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Flatfoot deformity affected the kinematics of the foot and ankle in proportion to the severity of deformity

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ABSTRACT

Background: : Flatfoot deformity is thought to affect gait kinematics, but the effect of flatfoot on segmental motion of the foot during gait remains unclear. Recently, multi-segmental foot models (MFMs) have been introduced for the in vivo analysis of dynamic foot kinematics. The objective of this study was to find the effect of flatfoot on segmental motion of the foot during gait in females by comparisons with age and gender controlled healthy adults.

Methods: : Thirty six symptomatic flatfeet patients (52–80 years old) and 42 symptom-free female participants without flatfoot (60–69 years old) were included in this study. According to the Meary angle (MA) on standing lateral radiograph, flatfoot patients are divided into severe (SFF, MA > 20°) and moderate (MFF, 10° < MA < 20°) flatfoot group. Segmental foot kinematics were evaluated using a 3D MFM of a 15-marker set (DuPont Foot Model).

Results: : The cadence, speed, stride length, and step width are significantly lower in flatfoot patients. ROM of sagittal and transverse plane of the hindfoot, transverse plane of the forefoot and sagittal plane of the hallux were lower in severe flatfoot group. In the SFF group, there was loss of hindfoot adduction motion during the terminal stance and pre-swing phase. In forefoot kinematics, the SFF group showed significantly supinated and abducted position throughout the gait cycle. In hindfoot kinematics, plantar flexion motion in the pre-swing phase was significantly lower in flatfoot patients in proportion to the severity of the deformity.

Conclusions: : We showed that flatfoot deformity affected the kinematics of the foot and ankle in proportion to the severity of deformity. We cautiously suggest that there might be a threshold of flatfoot precluding normal foot kinematics because normal kinematic pattern of the foot might not collapse in moderate flatfoot with a Meary angle of less than 20 degrees.

1. Introduction

Adult-acquired flatfoot deformity (AAFD) is defined as a symptomatic, progressive deformity of the foot caused by a loss of dynamic and static supportive structures of the medial longitudinal arch. [1] The deformity of the foot usually refers to a three-dimensional deformity with hindfoot valgus, forefoot abduction and supination. [2,3]

Current evaluation systems in the orthopedic clinic mostly rely on static measurements such as standing X-ray, CT and MRI. Recently, gait analysis has been suggested as a good tool for assessment of functional impairment. While clinicians agree that AAFD might cause gait impairment, it is still unclear what the specific changes in gait kinematics are caused by flatfoot deformity. Generally, individuals with flatfoot have great foot mobility compared to those with cavus foot. [4] There are some kinematic studies showing that flatfoot posture is related with increased motion. [4,5], while less midfoot ROM during pre-swing was observed in flatfoot group in other study. [6] To our knowledge, there are few triplanar multi-segmental investigations of AAFD patients with posterior tendon dysfunction. [7–9] Van de Velde et al. [7] showed significant differences in range of motion in patients with tibialis posterior tendon dysfunction. These authors demonstrated that decreased mobility occurred mainly in the rearfoot and midfoot.

However, to our best knowledge, many previous studies generally relied on foot postures such as foot posture index for definition of flatfoot, and just categorized feet as flatfoot, normal foot and cavus foot without subgrouping by severity. [5,6,10,11] There are few study which investigated effect of flatfoot on intersegmental motion of the foot and ankle according to the severity of deformity based on X-ray

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results. Also, previous reports on inter-segmental foot motions of patients with AAFD have been composed of a limited number of subjects with diverse ages and without gender-matched control group. Recently, we demonstrated that there are substantial gender and age difference in inter-segmental motions of the foot in healthy adults. [12,13]

The objective of this study was to identify the effect of flatfoot on segmental motion of the foot during gait in females by comparisons with age- and gender-matched healthy adults using an MFM with 15-marker set (DuPont foot model, DFM).

2. Materials and methods

The study protocol and consent forms were reviewed and approved by our institutional review board. Thirty-six symptomatic flatfeet patients (52–80 years old) were included in this study. The inclusion criteria were as follows: (1) clinically diagnosed flatfoot deformity (hindfoot valgus and forefoot abduction); (2) female; (3) over 50 years old; and (4) lateral talus-first metatarsal angle (Meary angle, MA) more than 10 degrees on standing lateral radiograph. The exclusion criteria were: (1) arthritis of more than moderate degree with symptoms associated with the lower extremity joints other than the ankle (hip and ankle joints); (2) neuromuscular involvement of the lower extremities such as cerebral palsy; (3) spinal pathology limiting activities of daily living; (4) other deformities such as tarsal coalition and vertical talus; and (5) any history of surgery involving both lower extremities.

Forty-two symptom-free female participants (60–69 years old) without flatfoot (CON group, MA $< 10°$) were recruited from local volunteers, as reported previously. [12] The inclusion criteria of the control group were: (1) elderly females (60–69 years old); (2) no history of fracture or surgery involving the lower extremities; (3) no subjective symptoms; (4) no observed radiographic features of progressive osteoarthritis (grade 3/4 osteoarthritis on the Kellgren-Lawrence scale) of the hip, knee, ankle and foot (whole leg, knee anteroposterior and lateral radiographs) and no abnormal findings detected in the knee radiograph; and (5) no history of cardiac or respiratory disease, or uncorrected visual impairment.

2.1. Study design

Radiographs were obtained with the patients of flatfoot and control group in the standing position. All radiographic measurements were performed using a picture archiving and communication system (PACS) (IMPAX; Agfa HealthCare, Mortsel, Belgium) software. Depending on the Meary angle (MA), flatfoot patients were divided into severe (SFF, MA $> 20°$) and moderate (MFF, $10° <$ MA $< 20°$) flatfoot groups. The more severely affected foot was selected in patients with bilateral flatfoot for statistical clarity.

2.2. Experimental procedures

Gait data were collected in the Human Motion Analysis Laboratory of Seoul National University Hospital. For evaluation of intersegmental foot motion, we used DuPont foot model (DFM) proposed by Henley et al. [14,15] The placement of the markers, definition of the coordinate systems based on these markers, and method of calculating the joint rotation and arch parameters have been described previously. [14,16]

In brief, placement of the markers was as follows: 2 markers were placed on the knee (knee lateral and knee medial), 3 markers were placed on the tibial shank (shank upper, shank front, and shank rear), 2 markers were placed on the ankle (ankle lateral and ankle medial), 2 markers were placed on the hindfoot segment (heel and distal), 2 markers were placed on the midfoot segment (navicular and cuboid), 3 markers were placed on the forefoot segment (MTH1, toe, MTH5), and 1 marker was placed on the hallux. [16] The authors defined this foot model as consisting of the hindfoot, forefoot, first ray, fifth ray, and hallux. The relationships between segments were calculated in sagittal, coronal, and axial planes from a ZXY Euler decomposition of the relative orientation of the anatomical coordinate systems. The height of the arch was calculated as the height of the navicular with respect to the bottom of the foot, and the arch index was the ratio of this height to the distance between the bottom calcaneus markers to the first metatarsal markers.

Experimental procedures were the same as in our previous study. [16] In brief, participants were asked to perform easy walking for 5 min to warm up. A single operator with 18 years of experience then placed reflective markers from the Helen Hayes marker set. Baseline static data were obtained in a calibration trial with the foot positioned flat on the ground. Subjects were asked to walk at their usual speed along a 9 m track. Gait data were collected using 12 cameras at a height of 2 m with an optical motion capture system (Motion Analysis Co., Santa Rosa. CA) at a sample rate of 120 Hz. Eight cameras were set at each octant position (45° intervals). Four additional cameras were located at the back and front and bilaterally. The resolution of the cameras was 1.3 megapixels with 500 frames per second. The distance between the cameras and the participants ranged from 3 to 7 m. The translational accuracy was 0.5 mm root mean square and the angular resolution was 0.3°. Eva Real-Time software (Motion Analysis Co., CA, USA) and Microsoft Excel 2010 were used for real-time motion capture, post-processing and tracking of the marker data.

2.3. Gait data processing

The data of temporal and spatial gait parameters were obtained. To reduce inter-subject variation due to body size, the authors divided the speed(cm/s), stride length(cm), and step width(cm) by height(cm) and designated as n speed, n stride length and n step width, respectively. [17]

For analysis of kinematic data, three representative strides from 5 separate trials were selected, and the mean values were used. To assess the intersegmental position of the foot (hindfoot relative to tibia, forefoot to hindfoot, and hallux to forefoot) during the gait cycle, we divided the whole gait cycle into 100 times points with 1% interval and collected intersegmental angles (ISAs) at each time point. Parameters calculated were as follows: (1) hindfoot relative to tibia: dorsiflexion/plantarflexion (sagittal plane), pronation/supination (coronal plane), and internal/external rotation (transverse plane); (2) forefoot relative to hindfoot: dorsiflexion/plantarflexion (sagittal plane), pronation/supination (coronal plane), and abduction/adduction (transverse plane); (3) hallux relative to forefoot: dorsiflexion/plantarflexion (sagittal plane) and valgus/varus (transverse plane); and (4) arch data: arch height, arch length, and arch index (arch height/arch length).

2.4. Statistical analysis

Data were evaluated for completeness and normality using the Shapiro–Wilk test combined with normal distribution plots. Statistical analysis was performed using Student's *t*-test for continuous variable items satisfying the normality of distribution, and Mann-Whitney U was used for continuous variables that did not satisfy normality. Differences between degree of flatfoot (healthy normal, moderate, or severe flatfoot) were determined using analysis of variable (normality: one-way ANOVA; non-normality: Kruskall-Wallis test). Significance was set at $P \le 0.05$. SPSS for Windows, version 17.0 (SPSS, Chicago, IL, USA) was used for all statistical analyses.

3. Results

Demographic data of participating subjects are presented in Table 1. There was no significant difference between groups except body weight and body mass index (BMI). The absolute value of body weight was significantly higher in the flatfoot group and the BMI was also higher in

Table 1
Pertinent demographic data of participating subjects. Data are presented as the mean value ± standard deviation.

	Study Population			
	SFF (n = 16)	MFF (n = 20)	CON (n = 42)	P value*
Demographic measurements				
Age (year)	64.0 ± 9.0	62.5 ± 7.3	64.0 ± 2.8	0.616
Height (cm)	154.5 ± 5.5	154.0 ± 6.7	154.2 ± 5.2	0.959
Weight (kg)	67.2 ± 11.1	58.8 ± 7.7	57.8 ± 7.7	0.001
Body mass index (kg/m^2)	28.1 ± 4.8	24.8 ± 2.9	24.2 ± 3.1	0.001
Foot parameter				
Foot width (cm)	9.8 ± 0.7	10.1 ± 0.4	9.4 ± 0.6	0.002

* One-way ANOVA.

Table 2
Temporal gait parameters are presented as the mean value ± standard deviation.

	Study Population			
	SFF (n = 16)	MFF (n = 20)	CON (n = 42)	P value**
Cadence (step/min)	109.7 ± 12.3	112.4 ± 6.5	114.8 ± 7.4	0.122
Speed (cm/sec)	94.7 ± 23.9	104.3 ± 13.6	112.3 ± 7.9	0.000
n Speed*	60.9 ± 14.0	67.8 ± 8.5	72.8 ± 5.8	0.000
Stride length (cm)	102.2 ± 18.4	111.3 ± 10.8	116.9 ± 7.0	0.000
n Stride length*	65.9 ± 10.4	72.3 ± 6.5	75.8 ± 4.3	0.000
Step width (cm)	10.1 ± 2.6	9.5 ± 2.1	8.3 ± 2.1	0.017
n Step width*	6.5 ± 1.8	6.2 ± 1.4	5.4 ± 1.4	0.019
Step time (sec)	0.55 ± 0.06	0.53 ± 0.03	0.52 ± 0.03	0.074
Proportion of stance phase (%)	64.9 ± 3.2	63.3 ± 1.9	60.6 ± 1.1	0.000

* Normalized with the subject's height. (Speed, Stride length and width divided by subject's height and multiplied by 100).
** One-way ANOVA.

the flatfoot group.

Basic temporospatial gait parameters area presented in Table 2. The cadence (steps/min), speed, stride length, and step width are significantly lower in flatfoot patients. After being normalized to height, speed, stride length, and step width still remained significantly lower in flatfoot patients. The proportion of the stance phase in a gait cycle was longer in flatfoot patients.

The differences between severe flatfoot patients and healthy controls were most prominent in the range of motion during the whole cycle (Table 3). Range of motion was significantly decreased in severe flatfoot patients. ROM of sagittal plane of the hallux, coronal and transverse plane of the forefoot, sagittal and transverse plane of the hindfoot, were lower in SFF group. ROM of sagittal plane of forefoot was higher in flatfoot group but not significantly.

As for arches, flatfoot patients and healthy controls had different value of minimal arch height (SFF group, 26.21 mm, MFF group, 27.79 mm, and CON group, 34.30 mm) and minimal arch index (arch height divided by arch length, SFF group, 0.14, MFF group, 0.16, and CON group, 0.20), which could confirm flatfoot group from normal controls.

The ISAs (position) of the foot segment relative to proximal segment at each phase of whole gait cycle and the change of ISAs (motion) between adjacent gait phases are presented in Figs. 1–3.

In hallux kinematics relative to the forefoot, hallux valgus angle was larger in flatfoot patients throughout the whole gait cycle (Fig. 1). The dorsiflexion motion of the hallux in the pre-swing phase was significantly lower in the SFF group. In the SFF group, there was loss of hallux adduction motion during the terminal stance and pre-swing phase.

In forefoot kinematics relative to the hindfoot, sagittal motions in preswing phase was larger in SFF group (Fig. 2). The SFF group showed significantly supinated and abducted position throughout the gait cycle, while the MFF group showed similar position and motion with normal controls.

In hindfoot kinematics relative to the tibia, plantar flexion motion in the pre-swing phase was significantly lower in flatfoot patients in proportion to the severity of the deformity (Fig. 3). The SFF group showed significantly pronated and adducted position of the hindfoot throughout the gait cycle, while the MFF group showed similar position and motion with normal controls. There was a loss of adduction motion in SFF group in terminal stance and preswing phases.

4. Discussion

In this study, we presented kinematic characteristics of inter-segmental foot motion during bare foot gait at a comfortable speed in adult acquired flatfoot patients using a MFM with a 15-marker set (DuPont Foot Model).

We found that flatfoot deformity affected the kinematics of the foot and ankle in proportion to the severity of deformity. These findings generally concurred with those of previous studies that investigated the effect of flatfoot on gait and foot biomechanics, while there are some discrepancies. Houck et al. investigated the ankle and foot kinematics in stage II PTTD patients and reported that they showed great ankle plantarflexion prior to 74% of stance, greater hindfoot eversion across stance and greater first metatarsal dorsiflexion across stance. [18] Ness et al. showed (1) diminished dorsiflexion and increased eversion of the hindfoot; (2) decreased plantarflexion of the forefoot; (3) loss of varus thrust in the forefoot; and (4) decreased ROM with decreased dorsiflexion of the hallux in a study of patients with PTTD using the Milwaukee Foot Model. [8] Buldt et al. showed reduced midfoot frontal plane ROM in pes planus classified by the Foot Posture Index in a study of normal healthy adults. [6] However, the differences in foot kinematics were not substantial in their study which was performed on healthy adults, although there is a concern about whether a person with Foot Posture Index higher than 7 can be classified as normal healthy adults. Levinger et al. also studied the effect of flat-arched feet on foot motion and reported that participants with flat-arched feet demonstrated greater peak forefoot plantar-flexion, forefoot abduction and reafoot internal rotation. [10] This study was also composed of asymptomatic participants; a flat-arched group that showed differences of 12 degrees in calcaneal-first metatarsal angle from the normal-arched group might be similar to the moderate flatfoot group in our study.

However, this study had some aspects that distinguish it from previous studies. First, this was the first study, to our knowledge, that classified symptomatic flatfoot patients according to the severity of deformity defined by radiographic measurements (lateral talo-first metatarsal angle), enabling investigation of the effect of severity of deformity on foot kinematics. Second, we studied age- and gender-matched control groups using the DFM. Previously, needs for age- and gender-matched control group were postulated concerning false positive limitation of motion in unmatched control studies. [12,13] This model was demonstrated to have reproducibility and correlation with the conventional radiographic indices. [16,19,20]

Most discrepancies from previous studies were found in sagittal motion of the forefoot and position of the hindfoot. Our study showed that differences in sagittal motions of the forefoot among groups were not substantial (Fig. 2), while other studies showed decreased plantarflexion of the forefoot in flatfoot group [8] or greater first metatarsal dorsiflexion across stance. [18] We think sagittal motions of the forefoot in flatfoot still needs to be elucidated. We also showed that plantar flexion motion of the hindfoot in pre-swing phase was significantly lower in flatfoot patients in proportion to the severity of deformity (Fig. 3). However, there was no evidence of plantar flexed hindfoot position relative to the tibia in this study, contradictory to the results of

Table 3
Range of motion of foot segment. Data are presented as mean value ± standard deviation.

	Study Population							
	SFF (n = 16)	MFF (n = 20)	CON (n = 42)	P value**	F	P***	P****	P*****
Hallux relative to forefoot								
Max DF	19.81 ± 10.63	27.65 ± 5.78	24.00 ± 6.28	0.008	5.187	0.005	0.128	0.160
Max PF	9.75 ± 8.54	7.85 ± 4.08	12.10 ± 4.19	0.014	4.505	0.540	0.298	0.012
ROM	29.55 ± 6.57	35.44 ± 3.63	36.08 ± 4.16	0.000	11.950	0.001	0.000	0.866
Max Var	−15.55 ± 12.27	−13.27 ± 9.54	−5.57 ± 6.45	0.000	10.001	0.716	0.001	0.005
Max Val	24.55 ± 13.17	20.16 ± 9.21	14.09 ± 5.67	0.000	9.611	0.287	0.000	0.030
ROM	8.99 ± 3.87	6.89 ± 2.24	8.51 ± 2.95	0.075	2.684	0.100	0.853	0.122
Forefoot relative to hindfoot								
Max DF	6.70 ± 5.58	5.64 ± 2.00	4.92 ± 3.04	0.225	1.520	0.642	0.203	0.731
Max PF	8.81 ± 5.28	8.53 ± 2.68	8.77 ± 3.97	0.972	0.029	0.977	0.999	0.974
ROM	15.51 ± 3.83	14.17 ± 1.98	13.69 ± 3.45	0.169	1.823	0.441	0.143	0.847
Max Sup	19.12 ± 8.18	15.26 ± 4.83	15.70 ± 5.18	0.096	2.413	0.125	0.120	0.957
Max Pron	−10.27 ± 8.59	−4.69 ± 5.28	−5.58 ± 4.47	0.009	4.961	0.013	0.018	0.834
ROM	8.85 ± 3.21	10.57 ± 3.54	10.12 ± 3.30	0.293	1.249	0.285	0.407	0.875
Max Add	−14.97 ± 6.81	−2.27 ± 5.81	0.57 ± 4.86	0.000	45.990	0.000	0.000	0.148
Max Abd	22.23 ± 7.65	12.12 ± 5.25	10.85 ± 4.86	0.000	24.502	0.000	0.000	0.683
ROM	7.25 ± 1.87	9.85 ± 3.61	11.43 ± 2.74	0.000	16.790	0.022	0.000	0.111
Hindfoot relative to tibia								
Max DF	15.22 ± 3.81	14.69 ± 3.32	13.45 ± 2.95	0.126	2.131	0.878	0.158	0.341
Max PF	0.53 ± 6.15	5.27 ± 4.79	7.97 ± 4.16	0.000	14.130	0.011	0.000	0.103
ROM	15.76 ± 3.48	19.97 ± 3.63	21.43 ± 3.72	0.000	13.927	0.003	0.000	0.314
Max Sup	−2.74 ± 7.66	8.40 ± 4.37	7.57 ± 4.98	0.000	23.790	0.000	0.000	0.842
Max Pron	12.83 ± 7.98	4.71 ± 4.55	3.96 ± 4.06	0.000	17.634	0.000	0.000	0.856
ROM	10.08 ± 3.86	13.12 ± 4.29	11.53 ± 3.56	0.064	2.851	0.052	0.402	0.283
Max Add	11.89 ± 7.69	11.46 ± 5.75	10.06 ± 7.64	0.619	0.483	0.983	0.667	0.758
Max Abd	−3.38 ± 8.40	−1.13 ± 4.77	2.66 ± 5.85	0.003	6.366	0.530	0.004	0.069
ROM	8.50 ± 3.62	10.32 ± 4.46	12.73 ± 4.07	0.002	6.843	0.387	0.002	0.084
Arch								
Max Height	39.17 ± 7.42	41.02 ± 5.08	45.86 ± 5.19	0.000	10.092	0.598	0.000	0.007
Min Height	26.21 ± 7.64	27.79 ± 4.58	34.30 ± 5.00	0.000	16.790	0.676	0.000	0.000
Range	12.95 ± 4.01	13.22 ± 4.99	11.55 ± 3.12	0.211	1.590	0.975	0.438	0.253
Max Length	191.54 ± 6.44	183.39 ± 8.71	184.35 ± 7.42	0.003	6.299	0.006	0.005	0.889
Min Length	180.71 ± 6.06	168.82 ± 7.80	166.31 ± 6.61	0.000	26.080	0.000	0.000	0.371
Range	10.82 ± 3.12	14.57 ± 2.95	18.04 ± 2.91	0.000	35.993	0.001	0.000	0.000
Arch index*								
Max	0.21 ± 0.03	0.23 ± 0.03	0.25 ± 0.03	0.000	16.772	0.111	0.000	0.003
Min	0.14 ± 0.03	0.16 ± 0.03	0.20 ± 0.03	0.000	23.074	0.173	0.000	0.000
Range	0.06 ± 0.02	0.06 ± 0.02	0.05 ± 0.01	0.099	2.387	0.984	0.262	0.142
Foot progression angle								
Max ER	23.45 ± 8.25	19.18 ± 6.22	20.97 ± 6.46	0.180	1.754	0.154	0.434	0.597
Min ER	11.84 ± 7.94	6.03 ± 5.21	6.25 ± 5.92	0.007	5.271	0.019	0.009	0.991
Range	11.61 ± 4.98	13.14 ± 3.96	14.72 ± 4.15	0.044	3.263	0.537	0.041	0.370

* Arch index = Arch height / Arch length.
** Result of ANOVA.
*** Results of multiple comparisons according to Bonferroni correction method between SFF and MFF.
**** Between SFF and CON.
***** Between MFF and CON.

great ankle plantarflexion in flatfoot in PTTD. [8,21]. We think sagittal position of segment would be significantly influenced by position of markers; [16] therefore, we should be careful in interpretation, especially when there is parallel shift of the graph without distortion.

In this study, while we showed that flatfoot deformity affected the kinematics of the foot and ankle in proportion to the severity of deformity, we also found that there were substantial differences between severe flatfoot and moderate flatfoot. The curve patterns for foot kinematics of moderate flatfoot group were rather closer to those of the normal controls than to those of the severe flatfoot group, suggesting there might be a threshold when normal foot kinematic pattern collapse. We cautiously suggest that the normal kinematic pattern might not collapse in moderate flatfoot with a Meary angle of less than 20 degrees. Therefore, we believe assessment of functional impairment should precede surgical intervention of flatfoot deformity. However, unfortunately, evidences in this study were insufficient to provide specific cut off points. We will further investigate the relationship of clinical functional impairment and gait abnormality in following studies.

The current study has some limitations. First, the number of subjects in each group may not be sufficient to characterize the effect of flatfoot on foot kinematics. However, considering that our study population was confirmed by radiographic examination and compared with age- and gender-matched controls, we believe our results can be considered to reflect flatfoot group reliably. Second, we did not consider the effect of weight on inter-segmental motion of the foot. Similar to previous studies, the flatfoot patient group showed higher BMI than control group. However, even in the SFF group, BMI was lower than 30. The effect of weight on inter-segmental motion of the foot should be clarified further. Third, while previous publications suggest this model is accurate and reliable, [16,20] differences of 2 to 3° in position and motion should be interpreted cautiously because there might be inborn error of marker placement in MFMs. However, the authors think collapse of normal kinematic pattern in flatfoot patients group in this study would have significant clinical relevance. Finally, tibialis posterior tendon status and function was not considered in classifying the flatfoot group. Further research should be undertaken to evaluate the effect of these potential confounders.

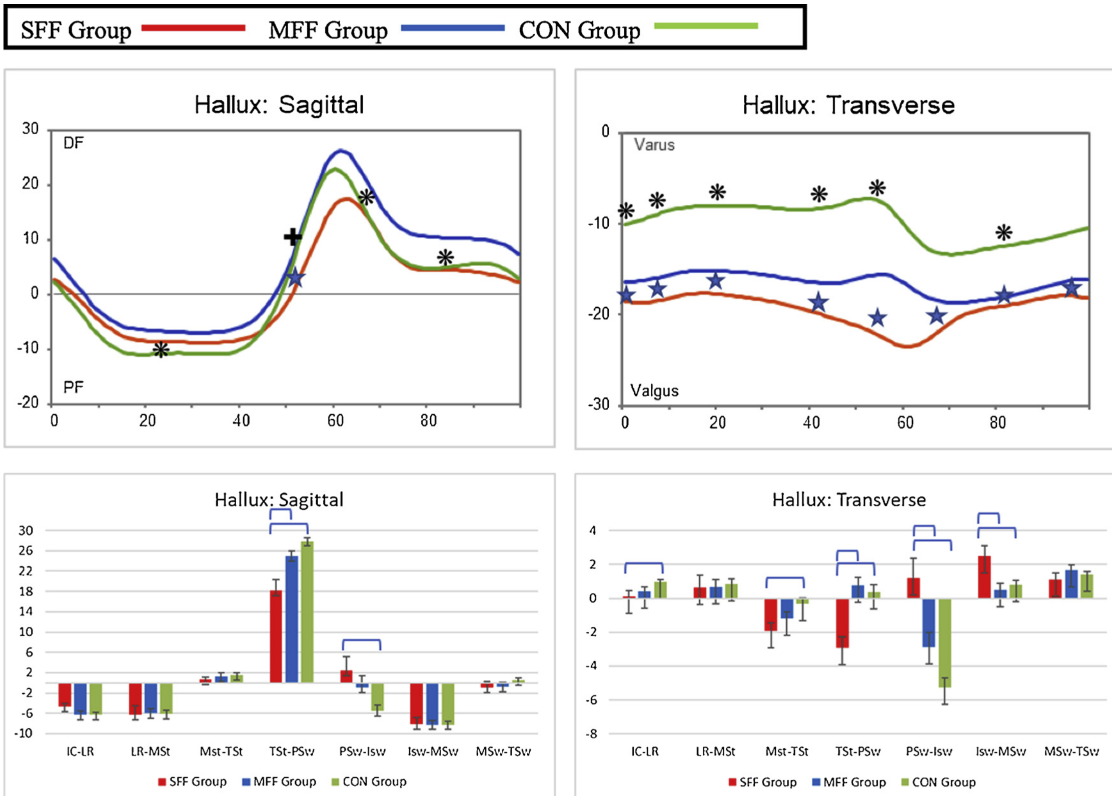

Fig. 1. Average kinematics of the hallux relative to the forefoot during the whole gait cycle according to the severity of flatfoot. In the upper part of figure, blue stars, black crosses and asterisks denote phases of gait cycle with significantly different positions between two groups of three groups. (blue star: between CON and SFF; black cross: between MFF and SFF; asterisk: between CON and MFF) In the lower part of figure, brackets denote phases of gait cycle with significantly different range of motions.

5. Conclusion

Acquired adult flatfoot patients showed different gait parameters & inter-segmental motion during gait when compared with age- and gender-matched controls. Furthermore, flatfoot deformity affected the kinematics of the foot and ankle in proportion to the severity of deformity. However, the curve patterns for foot kinematics of moderate flatfoot group were rather closer to those of the normal control than to those of the severe flatfoot group, suggesting there might be the threshold when normal foot kinematic pattern collapse.

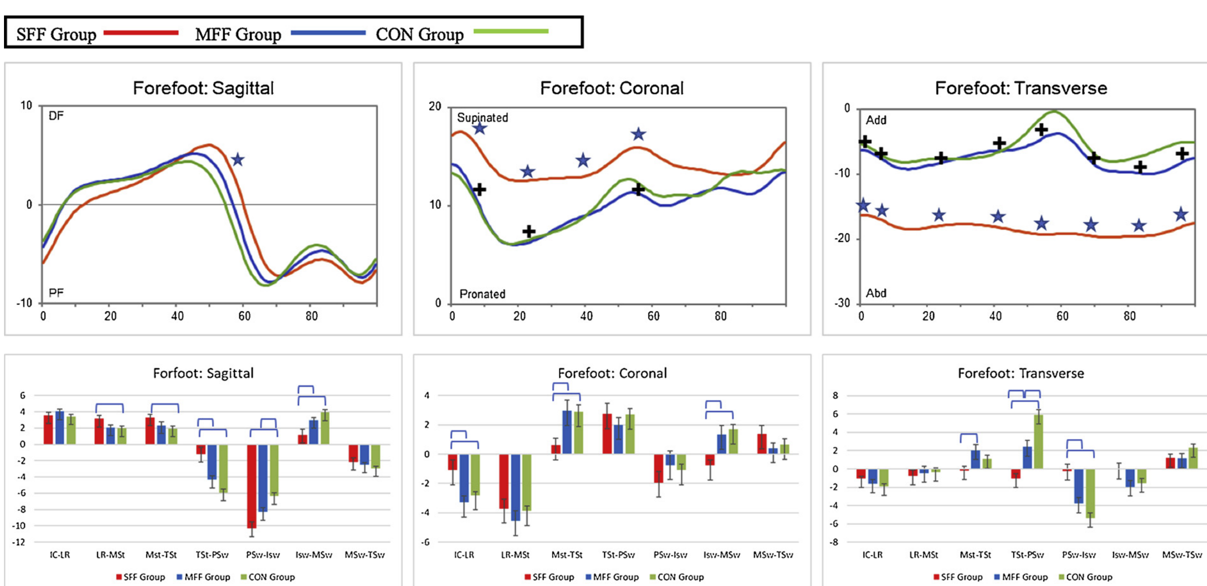

Fig. 2. Average kinematics of the forefoot relative to the hindfoot during the whole gait cycle according to the severity of flatfoot. In the upper part of figure, blue stars, black crosses and asterisks denote phases of gait cycle with significantly different positions between two groups of three groups. (blue star: between CON and SFF; black cross: between MFF and SFF; asterisk: between CON and MFF) In the lower part of figure, brackets denote phases of gait cycle with significantly different range of motions.

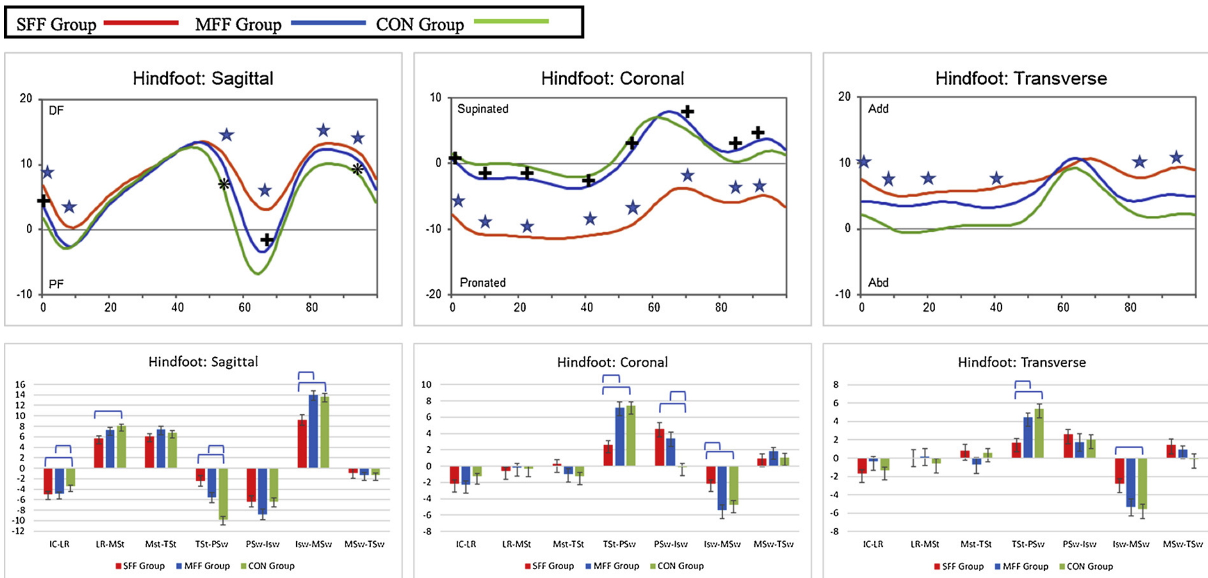

Fig. 3. Average kinematics of the hindfoot relative to the tibia during the whole gait cycle according to the severity of flatfoot. In the upper part of figure, blue stars, black crosses and asterisks denote phases of gait cycle with significantly different positions between two groups of three groups. (blue star: between CON and SFF; black cross: between MFF and SFF; asterisk: between CON and MFF) In the lower part of figure, brackets denote phases of gait cycle with significantly different range of motions.

Author's contributions

HSS participated in data collection, performed data analysis, interpretation, conception and design of the study, and drafted the manuscript. JHL, EJK, and MGK participated in data collection, and interpretation, conception and design of the study. HJY participated in data collection and performed data analysis. DYL participated in conception and design of the study, and data interpretation. All authors participated in reviewing and editing the manuscript, and approved the final manuscript.

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