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Effects Of Arch-Shaped Slippers On Gait Parameters, Ground Reaction Force, And Lower Limb Muscle Activity During Walking

JaeHo Yu[1]
[1]Department of Physical therapy, Sunmoon University
Address :70, Sunmoon-ro 221 beon-gil, Tangjeong-myeon, Asan-si, Chungcheongnam-do, Republic of Korea, 31460, naresa@sunmoon.ac.kr

Abstract
Purpose: *This study aimed to evaluate the biomechanical effects of wearing double arch-shaped (DAS) slippers during gait, specifically focusing on joint range of motion (ROM), ground reaction force (GRF), and lower extremity muscle activation. The study also compared the DAS with single arch-shaped (SAS) slippers and conventional slippers to assess improvements from previous designs.*
Methods: *This repeated cross-sectional study recruited 23 healthy adults. Each participant performed gait tasks under three different conditions: (1) wearing DAS slippers, (2) SAS slippers, and (3) standard slippers. Lower extremity muscle activation was measured using surface electromyography (EMG) during treadmill walking, while joint ROM and GRF were assessed using a 3D motion capture system and a force plate. Paired sample t-tests were employed for statistical comparison.*
Results: *Compared with standard slippers, the DAS slippers significantly reduced GRF across all axes (X, Y, Z) and total force, as well as knee ROM in the vertical (Y) direction and total knee ROM ($p<0.05$). When compared with SAS, DAS also showed significant reductions in GRF in the Z axis and total force, a reduction in knee ROM along the Y axis, and an increase in ankle ROM along the Z axis ($p<0.05$). Muscle activation did not differ significantly across conditions.*
Conclusion: *The DAS slippers attenuated impact forces on the hip, knee, and ankle joints in all directions and limited excessive knee motion, potentially reducing joint overuse during gait. Compared with the SAS slippers, the DAS design further minimized lateral impact forces while enhancing rotational ankle mobility, thereby supporting more stable and efficient gait mechanics.*
Keywords: *Gait biomechanics, Joint range of motion, Ground reaction force, Muscle activation, Arch support footwear*

I. INTRODUCTION

The prevalence of musculoskeletal (MSK) symptoms continues to rise due to population aging, changing lifestyles, and increased screen time leading to VDT (Visual Display Terminal) syndrome. While regular visits to healthcare providers are recommended for managing MSK disorders, access issues and time constraints often result in inadequate treatment and chronicity. Although various consumer-grade wearable devices (e.g., TENS units, massage tools, heat stimulators) have been developed, most provide only superficial relief and fall short in addressing the root causes of MSK symptoms.
Recent studies report that up to 37% of individuals experience plantar fasciitis at some point in their lives (Khired et al., 2022). Repeated impact on the plantar fascia can result in cumulative stress on the calcaneus, gradual degradation of the heel pad, and onset of pain, joint cartilage degeneration, and arthritis. MSK fatigue and pain impair physical equilibrium and gait performance, disrupt neuromuscular signaling, and contribute to muscle weakness, joint deformity (Park et al., 2018), and postural imbalance. During warmer seasons, increased use of low-profile footwear exacerbates plantar fasciitis, while excessive pronation heightens plantar loading, further aggravating symptoms (Kim et al., 2014).
The arch-shaped slippers used in this study differ from conventional models that often induce excessive muscle contractions leading to discomfort and fatigue. Instead, these slippers promote natural activation of medial lower leg muscles critical for knee stability during daily activities. Furthermore, the design aims to minimize mediolateral sway in joint ROM and reduce GRF during gait.
Thus, the objective of this study was to evaluate the efficacy of arch-structured slippers in preventing lower limb MSK disorders by analyzing their effects on gait-related joint ROM, GRF, and muscle activation.

II. METHODS

2.1 Study Design

This research was conducted as a repeated cross-sectional study within the Department of Physical Therapy at Sunmoon University.

2.2 Participants

A total of 23 healthy adults (9 males, 14 females) participated in the study. The age distribution included 10 individuals in their 20s, 3 in their 30s, 3 in their 40s, 3 in their 50s, 2 in their 60s, and 2 in their 70s. Sample size was calculated using G*Power version 3.1.9.7, targeting a repeated-measures within-factor analysis with $\alpha = 0.05$, power = 0.80, and an effect size of 0.3. The minimum required sample size was determined to be 20, and an additional 3 participants were recruited to accommodate potential dropouts.

Inclusion criteria were as follows:

(a) good general health status,
(b) no recent ankle or knee pain within the past 3 months,
(c) no diagnosis of arthritis, gout, or foot trauma.

Exclusion criteria included:

(a) recent (within the past month) lower limb joint pain,
(b) systemic musculoskeletal or inflammatory disorders,
(c) history of foot or ankle surgery,
(d) chronic ankle instability.

All participants were informed of the study's purpose and procedures, and provided written informed consent prior to participation. Participant height and weight were measured using an automatic BMI measurement device (BSM 370, Korea) and a body composition analyzer (InBody 6570, Biospace, Korea), respectively.

2.3 Sample Size Estimation

Sample size was estimated using G*Power 3.1.9.7 (Heinrich Heine University, Düsseldorf, Germany). The analysis was set for a repeated-measures within-subject design, with $\alpha = 0.05$, power = 0.80, and an effect size of 0.3. A minimum of 20 participants was required, and 3 additional subjects were included to ensure robustness.

2.4 Experimental Procedure

Each participant completed three experimental sessions, wearing:

1. **Double arch-shaped slippers (DAS)** – Experiment 1
2. **Single arch-shaped slippers (SAS)** – Experiment 2
3. **General slippers** – Experiment 3

In each condition, gait parameters were measured once. Prior to the experiment, height and weight were assessed. The order of slipper conditions was consistent for all participants to reduce variance.

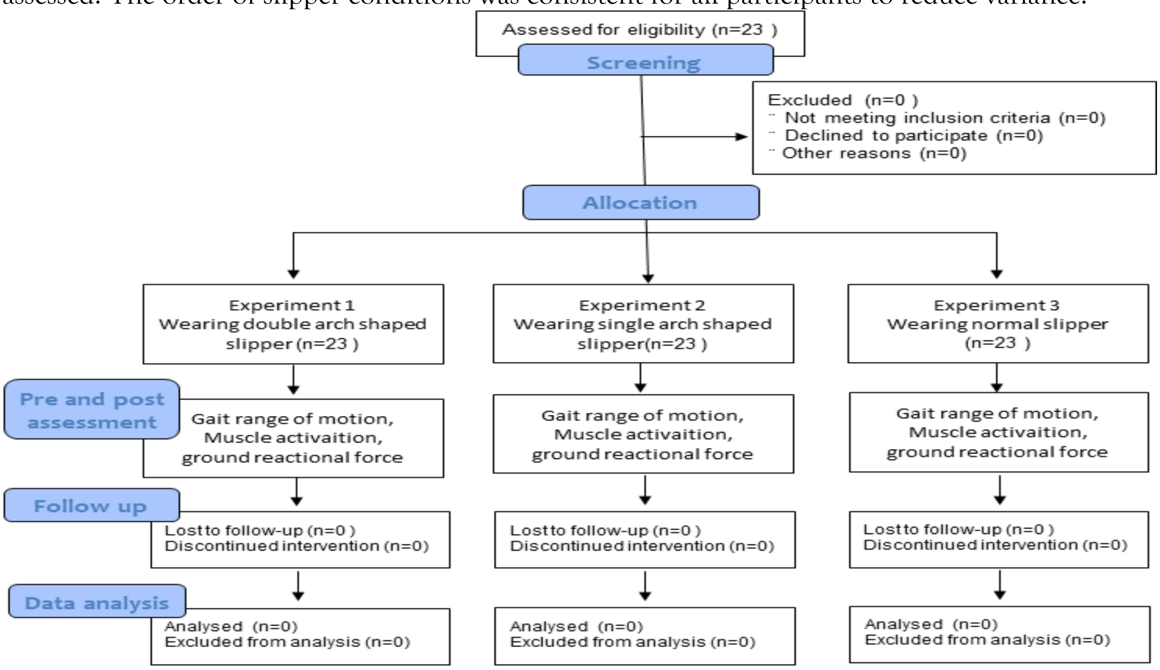

Figure 1. CONSORT flowchart

2.5 Measurement Instruments and Variables

The **dependent variables** were:Joint range of motion (ROM) of the hip, knee, and ankle joints in the X (sagittal), Y (frontal), and Z (transverse) axes, Ground reaction force (GRF) in the same three axes and total force, Electromyographic (EMG) activity of selected lower limb muscles

ROM measurements were obtained using a 3D motion capture system (Qualisys Medical), with participants walking across a Kistler force plate while five Oqus 300 cameras recorded kinematic data.

GRF was measured via the Kistler force plate during treadmill walking at a self-selected speed under each slipper condition.

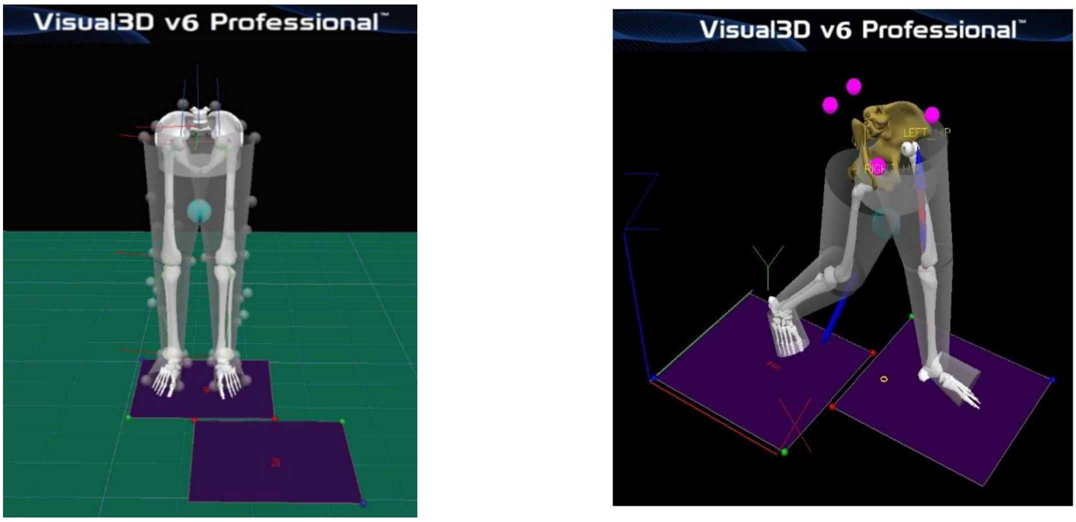

Figure 2. Gait motion analysis for range of motion

Surface EMG (myoMUSCLE™, Noraxon, USA) was used to assess muscle activity during 5 minutes of treadmill walking at 5 km/h. EMG electrodes were placed on the right-side,:

- Vastus medialis (VM)
- Vastus lateralis (VL)
- Tibialis anterior (TA)
- Medial gastrocnemius (MG)

Electrodes were aligned parallel to the muscle fibers at the mid-belly location. Skin preparation included alcohol cleansing to reduce impedance.

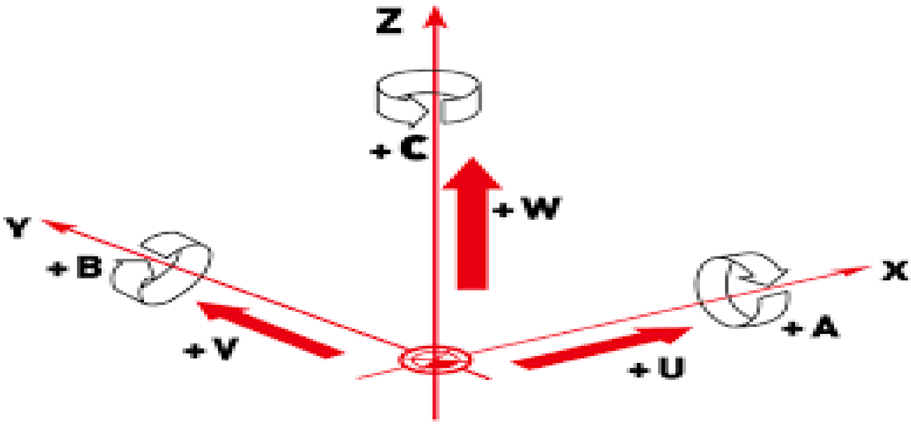

Figure 3. Ground reactional force and axis

2.6 Statistical Analysis

All statistical analyses were performed using SPSS software (version 29.0; IBM, Armonk, NY). Descriptive statistics (mean ± standard deviation) were calculated for participant demographics. To evaluate differences across slipper conditions, one-way analysis of variance (ANOVA) and paired sample t-tests were conducted.

A significance threshold was set at **$p < 0.05$** for all comparisons.

3. RESULTS

3.1 General Characteristics of Participants

Table 1 presents the general demographic characteristics of the 23 participants. The mean age was 39.22 ± 17.99 years, with an average height of 167.65 ± 7.92 cm, body weight of 68.48 ± 15.26 kg, and body mass index (BMI) of 24.13 ± 3.81 kg/m². The participant group consisted of 9 males and 14 females. All participants completed all three experimental conditions.

Variable	Mean	Standard deviation	Range
Sex (Male/Female)	9/14	-	-
Age (years)	39.22	17.99	21-74
Height (cm)	167.65	7.92	156-187
Weight (kg)	68.48	15.26	50-95
BMI(kg/m^2)	24.13	3.81	19.5-31.4

Table 1. General Characteristics of Participants

EMG data were collected from four muscles during treadmill walking. As shown in Table 2, no statistically significant differences in muscle activation were observed among the three slipper conditions (DAS, SAS, and general slippers) across all muscle groups ($p > 0.05$).

Table 2. Comparison of Muscle Activation Across Slipper Conditions

Muscle	DAS	SAS	Normal	F	p
Vastus lateralis	27.08±5.22	25.92±4.80	25.48±4.46	0.676	0.512
Biceps femoris	40.16±15.22	38.97±14.41	37.70±14.63	0.160	0.853
Tibialis anterior	36.42±6.32	35.54±6.23	34.71±5.25	0.473	0.625
Lateral gastrocnemius	34.15±4.79	33.31±5.10	32.57±5.03	0.576	0.565

*p<0.05, mean±standard deviation

As shown in Table 3, the DAS condition resulted in a statistically significant reduction in GRF in the mediolateral (X-axis), anteroposterior (Y-axis), vertical (Z-axis), and total force components when compared to the general slipper condition ($p < 0.05$).

Table 3. GRF Comparison Between DAS and General Slippers

Axis	DAS	일반 슬리퍼	t	p
X (medial-lateral)	10.14±0.78	11.23±0.56	**-5.446**	**0.000***
Y (anterior-posterior)	41.32±1.33	42.44±1.44	**-2.734**	**0.009***
Z (vertical)	98.38±3.09	105.14±3.41	**-7.037**	**0.000***
total	**107.20±2.90**	**113.94±3.46**	**-7.159**	**0.000***

***p<0.05,** , mean±standard deviation

In comparison with the SAS slippers, the DAS condition significantly reduced GRF in the Z-axis and total force components ($p < 0.05$), while no significant differences were found in the X or Y axes.

Table 4. GRF Comparison Between DAS and SAS

Axis	DAS	SAS	t	p
X (medial-lateral)	10.14±0.78	**10.42±.55**	**-1.418**	**0.163**
Y (anterior-	41.32±1.33	**41.87±1.16**	**-1.517**	**0.136**

posterior)				
Z (vertical)	98.38±3.09	**101.10±3.51**	**-2.791**	**0.008***
total	**107.20±2.90**	**109.93±3.52**	**-2.87**	**0.006***

***p<0.05,** , mean±standard deviation

Compared to general slippers, DAS significantly reduced knee joint ROM in the Y-axis (superior-inferior direction) and total ROM ($p < 0.05$). Ankle rotation (Z-axis) showed a tendency to increase, though not statistically significant.

표 5. DAS와 일반슬리퍼 간 보행 관절가동범위 분석

Lower joint		DAS	Normal	t	p
Hip ROM (°)	X (medial-lateral)	8.15±0.99	8.52±1.31	**1.075**	**0.288**
	Y (anterior-posterior)	39.01±3.01	38.19±3.28	**-0.893**	**0.377**
	Z (vertical)	13.98±0.91	38.19±3.28	**0.632**	**0.531**
	total	**41.61±3.58**	**42.24±3.25**	**-0.624**	**0.536**
Knee ROM (°)	X (medial-lateral)	3.19±3.02	3.31±3.08	**0.132**	**0.896**
	Y (anterior-posterior)	58.24±1.21	56.18±1.40	**-5.344**	**0.000***
	Z (vertical)	8.37±1.12	8.52±1.32	**-0.503**	**0.617**
	total	**57.93±2.75**	**60.01±2.45**	**-2.701**	**0.010***
Ankle ROM (°)	X (medial-lateral)	-10.66±4.21	-11.29±4.42	**-0.944**	**0.350**
	Y (anterior-posterior)	13.29±8.12	13.82±7.40	**0.231**	**0.818**
	Z (vertical)	-7.91±3.59	-6.31±1.38	**1.996**	**0.052**
	total	**20.57±2.85**	**20.49±3.76**	**0.082**	**0.935**

***p<0.05,** , mean±standard deviation

Compared to SAS, DAS significantly reduced knee ROM in the Y-axis and increased ankle rotation in the Z-axis ($p < 0.05$). There was also a non-significant trend toward reduced total knee ROM.

표 6. DAS와 SAS 간 보행 관절가동범위 분석

Lower joint		DAS	SAS	t	p
Hip ROM (°)	X (medial-lateral)	8.15±0.99	8.43±1.04	**0.257**	**.799**
	Y (anterior-posterior)	39.01±3.01	38.43±2.97	**-0.584**	**.562**
	Z (vertical)	13.98±0.91	38.73±2.97	**0.285**	**.777**

	total	**41.61±3.58**	**42.06±3.18**	-0.452	.653
Knee ROM (°)	X (medial-lateral)	3.19±3.02	3.24±3.03	0.067	.947
	Y (anterior-posterior)	58.24±1.21	58.01±1.83	-3.808	.000*
	Z (vertical)	8.37±1.12	8.43±1.04	-0.191	.849
	total	**57.93±2.75**	**59.65±3.04**	-2.013	.050
AnkleROM (°)	X (medial-lateral)	-10.66±4.21	-10.60±4.05	-0.544	.589
	Y (anterior-posterior)	13.29±8.12	13.48±8.71	0.143	.887
	Z (vertical)	-7.91±3.59	-7.66±2.16	2.528	.015*
	total	**20.57±2.85**	**20.93±2.79**	-0.430	.670

***p<0.05,** , mean±standard deviation

IV. DISCUSSION

Slippers designed to support the plantar fascia not only aid in the prevention of plantar fasciitis but also contribute to the overall stability of the ankle and knee joints, as highlighted in several previous studies. This study aimed to examine the biomechanical effects of wearing double arch-shaped slippers (DAS) on gait-related parameters such as joint range of motion (ROM), ground reaction force (GRF), and lower limb muscle activity. In addition, improvements made over the single arch-shaped (SAS) slipper design were evaluated to assess functional advancements.

The key findings indicated that while muscle activation did not significantly differ among the three slipper conditions, GRF was significantly reduced across all directions (X, Y, Z axes and total) when DAS were worn, compared to general slippers. Furthermore, knee joint ROM in the superior-inferior (Y) axis and overall total ROM were also reduced. When comparing DAS with SAS, reductions in GRF were observed in the vertical (Z) axis and in total force, while ankle rotational ROM (Z-axis) was increased.

The observed reduction in GRF across all directional axes when using DAS may be attributed to the enhanced shock absorption properties offered by the dual arch structure. Particularly, the decrease in Z-axis (vertical) force suggests a dampening of impact forces during heel strike, which could translate into reduced mechanical loading on the lower extremity joints. This has implications not only for the prevention of plantar fasciitis but also for long-term joint health in the knee and hip. These findings align with Cho et al. (2021), who reported that arch-supporting insoles effectively redistribute GRF during gait.

The decrease in knee ROM along the Y-axis and in total range, observed in the DAS condition, suggests a restriction of excessive joint movement during gait. This may enhance joint stability, particularly in populations at risk for knee overuse or instability, such as older adults. On the other hand, the increase in ankle ROM along the Z-axis relative to SAS indicates that the DAS design allows for more flexible rotational movement of the ankle. This could reflect improved design features facilitating natural toe-off and lateral roll-through mechanics. These outcomes are in agreement with the findings of Kim et al. (2020), who demonstrated that foot orthoses can enhance gait adaptability by modulating ankle kinematics.

Despite changes in joint kinematics and GRF, no significant differences were observed in EMG activity across the four monitored muscles. This suggests that the DAS slippers do not impose additional neuromuscular demand, but rather improve mechanical efficiency through structural design. The functional benefit is thereby achieved via shock absorption and joint stabilization without altering baseline muscular effort.

The improvements in GRF and ankle ROM with DAS over SAS highlight the efficacy of the redesigned dual arch structure. Notably, the reduction in mediolateral impact forces in the DAS condition supports the hypothesis that the newer design better manages load distribution during stance. Enhanced ankle rotation may further facilitate smoother weight transfer from heel to toe, potentially optimizing gait dynamics and comfort in daily use.

This study was limited to short-term assessments in a healthy adult population. Therefore, findings may not be directly generalizable to clinical populations such as individuals with chronic plantar fasciitis, arthritis, or postural instability. Furthermore, gait was assessed under standardized treadmill conditions, which may differ from overground walking in real-world environments.

Future research should incorporate long-term trials in symptomatic populations and analyze additional parameters such as plantar pressure distribution, perceived comfort, fatigue indices, and fall risk indicators. Integration with real-time gait analysis systems and wearable monitoring could further advance understanding of slipper-related gait biomechanics.

V. CONCLUSION

This study evaluated the biomechanical effects of double arch-shaped (DAS) slippers on gait parameters, including joint range of motion (ROM), ground reaction force (GRF), and lower limb muscle activation. The following key conclusions were drawn:

1. **Compared with general slippers**, the DAS condition significantly reduced GRF across all axes (X, Y, Z) and in total force. Additionally, knee ROM in the superior-inferior (Y-axis) direction and overall total knee ROM were significantly decreased.
2. **Compared with single arch-shaped slippers (SAS)**, the DAS condition demonstrated a significant reduction in GRF along the vertical (Z) axis and total force, along with a significant decrease in knee Y-axis ROM and a significant increase in ankle Z-axis ROM.

These findings suggest that DAS slippers offer mechanical advantages for gait efficiency and joint protection and may serve as a practical preventive tool for musculoskeletal health in both general and at-risk populations.

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