Effects of Hallux Valgus Orthoses on Ground Reaction Force Using 3D Motion Analysis in Individuals With Hallux Valgus Deformity

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Key Words

Foot orthoses

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Background: Hallux valgus (HV) is a foot deformity developed by mediolateral deviation of the first metatarsophalangeal joint. Although various foot-toe orthoses were used to correct the HV angle, verification of the effects of kinetics variables such as ground reaction force (GRF) through three-dimensional (3D) gait analysis according to the various type of orthoses for HV is insufficient.

Objects: This study aimed to investigate the effect of soft and hard types of foot and toe orthoses to correct HV deformity on the GRF in individuals with HV using 3D motion analysis system during walking.

Methods: Twenty-six subjects participated in the experiment. Participants had HV angle of more than 15° in both feet. Two force platforms were used to obtain 3D GRF data for both feet and a 3D motion capture system with six infrared cameras was used to measure exact stance phase point such as heel strike or toe off period. Total walk trials of each participant were 8 to 10, the walkway length was 6 m. Two-way repeated measures ANOVA was used to determine the effects of each orthosis condition on the various GRF values.

Results: The late anteroposterior maximal force and a first vertical peak force of the GRF showed that the hard type orthosis condition significantly increased GRF compared to the other orthosis conditions ($p < 0.05$).

Conclusion: There were significant effects in GRF values when wearing the hard type foot orthosis. However, the hard type foot orthosis was uncomfortable to wear during walking. Therefore, it is necessary to develop a new foot-toe orthosis that can compensate for these disadvantages.

INTRODUCTION

Hallux valgus deformity (HVD) is one of the most common foot disorders associated with chronic pain, and as the hallux deviates outward, the first metatarsal bone head protrudes inward [1]. When HVD occurs, patients usually complain of bunion pain on the medial head area of the first metatarsal bone, lateral subluxation of the first metatarsophalangeal joint, lateral displacement of the sesamoid bone, and pronation of the hallux [2-4]. The causes of HVD have not yet been clearly identified but can be largely divided into extrinsic and intrinsic causes. The extrinsic causes include wearing high-heeled shoes and long-term weight-bearing on the medial forefoot during standing and walking. The intrinsic causes include genetic causes, sex, ligament relaxation, age, metatarsal shape,

flat feet, hallux limits, and shortening of the Achilles tendon [5-7].

Imbalances in the muscle activity of the abductor hallucis and the adductor hallucis during walking are characteristics of patients with HVD [8]. In addition, it has been reported that the center of pressure (COP) in the first metatarsophalangeal joint is moved in the medial direction during the terminal stance in the gait cycle. This medial movement of the COP has been reported to increase hip internal rotation, decrease the toe-out angle, and increase knee deformation [9]. Compared to normal subjects, the gait patterns of patients with HVD showed decreased walking speed and stride length [10], and decreased range of motion of the lower limb joints [11].

The clinical interventions for HVD include therapeutic exercises, foot orthoses, drug therapy, and surgical therapy [1,2,4].

Among those, the application of foot and toe orthoses to correct the alignment of the first metatarsophalangeal joint is preferred for minor to moderately severe HVD [12,13]. However, previous studies on the effect of foot and toe orthoses in HVD have only verified relatively simple variables such as satisfaction with wearing a foot and toe orthosis or changes in the angle of the big toe spread [11-13]. Thus, verification of the effects of kinetic variables such as the ground reaction force (GRF) through three-dimensional (3D) gait analysis according to the various type of orthoses for HVD is lacking.

Therefore, the purpose of this study was to investigate the effect of soft and hard types of foot and toe orthoses to correct HVD on the GRF in individuals with HVD using a 3D motion analysis system during gait.

MATERIALS AND METHODS

1. Subjects

The participants in this study were 26 adults (five males and 21 females) with HVD. The inclusion criteria were a hallux valgus angle of more than 15° measured using an universal goniometer in both feet and no severe pain of the hallux area or history of foot surgery. The average hallux valgus angle was $25.3^\circ \pm 6.9^\circ$ in the right toe and $26.1^\circ \pm 7.4^\circ$ in the left toe. All participants fully understood the purpose and method of the study, provided written informed consent, and voluntarily participated in this study. The study was approved by the Institutional Review Board of Jeonju University (jjIRB-

180905-HR-2018-0904). The mean age, height, and weight of all participants were 21.5 ± 0.8 years, 164.9 ± 7.3 cm, and 60.5 ± 10.1 kg, respectively.

2. Measurement Devices and Procedure

Two force platforms (BP400600; AMTI, Watertown, MA, USA) were used to obtain the 3D GRF data while walking in three different foot orthosis conditions (barefoot, soft-type, and hard-type orthoses). A Vicon Motion Capture System (Vicon Inc., Oxford, England) with six infrared cameras (model T10) was used to select the exact gait cycle points such as the heel strike or toe-off moment, and the sampling rate was set at 100 Hz. Nexus 1.8.5 software (Vicon Inc.) was used to process the captured motion and GRF data in the 3D space. A 7.5 cm T-frame wand was used to calibrate the motion capture system, and a calibration reference object was used to identify the lab origin.

Four cluster reflective markers were attached bilaterally to the thigh and calf segment according to the six-degrees-of-freedom (6DOF) model [14]. A total of 40 reflective markers (1.4 cm) were attached bilaterally to the participant's anterior and posterior superior iliac spine, greater trochanter, femur epicondyle, malleolus, rear feet, mid-feet, and fore-feet (Figure 1). Before the collection of the dynamic walking motion capture data of the lower extremities, static calibration data were obtained from each subject to make a template model for later analysis of the GRF during the walking trials. Following the data collection of static calibration capture, the calibrated anatomical system technique was used to obtain the changes in the kinetic GRF data of the lower extremities while the participants walked freely under the three different foot orthosis

Figure 1. Reflective marker settings on the lower extremities and pelvis during the static calibration and walking trials.

Figure 2. Hallux valgus orthoses. (A) Soft-type orthosis. (B) Hard-type orthosis.

conditions of a soft-type orthosis (STO), a hard-type orthosis (HTO), and barefoot (BF) (Figure 2). To obtain the dynamic GRF data from two force platforms installed in the middle of the walkway, the participants were asked to walk along a 6 m walkway in the laboratory at their self-selected speed. A total of 8 to 10 walk trials was collected for each orthosis condition and the average GRF data were obtained bilaterally through all walk trials. The application order of the orthosis conditions was assigned randomly before the experimental trials began.

Following the data collection using the 3D motion capture system and the Vicon Nexus software program, Visual3D analysis software (C-Motion, Rockville, MD, USA) was used to obtain the final GRF results and graph the reports of each joint of the lower limbs. The GRF kinetic data were low-pass filtered with a fourth-order Butterworth filter and a cutoff frequency of 15 Hz. Following the right-hand rule for the segment coordinate system axes, the X-Y-Z Cardan sequence was used to define the order of the rotations [14]. Visual3D produced a visual representation of the magnitudes and directions of the GRF bilaterally in space, which enabled the related stance phase to be calculated (Figures 3 and 4). The GRF data were normalized for body weight.

3. Data Analysis

The Kolmogorov-Smirnov test was used to confirm that the GRF data were distributed normally. Two-way repeated-measures ANOVA was used to determine the effects of each orthosis condition and foot side. When a significant F-value

Figure 3. Visual3D representation of the magnitudes and directions of the ground reaction force bilaterally in space during the walking trial.

Figure 4. Intra-individual 3D variability of the GRFs during the stance phase. Barefoot GRF (solid line), soft-type orthosis GRF (dashed line), and hard-type orthosis GRF (dotted line) from 24 repetitive trials. The means (lines) and standard deviation (bands) are shown. GRF, ground reaction force.

was confirmed, the Bonferroni post hoc test was used to verify the pairwise comparison. The GRF values developed bilaterally during each stance phase point (initial and late anteroposterior maximal force, initial and late mediolateral maximal force, first peak force, midstance minimal force, and second peak force) were used for the comparison of each orthosis condition. All analyses were conducted using SPSS version 25.0 (IBM Corp., Armonk, NY, USA). Differences were considered significant at the $\alpha = 0.05$ level.

RESULTS

The mean walking speed in the BF, STO, and HTO conditions of all participants was 1.401 ± 0.122 m/s, 1.406 ± 0.131 m/s, and 1.405 ± 0.127 m/s, respectively, and there was no significant difference in walking speed according to the orthosis conditions ($p > 0.05$). There were significant differences in the GRFs between the orthosis conditions in various stance phases (Table 1). The late anteroposterior maximal force during loading (75%–100% of the stance phase) and the first vertical peak force of the GRF showed significant differences according to the orthosis conditions ($p < 0.05$) (Table 1). However, there

were no significant differences in any GRF variables between the foot sides ($p > 0.05$) (Table 1). There were also no interactive effects between the orthosis conditions and the foot sides in any of the GRF values ($p > 0.05$) (Table 1).

The specific mean and standard deviation values of each stance phase of the GRF according to the orthosis conditions and foot sides are shown in Table 2. The late anteroposterior maximal force of the GRF showed that the hard-type orthosis condition significantly increased the GRF for the left foot side ($p = 0.0008$) and the right foot side ($p = 0.013$) (Table 2). In addition, the first vertical peak force of the GRF showed that the hard-type orthosis condition significantly increased the GFR when comparing the two orthosis conditions for both foot sides ($p < 0.05$) (Table 2). However, there were no significant differences in the other GRF variables between the orthosis conditions ($p > 0.05$) (Table 2).

DISCUSSION

This study verified the changes in the various GRF values according to three different foot orthosis conditions using 3D motion analysis in individuals with HVD. The results showed that the HTO condition significantly increased the GRF late anteroposterior maximal force (75%–100% stance phase) compared to the STO condition. The first vertical peak force during loading (around the 25% phase) in the HTO condition was increased significantly compared to the other orthosis conditions. Patients with HVD showed the most noticeable changes in ankle range of motion during walking compared to normal subjects [15]. The repulsive force applied to the feet and toes from the ground during walking is known as a very important variable when evaluating the function of the foot and ankle joints in gait patterns and daily activities such as balance [16,17]. The results of this study showed greater GRF changes in the late anteroposterior maximal force and the first peak force in both foot sides when wearing the HTO. Although no previous studies compared these results directly, a previous study evaluated the effect of HVD on gait patterns and foot plantar pressure distribution compared to those of healthy feet using a treadmill installed with an electric pressure sensor mat [18]. There was a significantly higher plantar pressure in the fourth and fifth toes and the second and third metatarsal heads than in the healthy control feet [18]. The previous study results suggested that the application of the HTO in this study elicited

Table 1. Repeated-measures ANOVA comparing 3D plane ground reaction force according to each level (N = 26)

Variables [N/kg]	Level	F	p-value
IAPMF	Orthosis conditions	2.517	0.094
	Foot sides	0.521	0.467
	Interaction effects	0.524	0.459
LAPMF	Orthosis conditions	7.120	0.012*
	Foot sides	0.960	0.342
	Interaction effects	1.512	0.232
IMLMF	Orthosis conditions	0.257	0.760
	Foot sides	1.630	0.211
	Interaction effects	2.550	0.097
LMLMF	Orthosis conditions	0.198	0.791
	Foot sides	1.144	0.288
	Interaction effects	0.527	0.443
1st VPF	Orthosis conditions	3.812	0.040*
	Foot sides	0.961	0.340
	Interaction effects	1.524	0.224
MMF	Orthosis conditions	1.942	0.152
	Foot sides	0.897	0.363
	Interaction effects	1.444	0.255
2nd VPF	Orthosis conditions	1.155	0.266
	Foot sides	2.633	0.088
	Interaction effects	2.520	0.094

IAPMF, initial anteroposterior maximal force; LAPMF, late anteroposterior maximal force; IMLMF, initial mediolateral maximal force; LMLMF, late mediolateral maximal force; VPF, vertical peak force; MMF, midstance minimal force. * $p < 0.05$.

Table 2. Repeated-measures ANOVA comparing each variable of ground reaction force under the orthosis conditions and foot sides in the stance phase during walking (N = 26)

Variables (N/kg)	Sides	Barefoot	Soft type orthosis	Hard type orthosis	F	p-value
IAPMF	Left	1.83 ± 0.31	1.87 ± 0.43	1.95 ± 0.37	2.693	0.090
	Right	1.79 ± 0.31	1.84 ± 0.22	1.90 ± 0.31	2.468	0.093
LAPMF	Left	2.12 ± 0.23	1.96 ± 0.33	2.17 ± 0.32	9.452	0.000*
	Right	2.14 ± 0.28	2.05 ± 0.28	2.19 ± 0.28	4.787	0.013*
IMLMF	Left	0.64 ± 0.15	0.67 ± 0.13	0.65 ± 0.12	0.378	0.607
	Right	0.69 ± 0.38	0.66 ± 0.47	0.66 ± 0.37	0.135	0.724
LMLMF	Left	0.54 ± 0.17	0.57 ± 0.14	0.56 ± 0.14	0.064	0.819
	Right	0.52 ± 0.40	0.50 ± 0.55	0.54 ± 0.40	0.331	0.653
1st VPF	Left	10.50 ± 0.90	10.96 ± 1.39	11.05 ± 1.38	3.481	0.038*
	Right	10.62 ± 1.28	10.82 ± 1.21	11.90 ± 1.21	3.343	0.041*
MMF	Left	6.68 ± 1.01	6.93 ± 1.24	6.76 ± 1.08	1.402	0.256
	Right	6.87 ± 0.85	6.94 ± 0.89	7.10 ± 0.82	2.483	0.094
2nd VPF	Left	11.07 ± 0.89	11.05 ± 1.52	11.19 ± 1.30	0.251	0.779
	Right	11.12 ± 1.40	11.03 ± 1.54	11.45 ± 1.56	2.017	0.144

Values are presented as mean ± standard deviation. IAPMF, initial anteroposterior maximal force; LAPMF, late anteroposterior maximal force; IMLMF, initial mediolateral maximal force; LMLMF, late mediolateral maximal force; VPF, vertical peak force; MMF, midstance minimal force. *p < 0.05.

more medial transfer of foot plantar pressure, which resulted in more effective forward propulsion in the terminal stance phase during walking. The results of this study showed no significant change in any GRF variables between the BF and STO conditions. This may be because the STO was not able to push the first metatarsophalangeal joint inward enough to change the hallux valgus angle due to the characteristics of the soft material of the STO compared to the rigid material of the HTO.

In this study, most of the GRF variables were not affected when applying the foot orthoses except for the late anteroposterior maximal force and the first vertical peak force. Many previous studies reported that there were no significant differences in the spatiotemporal gait parameters between HVD and healthy feet [11,19-21] and a previous study reported a difference in GRF between HVD and healthy feet. Therefore, HVD seems not to affect the overall walking pattern [18]. Although in a forefoot deformity such as HVD, compensation occurs in the foot or ankle joint, the overall gait parameters such as step width, step length, and single-limb support are not affected.

Most of the previous studies verifying the changes in GRF following HVD interventions were performed by surgical treatments of the foot or ankle such as scarf osteotomy and first metatarsophalangeal arthrodesis [22,23]. However, this study applied conservative intervention, not a surgical treatment for HVD, to verify the effect on the GRF through more objective and quantitative 3D motion analysis and a force platform. Therefore, in this study, significant changes in the GRF could be verified through various types of foot orthoses. However, this study had some limitations. Although the participants had

HVD, this study was executed on healthy individuals who had no pain or discomfort in their feet and toes. Therefore, it is difficult to generalize these results to those with painful HVD. This study was a cross-sectional study design and did not verify the long-term effects of foot orthoses for HVD. Considering the difficulty in the analysis, the verification of kinetic variables other than the GRF occurring in various lower limb joints such as the hip, knee, and ankle was not conducted. Further studies are needed to verify the effects of the various interventions on the kinetics and kinematic changes over time in individuals with HVD.

CONCLUSIONS

This study examined the effects of 3D dynamic GRF by applying two different foot orthoses and barefoot conditions when walking in 26 individuals with HVD. The results showed significant effects in the late anteroposterior maximal force and the first vertical peak force of the GRF when wearing the HTO during walking. However, the HTO had the disadvantages of being uncomfortable when wearing and made it difficult to wear shoes due to the characteristics of the hard material. Therefore, it is necessary to develop a new type of foot-toe orthosis for HVD that addresses the disadvantages of HTOs and STOs.

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CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

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