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Correlation between three-dimensional medial longitudinal arch joint complex mobility and medial arch angle in stage II posterior tibial tendon dysfunction

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ABSTRACTS

Background: The purpose of this study was to evaluate correlation between three-dimensional medial longitudinal arch joint complex mobility and medial arch angle in stage II posterior tibial tendon dysfunction flatfoot under loading.

Methods: CT scans of 15 healthy feet and 15 feet with stage II posterior tibial tendon dysfunction flatfoot were taken both in non- and simulated weight-bearing condition. The CT images of the hindfoot and medial longitudinal arch bones were reconstructed into three-dimensional models with Mimics and Geomagic reverse engineering software. The three-dimensional complex mobility of each joint in the medial longitudinal arch and their correlation with the medial arch angle change were calculated.

Results: From non- to simulated weight-bearing condition, the medial arch angle change and the medial longitudinal arch joints mobility were significant larger in stage II posterior tibial tendon dysfunction flatfoot ($p < 0.05$). The eversion of the talocalcaneal joint, the proximal translation of the calcaneus relative to the talus, the dorsiflexion of the talonavicular joint, the dorsiflexion and abduction of the medial cuneonavicular joint, and the lateral translation of the medial cuneiform relative to the navicular, and the dorsiflexion of the first tarsometatarsal joint were all significantly correlated to the medial arch angle change in stage II posterior tibial tendon dysfunction flatfoot (all $r > 0.5$, $p < 0.05$).

Conclusions: There is increased mobility in the medial longitudinal arch joints in stage II posterior tibial tendon dysfunction flatfoot and the medial arch angle change under loading causes displacement not only at hindfoot joints but also involve midfoot and forefoot joint.

1. Introduction

Posterior tibial tendon dysfunction (PTTD) is thought to be the main cause of adult acquired flatfoot deformity (AAFD) [1]. According to the classification system described by Johnson and Strom [2], stage II PTTD flatfoot is regarded as flexible deformity with the collapse of the medial longitudinal arch (MLA) under loading [1]. The MLA is constructed from first metatarsal, medial cuneiform, navicular, talus, and calcaneus. Patients with stage II PTTD flatfoot are usually treated with various surgical procedures including combinations of osteotomy, tendon transfer, to achieve realignment of the MLA [3–6].

Recently, there have been attempts to objectify classification criterion and surgical decision making with pre-operative data for stage II PTTD flatfoot. Some studies on how the structure of the MLA was destroyed and dealt with foot orthoses or multiple surgical procedures had been carried out by using cadaveric flatfoot models [7–10]. Clinically, two-dimensional investigations of the height of the navicular or medial cuneiform [11,12] in the MLA, and deformations of subtalar joint on CT Images [13,14] were performed to evaluate alignment.

However, to the best of our knowledge, no previous study had investigated the three-dimensional complex mobility of each joint in the MLA in healthy foot and stage II PTTD flatfoot under weight-bearing. We hypothesize that MLA joints mobility is greater in stage II PTTD flatfoot than that in healthy foot under weight-bearing and the medial arch angle (MAA) change under loading causes significant displacement in MLA joints in stage II PTTD flatfoot. In the present study, we evaluate the correlation between the three-dimensional complex mobility of these joints in the MLA and the MAA change in stage II PTTD flatfoot under loading.

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2. Patients and methods

A total of 30 subjects were recruited for the present study in the Department of Orthopedic Surgery, The First Affiliated Hospital, College of Medicine, Zhejiang University from May 2016 to May 2017. 15 healthy volunteers [15 right feet; median age 30.6 [SD 4.0] (28–38) years; median weight 61.4 [SD 4.4] (58–71) kg; 7 men and 8 women] participated, with no history of foot or ankle injuries or instability. They also did not fulfill any of the criteria for patients with either PTTD or cavus foot [15]. Stage II PTTD flatfoot was defined using PTTD stage classification described by Johnson and Strom [2]. 15 patients with 15 right feet classified as stage II PTTD flatfoot [median age 32.4 [SD 4.2] (30–40) years; median weight 62.2 [SD 4.3] (56–70) kg; 9 men and 6 woman] were included. Two orthopedic specialists made the diagnosis of stage II PTTD flatfoot deformity. Only patients with feet for which both surgeons made the same diagnosis were accepted. This study was conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics Committee of The First Affiliated Hospital, College of Medicine, Zhejiang University. Written informed consent was obtained from all participants.

A custom-made foot-loading device was designed and constructed to simulate body-weight-bearing, counterbalanced by the constraints of a modern CT scanner [16,17]. CT scanning was undertaken with participants in the supine position, which was set to neutral in all axes to make a vertical line connecting the center of the heel and the second metatarsal, with the tibial shaft through the ankle center horizontal and parallel to the CT bed [16–19]. CT images of right feet were scanned from 10 cm proximal to the tibiotalar joint to the sole, using a 256 multi-slice CT scanner (100 kV × 150 mA, volume EC, 512 × 512 matrix; 0.67 mm thickness; 0.67 mm interval) (Philips Brilliance 256; Philips Medical Systems, Best, The Netherlands). Firstly, the CT images were taken in a non-weight-bearing condition and then followed by loading with each subject's simulated weight bearing [16,17,20] (Fig. 1).

Three-dimensional image data were reconstructed from two-dimensional Digital Imaging and Communications in Medicine image data obtained from the CT examination. The three-dimensional models of first metatarsal, medial cuneiform, navicular, talus and calcaneus were created through a three-dimensional reconstruction software package (Mimics 18.0; Materialise Inc., Leuven, Belgium) [16,17]. The mobility of the following joints were calculated: the first metatarsal relative to the medial cuneiform at the first tarsometatarsal joint; the medial cuneiform relative to the navicular at the medial cuneonavicular joint; the navicular relative to the talus at the talonavicular joint; the calcaneus to the talus at the talocalcaneal joint. Three-dimensional complex mobility of these joints were evaluated in a reverse engineering software package (Geomagic Studio 13.0; Geomagic Co., Morrisville, North Carolina) by a twice registration method [16,17]. Accuracy of the method was 0.1 mm in translation and 0.1° in rotation [16–18,21,22]. A global X–Y–Z coordinate system corresponding to anatomical axes was used to describe the orientation of the tarsal bones [20] (Fig. 2). Segmental movements of each joint from non- to simulated weight bearing were calculated from the displacement of each bone. In accordance with previous studies, rotation angles of each bone were defined relative to the three major axes of rotation for examination: plantarflexion/dorsiflexion, adduction/abduction and eversion/inversion. Dorsiflexion, eversion, and abduction were defined as positive while plantarflexion, inversion, and adduction were defined as negative. Translations of each bone were defined relative to the three major axes: medial/lateral, anterior/posterior and proximal/distal. Medial, anterior, and proximal were defined as positive while lateral, posterior, and distal were defined as negative (Fig. 2) [16,17]. The definition and measurement of the MAA was calculated according to the previous study [16]. One line was drawn between the lowest point of the calcaneus and the lowest point of the talus and another one between the lowest point of the talus and the lowest point of the first metatarsal head. The lowest point of the talus would be the angular vertex of the MAA (Fig. 3).

The data were analyzed with t-test and Pearson liner correlation. The results were presented as the mean with standard deviation (SD). A significant difference was defined as $p < 0.05$. All analyses were performed using SPSS v20.0 software (SPSS Inc., Chicago, Illinois).

Fig. 1. CT scanning of each subject's right foot and ankle under loading.

3. Results

3.1. Load response of the MAA change

All the participants did not complain of any discomfort during loading. During non-weight-bearing condition, the MAA was 122.2

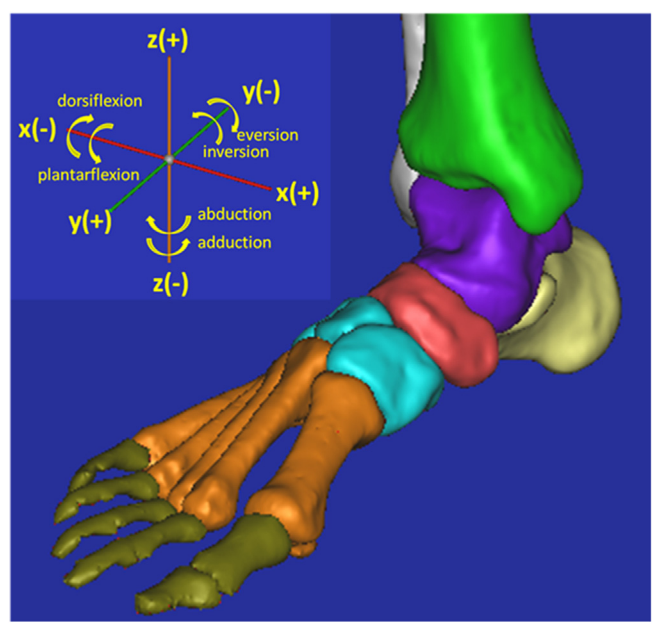

Fig. 2. A three-dimensional CT model of foot and ankle. A global X–Y–Z coordinate system corresponding anatomical axes was used to describe the orientation of tarsal bones. The Z-axis was set along the tibial shaft through the center of the ankle and the Y-axis was set parallel to the projection of a line connecting the center of the heel and the second metatarsal head on a plane perpendicular to the Z-axis. The X-axis was determined according to a right-hand rule from the Y and Z-axis. The coronal (XY) plane, sagittal (XZ) plane, and transverse (YZ) plane were defined from these X–Y–Z axes.

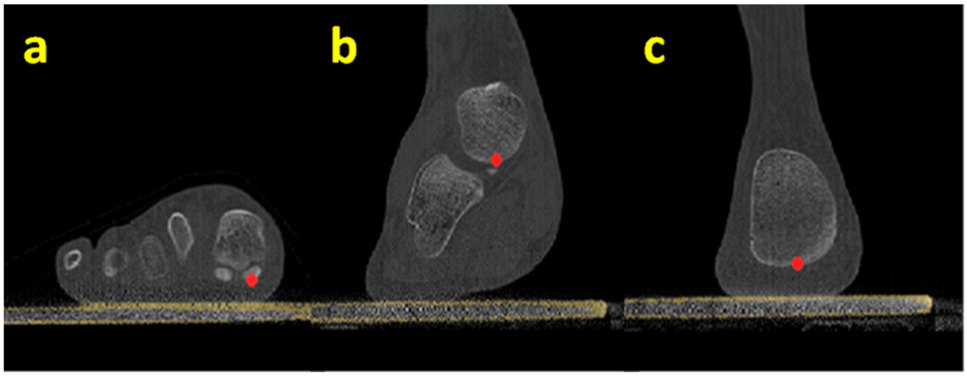

Fig. 3. The lowest point of the first metatarsal head (a), the talus (b) and the calcaneus (c) in a two-dimensional CT coronal image (red dot). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[SD 8.1°] in healthy foot compared with 123.5 [SD 8.1°] in stage II PTTD flatfoot ($p = 0.72$). After simulated weight-bearing condition, the MAA change was significantly larger in stage II PTTD flatfoot compared to that in healthy foot ($p = 0.017$), indicating the MLA collapse under loading in stage II PTTD flatfoot (Table 1).

3.2. Load response of joint complex mobility in the MLA

3.2.1. Talocalcaneal joint

The rotation of the talocalcaneal joint was significantly larger in the dorsiflexed and everted direction in stage II PTTD flatfoot compared with the healthy foot ($p = 0.0026$ and $p = 0.0005$, respectively), but not in the transverse plane ($p = 0.1187$) (Fig. 4a). Translation of the calcaneus relative to the talus at the talocalcaneal joint was more anterior ($p = 0.0432$) and more proximal ($p = 0.0072$) in stage II PTTD flatfoot, but there was no statistically significant difference in the mediolateral direction ($p = 0.0790$) (Fig. 5a).

3.2.2. Talonavicular joint

The rotation of talonavicular joint was significantly larger in the everted direction in stage II PTTD flatfoot compared with the healthy foot ($p = 0.0001$). No significant difference was observed in the sagittal or transverse planes ($p = 0.1537$ and $p = 0.0504$, respectively) (Fig. 4b). The translation of the navicular relative to the talus at the talonavicular joint was significantly more anterior, more proximal and more lateral in stage II PTTD flatfoot compared with the healthy foot ($p = 0.0001$, 0.0001 and 0.0387), respectively (Fig. 5b).

3.3. Medial cuneonavicular joint

The rotation of the cuneonavicular joint was significantly larger in dorsiflexed and abducted direction direction in stage II PTTD flatfoot compared with the healthy foot ($p = 0.0296$ and $p = 0.0451$). No significant difference was observed in the coronal planes ($p = 0.1272$) (Fig. 4c). Translation of the medial cuneiform relative to the navicular at the medial cuneonavicular joint was more lateral ($p = 0.0024$) in stage II PTTD flatfoot, but there was no statistically significant difference in the anteroposterior ($p = 0.1904$) or distal-proximal direction ($p = 0.2332$) (Fig. 5c).

Table 1
The MAA change in healthy foot and stage II PTTD flatfoot from non- to simulated weight-bearing condition.

	Healthy foot Mean (SD) (°)	Stage II PTTD flatfoot Mean (SD) (°)	p-Value
Non-weight-bearing	122.2 (8.1)	123.5 (8.1)	0.72
Simulated weight-bearing	125.3 (8.0)	133.9 (6.7)	0.017*
Difference	3.1 (0.8)	10.5 (3.6)	

Data are expressed as mean (SD).
* Significant difference: p value <0.05.

3.4. First tarsometatarsal joint

The rotation of the first tarsometatarsal joint was significantly larger in dorsiflexed direction direction in stage II PTTD flatfoot compared with the healthy foot ($p = 0.0339$). No significant difference was observed in the coronal ($p = 0.3808$) or transverse plane ($p = 0.0710$) (Fig. 4d). In addition, for translation of the first metatarsal relative to the medial cuneiform at the first tarsometatarsal joint, there was no statistically significant difference between healthy foot and stage II PTTD flatfoot in the anteroposterior ($p = 0.1820$) or distal-proximal ($p = 0.0529$) or mediolateral direction ($p = 0.0681$) (Fig. 5d).

3.5. Correlation between three-dimensional joint complex mobility and the MAA change under loading

The three-dimensional complex mobility of the talocalcaneal joint, the talonavicular joint, the medial cuneonavicular joint, and the first tarsometatarsal joint had not any statistically significant correlation with the MAA change in healthy foot (all $r < 0.5$, $p > 0.05$) (Table 2). However, in stage II PTTD flatfoot, the eversion of the talocalcaneal joint ($r = 0.6548$, $p = 0.0399$), the proximal translation of the calcaneus relative to the talus ($r = 0.7304$, $p = 0.0164$), the dorsiflexion of talonavicular joint ($r = 0.7187$, $p = 0.0192$), the dorsiflexion ($r = 0.6504$, $p = 0.0418$) and abduction ($r = -0.6349$, $p = 0.0486$) of the medial cuneonavicular joint, and the lateral ($r = 0.7077$, $p = 0.0220$) translation of the medial cuneiform relative to the navicular, and the dorsiflexion of the first tarsometatarsal joint ($r = 0.6445$, $p = 0.0443$) were all significantly correlated to the MAA change (Table 3).

4. Discussion

The MLA is three-dimensional and complex, consisting of bones from the calcaneus in the hindfoot to metatarsals in the forefoot, and soft tissues such as ligaments, capsules, and muscles. When PTTD is prolonged and has progressed to stage II, the MLA drops, causing a flexible flatfoot deformity [23].

Commonly, the evaluation of the MLA is based on the two-dimensional X-ray under loading [24–28]. But it will cause difference through three-dimensional evaluation. In the present study, we evaluated the MAA change three-dimensionally and analyzed the correlation between the change and MLA joints complex mobility healthy foot and stage II PTTD flatfoot under

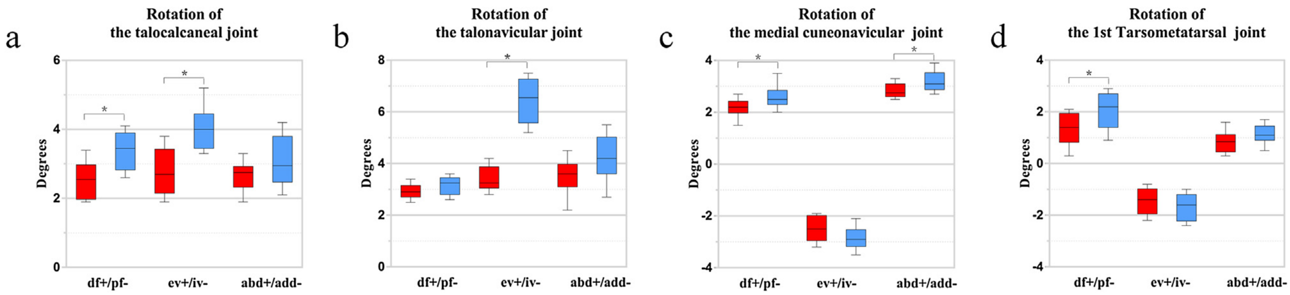

Fig. 4. Comparison between healthy foot group (red) and stage II PTTD flatfoot group (blue) for rotation of each joint in the MLA. The boxes indicate the interquartile range (from 25% to 75%); the horizontal lines within the boxes indicate the median; the whiskers indicate the range (non-outliers); *: $p < 0.05$. (a) Talocalcaneal joint (b) talonavicular joint (c) medial cuneonavicular joint (d) first tarsometatarsal joint. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

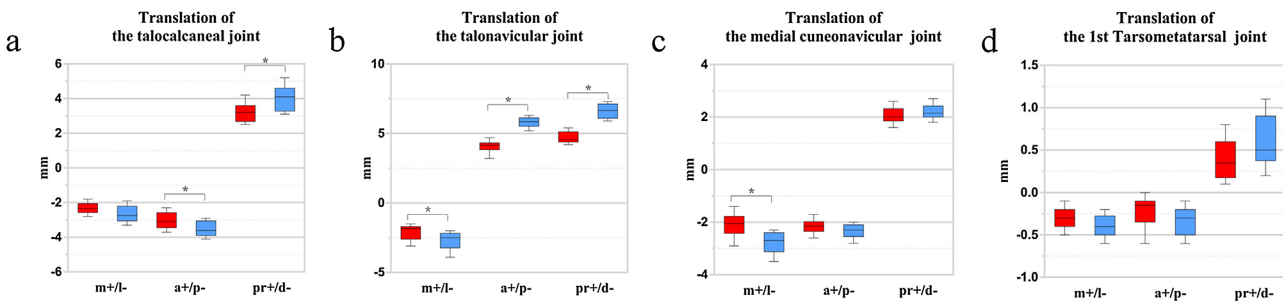

Fig. 5. Comparison between healthy foot group (red) and stage II PTTD flatfoot group (blue) for translation of each joint in the MLA. The boxes indicate the interquartile range (from 25% to 75%); the horizontal lines within the boxes indicate the median; the whiskers indicate the range (non-outliers); *: $p < 0.05$. (a) Talocalcaneal joint (b) talonavicular joint (c) medial cuneonavicular joint (d) first tarsometatarsal joint. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Correlation between each joint complex mobility in the MLA and the MAA change in healthy foot.

MLA joints		Direction	Mean (SD)	MAA change	Correlation coefficient r	p-Value
Talocalcaneal joint	Rotation (°)	df+/pf−	2.5 (0.5)	3.1 (0.8)	0.0679	0.8522
		ev+/iv−	2.8 (0.7)		0.0867	0.8118
		abd+/add−	2.7 (0.4)		0.0365	0.9203
	Translation (mm)	m+/l−	−2.3 (0.3)		0.2244	0.5330
		a+/p−	−3.0 (0.5)		−0.0184	0.9598
		pr+/d−	3.2 (0.5)		0.4356	0.2083
Talonavicular joint	Rotation (°)	df+/pf−	3.0 (0.3)		0.1590	0.6609
		ev+/iv−	3.4 (0.5)		0.1931	0.5929
		abd+/add−	3.5 (0.7)		0.1819	0.6151
	Translation (mm)	m+/l−	−2.1 (0.6)		−0.0563	0.8773
		a+/p−	4.1 (0.4)		0.0841	0.8173
		pr+/d−	4.7 (0.4)		−0.1810	0.6169
Medial cuneonavicular joint	Rotation (°)	df+/pf−	2.2 (0.3)		0.3253	0.3590
		ev+/iv−	−2.5 (0.5)		−0.4546	0.1868
		abd+/add−	2.8 (0.3)		−0.1103	0.7616
	Translation (mm)	m+/l−	−2.1 (0.4)		0.2714	0.4480
		a+/p−	−2.2 (0.3)		0.3831	0.2745
		pr+/d−	2.1 (0.3)		0.3967	0.2564
1st tarsometatarsal joint	Rotation (°)	df+/pf−	1.3 (0.6)		0.1353	0.7095
		ev+/iv−	−1.5 (0.5)		0.3511	0.3199
		abd+/add−	0.8 (0.4)		0.1312	0.7179
	Translation (mm)	m+/l−	−0.3 (0.1)		−0.1797	0.6193
		a+/p−	−0.2 (0.2)		−0.0940	0.7962
		pr+/d−	0.4 (0.2)		0.4591	0.1820

df: dorsiflexion+/pf: plantarflexion−; ev: eversion+/iv: inversion−; abd: abduction+/add: adduction−; m: medial+/l: lateral−; p: posterior+/a: anterior−; pr: proximal+/d: distal−.
Data are expressed as mean (SD).
*Significant difference: p value <0.05.

Table 3
Correlation between each joint complex mobility in the MLA and the MAA change in stage II PTTD flatfoot.

MLA joints		Direction	Mean (SD)	MAA change	Correlation coefficient r	p-Value
Talocalcaneal joint	Rotation (°)	df+/pf−	3.4 (0.6)	10.5 (3.6)	0.2945	0.4089
		ev+/iv−	4.0 (0.6)		0.6548	0.0399*
		abd+/add−	3.1 (0.7)		0.0079	0.9828
	Translation (mm)	m+/l−	−2.7 (0.5)		0.1996	0.5803
		a+/p−	−3.5 (0.4)		−0.4179	0.2295
		pr+/d−	4.0 (0.7)		0.7304	0.0164*
Talonavicular joint	Rotation (°)	df+/pf−	3.2 (0.3)		0.7187	0.0192*
		ev+/iv−	6.4 (0.9)		0.2234	0.5349
		abd+/add−	4.2 (0.9)		0.3411	0.3347
	Translation (mm)	m+/l−	−2.7 (0.6)		−0.0068	0.9851
		a+/p−	5.8 (0.4)		0.1796	0.6196
		pr+/d−	6.6 (0.5)		−0.2902	0.4160
Medial cuneonavicular joint	Rotation (°)	df+/pf−	2.6 (0.4)		0.6504	0.0418*
		ev+/iv−	−2.8 (0.4)		−0.4331	0.2112
		abd+/add−	3.2 (0.4)		−0.6349	0.0486*
	Translation (mm)	m+/l−	−2.8 (0.4)		0.7077	0.0220*
		a+/p−	−2.3 (0.3)		0.4200	0.2269
		pr+/d−	2.2 (0.3)		0.1550	0.6690
1st tarsometatarsal joint	Rotation (°)	df+/pf−	2.0 (0.7)		0.6445	0.0443*
		ev+/iv−	−1.7 (0.5)		0.4348	0.2092
		abd+/add−	1.2 (0.4)		0.1527	0.6736
	Translation (mm)	m+/l−	−0.4 (0.1)		−0.0882	0.8085
		a+/p−	−0.3 (0.2)		−0.3056	0.3906
		pr+/d−	0.6 (0.3)		0.4176	0.2299

df: dorsiflexion+/pf: plantarflexion−; ev: eversion+/iv: inversion−; abd: abduction+/add: adduction−; m: medial+/l: lateral−; p: posterior+/a: anterior−; pr: proximal+/d: distal−.
Data are expressed as mean (SD).
* Significant difference: p value <0.05.

loading. The results indicated that the MAA had a significant increase under loading in stage II PTTD flatfoot while compared with healthy foot. In addition, the mobility of MLA joints was increased in stage II PTTD flatfoot compared with healthy foot.

Takai had reported that the talocalcaneal joint was important component of the lateral and medial foot arch [29]. But Kanatli et al. found that there was no relationship between the hindfoot position and MLA height as measured by the arch index in healthy foot [28]. Recently, Wen et al. reported the three-dimensional motion of the talocalcaneal joint had little influence on the MLA in healthy foot [30]. The present study showed there was no relationship between the talocalcaneal joint motion and the MAA change under loading in healthy foot. But in stage II PTTD flatfoot, the current results showed that the eversion of the talocalcaneal joint and the proximal translation of the calcaneus relative to the talus had significant influence on the MLA under loading. It might be that much of the flatfoot malalignment was caused by deformation movement at the talocalcaneal joint. Therefore, in the treatment of the flatfoot deformity, it would be necessary to provide supports both for the MLA in the sagittal direction and for the talocalcaneal joint in the coronal direction.

Sammarco [31] reckoned the MLA was supported by the talonavicular joint. A previous cadaveric study reported that the inversion of the forefoot would result in the MLA collapse while the eversion would lead to elevation, which was caused by the inversion of the talonavicular joint [32]. Wen et al. [30] reported that the medial translation of the navicular relative to the talus had significant correlation with the MAA change in the healthy foot with ankle from neutral to maximal inversion-abduction-dorsiflexion position under no loading. But they didn't evaluate the correlation between the talonavicular joint mobility and the MAA change in flatfoot. Our study found that the dorsiflexion of the talonavicular joint had significant correlation with the MAA change in stage II PTTD flatfoot ($r = 0.7187$, $p = 0.0192$). It indicated that the MAA change was mainly influenced by the dorsiflexion of the talonavicular joint in stage II PTTD flatfoot under loading. Our in vivo study results were different with previous studies and the possible reasons for the difference were that the foot position and activities were different and other authors used a cadaveric model with ligaments resection or regardless of tendon and muscle factors. Moreover, the complex mobility of the talonavicular joint was the largest among the MLA joints in the present study and it was considered to be mainly because this joint was on the top of the triangular structure and loaded the most [33,34].

There were few studies reported regarding the load response of the medial cuneonavicular joint and the first tarsometatarsal joint in the MLA. Greisberg et al. [35] observed osteoarthritis in the medial cuneonavicular joint as well as sagittal subluxation in the first tarsometatarsal joint, and evaluated that the medial cuneiform relative to the navicular in the medial cuneonavicular joint in flatfoot dorsiflexed 15° more than in healthy foot. In our study, the difference in the sagittal bone rotation between stage II PTTD flatfoot and healthy foot during weight-bearing was 0.4° in the medial cuneonavicular joint and 0.7° in the first tarsometatarsal joint. However, despite the rotation difference between stage II PTTD flatfoot and healthy foot in these two joints may be small, the difference was significant and they might play an important role in the diagnosis, sub-classification and treatment of stage II PTTD flatfoot. No studies concerning the correlation between the first tarsometatarsal joint and the medial cuneonavicular joint with the MAA change under loading were reported previously. In this study, we found that the three-dimensional complex mobility of the first tarsometatarsal and the medial cuneonavicular joint had no correlation with the MAA change in healthy foot. However, the dorsiflexion, abduction of the medial cuneonavicular joint, the lateral translation of the medial cuneiform relative to the navicular and the dorsiflexion of the first tarsometatarsal joint had a high correlation with the MAA change in stage II PTTD flatfoot under loading. Therefore, we suggest that the medial cuneonavicular joint and the first tasometatarsal joint should also be considered for surgical correction of stage II PTTD flatfoot in order to achieve anatomical restoration and normal MLA alignment with proper function of the foot.

The present study also had some limitations. Firstly, we had a small sample size of only 15 subjects each in stage II PTTD flatfoot group as well as in healthy group. Secondly, we only investigated the MLA joints complex mobility in quasi-static condition with ankle in neutral position at simulated weight-bearing condition. So in the further study, it is important to perform physiological weight bearing CT with present pedCAT (CurveBeam) devices and analyze joint complex mobility dynamically during gait cycle. Finally, we focused solely on the displacement of bones constituting joints, but surrounding soft tissues such as tendons, ligaments, muscles, and the plantar aponeurosis are deeply involved in actual joint dynamics. Therefore, further detailed investigation of these components will also be necessary to elucidate the pathology and sub-classification of stage II PTTD flatfoot.

In summary, by using an original custom-made foot-loading device, we were able to reproduce alignment in the standing position and perform detailed analysis of three-dimensional complex joint mobility in the MLA under loading. The results of this study suggest that there is increased mobility in the MLA joints in patients with stage II PTTD flatfoot and the MAA change under loading causes significant three-dimensional displacement not only at hindfoot joints (the talocalcaneal joint and the talonavicular joint) but also involve midfoot (the medial cuneonavicular joint) and forefoot joint (the first tarsometatatasal joint). The present study may promote further basic research of the etiology and objective sub-classification criterion of stage II PTTD flatfoot and contribute the designing of the surgical procedures and evaluate the effects of surgery for stage II PTTD flatfoot in the future.

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ICMJE conflict of interest

None declared.

Ethical review committee statement

This study was approved by the Medical Ethics Committee of the First Affiliated Hospital, College of Medicine, Zhejiang University. All the participants recruited in the study provided written informed consent.

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