

Influences of Personalized 3D-Printed Insole Orthoses on 3D Ankle Moments during Gait in Individuals with Pronated Hindfoot Deformity

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Background Various types of foot orthoses have been used to manage pronated hindfoot deformity (PHD), a common foot deformity. However, few studies have investigated the effects of personalized 3D-printed insole orthoses (3DPIO) for pronated flatfeet on peak ankle moments during gait.

Purpose To verify kinetic 3D ankle moments using a reliable motion analysis system with two force platforms among three different foot orthosis conditions.

Study design A repeated-measures and cross-sectional study design

Methods Kinetic 3D ankle moment data were acquired in twenty-one participants with pronated hindfeet based on three different foot orthosis conditions. A motion analysis system and force platforms were used to obtain the peak 3D ankle moment data during free walking. The participants performed successful 8 to 10 walking trials for each insole orthosis condition.

Results The peak ankle dorsiflexion moment was significantly greater in the 3DPIO condition than in the general shoe insole (GSI) condition ($F = 6.208, p = 0.017$). The peak ankle plantar flexion moments were significantly greater in the 3DPIO condition than in the GSI and prefabricated insole orthosis (PIO) conditions ($F = 9.520, p = 0.004$). The first peak eversion moments were significantly greater in GSI walking condition than in the PIO and 3DPIO conditions ($F = 12.662, p < 0.001$). Additionally, there were no interactive effects between the orthosis conditions and the foot sides in any of the peak ankle moment variables ($p > 0.05$).

Conclusions The results showed that the application of the 3DPIO increased gait efficiency by increasing the ankle dorsiflexion and plantar flexion moments and decreasing first peak eversion moment compared to other orthotic conditions. Therefore, insole orthotic interventions, such as the 3DPIO types, are considered to manage and prevent musculoskeletal problems in individuals with PHD.

Key words Ankle; Foot orthosis; Hindfoot; Moment; Pronation.

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INTRODUCTION

Pronated hindfoot deformity (PHD) is a common musculoskeletal dysfunction of the foot and ankle joints that affects approximately one-quarter of the world's population.¹⁻² Hyper-pronation hindfeet can cause negative kinetic changes in the foot and ankle joints and segments with discomfort and pain problems during walking.³ PHD causes

the medial aspect of the foot to roll inward during the stance phase of walking or running, increasing the medial weight load on the midfoot.⁴ This increased medial loading on the midfoot causes collapse of the medial longitudinal arch and increases lateral loading on the forefoot.⁵ Furthermore, PHD can contribute to lower extremity malalignment due to excessive internal rotation of the shank and thigh segments and pelvic drop during walking and running, which may

increase the risk of musculoskeletal injuries.^{6,7}

Previously reported evidence-based approaches to PHD include therapeutic stretching and strengthening exercises of the foot and ankle joints,⁸ various foot orthoses,^{9,10} conservative pain management,¹¹ and surgical treatment.¹² Therapeutic exercises, including conservative physical therapy, only shows temporary effects while no long-term studies have been conducted to evaluate their effectiveness and fundamental effects on skeletal alignment.^{8,11} Non-operative interventions such as foot orthoses to correct the subtalar joint and support medial longitudinal foot arch are typically preferred in individuals with PHD.¹³ Therefore, orthotic interventions such as foot insole orthoses, which provide continuous assistance in supporting the alignment of PHDs while standing or walking, and that are also easy and simple to apply, would be the most idealistic and preferable.⁹ Although previous studies investigated the effects of foot orthoses to manage PHD and support medial longitudinal arch on three-dimensional (3D) ankle kinetics such as moments during gait, they did not consider using personalized 3D-printed foot orthoses based on 3D scanner device to obtain precise foot and sole silhouette.^{14,15} Furthermore, only few studies have investigated that the kinetic 3D ankle moments during gait based on a quantitative and objective motion analysis system with force platforms.

It is important to verify the kinetic characteristics of the ankle joints that occurred in stance phase of walking when applying foot orthoses in individuals with PHD. A previous study investigated the kinetic effects of the 3D-printed foot orthosis fabricated through a 3D scanner and 3D printer system for eighteen participants but they did not use a 3D motion analysis system with force platforms and only verified the plantar pressure distribution.¹⁶ Additionally, most previous similar studies that verified the clinical effectiveness of foot orthotics for PHD applied prefabricated insole orthoses or did not performed kinetic verification using high-function gait analysis equipment. Therefore, advanced studies are needed to investigate the effects of 3D-printed foot orthoses fabricated using 3D scanner equipment to accurately measure the contours of PHD on the kinetic 3D ankle moments. The purpose of this study was to confirm the effects of personalized 3D-printed foot orthoses for PHD on the peak 3D ankle moments which are highly related to ankle and foot healthiness in individuals with both pronated feet during gait. The author hypothesized that participants who wear customized 3D-printed foot orthoses will show better the peak ankle moments compare with participants wearing prefabricated foot orthoses or general shoes.

METHODS

Participants

Twenty-one participants (13 males, 8 females) were participated in this study. The inclusion criteria for the study subjects were set as those with bilateral hyper pronated feet in a standing position, a foot posture index of 6 or more, and a plantar arch index of 0.9 or less indicating the PHD.¹⁷ G*Power was used to calculate a sample size based on the second peak ankle eversion moment when wearing the insole orthoses during gait in individuals with PHD. The sample size was calculated to be at least 14, considering an α level of 0.05, a statistical power of 0.08, and an expected effect size ($d=0.4$).¹⁸ This study was executed using a cross-sectional study design. All participants voluntarily participated in the study and provided written informed consent. The Institutional Review Board of Jeonju University approved the study design (JJIRB-230906-HR-2023-0713).

Instrumentation for foot and sole shape data collection

The participant's 3D foot and plantar shape data were obtained to make a customized 3D-printed insole orthosis (3DPIO). The MediACE Scan (MS320F, RealDimension, Korea) device was used as a 3D scanner to acquire the subjects' foot and sole shape (Figure 1A). The scanner configuration consisted of a seat, an acrylic footrest, a scan arm, and a scanner body. A USB 2.0 cable was used to connect the main computer for the operation of the scanner itself, and a USB 3.0 cable was used to transfer scan data obtained through a camera installed on the scanner arm to the main computer system. The foot and plantar sole shape contour models of the subjects collected through the scanner in a standing posture were finally processed using the computer-aided design (CAD) software (MediACE3D V1, RealDimension, Korea) for designing 3DPIO.

Design procedure and fabrication output of customized 3D-printed orthosis

The design of the 3DPIO using a CAD program was produced and personalized by reflecting each participant's individual foot shape model, the characteristics of the foot orthosis application, and the correction content. Mash smoothing process was executed on the orthosis sole contact surface, and the heel side based on the scanned foot and plantar contour. The boundary of the 3DPIO was extracted from the 3D scanned foot shape silhouette for the pattern layout. An insole bottom thickness was designed to be 3 mm, the usual thickness of general insole products.¹⁹

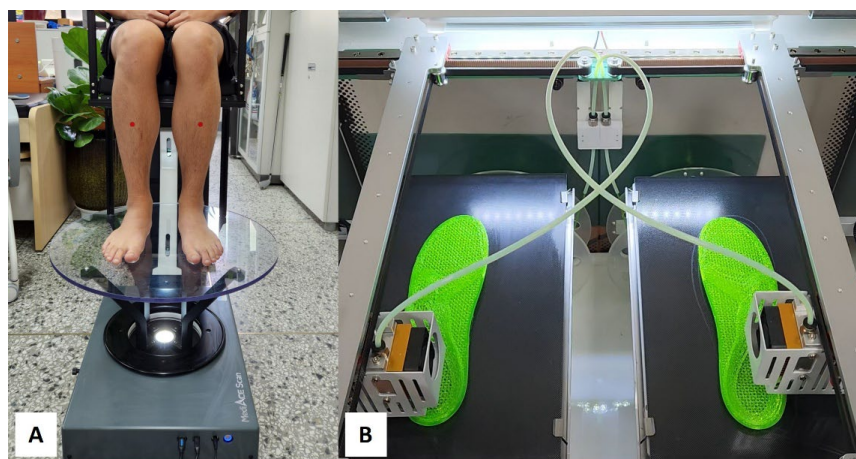


Figure 1. Instrumentation to fabricate the personalized 3D-printed insole orthoses: (A) MediAce Scan 3D scanner device; (B) 3D printer device to fabricate final insole orthoses.

Moreover, we designed the insole by identifying the individual heel cup and arch support area, and added 10mm heel raise and 3mm arch support to printed insole orthoses. The completed insole models designed through CAD program were configured to the 3D printing software (Simplify3D V4.0.1, Cincinnati, OH, USA).

According to the final insole CAD file completion, the 3DPIO was designed using a fused deposition modeling 3D printer (iSun3D Flx2, eSUN Industrial Co., Shenzhen, China) (Figure 1B). It has two printing platform stations with a capability of printing two insole orthoses simultaneously, and is composed of a 3.5-inch HD touchscreen and a 0.8 mm diameter nozzle. The 3D printer device has a high-speed flexible technology with a maximum printing speed of 120 mm/s. The printing filament for making the insole orthosis was thermoplastic polyurethane (TPU) material (TPU-flexible 95A, Cubicon Co., Sungnam, Korea). The average filament injection temperature was 235°C, and the insole orthosis production

time took an average of 45 minutes.

Instrumentation for gait analysis and acquisition of 3D peak ankle moment data

Two force platforms (BP400600, AMTI, USA) embedded in the middle walkway were used to obtain 3D GRF data during gait in different insole orthosis conditions: general shoe insole (GSI), prefabricated insole orthosis (PIO), and customized 3DPIO (Figure 2). The GSI was included in the general shoes (S260, Supercomet Co., Gimhae, Korea) provided according to each subject's foot size. The PIO (TPS, BioMechanics Co., Goyang, Korea) was a foot insole orthosis to correct flatfoot deformity sold on the public market. A Vicon motion analysis device (Vicon Inc., Oxford, UK) with six cameras (model T10) was used to capture precise stance phase points of gait cycle such as heel contact or toe off. A Nexus 1.8.5 software (Vicon Inc., Oxford, UK) was used to process the ankle kinetic data and gait kinematic variables in 3D space. A 750

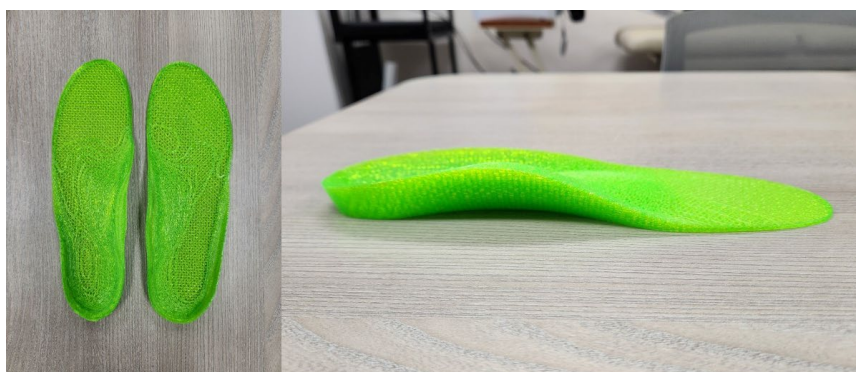


Figure 2. Customized 3D-printed insole orthoses fabricated through a 3D scanner and 3D printing system.

mm T-figure wand was used to calibrate the Vicon system and the force platforms, and a calibration reference object was used to identify the laboratory origin. The sampling rate of the motion capture system was set at 100 Hz, and the sampling rate of the force measuring plates was 500 Hz. The kinetic GRF data were processed using Nexus 1.8.5 software (Vicon Inc., Oxford, England) and exported as c3d files for final analysis. The c3d file data processed by Nexus software were sent in Visual3D motion analysis software (C-Motion, Rockville, MD, USA) for final processes and statistical analysis. The Visual3D program generated virtual lower joints and segments according to attached reflective markers to calculate the peak 3D ankle moment data during stance phase of free gait (Figure 3).

The participants wore 40 reflective markers (14 mm) with four-marker clusters attached to the participants' both anatomical landmarks of the lower extremity joints and the segments according to the six-degrees-of-freedom (6DOF) model.²⁰ To analyze the 3D peak ankle moment data during gait, three different insole orthosis conditions were applied to shoes, which are prepared according to the size of each participant's feet. Under the one orthosis condition, walking experiments were performed without rest between each gait trial, except in unexpected situations such as not stepping on the force platforms. The participants were asked to walk a 10 m walkway at a free walking speed for a total of 8-10

repetitions. The experimental order of each insole orthosis condition was randomly assigned.

Statistical analysis

Descriptive analysis was executed to confirm general characteristics of the participants, as well as moment mean and standard deviation of the peak ankle moments. All ankle moments were normalized by participants' weight. The Kolmogorov–Smirnov test was used to verify normal distribution and all analysis variables satisfied normal distribution. Two-way repeated-measures analysis of variance (ANOVA) with Bonferroni adjustment was used to confirm 3D kinetic ankle moment values for three different insole orthotic conditions and foot sides during free walking. If the main effect (orthosis intervention or foot side) was confirmed, post-hoc test was used to investigate the pairwise comparison according to the ANOVA results. Statistical significance was determined at an α level of 0.05. All analyses were executed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA).

RESULTS

All peak ankle moment variables obtained for repeated measures ANOVA analysis satisfied the normal distribution and Mauchly's assumption of sphericity. Table 1 showed the general characteristics of the participants and the means and standard deviations of typical gait parameters. There were no significant differences in walking speed, step length, and step width among the insole orthoses walking conditions (all $p > 0.05$) (Table 1). The participants' average FPI-6 score and plantar arch index were 7.33 ± 1.19 and 0.68 ± 0.20 , respectively.

There were significant differences in the peak dorsiflexion moment ($F=6.208$, $p=0.017$), the plantar flexion moment ($F=9.520$, $p=0.004$), and the first peak eversion moment ($F=12.662$, $p=0.001$) that developed in the stance phase of gait according to the insole orthotic conditions (Table 2). There were no interaction effects between foot sides and insole orthotic conditions for any moment variables of the ankle joints ($p > 0.05$) (Table 2). As a result of pairwise comparisons of peak ankle moments, the peak ankle dorsiflexion moment was significantly greater in the 3DPIO condition than in the GSI condition ($p=0.017$) (Table 3). Moreover, the peak ankle plantar flexion moments were significantly greater in the 3DPIO condition than in the GSI and PIO conditions (3DPIO compared to GSI, $p=0.003$; 3DPIO compared to PIO, $p=0.009$) (Table 3). The first peak eversion moments were significantly greater in GSI walking condition than in the PIO and 3DPIO conditions (GSI

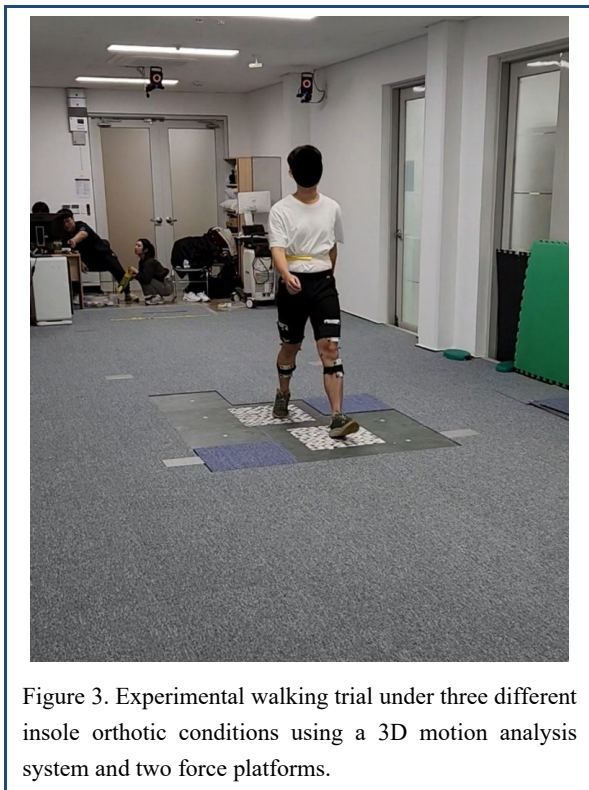


Figure 3. Experimental walking trial under three different insole orthotic conditions using a 3D motion analysis system and two force platforms.

Table 1. Characteristics of the study participants (N=21)

Characteristics	Mean (SD)
Gender	Male:13, Female: 8
Age (year)	25.3 (3.7)
Height (cm)	166.0 (4.9)
Weight (kg)	65.2 (8.8)
Gait speed (m/s)	GSI: 1.37 (0.32), PIO: 1.35 (0.40), 3DPIO: 1.38 (0.43)
Step length (cm)	GSI: 126.74 (10.18), PIO: 121.09 (9.55), 3DPIO: 127.00 (10.23)
Step width (cm)	GSI: 11.04 (2.77), PIO: 11.61 (3.61), 3DPIO: 11.52 (2.30)

SD: standard deviation; GSI: general shoe insole; PIO: prefabricated insole orthosis; 3DPIO: 3D-printed insole orthosis.

Table 2. Repeated measures ANOVA comparing three-dimensional ankle moments by three different insole orthotic conditions and foot sides during gait (N = 21)

Peak moment values (Nm/kg)	Level	F	p value
Dorsiflexion peak 0-25% stance	Insole conditions	6.208	0.017*
	Foot sides	0.018	0.847
	Conditions × sides	2.137	0.084
Plantar flexion peak 75-100% stance	Insole conditions	9.520	0.004*
	Foot sides	0.055	0.790
	Conditions × sides	1.756	0.157
Eversion first peak 0-25% stance	Insole conditions	12.662	0.001*
	Foot sides	1.009	0.334
	Conditions × sides	2.002	0.104
Eversion second peak 75-100% stance	Insole conditions	1.000	0.299
	Foot sides	0.470	0.693
	Conditions × sides	1.338	0.204
Internal rotation peak 0-50% stance	Insole conditions	1.590	0.183
	Foot sides	0.123	0.666
	Conditions × sides	0.660	0.401
External rotation peak 50-100% stance	Insole conditions	1.586	0.190
	Foot sides	0.462	0.593
	Conditions × sides	1.511	0.213

* $p < 0.01$.

compared to PIO, $p=0.002$; GSI compared to 3DPIO, $p<0.001$) (Table 3). However, no significant differences were found in the second peak eversion moment and the peak internal/external rotation moment among the three different orthotic walking conditions ($p>0.05$) (Table 3).

DISCUSSION

Previous studies have reported that insole orthoses used to manage PHD are largely mass-produced in the medical market orthoses for PHD have some clinical inconveniences

Table 3. Mean (SD) ankle moment variables presented for three insole orthotic conditions in stance phase during gait (2 × 2 repeated measures ANOVA with Bonferroni's correction, N = 21)

Peak moment values (Nm/kg)	GSI	PIO	3DPIO
Dorsiflexion peak 0-25% stance	0.164 (0.010)*	0.170 (0.016)	0.186 (0.011)
Plantar flexion peak 75-100% stance	-1.703 (0.059)*	-1.744 (0.072) ^{††}	-1.960 (0.053)
Eversion first peak 0-25% stance	0.212 (0.009)* [†]	0.166 (0.011)	0.152 (0.014)
Eversion second peak 75-100% stance	0.092 (0.007)	0.087 (0.009)	0.097 (0.008)
Internal rotation peak 0-50% stance	-0.011 (0.007)	-0.011 (0.005)	-0.009 (0.005)
External rotation peak 50-100% stance	-0.144 (0.008)	-0.139 (0.008)	-0.148 (0.009)

GSI: general shoe insole; PIO: prefabricated insole orthosis; 3DPIO: 3D-printed insole orthosis. *Significant differences between GSI and 3DPIO conditions, [†]Significant differences between GSI and PIO conditions, ^{††}Significant differences between PIO and 3DPIO conditions, $p < 0.05$.

because they are not custom-made to the individual user's feet, leading to discomfort and pain in the foot and ankle region.²¹ To overcome these discomforts, customized foot insole orthoses utilizing 3D scanners or 3D printing technologies have recently been developed to manage various foot deformities.²²⁻²⁴ They suggested that the 3D-printed foot insole orthoses offer superior fit and comfort of the foot and planar region, making them a promising clinical alternative to conventional insole orthotics. Therefore, clinical interventions using customized 3PIO based on 3D scanner acquisition of foot and plantar silhouette shape are necessary to address the disadvantages of previous prefabricated insole orthoses to support foot dysfunction, improve gait efficiency, and prevent various complications that may develop in the foot and ankle joints and segments.

The results of this study showed significant differences in some peak ankle moment variables during gait between the three insole orthosis conditions. This means that the 3D peak ankle moments during gait differs depending on the type of insole orthosis applied to individuals with PHD in this study. When the customized 3DPIO condition was applied compared to the other two insole conditions, a significant greater peak moment was confirmed in the ankle plantar flexion that occurred in frontal plane. A previous study was conducted to verify biomechanical variables during walking using personalized shoes and insole orthosis in 11 patients with pes planus and pronated feet.²⁵ Contrary to the results of this study, they reported a significantly reduced plantar flexion moment in the walking with shoes and insole orthotic condition compared to the walking with barefoot condition. The reason why the results in this study were contradictory to the peak plantar flexion moment

results can be considered as follows. First, the insole orthosis applied in this study was not a prefabricated orthosis manufactured by a conventional orthotic company, but a personalized insole orthosis using 3D scanner technology and a 3D printer device. Second, there was a difference in the walking experiment method because barefoot walking was not performed in the walking conditions of this study. Therefore, the results of previous studies are not considered to be sufficient to offset the plantar flexion moment results of this study. In a previous study supporting these claims, Lin et al.²⁶ used 3D scanning and 3D printing to evaluate the mechanical properties of a 3D-printed foot orthosis and determine its biomechanical effects on individuals with flexible flat feet. They reported a significant increase 3% in the plantar flexion moment under 3D-printed foot orthoses walking condition compared to normal shoe walking condition. This was similar to the experimental conditions of this study in terms of research materials and walking comparison conditions, and the plantar flexion moment results were also the same. Compared to other conditions, the increase in ankle plantar flexion moment in the 3DPIO condition may provide a kinetic advantage to push off the ground in the final phase of stance during gait, and is expected to contribute to acceleration in the pre-swing phase and increased gait efficiency.

In the 3DPIO and PIO gait conditions, a significant decrease in the first peak ankle eversion moment was observed compared to the GSI condition. The first peak eversion moments occurred in the mid-stance phase, and the significant decreases observed in both orthosis conditions suggest that both orthoses positively impacted pronated foot correction and medial longitudinal arch support. Many

previous studies support these results, a study reported that a significant 35% reduction in peak eversion moment when 3D printed foot orthoses were applied to patients with flexible flat feet compared to walking in regular shoes.²⁶ Another study also reported a significant decrease in ankle eversion moment during walking in the arch support insole and arch support insole with cushion pads conditions compared to the general insole condition.²⁷ The decrease in peak ankle eversion moment values is thought to have a positive effect on the reduction of the posture and alignment of the ankle and foot joints and segments in the frontal plane by providing sufficient arch support of the 3DPIO and PIO conditions. Therefore, it is thought that personalized insole orthoses such as 3DPIO based on high technology have a positive effect of an increased gait efficiency by affecting peak dorsiflexion, peak plantar flexion, and peak first eversion moments generated at the ankle joint compared to general insoles, and can limit the occurrence of secondary musculoskeletal pain and clinical symptoms of ankle osteoarthritis.

The strength of this study is that it analyzed the peak 3D kinetic moment values that occur in the stance phase during walking using two force platforms and a 3D motion analysis system, which is recognized as an objective and reliable evaluation technology in the field of biomechanics, to verify the clinical effectiveness of a personalized 3DPIO for hyper-pronated individuals fabricated using a 3D scanner and 3D printing equipment. To our knowledge, this study is the first experimental trial to investigate 3D peak ankle moments developed under the application of the 3DPIO, PIO, and GSI walking conditions in individuals with pronated flatfeet. The results showed that the application of the 3DPIO increased gait efficiency by improving ankle moments (dorsiflexion or plantar flexion) developed in the sagittal motion plane compared to other orthotic conditions. These results suggest that the clinical strengths of 3DPIO as follows. First, the technology for obtaining accurate foot models using 3D scanners enabled precise digitization of the physical characteristics of individual feet and soles. Obtaining such foot models using a 3D scanner reduces evaluation time and allows for easy and reliable acquisition of the patient's foot shape. Second, using CAD software to create 3DPIOs enhances the quality of personalized orthoses before the final 3D-printed insole orthoses. CAD software allows for precise modifications and reinforcements to the insole orthosis, tailored to each patient's foot deformity. The limitations of this study are as follows. The participants are generally healthy individuals with no musculoskeletal problems such as walking discomfort or pain in the foot and ankle joints and segments. Thus, it is

difficult to apply and generalize the study results to all individuals with PHD. In addition, since the materials of the three different insole orthotic conditions used in the experiment were not identical, the influence of various physical factors such as the weight and elasticity of the orthoses could not be confirmed. Therefore, further studies are needed under a research design that can overcome our study limitations.

CONCLUSIONS

The clinical intervention of the customized 3DPIO to individuals with PHD has significant effects on the peak ankle plantar flexion moment occurred in the stance phase of gait compared to the prefabricated foot insole and general shoe walking conditions. The 3DPIO, designed and fabricated based on 3D scanning and 3D printing technologies for the customization of individual foot conditions, can overcome the previous prefabricated foot orthoses. Abnormal increased or decreased ankle moments occurred during gait may cause to osteoarthritis of the ankle joints and foot segment deformities such as pronated foot, pes planus, or hallux valgus. Therefore, insole orthotic interventions, such as the 3DPIO introduced in this study, can be considered as an effective method to manage and prevent musculoskeletal problems in individuals with PHD.

Key Points

Question Does the customized 3D-printed insole orthosis walking condition impact the 3D peak ankle moments during gait in individuals with pronated hindfoot deformity?

Findings Significant changes were observed in some peak ankle moment variables when 3D-printed insole orthoses walking condition is applied as opposed to other foot insole orthosis walking conditions during gait in individuals with pronated hindfoot deformity.

Meaning The customized insole orthoses such as 3D-printed insole orthoses designed based on high technology can improve gait efficiency and can prevent the development of secondary musculoskeletal pain and ankle osteoarthritis.

Article information

Conflict of Interest Disclosures: None.

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Ethic Approval: This study was approved by the IRB of Jeonju University (jjIRB-230906-HR-2023-0713).

Informed consent for publication of the images was obtained from the patient.

Data Availability: The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

Conceptualization: YW Kim.

Data acquisition: YW Kim.

Design of the work: YW Kim.

Data analysis: YW Kim.

Project administration: YW Kim.

Interpretation of data: YW Kim.

Writing – original draft: YW Kim.

Funding acquisition: YW Kim.

Writing–review&editing: YW Kim.

Additional contributions: YW Kim.

REFERENCES

1. Mousavi SH, Khorramroo F, Jafarnezhadgero A. Gait retraining targeting foot pronation: A systematic review and meta-analysis. *PLoS One*. 2024;19(3):e0298646.
2. Yazdani F, Razeghi M, Karimi MT, Shahraki HR, Bani MS. The influence of foot hyperpronation on pelvic biomechanics during stance phase of the gait: A biomechanical simulation study. *Proc Inst Mech Eng H*. 2018;232(7):708-717.
3. Horwood AM, Chockalingam N. Defining excessive, over, or hyper-pronation: A quandary. *Foot (Edinb)*. 2017;31:49-55.
4. Gomes RBO, Souza TR, Paes BDC, et al. Foot pronation during walking is associated to the mechanical resistance of the midfoot joint complex. *Gait Posture*. 2019;70:20-23.
5. Monaghan GM, Lewis CL, Hsu WH, Saltzman E, Hamill J, Holt KG. Forefoot angle determines duration and amplitude of pronation during walking. *Gait Posture*. 2013;38(1):8-13.
6. Menz HB, Dufour AB, Riskowski JL, Hillstrom HJ, Hannan MT. Foot posture, foot function and low back pain: the Framingham Foot Study. *Rheumatology (Oxford)*. 2013;52(12):2275-2282.
7. Farahpour N, Jafarnezhad A, Damavandi M, Bakhtiari A, Allard P. Gait ground reaction force characteristics of low back pain patients with pronated foot and able-bodied individuals with and without foot pronation. *J Biomech*. 2016;49(9):1705-1710.
8. Andreasen J, Mølgaard CM, Christensen M, et al. Exercise therapy and custom-made insoles are effective in patients with excessive pronation and chronic foot pain—a randomized controlled trial. *Foot (Edinb)*. 2013;23(1):22-28.
9. Desmyttere G, Hajizadeh M, Bleau J, Begon M. Effect of foot orthosis design on lower limb joint kinematics and kinetics during walking in flexible pes planovalgus: A systematic review and meta-analysis. *Clin Biomech (Bristol)*. 2018;59:117-129.
10. Pinto RZ, Souza TR, Maher CG. External devices (including orthotics) to control excessive foot pronation. *Br J Sports Med*. 2012;46(2):110-111.
11. Lee J, Yoon J, Cynn H. Foot exercise and taping in patients with patellofemoral pain and pronated foot. *J Bodyw Mov Ther*. 2017;21(1):216-222.
12. Graham ME, Jawrani NT, Chikka A, Rogers RJ. Surgical treatment of hyperpronation using an extraosseous talotarsal stabilization device: radiographic outcomes in 70 adult patients. *J Foot Ankle Surg*. 2012;51(5):548-555.
13. Braga UM, Mendonça LD, Mascarenhas RO, Alves COA, Filho RGT, Resende RA. Effects of medially wedged insoles on the biomechanics of the lower limbs of runners with excessive foot pronation and foot varus alignment. *Gait Posture*. 2019;74:242-249.
14. Cheng KW, Peng Y, Chen TL, et al. A three-dimensional printed foot orthosis for flexible flatfoot: an exploratory biomechanical study on arch support reinforcement and undercut. *Materials (Basel)*. 2021;14(18):5297.
15. Park K. Effects of wearing functional foot orthotic on pelvic angle among college students in their 20s with flatfoot. *J Phys Ther Sci*. 2017;29(3):438-441.
16. Jandova S, Mendricky R. Benefits of 3D printed and customized anatomical footwear insoles for plantar pressure distribution. *3D Print Addit Manuf*. 2022;9(6):547-556.
17. Redmond AC, Crosbie J, Ouvrier RA. Development and validation of a novel rating system for scoring standing foot posture: the foot posture index. *Clin Biomech (Bristol)*. 2006;21(1):89-98.
18. Ho M, Nguyen J, Talbot K, et al. Immediate comfort perception of 3D-printed foot orthoses in individuals with unilateral heel pain. *Prosthet Orthot Int*. 2022;46(1):31-36.
19. Mendes AAMT, Silva HJA, Costa ARA, Pinheiro YT, Lins CAA, de Souza MC. Main types of insoles described in the literature and their applicability for musculoskeletal disorders of the lower limbs: A

- systematic review of clinical studies. *J Bodyw Mov Ther.* 2020;24(4):29-36.
20. Collins TD, Ghoussayni SN, Ewins DJ, Kent JA. A six degrees-of-freedom marker set for gait analysis: repeatability and comparison with a modified Helen Hayes set. *Gait Posture.* 2009;30(2):173-180.
 21. Chang MC, Choo YJ. Comparative efficacy of 3D-printed insoles in managing common foot conditions: a review. *Med Sci Monit.* 2025;31:e947252.
 22. Hsu CY, Wang CS, Lin KW, Chien MJ, Wei SH, Chen CS. Biomechanical analysis of the flatfoot with different 3D-printed insoles on the lower extremities. *Bioengineering (Basel).* 2022;9(10):563.
 23. Kumar R, Sarangi SK. 3D Printed customized diabetic foot insoles with architecture designed lattice structures - a case study. *Biomed Phys Eng Express.* 2023;10(1).
 24. Chen CS, Chang YS, Lin KW, Chien MJ, Wang CS. Biomechanical evaluation of 3D-printed joint-type orthosis for hallux valgus. *J Chin Med Assoc.* 2024;87(8):809-814.
 25. Chen YC, Lou SZ, Huang CY, Su FC. Effects of foot orthoses on gait patterns of flat feet patients. *Clin Biomech (Bristol).* 2010;25(3):265-270.
 26. Lin KW, Hu CJ, Yang WW, et al. Biomechanical evaluation and strength test of 3D-printed foot orthoses. *Appl Bionics Biomech.* 2019;2019:4989534.
 27. Han K, Bae K, Levine N, Yang J, Lee J. Biomechanical effect of foot orthoses on rearfoot motions and joint moment parameters in patients with flexible flatfoot. *Med Sci Monit.* 2019;25:5920-5928.