characteristic data among four groups were assessed using Kruskal-Wallis test. Foot kinematics and the morphology of the intrinsic musculature were compared among the four groups using ANOVA with Bonfferoni test as a post hoc test. All statistical approaches used SPSS statistics ver.25 (IBM Co.), and the level of significance was preset at $p<0.05$.

RESULTS

Thirty-five feet and 32 feet were classified into abduction type and adduction type, respectively. In the normal arch group, 21 feet and 11 feet were classified into abduction type and adduction type, respectively. In the flat foot group, 14 feet and 21 feet were classified into abduction type and adduction type, respectively. The distribution of the abduction type and adduction type were significantly different between the normal arch group and the flat foot group. There were no significant difference of the general characteristic data among the four groups (Table 1).

The dorsi-flexion angle of the flat foot-adduction type was significantly larger than that of the normal arch-abduction type at the IC, FF, MSt, and HO. In addition, deviation of dorsi-flexion of the flat foot-adduction type from the MSt to the HO was

Table 1. General characteristic data among four groups

	Normal-add type	Normal-abd type	Flatfeet-add type	Flatfeet-abd type	p-value
Number (feet)	11.0	21	21	14	
Gender (Female/Male)	3/8	10/11	9/12	7/7	0.38
Age (years)	21 (21–21)	21 (21–21)	21 (21–21)	21 (21–24)	0.92
Hieght (cm)	161 (159–173.5)	173 (160–177)	164 (152–169)	170.5 (168–173)	0.09
Weight (kg)	59 (55–68.5)	60 (55–67)	56 (46–60.7)	60.9 (60–65.3)	0.10

add: adduction; abd: abduction.
Median value and (25% value–75% value) was written.

Table 2. Difference of the forefoot kinematics among foot types

		Normal-add type	Normal-abd type	Flatfeet-add type	Flatfeet-abd type	p-value
D/F angle (degrees)	IC	3.18 ± 7.15	−1.98 ± 5.09	4.32 ± 5.08†	0.89 ± 6.44	0.01
	FF	5.99 ± 7.22	0.86 ± 5.07	6.89 ± 4.84†	3.68 ± 6.67	0.01
	MSt	7.38 ± 7.57	3.05 ± 5.65	9.86 ± 5.80†	5.00 ± 6.32	0.01
	HO	−5.20 ± 9.09	−10.22 ± 5.07	−0.51 ± 5.27†	−5.35 ± 8.64	<0.001
	TO	11.80 ± 8.21	6.69 ± 5.66	15.16 ± 5.88†	10.20 ± 7.73	<0.001
	TO-MSt	4.42 ± 0.97	3.64 ± 1.67	5.30 ± 1.30†	5.20 ± 2.62	0.01
Inversion (degrees)	IC	−1.93 ± 6.98	1.76 ± 6.34	−5.32 ± 6.75†	−5.01 ± 6.34†	<0.001
	FF	−5.04 ± 6.57	−1.07 ± 6.74	−7.21 ± 7.22	−6.01 ± 5.73	0.03
	MSt	−4.83 ± 6.78	−1.31 ± 6.54	−7.11 ± 6.97	−5.67 ± 5.94	0.04
	60%	3.95 ± 7.39	6.73 ± 6.11	0.81 ± 6.93†	0.29 ± 5.92†	0.01
	TO	4.45 ± 7.29	7.12 ± 5.98	0.96 ± 6.95†	0.58 ± 5.83†	0.01
	TO-MSt	9.28 ± 1.75	8.43 ± 2.87	8.07 ± 1.86	6.25 ± 2.47*	0.01
Adduction (degrees)	IC	2.96 ± 6.65	3.12 ± 6.84	2.50 ± 8.73	3.16 ± 7.43	0.99
	FF	−2.92 ± 6.39	−0.78 ± 6.56	−2.91 ± 7.52	0.07 ± 8.07	0.56
	MSt	−2.18 ± 6.89	−0.14 ± 6.73	−2.60 ± 7.34	0.23 ± 7.99	0.58
	60%	1.65 ± 5.72	−0.72 ± 7.13	1.76 ± 7.39	0.52 ± 7.33	0.68
	TO	5.05 ± 5.64	4.35 ± 7.00	4.22 ± 8.71	5.10 ± 7.15	0.98
	TO-MSt	7.23 ± 1.71†‡	4.50 ± 2.02	6.81 ± 2.24†‡	4.87 ± 1.64	<0.001

add: adduction; abd: abduction; D/F: dorsi-flexion.
†: difference with Normal arch + Abduction type.
‡: difference with Flatfoot + Abduction type.
*: difference with Normal arch − Adduction type.

greater than that of the normal arch-abduction type. The normal arch-adduction type and the flat foot-abduction type did not show any significant difference.

The inversion angle of the normal arch-abduction type was significantly smaller than that of both the flat foot-adduction type and flat foot-adduction type at the IC and TO. The inversion deviation from MSt to TO of the normal arch-adduction type was significantly larger than that of the flat foot-abduction type.

There was no significant difference in the adduction angle of the IC, FF, MSt, and TO among the four foot types. The adduction angle deviation of both the normal arch-adduction type and the flat foot-adduction type were significantly larger than both the normal arch-abduction type and the flat foot-abduction type (Table 2).

The hindfoot dorsi-flexion angle of the flat foot-adduction type was significantly smaller than that of the normal arch-abduction type at the IC, FF, MSt, and TO. Inversion and adduction movements were not significantly different among the four types ($p<0.05$) (Table 3).

The thickness of the ADM of the flat foot-adduction type was significantly thinner than that of the normal arch-abduction type. Other parameters of the intrinsic foot musculature showed no significant difference among the four foot types (Table 4).

DISCUSSION

During the late stance, the forefoot shows planter flexion and inversion relative to the hindfoot. However, the horizontal movements of the forefoot can be classified as abduction type and adduction type. Elevation of the arch movement of the forefoot consists of plantar flexion, inversion, and adduction. In this study, the number of feet classified as abduction type in the normal arch group was greater than feet classified as abduction type in the flat foot group. In addition, the number of feet classified as adduction type in the flat foot group was greater than that classified as adduction type in the normal arch group. Thus, adduction type indicated an excessive elevation of the medial longitudinal arch of the foot at the late stance during gait.

There is evidence that the flat foot posture is related positively with increased frontal plane motion of the rear foot, some studies show a small effect size and the relationship between foot posture and kinematics of gait is controversial[14]. In this

Table 3. Difference of the hindfoot kinematics among foot types

		Normal-add type	Normal-abd type	Flatfeet-add type	Flatfeet-abd type	p-value
D/F angle (degrees)	IC	−2.57 ± 5.21	−0.41 ± 4.12	−6.13 ± 5.07†	−3.54 ± 6.95	0.01
	FF	−3.35 ± 6.08	−2.31 ± 3.71	−8.21 ± 4.55†	−5.70 ± 7.88	0.01
	MSt	6.23 ± 5.29	8.33 ± 3.69	1.66 ± 5.45†	4.28 ± 6.96	0.00
	HO	9.15 ± 5.48	11.00 ± 4.08	4.07 ± 6.59†	6.97 ± 6.37	<0.001
	TO	−13.60 ± 4.25	−11.70 ± 5.69	−15.35 ± 4.59†	−14.18 ± 5.91	0.16
	TO-MSt	2.91 ± 1.36	2.67 ± 1.55	2.60 ± 1.95	2.69 ± 1.97	0.97
Inversion (degrees)	IC	21.25 ± 8.54	18.94 ± 10.95	20.50 ± 10.11	17.57 ± 13.86	0.83
	FF	8.06 ± 8.53	6.84 ± 9.99	9.71 ± 10.83	4.44 ± 14.22	0.58
	MSt	17.90 ± 6.24	13.33 ± 10.61	17.68 ± 9.80	12.41 ± 12.97	0.32
	HO	25.83 ± 7.62	21.03 ± 10.36	23.89 ± 9.75	20.86 ± 13.02	0.55
	TO	7.62 ± 8.65	6.26 ± 9.93	8.61 ± 10.51	3.20 ± 13.86	0.54
	TO-MSt	7.93 ± 4.03	7.70 ± 3.48	6.85 ± 2.54	8.45 ± 4.83	0.63
Adduction (degrees)	IC	2.36 ± 7.32	1.36 ± 6.38	−1.63 ± 6.50	0.88 ± 7.94	0.38
	FF	−0.28 ± 6.12	−1.24 ± 5.33	−3.46 ± 6.35	−2.33 ± 7.47	0.53
	MSt	−0.36 ± 5.80	−0.48 ± 5.39	−2.90 ± 5.69	−1.99 ± 8.27	0.57
	HO	1.96 ± 8.01	1.13 ± 7.16	0.08 ± 5.99	2.82 ± 6.23	0.68
	TO	−2.31 ± 6.52	−3.39 ± 6.43	−4.84 ± 6.43	−4.93 ± 8.51	0.73
	TO-MSt	7.22 ± 2.87	5.32 ± 3.25	5.43 ± 3.02	7.03 ± 3.60	0.22

add: adduction; abd: abduction; D/F: dorsi-flexion.
†: significant difference from the normal arch-abduction type.

Table 4. Difference of the intrinsicfoot muscle

	Flatfeet-add type	Normal-add type	Flatfeet-add type	Flatfeet-abd type	p-value
ABDH CSA/height (cm^2/cm)	1.23 ± 0.29	1.39 ± 0.31	1.39 ± 0.28	1.50 ± 0.30	0.18
ABDH thickness/height (cm/cm)	6.97 ± 1.19	7.29 ± 1.08	7.78 ± 1.08	7.30 ± 1.12	0.22
ADHO thickness/height (cm/cm)	8.12 ± 1.36	7.71 ± 0.74	7.56 ± 0.89	7.73 ± 0.90	0.48
ABDM CSA/height (cm^2/cm)	0.67 ± 0.20	0.61 ± 0.16	0.60 ± 0.18	0.67 ± 0.16	0.51
ABDM thickness/height (cm/cm)	4.62 ± 0.85	4.74 ± 0.79	4.04 ± 0.59*	4.51 ± 0.75	0.02
FDB CSA/height (cm^2/cm)	1.21 ± 0.23	1.28 ± 0.42	1.08 ± 0.23	1.18 ± 0.19	0.19
FDB thickness/height (cm/cm)	5.09 ± 0.73	4.86 ± 0.70	4.89 ± 0.73	5.14 ± 0.94	0.64

add: adduction; abd: abduction.
*: significant difference from the normal arch-abduction type.

study, the flat foot-adduction type showed some difference from the normal arch- abduction type. The kinematics of both dorsi-flexion of the forefoot and plantar flexion of the hind foot showed collapse of the longitudinal arch of the foot. Those kinematics of the flat foot-adduction type were increased over those of the normal arch-abduction type, indicating a decreased foot function to buffer the loading force from the ground in the flat foot-adduction type. In the flat foot-abduction type, there was no significant difference from the normal arch group. Thus, there may be some variation in the flat foot group, and the flat foot-abduction type might not be a risk factor for overuse injuries.

The thickness of the ADM of the flat foot-adduction type was significantly less than that of the normal arch-abduction type. Angin et al. showed that the AH of the flat foot was smaller than that of the normal foot, but they did not assess the ADM[15]. Zhang et al. reported that flat feet have a larger AH, flexor digitorum brevis and longus, and a smaller ADM muscle than controls[11]. Results of our studies are similar to their results. However, their studies did not refer to a relationship between intrinsic foot musculature and foot kinematics. We divided the foot types based on the both static foot posture and function. We considered that the thinner ADM in the flat foot-adduction type may decrease the abduction force of the forefoot at the stance phase of gait. Moreover, abductor muscles, such as the peroneus longus muscle, showed decreased muscle activity, while adductor muscles, such as the tibialis posterior muscle, show increased activity during terminal stance in the flat foot group. This extrinsic foot muscle activity may influence the foot kinematics.

As a limitation to this study, we were unable to assess muscle activity during gait. Therefore, it is unclear whether the tension of the ADM of the flat foot-adduction type was lower than that of the normal arch-abduction type during gait. Accurately estimating the intrinsic muscle force during movement of the weight-loaded foot is difficult. Second, the results of the foot kinematics data in this study included skin impedance. However, the Oxford Foot Model is a common multi-segment foot model. Thirdly, the windlass function had strong relationship with stiffness of the arch. The stiffness of the arch was divined as the relationship between arch deformation and external force. The biggest external force was the ground reaction force, however, the deformation of the arch calculated from the total amount of the forefoot plantar flexion, inversion and addiction related to the hind foot in this study. Thus, we could not explain which direction of the ground reaction force deformed the arch during the late stance of the gait. And the body weight had no difference among the four groups. Therefore, we cannot discuss between the stiffness of the arch. Lastly, the participants of this study did not report any pain of the lower limbs and trunk. We do not know how the windlass function changes in the flat foot with pain of the foot or ankle. Further study is needed to investigate the windlass function in overuse injury related to the foot type.

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Conflict of interest

The authors declare that they have no conflict of interest.

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