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RESEARCH ARTICLE

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Inter-segmental foot kinematics during gait in elderly females according to the severity of hallux valgus

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Abstract

The objective of this study was to find the effect of hallux valgus (HV) deformity on the inter-segmental motion of the foot using an MFM with a 15-marker set (DuPont Foot Model, DuFM) in comparison with age and sex controlled healthy adults. Fifty-eight female symptomatic HV patients and 50 female asymptomatic older female volunteers were included in this study. According to the radiographic hallux valgus angle (HVA), the study population was divided into severe HV (SHV, HVA ≥ 40°, n = 25), moderate HV (MHV, 20° ≤ HVA < 40°, n = 47), and control (CON, n = 36). MHV group was divided into symptomatic MHV group (S-MHV, n = 33) and asymptomatic MHV group (A-MHV, n = 14) according to the symptoms associated with HV. For temporal parameters, gait speed and stride length were diminished according to the severity of HV deformity. Sagittal range of motion of hallux and hindfoot decreased significantly in SHV group. Loss of push-off during the preswing phase was observed and forefoot adduction motion during terminal stance was decreased in SHV group. In a subgroup analysis of MHV, asymptomatic HV minimally affects gait and inter-segmental motion during gait. HV deformity affects gait parameters and inter-segmental motion of the foot during gait in proportion to the severity of the deformity. However, the effect of MHV itself on foot kinematics might be limited while pain or arthritic change of the joint might cause changes in gait in patients with symptomatic HV.

KEYWORDS

gait analysis, hallux valgus, inter-segmental foot motion, multi-segment foot model

1 | INTRODUCTION

Hallux valgus (HV), which is characterized by the valgus angulation of the first metatarsophalangeal joint, is one of the common conditions encountered in foot and ankle clinics. According to Nix and Vicenzino[1], the prevalence of HV is 23% to 35.7%, increasing with age and higher in women. Although it is assumed that HV may cause considerable pain and disability during gait, it is still not clear how HV affects gait patterns. Several studies have shown that basic spatio-temporal parameters do not differ significantly between those with and without HV.[2-5] However, the previous finding of less stable gait patterns on an irregular surface in older adults with significant HV[4] suggested that there might be significant differences in inter-segmental motion in the foot and ankle, which cannot be recognized in conventional gait analysis. According to Mickle et al, older people with HV and lesser toe deformities display altered foot loading patterns through the forefoot and lesser toes. And this altered foot loading is likely to affect foot function and mechanical stability during more challenging locomotor tasks such as recovering from a perturbation, changing direction or stair ascent and descent, although this notion warrants further investigation.[4] If the results were different from the normal foot pressure, this may also affect the segmental motion of the foot during gait and we think it will be necessary to verify that the motion is actually different.

In the last three decades, several multisegmental foot models (MFMs) have been introduced for the in vivo analysis of dynamic foot kinematics.[6-11] To our knowledge, there are few triplanar multisegmental investigations of patients with HV.[3,12-14] Canseco et al have shown decreased velocity, stride length, and a prolonged stance phase in HV patients.[12,13] Deschamps et al found no difference in temporal parameters.[3] However, previous reports on inter-segmental foot motions of patients with HV have been composed of the limited number of subjects with diverse ages and without a sex-matched control group. Most of them did not show the severity of HV by radiographic evaluation. However, it has been reported that age- and sex-matched control was required for assessment of the specific effect on the inter-segmental motion of the foot.[15,16]

The objective of this study was to find the effect of radiographic severity of HV deformity on the inter-segmental motion of the foot by comparison with age and sex controlled healthy adults. We adopted DuPont Foot Model (DuFM, an MFM with 15-marker set) which was validated previously.[17-19]

2 | METHODS

2.1 | Level of evidence

Level IV, case-control study.

2.1.1 | Study population

This study was approved by the institutional review board, and all subjects submitted informed consent prior to participation. Fifty-eight female symptomatic HV patients and 50 female nonsymptomatic older volunteers from local area[16] were tested at the Laboratory of Human Motion Analysis in Seoul National University Hospital. Inclusion criteria for HV patients were (a) foot discomfort associated with HV deformity (pain, bunion, and/or metatarsalgia); (b) more than 20 degrees of hallux valgus angle (HVA); (c) no history of fracture or surgery on the lower extremities; and (d) no history of cardiac, respiratory, neuromuscular, or ocular impairment which can cause gait disturbance. They were divided into severe HV group (SHV group, HVA ≥ 40°, n = 25), moderate HV group (MHV group, 20° ≤ HVA < 40°, n = 47), and control group (CON group, HVA < 20°, n = 36) according to HVA measured using standing anteroposterior radiograph of the foot. The MHV group included patients with MHV without symptoms because the HV group was identified only by HVA measured on radiography. These patients were divided into asymptomatic MHV groups and used in the subgroup analysis described later. For subgroup analysis, MHV group was divided into symptomatic MHV group (S-MHV group, n = 33) and asymptomatic MHV group (A-MHV group, n = 14) according to presence or absence of symptoms associated with HV.

2.1.2 | Experimental procedures

For evaluation of inter-segmental foot motion, we used a DuFM using a 15-marker set that was recently proposed by Henley and Miller.[11,20] The placement of the markers, definition of the coordinate systems based on these markers and the method to calculate the joint rotation and arch parameters had been described previously (Figure 1).[11,17] Each segment of DuFM is named Knee Medial, Knee Lateral, Shank Upper, Shank Front, Shank Rear, Ankle Medial, Ankle Lateral, Heel Proximal, Heel Distal, Navicular, Cuboid, First Metatarsal Head (MTH1), Toe, Fifth Metatarsal Head (MTH5), and Hallux.

Experimental procedures were described thoroughly in previous studies.[17,18] In brief, the participants performed a 5-minute warm-up protocol of comfortable walking. After warming up, each subject had 15 reflective markers placed on each side of the foot and lower extremities. They walked along the 8-m walkway at a comfortable speed. Gait data were collected using 12 cameras with an optical motion capture system (Motion Analysis Co., Santa Rosa, CA) at a sample rate of 120 Hz. Of the 12 cameras manufactured by Motion analysis Co, 8 are "Eagle digital motion capture 8 camera system" and 4 are "Osprey digital motion capture 4 camera system." Cortex 1.3.0675 (Motion Analysis Co) was used for real-time motion capture, post-processing and tracking the marker data. Two force plates (Kistler Instruments, Winterthur, Switzerland) at a sampling rate of 1200 Hz were installed on the walkway to obtain the kinetic data, and the kinetic data were obtained when the subject walked after attaching the marker. The data obtained from this pad was used to measure ankle push-off power using the Foot3D Multi-Segment Software (Motion Analysis Co). Three representative strides from five separate trials were selected and the mean value was used for analysis. Random numbers were used to randomly select three of the five trials. For radiographic examinations, the HVA was measured using a standing anteroposterior radiograph of the foot.

2.1.3 | Data acquisition, normalization, and analysis

We obtained demographics, temporospatial, kinematic, and kinetic data. The temporospatial data was represented by temporal gait parameters. As kinematic data, the inter-segmental angle (ISA) was measured to calculate the maximum, minimum angle and range of motion (ROM) of each segment. The marker set used in this study consisted of 6 additional markers per foot in addition to the conventional Cleveland clinic lower extremity marker set.[17] Similar to the Cleveland marker set, Euler-Lagrange formalism was applied to describe the movement of each segment.[21] Ankle push-off power was calculated using kinetic data. The temporal gait parameters (cadence, speed, n_speed, stride length,

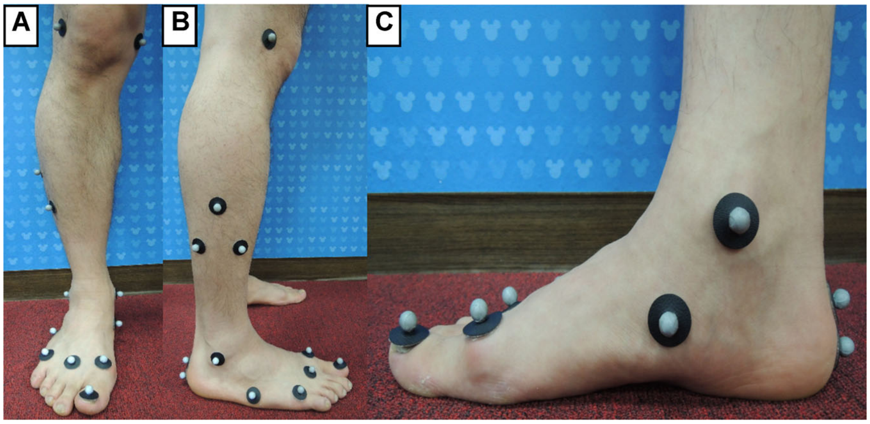

FIGURE 1 Marker placement of a three-dimensional multi-segment foot model with a 15-marker set, DuPont Foot Model (DuFM). Ten markers were placed around the foot and ankle. (A and B) Anterior and lateral view of marker placement. (C) Hallux marker was placed in the middle of the hallux nail bed, 1st metatarsal marker on the dorsal metatarsal head just proximal to the 1st metatarsophalangeal joint, navicular marker on the most prominent point of the navicular, and two calcaneus markers were applied to the hindfoot [Color figure can be viewed at wileyonlinelibrary.com]

n_stride length, step width, n_step width, step time, and proportion of stance phase) were calculated. The speed, stride length, and step width, which are variables that can affect the height, were measured by adjusting the n_speed, n_stride length, and n_step width corrected for height. Data of gait speed, stride length and width, foot length and width, arch height, and the arch length was normalized with the height of the subject to reflect the effect of body size.[22,23]

To assess the inter-segmental 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-time points with 1% interval and collected ISAs at each time point. Parameters calculated were as follows; (a) hindfoot relative to tibia: dorsiflexion/plantarflexion, pronation/supination, and internal/external rotation; (b) forefoot relative to hindfoot: dorsiflexion/plantarflexion, pronation/supination, and abduction/adduction; (c) hallux relative to forefoot: dorsiflexion/plantarflexion and valgus/varus; and (d) arch data: height, arch length, and arch index (arch height/arch length).[17,18] The range of ISAs during the whole cycle of the gait was evaluated by minimum value, maximum value, and the gap between minimum and maximum values of ISA. Ankle push-off power was measured simultaneously with the gait measurement using a marker. The kinetic data were linked with the gait cycle to determine how the ankle push-off power changes during the entire gait cycle. Subgroup analysis was performed in the S-MHV group and A-MHV group to determine the difference according to the presence or absence of symptoms in the same MHV group. A-MHV and CON groups were compared with confirm the effect of MHV itself in gait and inter-segmental motions.

2.1.4 | Statistical analysis

Data were evaluated for completeness and normality using the Shapiro-Wilk test combined with normal distribution plots. All data satisfy the normality distribution. Analysis of variance (ANOVA) test followed by multiple comparisons according to the Bonferroni correction method (post-hoc test) was performed to assess differences in the range of each inter-segmental motion between groups, with *P* values less than 0.05 regarded significant. For the subgroup analysis, independent-sample *t* test was performed to see the difference between the S-MHV group and A-MHV group in the MHV group. All statistics were used by SPSS version19 for Windows (SPSS Inc., Chicago, IL).

3 | RESULTS

The mean age of fifty-eight female symptomatic HV patients is 64.2 years old and the standard deviation is 6.7. The mean age and standard deviation of 50 non-symptomatic older volunteers are 64.6 ± 2.9. Demographic data are shown in Table 1. One-way ANOVA was used for analysis. Age, height, weight, and BMI in demographic data were not statistically different between groups. HVA was different among all groups. The foot width was found to be significantly statistically different between the SHV group and the CON group, and between the MHV group and the CON group.

The temporal gait parameters are presented in Table 2. Temporal gait parameters show significant differences in all items except cadence. As shown in Table 2, there was a substantial tendency of slower gait according to the severity of HV (*P* value: .004). The proportion of stance phase was significantly higher and gait speed was slower in more severity of the HV group.

ROM of each segment of the foot was presented in Table 3. The results of each segment's movement related to the results in Table 3 are described in detail as shown below with the figures. The ISAs (position) of the foot segment relative to the proximal segment at each phase of the whole gait cycle and the change of ISAs (motion) between adjacent gait phases are presented in Figures 2 to 4.

TABLE 1 Pertinent demographic data of participating subjects

Demographic measurements	Study population							
	SHV (n = 25)	MHV (n = 47)	CON (n = 36)	*P* value[a]	*F*	*P*[b]	*P*[c]	*P*[d]
Age, y	64.7 ± 6.3	63.0 ± 6.1	63.8 ± 2.9	.413	0.891			
Height, cm	154.0 ± 7.0	155.5 ± 5.3	153.6 ± 5.3	.292	1.245			
Weight, kg	59.5 ± 8.9	59.9 ± 8.4	57.5 ± 8.0	.423	0.868			
Body mass index, kg/m^2	25.1 ± 3.7	24.8 ± 3.1	24.4 ± 3.3	.699	0.359			
Hallux valgus angle	47.1 ± 5.3	31.5 ± 5.7	12.7 ± 4.1	<.001	344.178	<0.001	<0.001	<0.001
Foot parameter								
Foot width, cm	10.3 ± 0.8	10.1 ± 0.6	9.4 ± 0.6	<.001	19.804	0.553	<0.001	<0.001

Note: Data are presented as mean value ± standard deviation.
Abbreviations: CON, control; MHV, moderate hallux valgus; SHV, severe hallux valgus.
[a]Result of One-way analysis of variance.
[b]Results of multiple comparisons according to Bonferroni's correction method between SHV and MHV.
[c]Between SHV and CON.
[d]Between MHV and CON.

The sagittal ROM of hallux and hindfoot decreased in SHV group. In hindfoot kinematics relative to the tibia, plantarflexion motion in the preswing phase was significantly lower in HV patients in proportion to the severity of the deformity (Figure 2). In forefoot kinematics relative to the hindfoot, differences in sagittal motions among groups were not substantial (Figure 3). In hallux kinematics relative to the forefoot, the HVA was larger in HV patients throughout the whole gait cycle (Figure 4).

The plantarflexion motion of the hallux in the load response phase was significantly lower and hallux was in the more dorsiflexed position in the HV groups in proportion to the severity of the deformity. In the kinetic analysis, ankle power during terminal stance and preswing phase was lower in the HV in proportion to the severity of deformity (Figure 5).

Results from a subgroup analysis depending on the presence of symptom in MHV group was presented in Tables 4 and 5. In demographic findings, only HVA was a little larger in S-MHV group (mean, 33.0° ± 5.2) than in A-MHV group (mean, 28.0° ± 5.5). The difference in foot temporal gait parameters between the S-MHV group and the A-MHV group was not prominent except prolonged stance phase in the S-MHV group (Table 4). However, in kinematics, there is a tendency of transverse ROM of forefoot and hindfoot being lower in S-MHV group (Table 5). The plantarflexion motion of the hindfoot in the preswing phase was significantly lower in S-MHV than in the A-MHV group. Otherwise, there was no significant difference regardless of the presence of symptoms.

TABLE 2 Temporal gait parameters are presented as mean value ± standard deviation

	Study population							
	SHV (n = 25)	MHV (n = 47)	CON (n = 36)	*P*-value[a]	*F*	*P*[b]	*P*[c]	*P*[d]
Cadence, step/min	114.2 ± 6.8	111.8 ± 8.6	115.7 ± 5.9	.058	2.924			
Speed, cm/s	101.0 ± 13.3	106.1 ± 14.8	111.9 ± 7.5	.004	5.883	0.311	0.003	0.108
n_Speed[e]				.001	7.040	0.483	0.001	0.027
Stride length, cm	106.3 ± 13.3	113.2 ± 11.1	115.8 ± 7.6	.003	6.015	0.032	0.003	0.819
n_Stride length[e]				.001	7.566	0.043	0.001	0.230
Step width, cm	10.9 ± 3.3	9.7 ± 2.8	8.6 ± 2.2	.008	5.075	0.251	0.006	0.235
n_Step width[e]				.009	4.944	0.200	0.007	0.324
Step time, s	0.53 ± 0.03	0.54 ± 0.04	0.52 ± 0.03	.040	3.325	0.443	1.000	0.039
Proportion of stance phase, %	63.3 ± 1.8	61.9 ± 2.1	60.6 ± 1.1	<.001	17.454	0.006	<0.001	0.003

Abbreviations: CON, control; MHV, moderate hallux valgus; SHV, severe hallux valgus.
[a]Result of One-way analysis of variance.
[b]Results of multiple comparisons according to the Bonferroni correction method between SHV and MHV.
[c]Between SHV and CON.
[d]Between MHV and CON.
[e]Normalized with the subject's height (speed, stride length and width divided by subject's height and multiplied by 100).

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TABLE 3 Range of motion of foot segment

	Study population							
	SHV (n = 25)	MHV (n = 47)	CON (n = 36)	*P* value[a]	*F*	*P*[b]	*P*[c]	*P*[d]
Hallux relative to forefoot								
Sagittal	29.77 ± 8.07	34.94 ± 8.10	35.86 ± 4.36	.003	6.120	0.012	0.004	1.000
Transverse	6.82 ± 2.47	7.48 ± 2.92	8.94 ± 2.86	.010	4.816	1.000	0.013	0.062
Forefoot relative to hindfoot								
Sagittal	14.03 ± 2.91	14.38 ± 3.64	13.42 ± 3.29	.437	0.834			
Coronal	9.99 ± 2.85	10.10 ± 3.34	9.89 ± 3.06	.957	0.044			
Transverse	8.87 ± 3.36	10.33 ± 3.32	11.22 ± 2.60	.017	4.217	0.184	0.014	0.593
Hindfoot relative to tibia								
Sagittal	18.32 ± 3.33	20.92 ± 5.11	21.64 ± 3.85	.004	5.715	0.025	0.004	1.000
Coronal	10.94 ± 3.84	11.62 ± 4.14	11.23 ± 3.44	.760	0.275			
Transverse	10.24 ± 3.23	11.64 ± 4.57	12.09 ± 3.85	.202	1.623			
Arch								
Height	12.60 ± 3.64	12.96 ± 3.32	10.82 ± 2.75	.010	4.832	1.000	0.105	0.010
Length	12.85 ± 4.24	15.70 ± 4.09	17.85 ± 2.86	<.001	12.992	0.009	<0.001	0.034
Arch index[e]	0.06 ± 0.02	0.06 ± 0.02	0.05 ± 0.01	.003	6.136	1.000	0.027	0.004
Foot progression angle	13.36 ± 4.00	12.92 ± 4.25	14.84 ± 3.86	.100	2.354			

Note: Data are presented as mean value ± standard deviation.

Abbreviations: Abd, abduction; Add, adduction; CON, control; DF, dorsiflexion; ER, external rotation; IR, internal rotation; MHV, moderate hallux valgus; PF, plantarflexion; Pron, pronation; SHV, severe hallux valgus; Sup, supination; Val, valgus.

[a]Result of One-way analysis of variance.

[b]Results of multiple comparisons according to the Bonferroni correction method between SHV and MHV.

[c]Between SHV and CON.

[d]Between MHV and CON.

[e]Arch index = Arch height/Arch length.

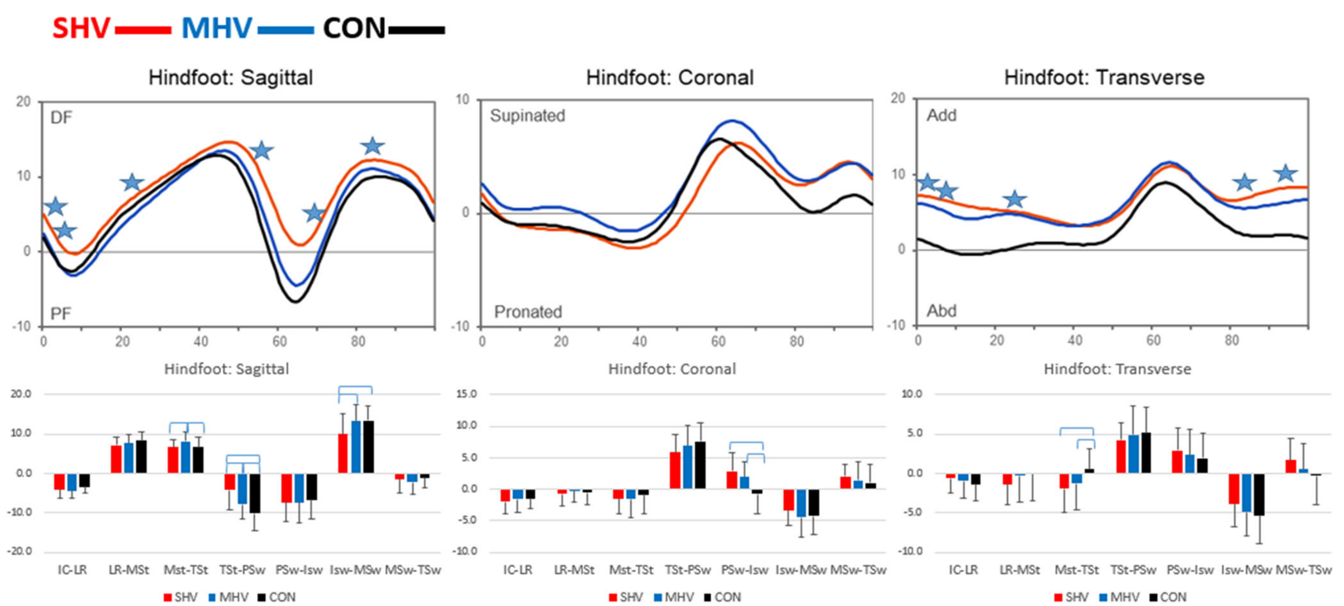

FIGURE 2 Average kinematics of the hindfoot relative to the tibia during the whole gait cycle according to the severity of hallux valgus. Asterisks and brackets denote phases of the gait cycle with significantly different positions (upper) and motions (lower). IC, initial contact; ISw, initial swing; LR, loading response; MSt, midstance; MSw, midswing; PSw, preswing; TSt, terminal stance; TSw, terminal swing [Color figure can be viewed at wileyonlinelibrary.com]

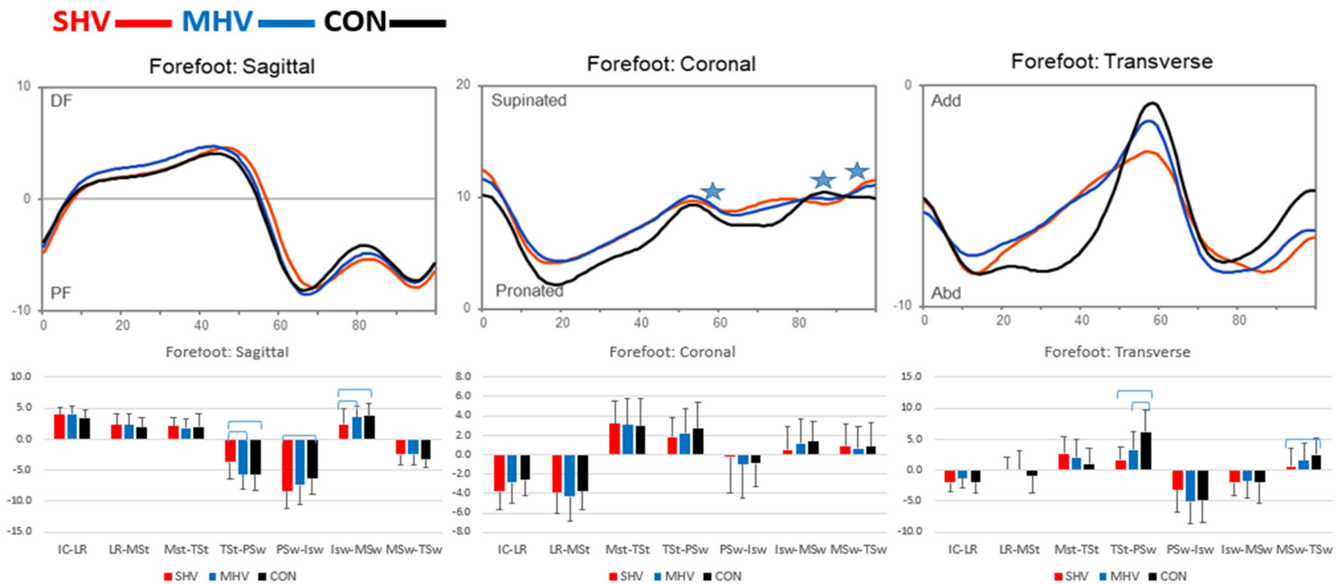

FIGURE 3 Average kinematics of the forefoot relative to the hindfoot during the whole gait cycle according to the severity of hallux valgus. Asterisks and brackets denote phases of the gait cycle with significantly different positions (upper) and motions (lower). IC, initial contact; ISw, initial swing; LR, loading response; MSt, midstance; MSw, midswing; PSw, preswing; TSt, terminal stance; TSw, terminal swing [Color figure can be viewed at wileyonlinelibrary.com]

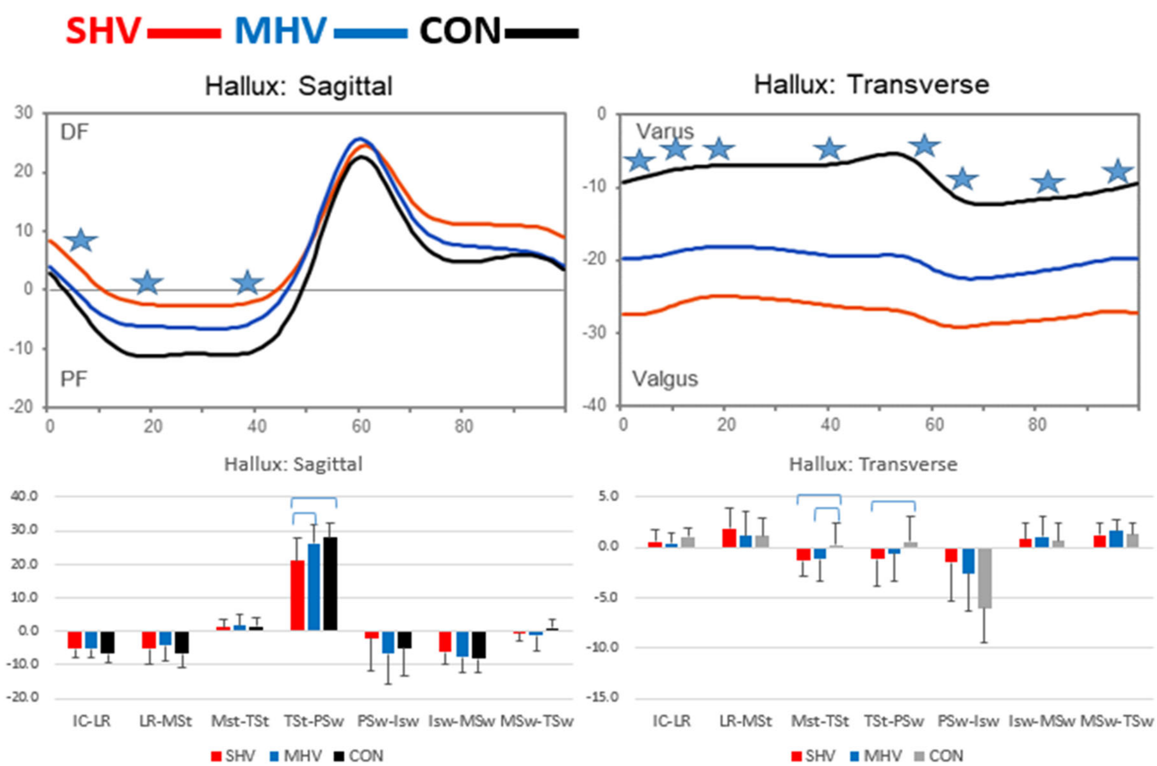

FIGURE 4 Average kinematics of the hallux relative to the forefoot during the whole gait cycle according to the severity of hallux valgus. Asterisks and brackets denote phases of the gait cycle with significantly different positions (upper) and motions (lower). IC, initial contact; ISw, initial swing; LR, loading response; MSt, midstance; MSw, midswing; PSw, preswing; TSt, terminal stance; TSw, terminal swing [Color figure can be viewed at wileyonlinelibrary.com]

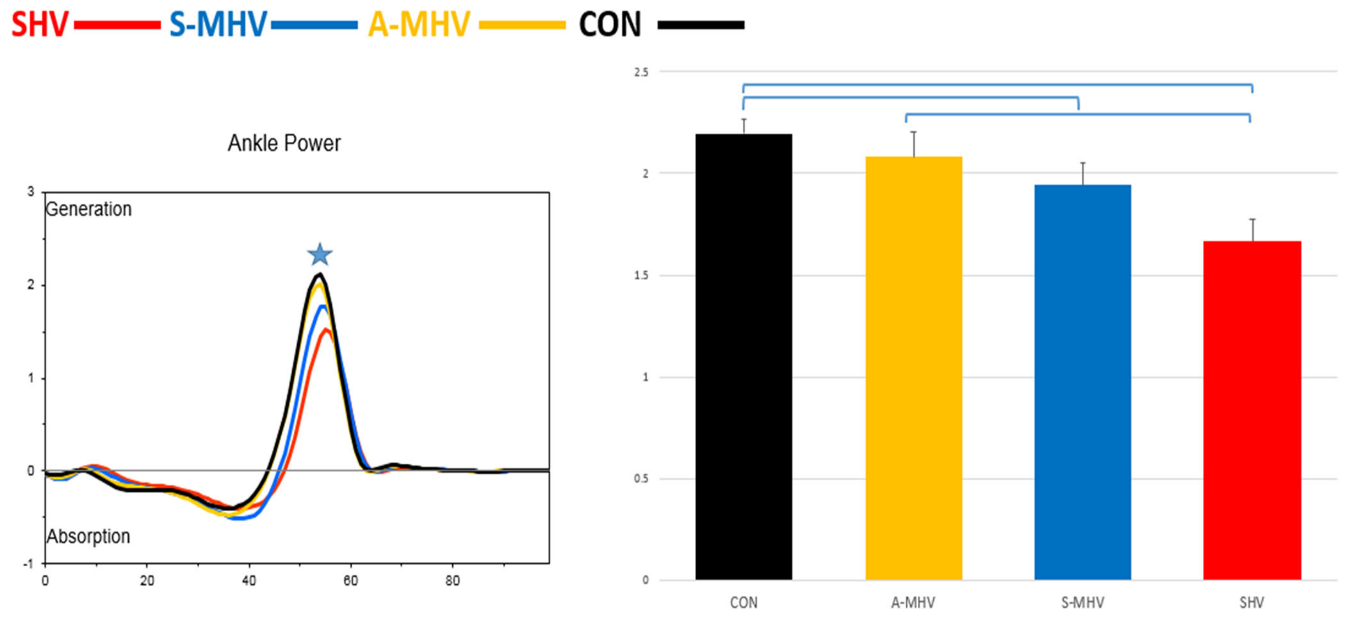

FIGURE 5 Average kinetics (power) of the ankle during the whole gait cycle according to the severity of hallux valgus. Asterisks and brackets denote phases of the gait cycle with significantly different power [Color figure can be viewed at wileyonlinelibrary.com]

There was no difference in demographic findings, temporospatial parameters and foot kinematics between the A-MHV group and the CON group. Results from a subgroup analysis depending on the presence of HV were presented in Tables 6 and 7. Also, only HVA was larger in A-MHV group (mean, 28.0° ± 5.5) than in the CON group (mean, 12.7° ± 4.1). There are no differences in temporal gait parameters between the A-MHV group and the CON group (Table 6). There was a significant difference only in transverse ROM of hallux, arch height, and arch index, but no difference in other parameters (Table 7).

TABLE 4 Temporal gait parameters of subgroups (S-MHV/A-MHV) are presented as mean value ± standard deviation

	Study population		
	S-MHV (n = 33)	A-MHV (n = 14)	*P* value[a]
Hallux valgus angle	33.0 ± 5.2	28.0 ± 5.5	.006
Cadence, step/min	111.6 ± 8.6	112.1 ± 8.9	.860
Speed, cm/s	104.2 ± 16.3	110.5 ± 9.3	.186
n_Speed[b]			.155
Stride length, cm	111.3 ± 12.2	117.6 ± 6.4	.077
n_Stride length[b]			.059
Step width, cm	10.2 ± 2.8	8.4 ± 2.3	.038
n_Step width[b]			.047
Step time, s	0.54 ± 0.04	0.54 ± 0.05	.877
Proportion of stance phase, %	62.5 ± 2.1	60.6 ± 0.9	<.001

Abbreviations: A-MHV, asymptomatic moderate hallux valgus; S-MHV, symptomatic moderate hallux valgus.
[a]Result of independent-sample *t* test.
[b]Normalized with the subject's height (speed, stride length, and width divided by subject's height and multiplied by 100).

4 | DISCUSSION

In this study, we presented kinematic characteristics of inter-segmental foot motion during barefoot gait at a comfortable speed in HV patients using an MFM with a 15-marker set (DuFM).

This is, to our best knowledge, the first study in which the foot kinematics of HV patients were assessed based on the radiographic severity of deformity using MFM. Since MFMs had been introduced for the in vivo analysis of dynamic foot kinematics, they are gaining more popularity in clinical gait analysis.[24,25] Although these models differ in the number of segments within the foot, the position of markers which defines each segment, and the way to interpret segmental motion mathematically, leading to different segmental motion patterns during gait cycle,[26] there has been accumulative evidence supporting that MFMs can be applicable to evaluate inter-segmental foot motions. DuPont model also was demonstrated to have reproducibility and correlation with conventional radiographic indices.[17,18,27]

Through MFM analysis, we found that there are statistically significant differences in the factors of the kinematics of the foot and ankle according to the severity of the deformity. For temporal parameters (Table 2), gait speed and stride length were diminished according to the severity of HV deformity. The proportion of stance phase is highest in the SHV group, the next highest in the MHV group and lowest in the CON group. Sagittal ROM of hallux and hindfoot decreased significantly in the SHV group compared with the CON group (Table 3). Loss of push-off during the preswing phase was observed and forefoot adduction motion during terminal stance was decreased in SHV group compared with the CON group and A-MHV group. In a subgroup analysis of the MHV group, there is a tendency of transverse ROM of forefoot and hindfoot being lower in the S-MHV valgus group.

TABLE 5 Range of motion of foot segment of subgroups (S-MHV/A-MHV)

	Study population		
	S-MHV (n = 33)	**A-MHV (n = 14)**	***P* value**[a]
Hallux relative to forefoot			
Sagittal	34.46 ± 9.32	36.06 ± 4.10	.541
Transverse	7.65 ± 3.09	7.09 ± 2.55	.556
Forefoot relative to hindfoot			
Sagittal	14.61 ± 3.77	13.85 ± 3.36	.519
Coronal	9.77 ± 3.29	10.87 ± 3.43	.308
Transverse	9.56 ± 3.26	12.15 ± 2.78	.013
Hindfoot relative to tibia			
Sagittal	20.96 ± 4.59	20.81 ± 3.24	.912
Coronal	11.62 ± 4.55	11.62 ± 3.13	.997
Transverse	10.64 ± 4.47	14.01 ± 3.99	.019
Arch			
Arch height	12.83 ± 3.59	13.28 ± 2.64	.675
Arch index[b]	0.06 ± 0.02	0.07 ± 0.01	.524
Foot progression angle	12.82 ± 4.00	13.16 ± 4.95	.809

Abbreviations: A-MHV, asymptomatic moderate hallux valgus; S-MHV, symptomatic moderate hallux valgus.
[a]Result of independent-sample *t* test.
[b]Arch index = Arch height/Arch length.

These findings are generally consistent with those of previous studies that investigated the effect of HV on gait and foot biomechanics, while there are some discrepancies. Canseco et al have shown decreased velocity and stride length. Canseco et al also has shown a prolonged stance phase in HV patients. However, there is no radiographic assessment for HV severity, and the subjects of the study had a wide range of age (24-72 years).[12,13] Deschamps et al found no difference in temporal parameters. Subjects of the study also had a wide range of age (18-65 years), and there was no information about the HVA of the control group.[3] Hwang et al used the data of 10 healthy adults (unknown age and sex) and 2 persons with HV (grade2 based on the HVA, sex, and age are unknown).[14] However, the current study had some aspects that distinguish it from previous studies. First, this was the first study, to our knowledge, that classified symptomatic HV patients according to the severity of deformity defined by radiographic measurements (HVA), enabling investigation of the effect of severity of deformity on foot kinematics. Second, we studied age- and sex-matched control groups using the DFM. Previously, the needs for age- and sex-matched control group were postulated concerning false-positive limitation of motion in unmatched control studies.[15,16]

TABLE 6 Temporal gait parameters of subgroups (A-MHV/CON) are presented as mean value ± standard deviation

	Study population		
	A-MHV (n = 14)	**CON (n = 36)**	***P* value**[a]
Hallux valgus angle	28.0 ± 5.5	12.7 ± 4.1	<.001
Cadence, step/min	112.1 ± 8.9	115.7 ± 5.9	.129
Speed, cm/s	110.5 ± 9.3	111.9 ± 7.5	.412
n_Speed[b]			.263
Stride length, cm	117.6 ± 6.4	115.8 ± 7.6	.592
n_Stride length[b]			.991
Step width, cm	8.4 ± 2.3	8.6 ± 2.2	.764
n_Step width[b]			.712
Step time, s	0.54 ± 0.05	0.52 ± 0.03	.097
Proportion of stance phase, %	60.6 ± 0.9	60.6 ± 1.1	.086

Abbreviations: A-MHV, asymptomatic moderate hallux valgus; CON, control.
[a]Result of independent-sample *t* test.
[b]Normalized with the subject's height (speed, stride length and width divided by subject's height and multiplied by 100).

TABLE 7 Range of motion of foot segment of subgroups (A-MHV/CON)

	Study population		
	A-MHV (n = 14)	**A-MHV (n = 14)**	***P* value**[a]
Hallux relative to forefoot			
Sagittal	36.06 ± 4.10	35.86 ± 4.36	.878
Transverse	7.09 ± 2.55	8.94 ± 2.86	.040
Forefoot relative to hindfoot			
Sagittal	13.85 ± 3.36	13.42 ± 3.29	.683
Coronal	10.87 ± 3.43	9.89 ± 3.06	.333
Transverse	12.15 ± 2.78	11.22 ± 2.60	.274
Hindfoot relative to tibia			
Sagittal	20.81 ± 3.24	21.64 ± 3.85	.479
Coronal	11.62 ± 3.13	11.23 ± 3.44	.716
Transverse	14.01 ± 3.99	12.09 ± 3.85	.123
Arch			
Arch height	13.28 ± 2.64	10.82 ± 2.75	.006
Arch index[b]	0.07 ± 0.01	0.05 ± 0.01	.001
Foot progression angle	13.16 ± 4.95	14.84 ± 3.86	.208

Note: Data are presented as mean value ± standard deviation.
[a]Result of independent-sample *t* test.
[b]Arch index = Arch height/Arch length.

One of the most prominent discrepancies from previous studies was the sagittal motion/position of the hallux relative to forefoot. Deschamps et al. presented an increased dorsiflexion motion during terminal stance with relatively decreased dorsiflexion angle throughout the first 30% of the gait cycle.[3] On the contrary, we found a decreased dorsiflexion motion in proportion to HV deformity with the more dorsiflexed position during the early stance phase (Figure 4) and this result were also observed by Canseco et al.[13]

We also showed that plantarflexion motion of the hindfoot in the preswing phase was significantly lower in HV patients in proportion to the severity of deformity (Figure 2). We think it was related to decreased power generation in the late stance phase (Figure 5). However, further evaluation would be necessary for clarifying whether symptomatic discomfort or severe deformity itself is the main cause of loss of effective push-off.

In this study, we compared the difference between S-MHV and A-MHV group, and between A-MHV and CON group to determine whether the difference in gait and inter-segmental foot motion was due to symptoms of HV such as pain, or because of deformity of the foot caused by HV. The step width and the proportion of stance phase, which differed between the S-MHV group and the A-MHV group, did not show any difference in comparison between the A-MHV group and the CON group. This should be regarded as a difference due to the presence or absence of symptoms. Because the A-MHV group and CON group did not show any significant difference in all temporal gait parameters, MHV itself without symptoms did not affect gait. In the MHV group, symptoms are the most important factor in changing gait. However, this has been confirmed only in the MHV group and cannot be equally applied to the SHV group. The plantarflexion motion of the hindfoot in the preswing phase and power generation was significantly lower in S-MHV than in the A-MHV group, while there was no difference between A-MHV and CON group. Based on these results, we can assume that the effect of MHV itself on foot kinematics might be limited while pain or arthritic change of the joint might cause changes in gait in patients with symptomatic HV. This may help determine whether or not surgical treatment should be performed in treating HV patients and prevent unnecessary surgery.

The current study has some limitations. First, the number of subjects in each group may not be sufficient to characterize the effect of HV on foot kinematics. In particular, the number of subjects in the A-MHV group is small. However, considering that our study population was confirmed by radiographic examination and compared with age- and sex-matched controls, we believe our results can be considered to reflect the HV group reliably. Second, we did not control gait speed in this research. While it is clear that the more SHV deformity, the slower the gait speed, we did not assess how slow gait speed affects kinematic changes. Further research should be undertaken to evaluate the effect of these potential confounders such as pain and osteoarthritic change.

5 | CONCLUSION

HV deformity affects gait parameters and inter-segmental motion of the foot during gait in proportion to the severity of the deformity. However, asymptomatic HV minimally affects gait and inter-segmental motion during gait. The results of this study suggest that the effect of MHV itself on foot kinematics might be limited while pain or arthritic change of the joint might cause changes in gait in patients with symptomatic HV.

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AUTHOR CONTRIBUTIONS

E.J.K. participated in data collection, performed data analysis, interpretation, conception and design of the study, and drafted the manuscript. H.S.S., N.T., and Y.J.C. participated in data collection, and interpretation, conception and design of the study. H.J.Y. participated in data collection and performed data analysis. W.J.Y. and D.Y.L. 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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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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