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Impact of different foot orthoses on gait biomechanics in individuals with chronic metatarsalgia

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ABSTRACT

Background: Foot orthoses (FOs) are commonly prescribed to reduce pain and improve function in individuals with musculoskeletal disorders, including those with chronic metatarsalgia (CM). Reducing the mechanical overload under the metatarsal heads during locomotion is the central point of the treatment for CM. Medially wedged FOs (MWFOs) with a metatarsal pad could further reduce pressure loading under the metatarsal heads and modify foot and ankle biomechanics compared to standard FOs (SFOs).
Research Question: Do MWFOs further decrease the peak plantar pressure under the metatarsal heads in individuals with CM compared to SFOs? What are the effects of these FOs on foot and ankle 3D kinematics and kinetics in individuals with CM?
Methods: Twenty-three individuals (17 females and 6 males) with CM were recruited in this cross-sectional descriptive study. Participants walked during three conditions: (1) Shod, (2) SFOs, and (3) MWFOs. Peak plantar pressure, midfoot and ankle angles and moments were calculated and compared across conditions with repeated measure ANOVAs using statistical parametric mapping.
Results: SFOs and MWFOs reduced plantar pressure under the metatarsal heads, ankle plantarflexion angle, and midfoot plantarflexion moment compared to shod. SFOs and MWFOs increased plantar pressure under the medial midfoot. MWFOs reduced plantar pressure under the 1st-2nd-3rd metatarsal heads during the second part of the stance phase and increased plantar pressure under the medial midfoot compared to SFOs. MWFOs also decreased midfoot dorsiflexion and inversion angles, ankle eversion angle, and ankle inversion moment compared to shod.
Significance: MWFOs were more effective than SFOs in reducing peak pressure under the 1st-2nd-3rd metatarsal heads and modifying lower limb biomechanics during walking. This reduction implies a pressure transfer from the metatarsal heads to the medial midfoot. These findings are promising to find the FOs model most suitable to reduce pain and improve physical function in individuals with CM.

1. Introduction

Foot musculoskeletal disorders cause significant impairments and disabilities to affected individuals [1]. Chronic metatarsalgia (CM) is an umbrella disorder that encompasses various primary and secondary conditions causing pain beneath one or more metatarsal heads [2], including predislocation syndrome of the metatarsophalangeal joint, hallux abducto-valgus, hallux limitus, and mechanical overload. It represents up to 88 % of all causes of foot pain [3], with a general prevalence of 13 to 36 % in adults [4]. It significantly reduces the quality of life of those affected, physically, psychologically, and socially [5]. Different treatment modalities are used for CM with overall good results, such as footwear modifications, stretching, and foot orthoses (FOs) [6].

Foot orthoses are commonly used to reduce pain and improve function in individuals with musculoskeletal disorders [7–9]. The treatment of CM is essentially based on reducing the mechanical

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overload under the metatarsal heads during locomotion [2,10,11], being strongly correlated with pain reduction in CM [6]. Foot orthoses reduce forefoot plantar pressure during locomotion in individuals with flatfeet and asymptomatic individuals [12,13] and redistribute plantar pressure in a more balanced way [14,15]. Adding a medial wedge to FOs further reduces forefoot peak pressure in healthy adults [16]. Another orthotic feature, often used to reduce plantar pressure under the metatarsal heads and relieve the symptoms of CM, is a metatarsal pad [6,17]. Foot orthoses also decrease midfoot inversion, dorsiflexion and abduction angles [18–20], and decrease midfoot plantarflexion moment in adults with flat-arched feet [21]. Unfortunately, the effects of different FOs models (e.g., with and without a metatarsal pad or a medial wedge) on plantar pressure as well as on foot and ankle angles and moments have not yet been investigated in individuals with CM. Studying their biomechanical effects in individuals with CM during locomotion is crucial to better inform the mechanical and clinical development of FOs with the overarching goal of alleviating pain and improving function in these individuals.

The main objective of this study was to investigate the effects of two FOs models in individuals with CM, namely standard FOs (SFOs) and medially wedged FOs with a metatarsal pad (MWFOs), on plantar pressure distribution during gait. The secondary objective was to assess their effects on foot and ankle angles and moments. The main hypothesis was that MWFOs would further reduce peak plantar pressure under the metatarsal heads compared to SFOs. The secondary hypothesis was that MWFOs would further decrease foot and ankle pronation, arch flattening, and ankle inversion moment compared to SFOs.

2. Methods

2.1. Participants

A group of 23 individuals composed of 17 females and 6 males (age: 50.5 $\pm$ 9.4 years; mass: 85.2 $\pm$ 20.6 kg; height: 167.6 $\pm$ 8.0 cm; Body Mass Index: 30.3 $\pm$ 6.8 kg.m^{-2}; FPI injured foot: 3.8 $\pm$ 2.4; FPI other foot: 3.7 $\pm$ 2.1) were recruited. Static foot posture was quantified with the Foot Posture Index (FPI) [22]. Participants were included in the study if they were aged between 18 and 65 years, had unilateral or bilateral CM for at least 3 months (pain score of $\geq$ 4 out of 10 on the Visual Analogue Scale (VAS)) [23], and were able to walk without assistive devices (e.g., cane). The pain score refers to the highest daily pain experienced over the week prior to their enrollment in the study. If they had bilateral CM, the most painful foot was used for data collection. The diagnosis was made by a podiatrist who, following the definitions of primary and secondary metatarsalgia and excluding other possible pathologies, determined whether the patient had metatarsalgia. Potential participants were excluded from the study if they had lower limb arthritis, neurological diseases (e.g., intermetatarsal neuroma) or other mechanical pain, plantar corns, and a history of orthopedic foot surgery. Participants were recruited from the *Université du Québec à Trois-Rivières* (UQTR) outpatient podiatric clinic or via email and social media invitations from December 2023 to April 2024. Participants provided written informed consent before their enrollment in the study. The research protocol was approved by the Université du Québec à Trois-Rivières Ethics Committee (CER-22–293–07.01).

2.2. Foot orthoses fabrication and clinical assessment

Two weeks before data collection, a podiatrist with 10 years of clinical experience took the negative foot impressions using a semi-weightbearing method with a foam box. Two pairs of custom-made FOs were manufactured for each participant (Fig. 1): (1) SFOs with a 3 mm Poron top cover and fabricated with a 3.2 mm polypropylene shell and (2) MWFOs made with a 3.2 mm polypropylene shell with 6° medially wedged forefoot-rearfoot posts, a full-length 3 mm Poron top cover and a metatarsal pad (15 shore A) located 5 mm proximal to the metatarsal heads [6]. The mean maximal pain score experienced daily in the past week was registered using VAS. No acclimatization period was given to participants to avoid changing participants' symptoms before the day of data collection [24].

The French-validated version of the Foot Function Index (FFI) was completed by each participant [25]. The FFI is a questionnaire of 23 items scored from 0 to 10 on a numeric scale and spread out in three subscales: pain (out of 90), function (out of 90), and activity limitations (out of 50). The maximum score was 230. To standardize the scores on a scale from 0 to 100, each individual score was divided by 230 and then multiplied by 100 to estimate the total level of pain/function/activity limitations.

2.3. Tools

To quantify plantar pressure, a Pedar-X in-shoe pressure measurement system (Novel Corporation, Munich, Germany), sampling at 100 Hz, was used. The plantar pressure insole was placed between the foot and the FOs. To quantify the spatial position of reflective markers placed over bony landmarks of the pelvis, thigh, leg, and foot segments based on a modified Oxford foot model [26], we used an OptiTrack motion capture system (Natural Point, Corvallis, OR, USA) with 12 cameras sampled at 200 Hz. A four-marker cluster frame (6 $\times$6 cm) was attached to the sacrum and the middle anterolateral aspect of the thigh and leg for tracking purposes. A triad plastic cluster with three markers affixed on a small-curved plastic base (20 $\times$25 mm) was firmly attached to the posterior superior aspect of the calcaneal tuberosity for the hindfoot, and markers were placed on the proximal posterior calcaneus, distal posterior calcaneus, peroneal tubercle, and sustentaculum tali. For the forefoot, markers were placed on the base and the head of the first and fifth metatarsals and between the second and third metatarsal head [27–29]. Each landmark was first identified by palpation and the skin

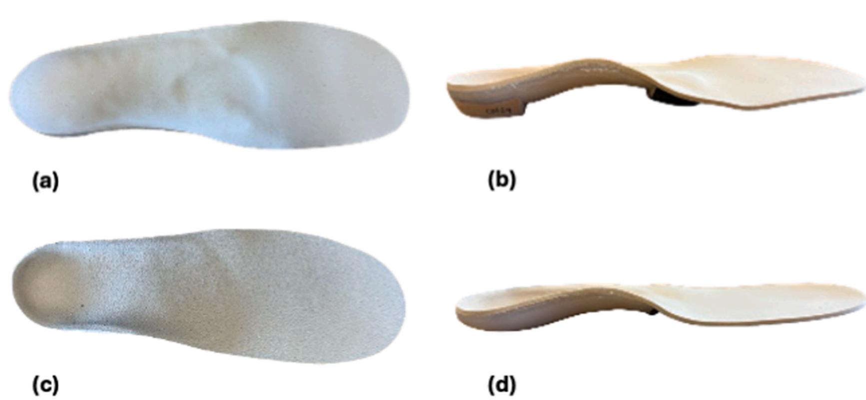

Fig. 1. Superior (a) and side (b) views of MWFOs and superior (c) and side (d) views of SFOs.

was marked with a pen to ensure identical repositioning in cases of marker fall during the task and when changing conditions. During the experimentation, foot markers were placed through holes that were made in a pair of linen sports shoes (Jogflow 500, Kalenji, Decathlon, CA).

Located in the middle of the calibrated space, a floor-embedded force plate sampling at 1 kHz (AMTI, Watertown, MA, USA) was used to record ground reaction forces. The force plate and the motion camera capture system were synchronized and monitored using Motive software (V3.0.0; OptiTrack; Natural Point, Corvallis, OR, USA).

To ensure that we studied the same steps for the analysis of joint angles and moments as well as plantar pressure, participants were positioned to take an identical number of steps between each trial, and each condition, which allowed us to analyze the same step for each trial.

2.4. Procedures

The same member of the research team undertook all participants' preparations, including the systems' calibration and markers placement. Before undertaking data collection, participants were given a 10-minute familiarization period to become acquainted with the environment. Participants were evaluated under three randomized conditions: shoes only condition, shoes with SFOs, and shoes with MWFOs, at a self-selected speed. Participants had to do four steps before the force plate, and they had to stop four steps after the force plate. Participants were asked to look straight ahead and to walk as naturally as possible. Six successful trials during each condition were performed: i) the evaluated foot was placed properly on the middle of the force plate, ii) the walking performance appeared in a continuous and smooth manner, and iii) all markers were visible throughout the gait cycle. Trials were only included if the walking speed was within ± 5 % of the participant mean walking speed.

The peak pressure during the stance phase was calculated using Pedar-X software (Novel Corporation, Munich, Germany) by dividing the foot into nine regions using masks: lateral heel, medial heel, lateral midfoot, medial midfoot, 1st metatarsal head, 2nd and 3rd metatarsal head, 4th and 5th metatarsal head, hallux, second to fifth toes (Fig. 2) [30].

To process the motion capture and force plate data, Visual 3D software (v6.01.36, C-motion, Inc., Germantown, MD, USA) was used. Local coordinate systems of the forefoot, hindfoot, shank, thigh, and pelvis were defined, and joint angles were expressed as Cardan angles for flexion, abduction, and rotation. The angle between the forefoot and hindfoot segments defined the midfoot kinematics. The angle between the hindfoot and shank segments defined the ankle kinematics. Midfoot, ankle, knee, and hip moments were calculated using inverse dynamics and were normalized to body weight. Kinematic and kinetic (except for midfoot moments) data during the stance phase were time normalized on 101 points for visual and statistical comparisons (0–100 % of the stance phase). Midfoot kinetic data were normalized from heel off (0 %) to toe off (100 %).

2.5. Sample size calculation

To determine if there were true differences in peak plantar pressure under the metatarsal heads, midfoot and ankle sagittal angles and moments and reject the null hypothesis, 20 participants were required for this study. We based this calculation on preliminary results of our research team, for within-subject crossover design with repeated-measures analysis of variance (ANOVAs) comparisons, with an effect size of 0.35, a power (β) of 0.80, and α≤ 0.05. Zero-dimensional variables (discrete variables) were used, for the calculations, rather than one-dimensional trajectories considering that one-dimensional statistical parametric mapping (SPM) currently does not support a priori sample size calculations for one-way repeated-measure ANOVAs. Three additional participants were included, for a total of 23, in case of technical difficulties during data collection.

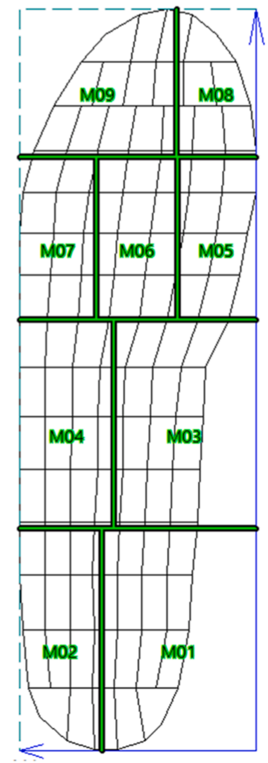

Fig. 2. Analysis of the peak plantar pressure using nine masks (M01 =medial heel, M02 =lateral heel, M03 =medial midfoot, M04 =lateral midfoot, M05 =1st metatarsal head, M06 =2–3rd metatarsal heads, M07 =4–5th metatarsal heads, M08 =hallux, M09 =2–5th toes).

2.6. Statistical analysis

All statistical analyses were performed in MATLAB R2023a (The MathWorks Inc., Boston, MA, USA) using the spm1d open-access toolbox (www.spm1d.org) [31,32]. The mean walking speed was also compared across conditions with a one-way repeated measures ANOVA. The maximal absolute difference (MD) was calculated for all significant results. We first assessed the normality of the distribution of the peak plantar pressure, mean joint angles, and joint moments (spm1d.stats.normality.anova1rm function). One-dimensional SPM one-way repeated-measure ANOVAs (SPM(F)) followed by SPM dependent t-tests SPM(t) as post hoc analyses were used to compare the biomechanical data across conditions, when the data were normally distributed. The non-parametric version, SnPM(F) and SnPM(t)) tests, was used when data were not normally distributed. To reduce the chances of committing a type I statistical error, only the foot and ankle angles and moments were analyzed. However, the results for the knee and hip are available in Supplementary Material 1-4, and the results for the mean plantar pressure are available in Supplementary Material 9 but were not analyzed.

The significance level was set at $\alpha < 0.050$ for all analyses. Cohen's d coefficients were calculated to evaluate the effect size of significant results and were interpreted as follows: $d < 0.2$ was considered small, $0.2 \leq d < 0.5$ moderate, $0.5 \leq d < 0.8$ good, and $d > 0.8$ large [33].

3. Results

Demographic data are displayed in Table 1, plantar pressure in Fig. 3, angles in Fig. 4, and moments in Fig. 5. Graphs of significant results with only one comparison (i.e., shod vs. MWFOs, shod vs. SFOs, or SFOs vs. MWFOs) for plantar pressure under the metatarsal heads are available in Supplementary Material 5, for plantar pressure under the

Table 1
Descriptive statistics for FFI total score and sub-scale score, P-values of one-dimensional statistical parametric mapping one-way repeated-measures ANOVAs for the masks of peak plantar pressure, angles, and moments of the ankle and midfoot (M: Mask, Df: Dorsiflexion, Pf: Plantarflexion, Inv: Inversion, Ev: Eversion, Abd: Abduction, Add: Adduction). For example, the P-values of one-dimensional statistical parametric mapping one-way repeated-measures ANOVAs for the mask M02 was 0.001, when comparing the 3 conditions on this mask.

FFI	Mean		Standard deviation		Min		Max	
Total Score	37.3		15.9		9.1		60.4	
Pain	39.5		14.5		20.0		64.0	
Function	40.3		21.8		1.0		77.0	
Activity limitation	6.1		6.0		0.0		21.0	
P-values (plantar pressure)	**Lateral Heel (M02)**	**Medial Heel (M01)**	**Lateral Midfoot (M04)**	**Medial Midfoot (M03)**	**1^{st} metatarsal head (M05)**	**$2^{nd}-3^{rd}$ metatarsal heads (M06)**	**$4^{th}-5^{th}$ metatarsal heads (M07)**	**Toes (M08-M09)**
P	**0.001**	**0.001**	**0.011**	**0.001**	**0.001**	**0.001**	**0.001**	> 0.050
P-values	**Midfoot**				**Ankle**			
	Df/Pf	Inv/Ev	Abd/Add		Df/Pf	Inv/Ev	Abd/Add	
P (angles)	**0.034**	**0.036**	**0.018**		**0.002**	**0.029**	> 0.050	
P (moments)	**0.004**	> 0.050	> 0.050		**0.001**	**0.007**	> 0.050	

midfoot and heel in Supplementary Material 6, and for angles and moments in Supplementary Material 7.

3.1. Demographic data

The mean walking speed was 1.32 ± 0.17 $m.s^{-1}$ for the shod condition, 1.30 ± 0.17 $m.s^{-1}$ for SFOs, and 1.30 ± 0.18 $m.s^{-1}$ for MWFOs. There was no difference in walking speed across conditions [F (2, 222) = 0.663, p = 0.262]. The pain duration was 81.5 ± 118.5 months and the maximal daily VAS score was 7.8 ± 1.5 out of 10. The mean total score of FFI was 37.25 ± 15.87. The repeated measures ANOVA revealed that the plantar pressure under the metatarsal heads, heel, midfoot was significantly different between conditions.

3.2. Comparisons between SFOs and Shod

3.2.1. Plantar pressure

During walking with SFOs, the peak plantar pressure was smaller under the medial heel (1–53 % of the stance phase (%SP); MD= 39.0 kPa, P = 0.001, d= 1.20), under the lateral heel (2–36 %SP; MD = 27.3 kPa, P = 0.001, d = 0.81), under the lateral midfoot (22–31 %SP, MD = 10.4 kPa, P = 0.015, d = 0.47), under the 1st metatarsal head (24–43 % SP; MD = 12.0 kPa, P = 0.001, d = 0.68; 48–70 %SP, MD = 9.0 kPa, P = 0.005, d = 0.45), under the 2nd-3rd metatarsal heads (12–70 %SP; MD = 10.9 kPa, P = 0.001, d = 0.65) and under the 4th-5th metatarsal heads (8–10 %SP; MD = 6.9 kPa, P = 0.019, d = 0.54; 14–16 %; MD = 6.80, P = 0.019, d = 0.39; 28–71 %SP; MD = 10.6 kPa, P = 0.001, d = 0.44) compared to shod condition. The peak plantar pressure under the medial midfoot (1–8 %SP; MD = 16.43 kPa, P = 0.001, d = 0.92) and under the lateral midfoot (0–6 %SP, MD = 12.5 kPa, P = 0.006, d = 1.20) were greater with SFOs compared to the shod condition (Fig. 3).

3.2.2. Kinematics

Smaller ankle plantarflexion angle was observed for SFOs compared to shod from 5 % to 8 %SP (MD = 2.0°, P = 0.021, d = 0.33) and from 88 % to 92 %SP (MD = 4.1°, P = 0.021, d = 0.43) (Fig. 4).

3.2.3. Moments

During walking with SFOs, midfoot plantarflexion moment (14–49 %SP; MD = 0.04 Nm/kg, P = 0.006, d = 0.41) was smaller and ankle abduction moment (67–82 %SP, MD = 0.04 Nm/kg, P = 0.003, d = 0.28) was greater compared to the shod condition (Fig. 5).

3.3. Comparisons between MWFOs and Shod

3.3.1. Plantar pressure

Smaller peak plantar pressure under the medial heel (4–48 %SP; MD= 29.7 kPa, P = 0.001, d = 0.85), under the lateral heel (5–11 %SP; MD = 14.9 kPa, P = 0.004, d = 0.57), under the lateral midfoot (25–31 %SP; MD = 14.8 kPa, P = 0.012, d = 0.60), under the 1st metatarsal head (10–89 %SP; MD = 44.0 kPa, P = 0.001, d = 0.98), under the 2nd-3rd metatarsal heads (60–86 %SP; MD = 24.5 kPa, P = 0.001, d = 0.75) and under the 4th-5th metatarsal heads (45–85 % SP; MD = 17.6 kPa, P = 0.001, d = 0.61) were observed with MWFOs compared to shod. Greater peak plantar pressure under the medial midfoot (0–8 %SP; MD = 17.9 kPa, P = 0.004, d = 1.07; 39–97 %SP; MD = 23.7 kPa, P = 0.001, d = 1.78), under the 2nd-3rd metatarsal heads (94–100 %SP; MD = 18.2 kPa, P = 0.001, d = 1.22) and under the 4th-5th metatarsal heads (95–98 %SP; MD = 9.2 kPa, P = 0.010, d = 0.65) were observed with MWFOs compared to shod (see Fig. 3).

3.3.2. Kinematics

During walking with MWFOs, smaller midfoot dorsiflexion angle (52–88 %SP; MD = 4.1°, P < 0.001, d = 0.54), midfoot inversion angle (90–100 %SP; MD = 3.2°, P = 0.012, d = 0.59), ankle plantarflexion angle (0–8 %SP; MD = 4.0°, P = 0.009, d = 0.52 and 35–100 %SP; MD = 5.4°, P = 0.001, d = 0.64) and ankle eversion angle (10–30 %SP; MD = 2.5°, P = 0.009, d = 0.62 and 43–82 %SP; MD = 2.6°, P < 0.001, d = 0.58) were observed compared to shod walking (see Fig. 4).

3.3.3. Moments

Smaller midfoot plantarflexion (0–61 %SP; MD = 0.07 Nm/kg, P = 0.001, d = 0.50) and ankle inversion (10–99 %SP; MD = 0.08 Nm/kg, P = 0.001, d = 0.52) moments were observed during walking with MWFOs compared to shod (Fig. 5).

3.4. Comparisons between MWFOs and SFOs

3.4.1. Plantar pressure

Smaller peak plantar pressure under the 1st metatarsal head (64–82 %SP; MD = 21.7 kPa, P = 0.002, d = 0.58) and under the 2nd-3rd metatarsal heads (76–86 %SP, MD = 15.34 kPa, P = 0.009, d = 0.42) were observed with MFWOs compared to SFOs. The peak plantar pressure under the medial heel (9–38 %SP; MD = 10.1 kPa, P = 0.001, d = 0.35), under the medial midfoot (43–90 %SP; MD = 27.7 kPa, P = 0.001, d = 1.34), under the 2nd-3rd metatarsal heads (14–33 %SP; MD = 17.4 kPa, P = 0.001, d = 1.20; 95–100 %SP, MD = 18.7 kPa, P = 0.005, d = 1.02) and under the 4th-5th metatarsal heads (96–100 % SP; MD = 10.8 kPa, P = 0.016, d = 0.79) were greater with MWFOs compared to SFOs (see Fig. 3).

3.4.2. Kinematics

No significant differences were observed during walking with MWFOs compared to SFOs (see Fig. 4).

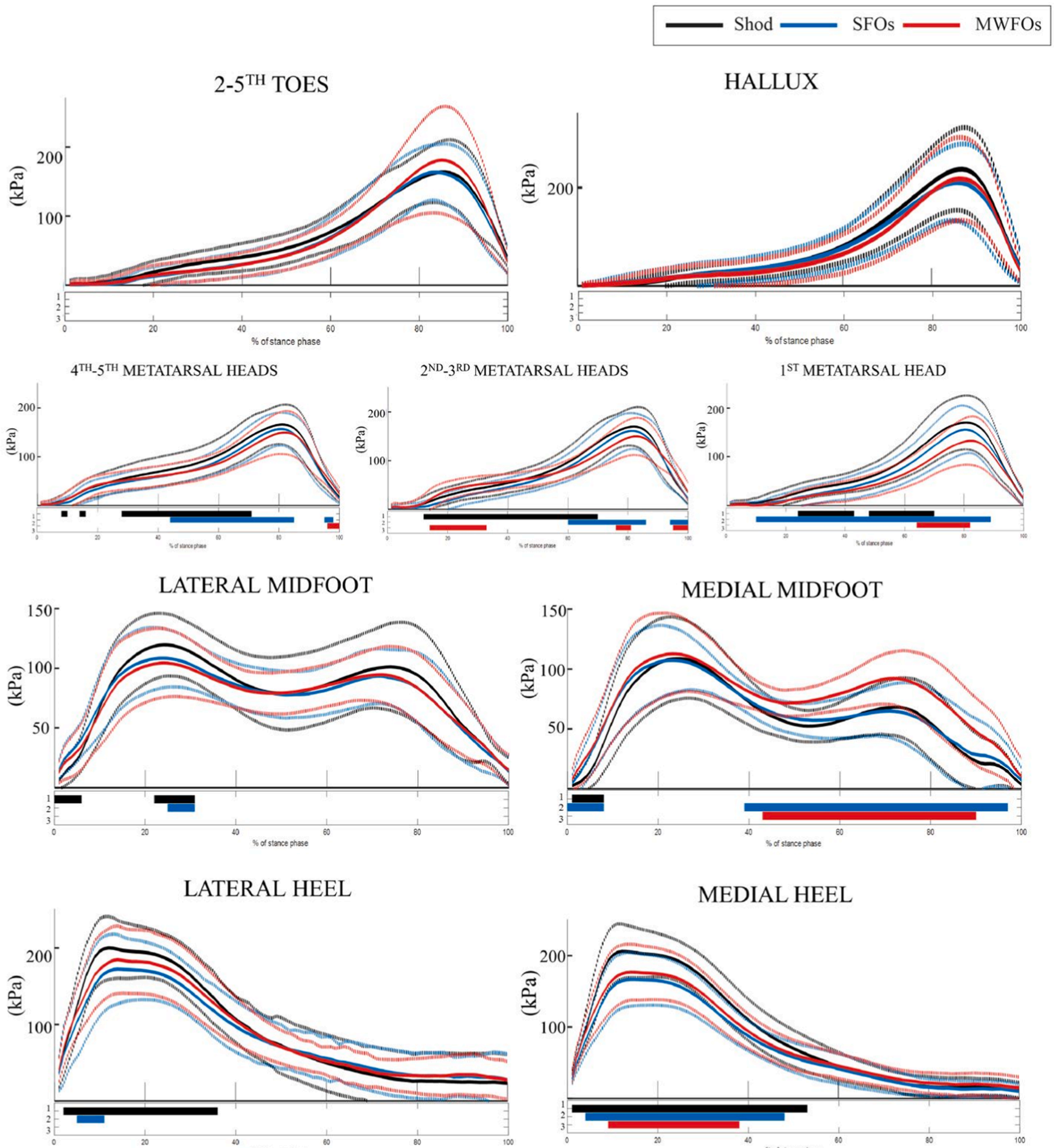

Fig. 3. Peak plantar pressure differences during the stance phase while shod (black), wearing SFOs (blue), and wearing MWFOs (red). 1.Black =significant differences between shod and SFOs. 2. Blue = significant differences between shod and MWFOs. 3. Red = significant differences between SFOs and MWFOs.

3.4.3. *Moments*

During walking with MWFOs, ankle abduction moment (0–6 %SP; MD = 0.01 Nm/kg, P = 0.002, d = 0.25; 11–26 %SP; MD = 0.01 Nm/kg, P = 0.001, d = 0.63 and 75–81 %SP; MD = 0.01 Nm/kg, P = 0.006, d = 0.24) was smaller than during walking with SFOs (see Fig. 5).

4. Discussion

The objective of this study was to investigate the effects of two FOs models in individuals with CM, on plantar pressure distribution, on foot and ankle angles and moments during gait. Consistent with our hypotheses, we found that MWFOs are more effective than SFOs in reducing pressure under the metatarsals during the period of peak pressure (around 60–90 %SP) and modifying the biomechanics of the lower limb during walking.

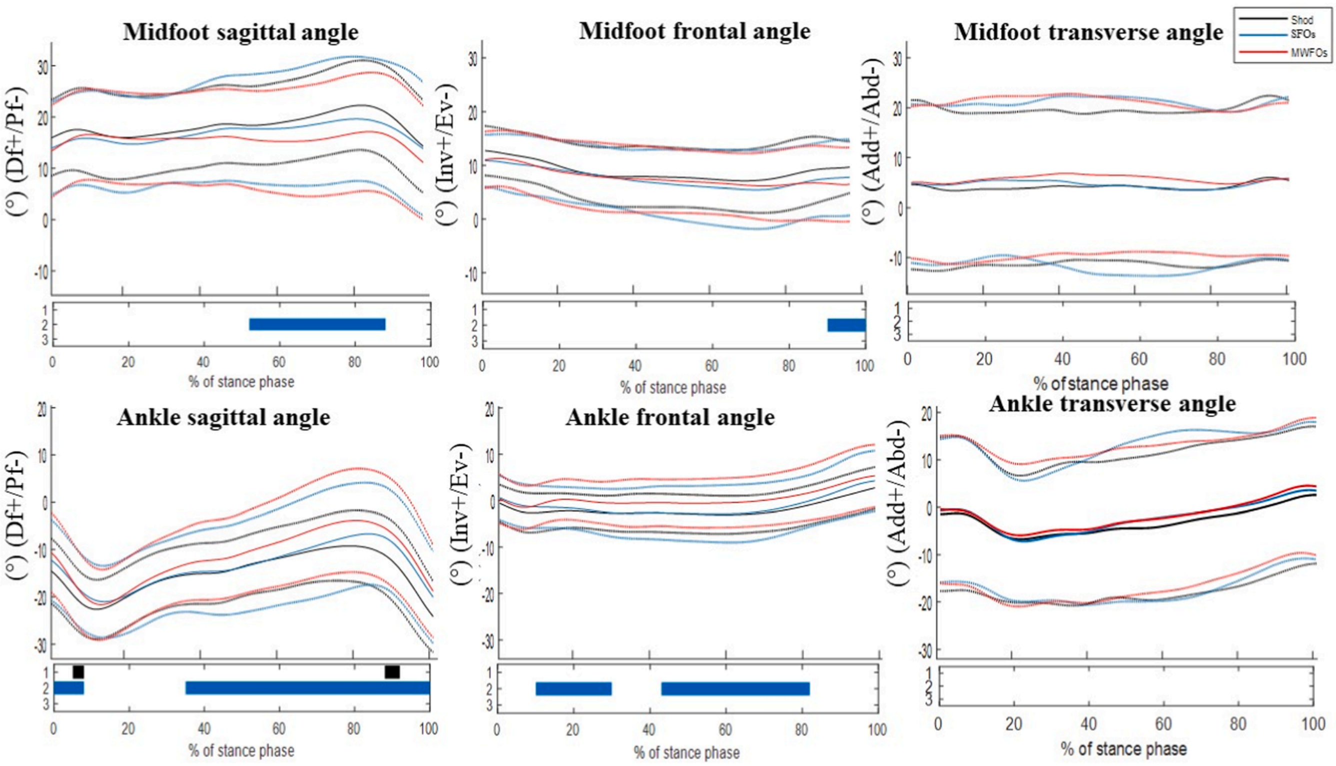

Fig. 4. Kinematic differences during the stance phase while shod (black), wearing SFOs (blue), and wearing MWFOs (red). 1. Black = significant differences between shod and SFOs. 2. Blue = significant differences between shod and MWFOs. 3. Red = significant differences between SFOs and MWFOs. Df = dorsiflexion, Pf = plantarflexion, Inv = inversion, Ev = eversion, Abd = abduction, Add = adduction.

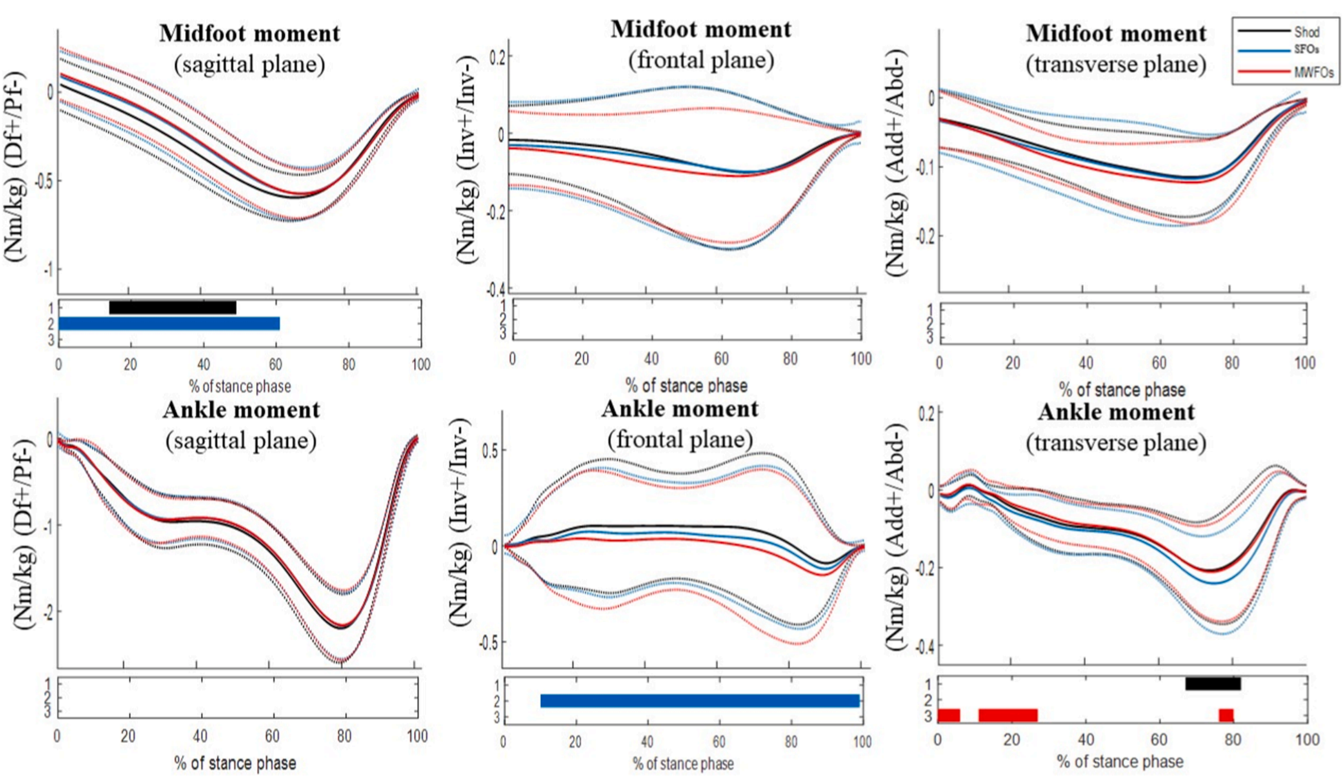

Fig. 5. Midfoot and ankle moments differences during the stance phase while shod (black), wearing SFOs (blue), and wearing MWFOs (red). 1. Black = significant differences between shod and SFOs. 2. Blue = significant differences between shod and MWFOs. 3. Red = significant differences between SFOs and MWFOs. Df = dorsiflexion, Pf = plantarflexion, Inv = inversion, Ev = eversion, Abd = abduction, Add = adduction.

4.1. Effects of MWFOs and SFOs

MWFOs were significantly more effective than SFOs in reducing peak plantar pressure under the metatarsal heads when compared to the shod condition. Plantar pressure decreased by 23.1 kPa under the 1st metatarsal head (MD=42.9 kPa vs. 19.8 kPa), 6.2 kPa under the 2nd and 3rd metatarsal heads (MD=26.0 kPa vs. 19.8 kPa), and 7.8 kPa under the 4th and 5th metatarsal heads (MD=18.9 kPa vs. 11.1 kPa). MWFOs also reduced plantar pressure under the 1st metatarsal head (MD=25.2 kPa) compared to SFOs during the second half of the stance phase.

Contrary to Desmyttere et al. [34], who reported lower peak pressure under the lateral forefoot and higher pressure under the medial forefoot in healthy participants when wearing rigid FOs compared to flexible FOs, we observed greater peak pressure for MWFOs compared to SFOs, with differences of 27–29 % (2nd-3rd metatarsal MD = 27.2 %, 4th-5th metatarsal MD = 29.0 %) in the first third and the end of the stance phase. Thus, this increased plantar pressure was observed when plantar pressure is low (i.e., ≈50 kPa) and the forefoot is either not in contact with the ground or experiencing only minimal pressure. The clinical significance of these results is low. However, consistent with our hypothesis, we observed smaller plantar pressure under the 2nd-3rd metatarsal heads with MWFOs compared to SFOs during the peak plantar pressure phase (76–86 %SP).

In a previous study, walking with a metatarsal pad resulted in a 26.7 kPa reduction in peak pressure under the metatarsal heads in individuals with CM [6]. In our study, MWFOs reduced peak pressure by an average of 29.3 kPa compared to shod conditions, with reductions of 42.9 kPa under the 1st metatarsal head and 26.0 kPa under the 2nd and 3rd metatarsal heads. Consistent with previous findings, the decreased pressure under the metatarsal heads with FOs corresponded to increased pressure under the medial midfoot and decreased pressure under the medial heel, with these effects being more pronounced for MWFOs than SFOs [34].

Overall, our results indicate that MWFOs redistributed peak plantar pressure away from the metatarsal to the midfoot regions during locomotion. This plantar pressure redistribution is highly relevant in individuals with CM considering that reducing peak plantar pressure under the metatarsal heads is correlated to subjective pain improvement in individuals with CM [6]. Despite this pain reduction in clinical trials, FOs remain a treatment modality that only partially helps some patients [35–37]. In a previous clinical trial [35], FOs may not have been optimal for mitigating the biomechanical deficits (peak plantar pressure) in patients with CM and therefore explain their partial effectiveness for certain patients. Indeed, the FOs models used in this trial were semi-rigid and soft while we found that they may have provided an inefficient reduction in plantar pressure under the metatarsal heads compared to MWFOs. Our results suggest that to achieve a greater reduction, a medial wedge, a semi-rigid shell and a top cover including a metatarsal pad need to be added to SFOs. We recommend that future clinical trials assessing the effectiveness of FOs in individuals with CM include these FO specificities to achieve greater plantar pressure reduction under the metatarsal heads and potentially greater pain reduction and improvement in foot function during locomotion.

For our secondary objective, MWFOs decreased midfoot dorsiflexion and ankle plantarflexion angles while reducing midfoot plantarflexion moments. Consistent with previous findings [18,20,34,38,39], adding rearfoot and forefoot posts to the FOs' shell amplifies the biomechanical effects on the foot and ankle. Both models of FOs had little effect during the first half of the stance phase. In other words, they did not help prevent flattening or the arch and inversion of the forefoot. However, they promoted "arch recoil", or the ability of the arch to elevate. This compression-recoil mechanism allows mechanical energy to be stored and subsequently released during each foot contact, thus improving the metabolic efficiency of gait [40]. Furthermore, when medially wedged rearfoot and forefoot posts are added to FOs, the force required to lower the FOs' medial longitudinal arch (i.e., the resistance to flattening) significantly increases [41]. These results could explain why MWFOs had more pronounced effects than SFOs on foot and ankle biomechanics in our study.

4.2. Research perspectives

Our results suggest that the use of FOs, specifically designed to reduce plantar pressure under the metatarsal regions holds promise for optimizing plantar pressure redistribution, biomechanical outcomes, and maximizing patient benefits. However, the minimal clinically significant differences in the efficiency of FOs on individuals with CM had not yet been established to guide clinicians and clinical studies. It would also be important to determine the differences in plantar pressure and foot and ankle biomechanics between individuals with CM and control participants. Targeting the biomechanical deficits in individuals with CM will also allow developing FOs specifically aimed at alleviating them.

4.3. Limitations

The biomechanical effects were quantified without giving acclimatization periods, while individuals may require some time to adapt to the FOs. Participants could also have experienced fatigue due to the lengthy data collection session but were given breaks as needed. Participants' foot shape was only evaluated using the FPI. Plain radiographs would have been a more precise technique to define characterize foot morphological characteristics [42]. No data were collected on patient preferences, comfort or pain perception which could have supplemented the biomechanical data obtained. Our study focused on individuals with CM without a history of surgery, which is not the case of all metatarsalgia (i.e., iatrogenic metatarsalgia) so our findings cannot be generalized to all individuals with CM. The influence of soft tissue artifacts on multi-segment foot kinematics should also be considered [43].

5. Conclusion

Both models of foot orthoses decreased peak plantar pressure under the same masks (medial heel, lateral heel, and metatarsals heads), ankle plantarflexion angle, and midfoot plantarflexion moment, MWFOs having more pronounced and diverse effects compared to SFOs. If researchers and clinicians aim to reduce the peak plantar pressure under the metatarsal heads during the second half of the stance phase and/or provide greater pronation control in individuals with CM, MWFOs are more effective than SFOs. The findings of this study have the potential to optimize orthotic prescription strategies and potentially benefit individuals with chronic metatarsalgia in future clinical trials.

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CRediT authorship contribution statement

(1) Conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted. EP: 1–2–3, MA: 1–2, PI: 2, KT: 1–2, MB: 1–2, JA: 2–3, GM:1–2–3.

CRediT authorship contribution statement

Moisan Gabriel: Writing – review & editing, Formal analysis, Conceptualization. **Abboud Jacques:** Writing – review & editing. **Begon Mickaël:** Writing – review & editing. **Turcot Katia:** Writing –

review & editing. **Isabelle Pier-Luc:** Writing – review & editing. **Acien Maxime:** Writing – review & editing, Funding acquisition, Formal analysis. **Payen Eléna:** Writing – original draft, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2025.01.022.

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