Taylor & Francis
Taylor & Francis Group

Assistive Technology
The Official Journal of RESNA

ISSN: 1040-0435 (Print) 1949-3614 (Online) Journal homepage: www.tandfonline.com/journals/uaty20

Enhancing postural stability and gait in older adults: The role of somatosensory foot orthoses on varied inclined terrains

Abu Jor, Toshiki Kobayashi, Chun Hei Lai, Yufan He, Shakawath Hosen Opu, Wing-Kai Lam, Stanley J. Winser, Fan Gao & Ming Zhang

To cite this article: Abu Jor, Toshiki Kobayashi, Chun Hei Lai, Yufan He, Shakawath Hosen Opu, Wing-Kai Lam, Stanley J. Winser, Fan Gao & Ming Zhang (06 Nov 2025): Enhancing postural stability and gait in older adults: The role of somatosensory foot orthoses on varied inclined terrains, Assistive Technology, DOI: 10.1080/10400435.2025.2582062

To link to this article: https://doi.org/10.1080/10400435.2025.2582062

ASSISTIVE TECHNOLOGY
https://doi.org/10.1080/10400435.2025.2582062

Enhancing postural stability and gait in older adults: The role of somatosensory foot orthoses on varied inclined terrains

Abu Jor, MSc [a,b], Toshiki Kobayashi, PhD [c], Chun Hei Lai, BSc [a], Yufan He, MSc [a], Shakawath Hosen Opu, BSc [b], Wing-Kai Lam, PhD [d], Stanley J. Winser, PhD [e], Fan Gao, PhD [f], and Ming Zhang, PhD [a,g]

[a]Department of Biomedical Engineering, Faculty of Engineering, The Hong Kong Polytechnic University, Hong Kong, China; [b]Department of Leather Engineering, Faculty of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh; [c]Orthocare Innovations, Edmonds, Washington, USA; [d]Department of Sports and Health Sciences, Academy of Wellness and Human Development, Faculty of Arts and Social Sciences, Hong Kong Baptist University, Hong Kong, China; [e]Department of Rehabilitation Sciences, Faculty of Health and Social Sciences, The Hong Kong Polytechnic University, Hong Kong, China; [f]Department of Kinesiology and Health Promotion, University of Kentucky, Lexington, Kentucky, USA; [g]Research Institute for Sports Science and Technology, The Hong Kong Polytechnic University, Hong Kong, China

ABSTRACT
This study aimed to investigate the effects of somatosensory foot orthoses (SFO) with tactile stimulating knobs on postural stability and gait in older adults across varied inclined terrains. Twenty-three participants walked on level, uphill, and downhill terrains and performed standing tasks with eyes open and closed, using either SFO or flat foot orthoses (FFO) on an instrumented treadmill. Key parameters measured included center of pressure (CoP) trajectories, ground reaction forces, and plantar pressures. SFO reduced mediolateral CoP displacement during 15–65% of the stance phase on downhill terrain ($p <$ 0.001). Vertical ground reaction forces increased at 35–45% ($p = 0.001$) of stance on level terrain and decreased at 5–10% ($p = 0.020$) and 55–60% ($p = 0.025$) of stance on uphill terrain. Maximum plantar pressure decreased with SFO at the inner forefoot [level ($p = 0.007$), uphill ($p = 0.001$), and downhill ($p <$ 0.001)], toes [uphill ($p = 0.003$) and downhill ($p = 0.019$)], and medial forefoot [uphill ($p < 0.001$) and downhill ($p = 0.013$)] on varied terrains. These findings underscore the importance of incorporating stimulating knobs into foot orthoses to enhance somatosensory feedback and improve plantar pressure distribution. Further studies are warranted to confirm and expand clinical applications for populations with balance impairments or increased fall risks.

ARTICLE HISTORY
Accepted 24 October 2025

KEYWORDS
Balance; center of pressure; inclined surfaces; somatosensory stimulation; texture insole

Introduction

Postural stability and gait are essential components of daily human activities, relying on a complex balance system that integrates sensory inputs from the visual, vestibular, and somatosensory systems (Peterka, 2018). These inputs are processed by the central nervous system to generate appropriate motor responses through the musculoskeletal system, helping to maintain equilibrium. Age-related declines in sensory function, muscle strength, and cognitive processing can compromise these systems, leading to impaired balance in about 30% of older adults aged 65 and above (Lin & Bhattacharyya, 2012; Osoba et al., 2019; Wang et al., 2024). Such balance deficits are associated with an increased risk of instability, falls, severe injuries, and even mortality (Lajoie & Gallagher, 2004; Wang et al., 2024). Therefore, developing strategies to enhance postural stability and gait in older adults is of paramount importance.

A variety of conservative interventions, including physical therapy, balance exercises, and assistive devices, have been developed to address balance and stability issues in older adults (Halvarsson et al., 2015; Labata-Lezaun et al., 2023; West et al., 2015). While effective, these interventions often require substantial time, effort, cost, and adherence from individuals. Foot orthoses, including insoles, shoe inserts, and specialized footwear, are an additional strategy to enhance postural stability and gait (Nor Azhar et al., 2024). These orthoses provide structural support to the foot, redistribute plantar pressure and force, and improve alignment. Traditional foot orthoses, such as flat or contoured designs with arch-supports, raised heel cups, or mediolateral wedges, have been shown to offer benefits in support, stability, and comfort (Aboutorabi et al., 2016; Ma et al., 2020). However, their effects on sensory feedback and proprioception remain unclear.

Recent developments in somatosensory foot orthoses (SFO) have focused on incorporating protruding knobs or textured surfaces to stimulate plantar mechanoreceptors, aiming to improve postural stability and gait via enhancing somatosensory activation and feedback on intrinsic muscles (Ma et al., 2020; Nor Azhar et al., 2024). Several studies have reported improved postural control with SFO, suggesting that tactile protrusions/knobs can positively influence balance via enhanced somatosensory feedback (Jor et al., 2025). However, most of these studies have been conducted during

CONTACT Toshiki Kobayashi tkobayashi@orthocareinnovations.com Orthocare Innovations, 123 2nd Ave S Suite 220, Edmonds, WA 98020, USA; Ming Zhang ming.zhang@polyu.edu.hk Department of Biomedical Engineering, Faculty of Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China.
Supplemental data for this article can be accessed online at https://doi.org/10.1080/10400435.2025.2582062

static standing or walking on level terrains, which are less challenging and do not fully represent the varied and dynamic environments encountered in daily life (Asgari et al., 2022; de Morais Barbosa et al., 2018; Hatton et al., 2012; Huang et al., 2020; Kiaghadi et al., 2020; Li et al., 2019; Qu, 2015). Real-world environments often involve varied inclined terrains, such as level, uphill, or downhill walking, which pose additional challenges to balance and stability. A comprehensive understanding of whether SFO with tactile stimulating knobs can enhance postural stability and gait under these varied static and dynamic conditions in older adults is still lacking. Thus, this study aimed to evaluate the effects of SFO with stimulating knobs on postural balance and stability while walking across varied inclined terrains as well as standing with eyes open and closed in older adults.

Methods

Participants

Eligible participants were community-dwelling older adults aged 65 years or older, capable of walking for 30 min without breaks or external assistance (e.g., walking aids), and engaging in at least 150 min of walking per week. Exclusion criteria included obesity (BMI > 40), vestibular disorders, central nervous system disorders (e.g., stroke, dementia, Parkinson's disease), pes planus or pes cavus, foot pain, and peripheral neuropathy or ulcers. Protective tactile sensation was confirmed using a Semmes-Weinstein Monofilament (SWM) test at 10 plantar locations (Mueller, 1996). Participants unable to follow the experimental protocol were also excluded.

A priori power analysis was conducted using G-power software (version 3.1.9.7) based on the mediolateral CoP displacement data from Huang et al. (Huang et al., 2020) (a within-subject repeated measures ANOVA, $\alpha = 0.05$, $\beta = 0.20$, power = 80%, number of groups = 2, number of measurements = 6, and correlation among repeated measures = 0.30), indicated a required sample size of 23. Previous study on SFO in older adults support this sample size (de Morais Barbosa et al., 2018). The study protocol adhered to the Declaration of Helsinki's guidelines and was approved by the Human Subject Ethics Sub-Committee of the Institutional Review Board at The Hong Kong Polytechnic University (HSEARS20231115003). Participants were informed about the study protocol and provided their written consent before participation.

Foot orthoses

Participants were assessed under two foot orthoses conditions: (a) flat foot orthoses (FFO) without protruding knobs; and (b) prefabricated somatosensory foot orthoses (SFO) with protruding knobs (Figure 1). The SFO (Copper Fit Zen Step Comfort, China) had evenly distributed rounded protruding knobs (large knobs: 15 mm in length, 10 mm in width, 3 mm in height; small knobs: 12 mm in length, 8 mm in width, 2 mm in height; hardness: Shore A 30) and a raised heel cup with medial

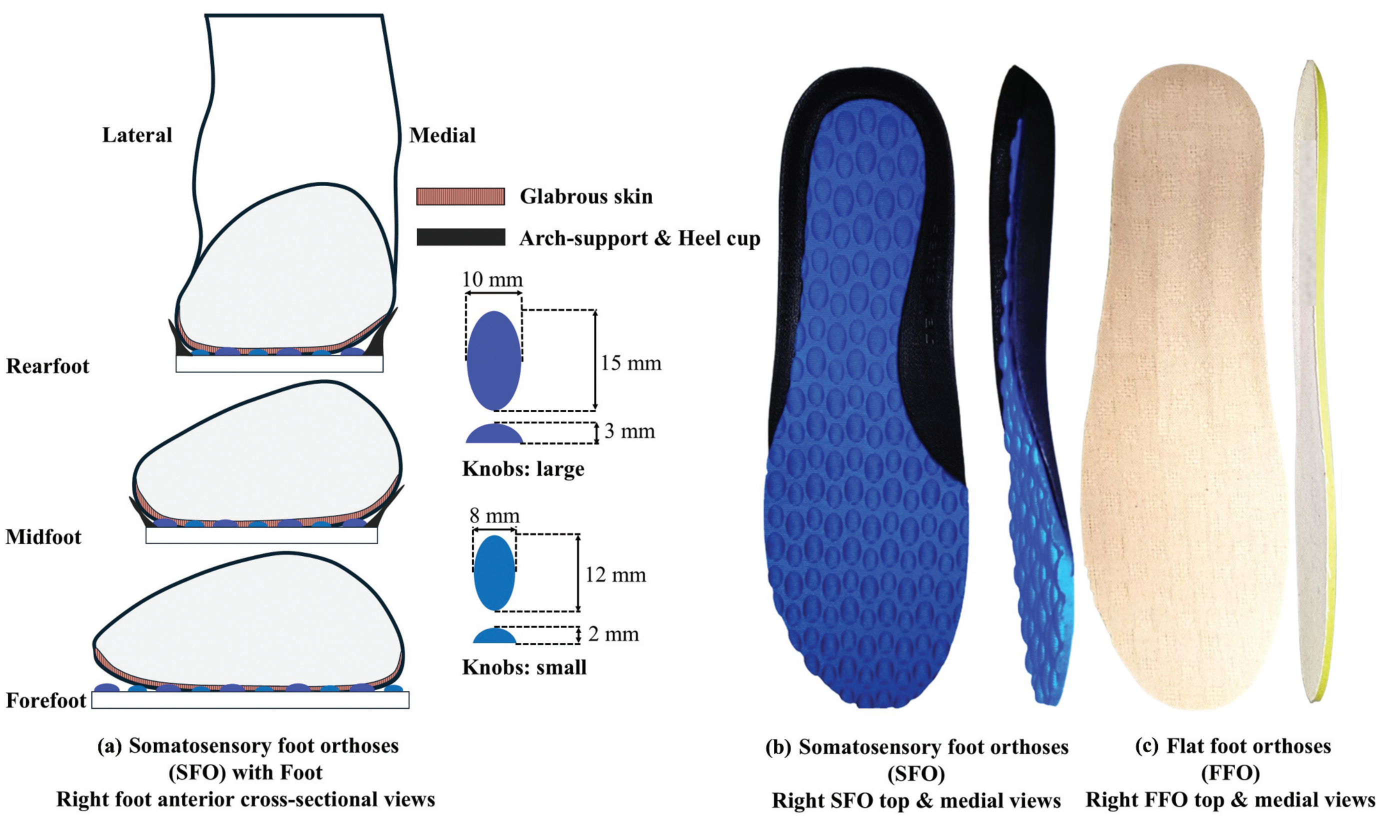

Figure 1. Illustration of somatosensory foot orthoses (SFO): (a) Anterior cross-sectional views of the SFO on the right foot, showing the position and function of the protruding knobs in contact with the glabrous skin; (b) Right SFO with stimulating knobs (large and small); and (c) Right flat foot orthoses (FFO) without knobs, used for comparison.

and lateral arch supports (hardness: Shore A 40). Foot orthoses were placed inside standard footwear (Shiying 520A, Shiying Trading Co. Ltd., China), and participants wore identical 1-mm-thick cotton socks (Zhuji Dongling Needle Textile Co., Ltd., China) to minimize confounding footwear effects.

Experimental procedure

Five conditions were tested: three dynamic (walking on level terrain: 0-degree inclination, uphill terrain: +5 degrees inclination, and downhill terrain: −5 degrees inclination) and two static (standing with eyes open and closed), with participants wearing either FFO or SFO (Figure 2(a)). Three successful trials were collected per condition. Outcome measures included center of pressure (CoP) trajectory/progression, ground reaction force (GRF), spatiotemporal parameters, and plantar pressures (Gao et al., 2019). Assessments were conducted using an instrumented treadmill Zebris FDM-T with a capacitance-based force platform (Zebris Medical GmbH, Germany). The vertical reaction forces applied by the feet were recorded by the force plate at a sampling frequency of 120 Hz, which has been reported to provide highly reliable measurements for gait analysis using an instrumented treadmill (GmbH zM, 2013; Nüesch et al., 2018; Reed et al., 2013). Upon arrival at the laboratory, participants were seated and rested barefoot for approximately 30 min to allow plantar pressures to return to baseline and minimize any residual effects from prior activity (Haris et al., 2023). They then had a 5-min adaptation period to familiarize themselves with the instrumented treadmill while wearing the tested foot orthoses to ensure comfort and reduce learning effects. Walking speed was individualized and maintained consistently across all foot orthoses conditions. The order of orthoses conditions was randomized with a rest period of 5 to 7 minutes between conditions to minimize fatigue (Malatesta et al., 2017). Safety harness was used during all dynamic assessments.

Data collection and processing

Data were collected and processed using the Zebris FDM software (Zebris Medical GmbH, Germany) (Van Alsenoy et al., 2019), which computes CoP trajectories, GRFs, spatiotemporal gait parameters, and maximum plantar pressure for each participant (Figure 2(b)). The Zebris instrumented treadmill demonstrated good to excellent reliability for these measures: maximum forces and plantar pressure (ICC ≥ 0.8), and spatiotemporal parameters (ICC ≥ 0.8–0.9) (Mawarikado et al., 2025; Nüesch et al., 2018; Van Alsenoy et al., 2019). Dynamic gait outcome measures included anteroposterior (AP) and mediolateral (ML) CoP displacements, AP and ML CoP ranges, CoP maximum velocity, gait line length, anterior/posterior position, and lateral symmetry. Static outcome measures included AP and ML CoP ranges, CoP average velocity, and CoP path length.

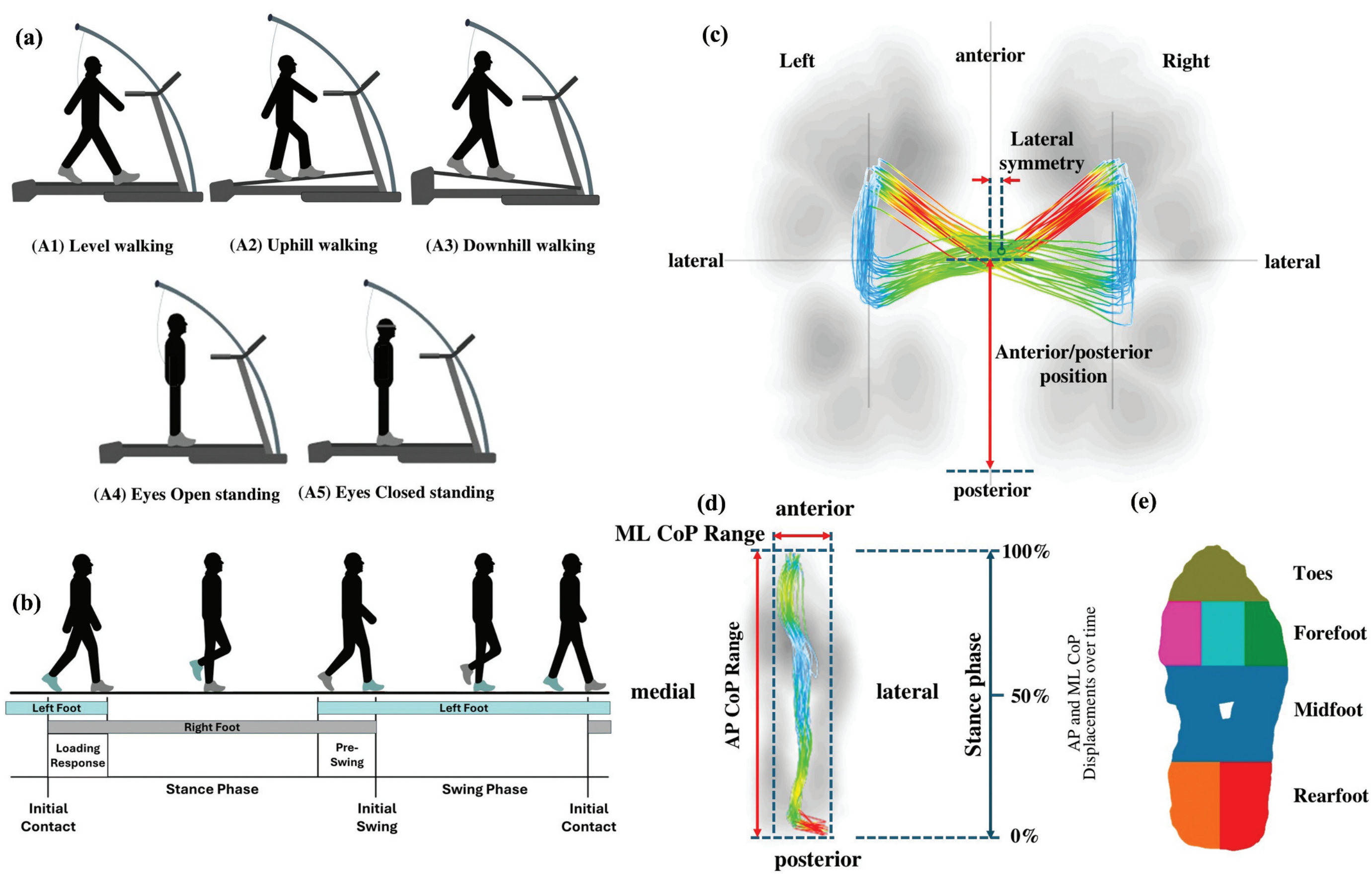

Figure 2. Illustration of the experimental setup for gait and posture analyses: (a) Illustration of walking and standing posture on the treadmill: (A1) level walking, (A2): uphill walking, (A3) downhill walking, (A4) standing-eyes open, (A5) standing-eyes closed; (b) Illustration of a gait cycle; (c) Illustration of center of pressure (CoP) trajectory with butterfly diagram; (d) Gait line (CoP) progression on the right foot; (e) seven zones of plantar forces/pressure distribution on the right foot.

Table 1. Mean, standard deviation, effect sizes, and statistical significance in pairwise comparisons of CoP parameters during walking on varying inclined terrains as well as static standing with eyes open and eyes closed conditions.

			FFO		SFO			
Parameters (Walking)	Testing conditions	Norm	Mean	SD	Mean	SD	Effect size (Cohen's d)	*P* value
ML CoP Range, mm	Walking Level	Yes	28.15	14.86	30.56	14.35	0.3	0.052
	Walking Uphill	Yes	29.13	12.57	32.41	14.40	0.3	0.069
	Walking Downhill	Yes	33.15	13.09	33.95	14.25	0.2	0.476
AP CoP Range, mm	Walking Level	Yes	200.33	37.67	199.02	40.50	0.1	0.766
	Walking Uphill	Yes	189.69	39.96	188.37	41.64	0.1	0.697
	Walking Downhill	Yes	192.77	42.68	195.99	40.71	0.1	0.547
CoP max velocity, cm/sec	Walking Level	Yes	657.36	326.08	635.29	370.00	0.1	0.586
	Walking Uphill	Yes	672.29	271.48	680.64	301.02	0.1	0.751
	Walking Downhill	Yes	682.06	313.68	715.93	334.65	0.2	0.384
Length of gait line, mm	Walking Level	Yes	204.32	35.85	203.74	37.33	0.0	0.901
	Walking Uphill	Yes	193.94	35.50	190.24	37.21	0.2	0.378
	Walking Downhill	Yes	200.93	38.01	204.21	36.79	0.1	0.564
Anterior/posterior position, mm	Walking Level	No	0.40	0.35	0.42	0.38	0.1	0.201
	Walking Uphill	Yes	0.35	0.40	0.30	0.40	0.3	0.200
	Walking Downhill	No	0.68	0.53	0.62	0.52	0.2	0.412
Lateral symmetry, mm	Walking Level	No	10.10	10.03	10.03	10.33	0.0	0.795
	Walking Uphill	No	13.09	11.98	13.45	11.53	0.1	0.503
	Walking Downhill	No	10.90	8.96	10.72	10.01	0.0	0.715
Parameters (Standing)								
ML CoP Range, mm	Eyes open	No	3.43	1.57	3.78	1.92	0.1	0.693
	Eyes closed	Yes	3.21	0.99	3.50	1.23	0.1	0.302
AP CoP Range, mm	Eyes open	Yes	19.69	7.68	19.73	5.49	0.0	0.978
	Eyes closed	Yes	20.52	4.62	22.71	6.35	0.3	0.102
CoP avg. velocity, mm/sec	Eyes open	Yes	13.53	7.34	13.06	4.59	0.1	0.751
	Eyes closed	No	17.24	8.20	18.63	7.35	0.1	0.693
COP path length, mm	Eyes open	Yes	135.31	73.43	130.65	45.94	0.1	0.751
	Eyes closed	No	172.41	81.95	186.32	73.44	0.2	0.693

FFO: flat foot orthoses; SFO: somatosensory foot orthoses; CoP: center of pressure, ML: mediolateral, AP: anteroposterior; max.: maximum; avg.: average; SD: standard deviation.

CoP was computed for each limb during stance phase using measured ground reaction forces and moments, with a threshold of 20 N for heel strike to toe-off based on vertical GRF components. CoP coordinates were transformed into foot-based coordinate system, with anteroposterior and mediolateral directions normalized by foot length and width (Lugade & Kaufman, 2014; Van Alsenoy et al., 2019), where positive values indicated anterior and lateral displacements, respectively, while negative values represented posterior and medial displacements. Left-sided CoP trajectories were mirrored to the right. AP and ML CoP displacements represent movement or progression of CoP in the anteroposterior/mediolateral directions over the stance phase, and the AP and ML CoP ranges were calculated as the difference between maximum and minimum values in each direction (Figure 2(c,d)) (He et al., 2024; Huang et al., 2020; Piri et al., 2025). Average CoP velocity is the mean speed of CoP displacement measured over the entire static analysis period, whereas maximum CoP velocity is the peak instantaneous speed of CoP displacement during walking (Remaud et al., 2016). Gait line (during walking)/CoP path (during standing) length is the total length of CoP progression/path covered including both anteroposterior and mediolateral movements during stance phase of one limb (Chan et al., 2024; GmbH zM, 2019; Rhea et al., 2014; Yoo et al., 2017). Lateral symmetry was defined by the left/right shift of the butterfly intersection point, with zero indicating perfect symmetry. Anterior/posterior position of CoP was defined as the distance between the butterfly intersection point and the initial contact position, normalized by foot length.

For statistical parametric mapping (SPM) analysis, AP and ML CoP displacements, as well as vertical GRFs across the stance phase of gait, were normalized to 101 data points (0% to 100% stance). Maximum values of the vertical GRFs (normalized to participants' body weight) and plantar forces/pressure were recorded for seven foot regions: toes, medial forefoot, inner forefoot, lateral forefoot, midfoot, medial rearfoot, and lateral rearfoot (Figure 2(e)). Left and right feet values were averaged due to minimal side differences in healthy older participants.

Statistical analysis

Normality was assessed using the Shapiro–Wilk test. Paired sample t-tests compared normally distributed parameters across orthoses conditions. Wilcoxon signed-rank test was used for non-normally distributed data. Mixed factorial ANOVA was utilized to examine the interaction of gender and terrain/visual conditions to foot orthoses effects. Statistical parametric mapping (SPM) analysis was conducted using open source spm1d code (Version 0.4, available at https://spm1d.org/) in Python (Version 3.11) to evaluate CoP and GRF curves across the stance phase of the gait cycle. Post-hoc paired sample *t*-tests were

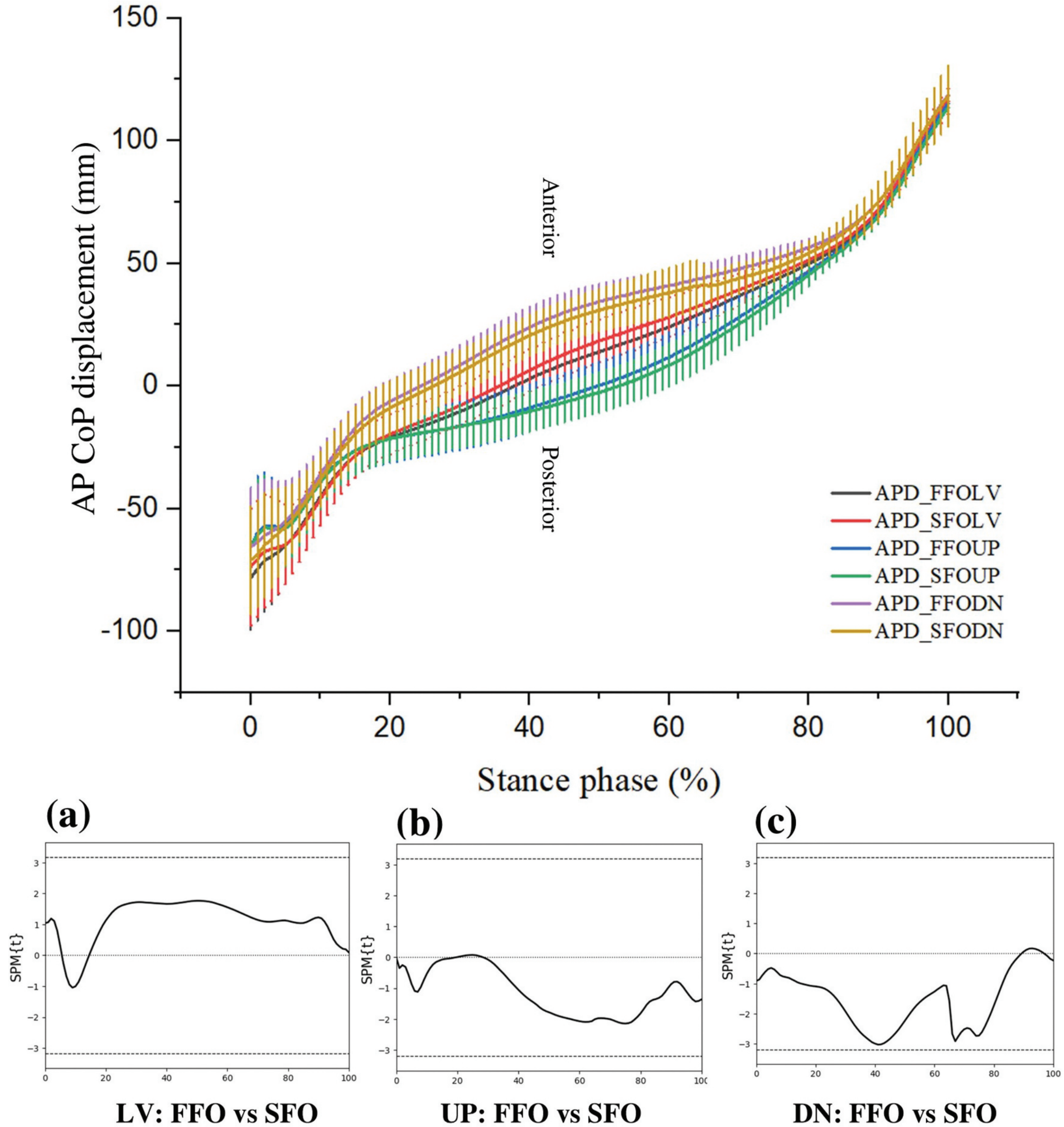

Figure 3. Anteroposterior displacement (APD) of the center of pressure (CoP) with standard deviations across 0 to 100% stance where black (APD_FFOLV) and red (APD_SFOLV) represent flat and somatosensory foot orthoses on level terrain, blue (APD_FFOUP) and green (APD_SFOUP) represent flat and somatosensory foot orthoses on uphill terrain, and purple (APD_FFODN) and brown (APD_SFODN) represent flat and somatosensory foot orthoses on downhill terrain. In the results of statistical parametric mapping (SPM) analysis, (a) shows a comparison between flat and somatosensory foot orthoses on level terrain (LV: FFO vs SFO), (b) shows a comparison between flat and somatosensory foot orthoses on uphill terrain (UP: FFO vs SFO), and (c) shows a comparison between flat and somatosensory foot orthoses on downhill terrain (DN: FFO vs SFO).

employed to compare foot orthoses conditions across terrains. Statistical significance was set at $p < 0.05$. All statistical analyses were performed in IBM SPSS software (version 22, SPSS Inc., Chicago, IL).

Results

Participant characteristics

Twenty-three participants met the eligibility criteria, including 16 females (Age = 72 ± 3 years; BMI = 22.5 ± 3.4 kg/m^2; SWM = 9.9 ± 0.2) and 7 males (Age = 72 ± 4 years; BMI = 22.8 ± 2.0 kg/m^2; SWM = 9.5 ± 0.9). No significant interactions were found between gender and foot orthoses effects, indicating that gender did not influence the outcome variables (Supplementary Table S1).

Center of pressure trajectory and gait

There were no significant differences between FFO and SFO in AP/ML CoP ranges, CoP maximum velocity, gait line length, anterior/posterior position, and lateral symmetry across varying inclined terrains (Table 1). Terrain conditions had significant main effects on AP CoP range ($F_{(2)} = 4.51$, $p = 0.017$, $\eta2 = 0.170$) and length of gait line ($F_{(2)} = 6.34$, $p = 0.004$, $\eta2 = 0.232$), but no significant terrain-foot orthoses interactions were observed (Supplementary Table S1). SPM analysis showed

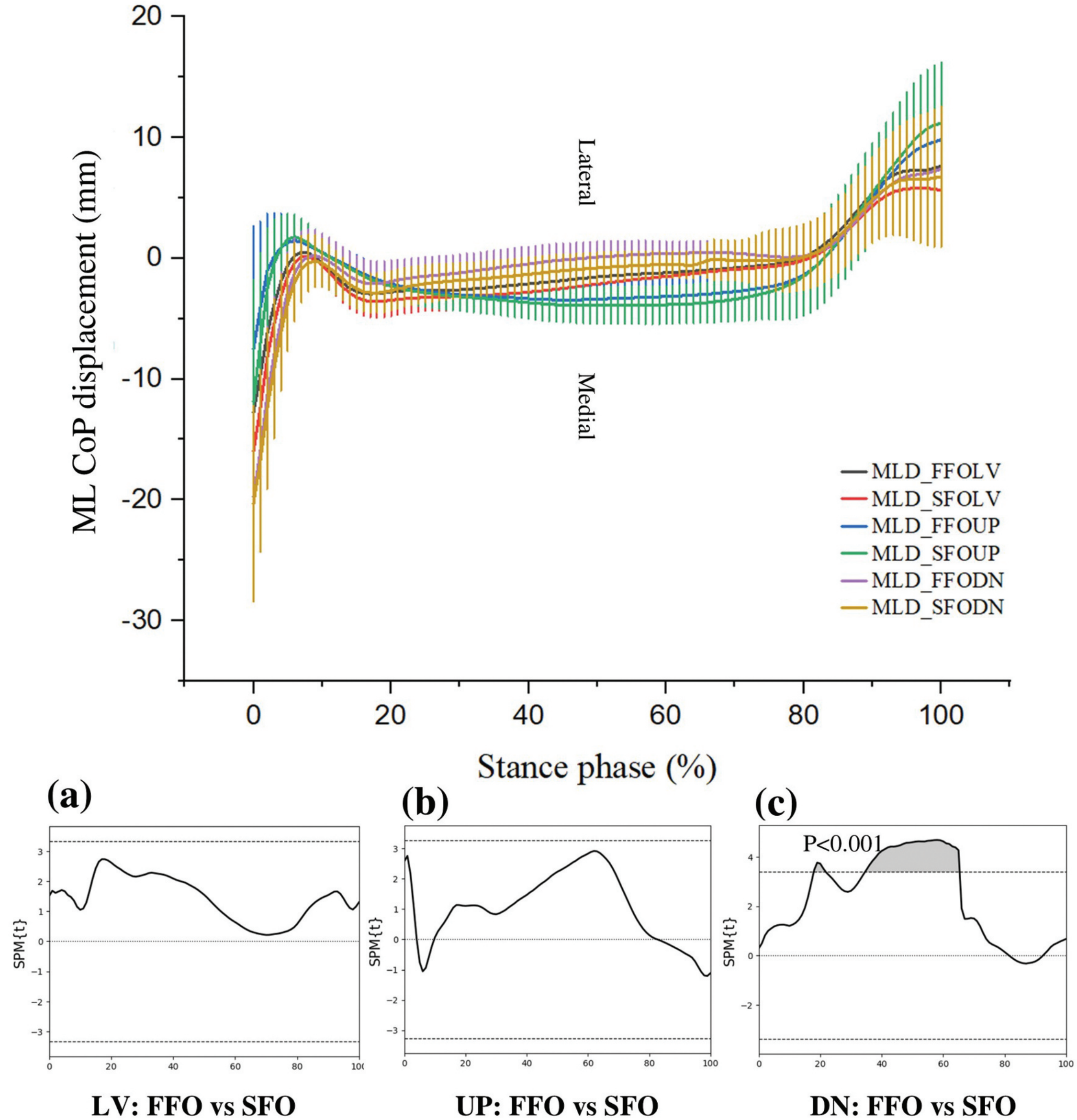

Figure 4. Mediolateral displacement (MLD) of the center of pressure (CoP) with standard deviations across 0 to 100% stance where black (MLD_FFOLV) and red (MLD_SFOLV) represent flat and somatosensory foot orthoses on level terrain, blue (MLD_FFOUP) and green (MLD_SFOUP) represent flat and somatosensory foot orthoses on uphill terrain, and purple (MLD_FFODN) and brown (MLD_SFODN) represent flat and somatosensory foot orthoses on downhill terrain. In the results of statistical parametric mapping (SPM) analysis, (a) shows a comparison between flat and somatosensory foot orthoses on level terrain (LV: FFO vs SFO), (b) shows a comparison between flat and somatosensory foot orthoses on uphill terrain (UP: FFO vs SFO), and (c) shows a comparison between flat and somatosensory foot orthoses on downhill terrain (DN: FFO vs SFO).

lower mediolateral and anteroposterior CoP displacements with SFO across terrains (Figures 3 and 4). Specifically, ML CoP displacements decreased significantly at 15–65% of the stance phase on downhill terrain ($p < 0.001$). Maximum vertical GRFs and spatiotemporal gait parameters showed no significant differences between FFO and SFO across terrains (Table 2). Although terrain significantly affected stride length ($F_{(2)} = 5.74$, $p = 0.006$, $\eta2 = 0.215$), stride time ($F_{(2)} = 11.93$, $p < 0.001$, $\eta2 = 0.362$), and cadence ($F_{(2)} = 12.08$, $p < 0.001$, $\eta2 = 0.365$), no significant terrain-foot orthoses interactions were observed (Supplementary Table S1).

SPM analysis further showed that SFO increased vertical GRFs at 35–45% of stance on level terrain ($p = 0.001$) and decreased them at 5–10% and 55–60% of stance on uphill terrain ($p = 0.020$ and $p = 0.025$, respectively) (Figure 5). CoP trajectory analysis for static balance revealed no significant differences between FFO and SFO while standing with eyes open or closed (Table 1), and no visual-foot orthoses interaction effects were observed.

Significant differences were observed in maximum plantar forces and pressure distribution across foot regions between FFO and SFO while walking on various terrains (Table 3). SFO reduced maximum plantar forces at the medial forefoot (Uphill: MD [Mean Difference] = −0.12, d = 0.4, $p = 0.015$) and increased them at the lateral forefoot (Level: MD = 0.06, d = 0.3, $p = 0.044$). Maximum plantar pressure decreased with SFO at the toes (Uphill: MD = −0.66, d = 0.3, $p = 0.003$; Downhill: MD = −0.47, d = 0.3, $p = 0.019$) and medial forefoot (Uphill: MD = −1.06, d = 0.5, $p < 0.001$; Downhill: MD = −0.55, d = 0.3, $p = 0.013$). Across all terrains, maximum plantar

Table 2. Mean, standard deviation, effect size, and statistical significance in pairwise comparisons of ground reaction forces and spatiotemporal parameters during walking at varying inclined terrains.

			FFO		SFO			
Parameters (Walking)	Testing conditions	Norm	Mean	SD	Mean	SD	Effect size (Cohen's d)	*P* value
Maximum GRF peak1, N/kg	Walking Level	No	10.10	0.84	10.24	0.91	0.2	0.068
	Walking Uphill	No	9.52	0.92	9.40	1.14	0.1	0.927
	Walking Downhill	No	10.30	0.97	10.26	0.94	0.0	0.715
Time to maximum GRF peak1, %	Walking Level	Yes	20.98	2.32	21.17	2.86	0.1	0.539
	Walking Uphill	Yes	21.41	3.42	20.80	3.52	0.2	0.177
	Walking Downhill	Yes	19.25	3.07	19.23	2.96	0.0	0.951
Maximum GRF peak2, N/kg	Walking Level	No	8.74	1.93	8.27	2.63	0.2	0.277
	Walking Uphill	No	8.60	1.90	7.96	2.61	0.3	0.132
	Walking Downhill	No	7.88	2.53	7.91	2.52	0.0	0.931
Time to maximum GRF peak2, %	Walking Level	No	39.98	9.43	38.78	12.62	0.1	0.236
	Walking Uphill	No	40.77	9.42	38.44	12.91	0.2	0.372
	Walking Downhill	No	39.32	12.97	38.87	12.72	0.0	0.179
Stride length, cm	Walking Level	Yes	64.55	17.76	62.93	19.45	0.1	0.346
	Walking Uphill	Yes	63.50	17.92	61.53	19.09	0.1	0.073
	Walking Downhill	Yes	57.43	17.47	57.36	17.18	0.0	0.447
Stride time, sec	Walking Level	Yes	1.22	0.21	1.16	0.18	0.3	0.218
	Walking Uphill	Yes	1.25	0.22	1.19	0.20	0.3	0.054
	Walking Downhill	Yes	1.13	0.19	1.11	0.16	0.1	0.201
Step width, cm	Walking Level	Yes	13.54	3.13	13.04	3.02	0.2	0.136
	Walking Uphill	Yes	13.35	2.95	13.32	3.04	0.0	0.926
	Walking Downhill	Yes	13.85	3.42	13.89	3.48	0.0	0.865
Stance, %	Walking Level	Yes	68.68	1.97	68.65	2.17	0.0	0.869
	Walking Uphill	Yes	68.92	2.05	68.17	5.34	0.2	0.346
	Walking Downhill	Yes	68.01	2.88	68.00	2.64	0.0	0.945
Cadence, steps/min	Walking Level	Yes	101.20	18.27	105.49	17.88	0.2	0.212
	Walking Uphill	Yes	98.59	17.23	99.77	18.04	0.1	0.153
	Walking Downhill	Yes	109.57	18.22	110.50	15.76	0.1	0.274

FFO: flat foot orthoses; SFO: somatosensory foot orthoses; SD: standard deviation.

pressure at the inner forefoot was lower with SFO (Level: MD = −0.13, d = 0.1, $p = 0.007$; Uphill: MD = −1.15, d = 0.4, $p = 0.001$; Downhill: MD = 0.54, d = 0.5, $p < 0.001$). SFO also decreased medial rearfoot pressure on downhill terrain (Downhill: MD = −0.15, d = 0.1, $p = 0.018$).

Comparisons across terrains showed lower medial and inner forefoot pressures with SFO on uphill terrain (medial: MD = −1.13, 95% CI [−1.99, −0.27], $p = 0.008$; inner: MD = −1.08, 95% CI [−1.83, −0.33], $p = 0.003$) and higher lateral forefoot pressure on downhill terrain (MD = 0.74, 95% CI [0.09, 1.39], $p = 0.021$). FFO showed lower midfoot pressure on downhill terrain than uphill terrain (MD = −0.83, 95% CI [−1.61, −0.05], $p = 0.034$), but this difference was non-significant with SFO.

Discussion

This study investigated the effects of SFO with tactile stimulating knobs on postural balance and gait parameters across different terrains. The results revealed several key findings that advance our understanding of how tactile stimulation influence postural balance and stability, gait mechanics, and plantar pressure distribution. Postural control, assessed through CoP displacement, velocity, and gait line/CoP path lengths, is crucial for maintaining balance and stability (Chen et al., 2021; Rizzato et al., 2021). Older adults often experience reduced control over CoP movement because of declines in muscle strength and sensory feedback, both of which are critical for maintaining balance and preventing falls (Osoba et al., 2019). Increased CoP displacement reflects greater challenge in maintaining balance and higher stabilization effort. The reduced CoP lateral displacement observed in SPM analysis with SFO, may indicate improved control over CoP movements, particularly during midstance phase. One possible explanation is that tactile stimulation increases plantar forces in response to the protruding knobs, especially when the foot is in full contact with the SFO at midstance. The localized skin stretching induced by these protrusions may enhance mechanoreceptor activation, thereby improving somatosensory feedback (Hijmans et al., 2007). This enhanced feedback could contribute to a more stable and controlled gait pattern, potentially reducing the risk of falls in challenging conditions (Corbin et al., 2007; Qiu et al., 2012). Furthermore, the observed increase in vertical GRF at midstance on level terrain and decrease at early stance on uphill terrain with SFO suggest modulation of GRF to enhance dynamic stability and reduce impact forces.

The absence of significant changes in the AP/ML CoP ranges, CoP velocities, anterior/posterior position, and lateral symmetry between FFO and SFO aligns with previous studies showing minimal or no effects of tactile stimulating knobs on CoP parameters during gait (Asgari et al., 2022; Hatton et al., 2012; Palluel et al., 2008). Similarly, foot orthoses with only medial arch supports, or heel cups did not effectively improve static balance in older adults (Bae et al., 2016). In contrast, other studies have reported significant improvement in CoP parameters while wearing SFO (Li et al., 2019; Palluel et al., 2008; Qiu et al., 2012). For instance, SFO with protruding spikes or site-specific knobs improved postural stability in older adults (Li et al., 2019; Palluel et al., 2008). These findings

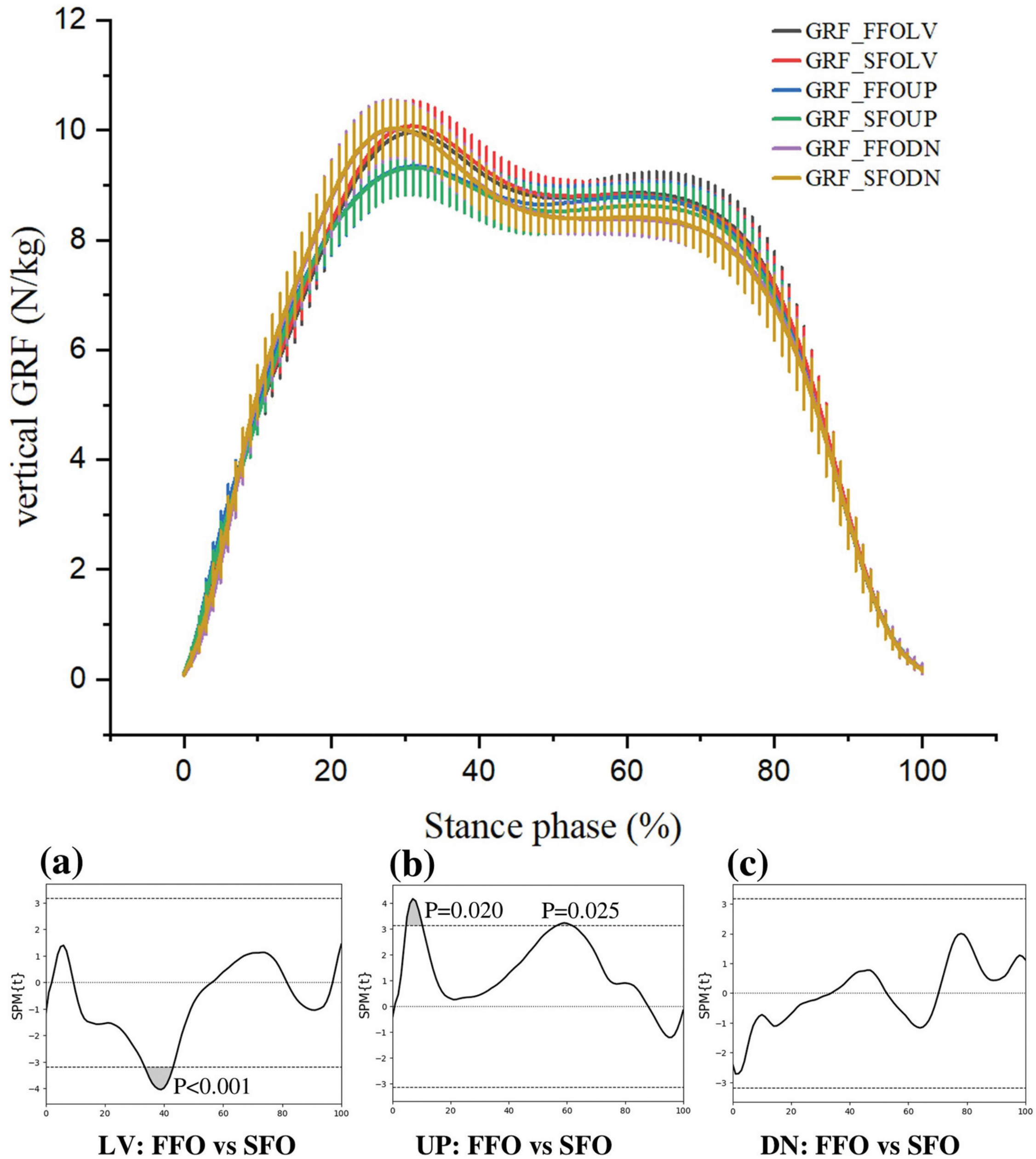

Figure 5. Vertical ground reaction force (GRF) with standard deviations across 0 to 100% stance where black (GRF_FFOLV) and red (GRF_SFOLV) represent flat and somatosensory foot orthoses on level terrain, blue (GRF_FFOUP) and green (GRF_SFOUP) represent flat and somatosensory foot orthoses on uphill terrain, and purple (GRF_FFODN) and brown (GRF_SFODN) represent flat and somatosensory foot orthoses on downhill terrain. In the results of statistical parametric mapping (SPM) analysis, (a) shows a comparison between flat and somatosensory foot orthoses on level terrain (LV: FFO vs SFO), (b) shows a comparison between flat and somatosensory foot orthoses on uphill terrain (UP: FFO vs SFO), and (c) shows a comparison between flat and somatosensory foot orthoses on downhill terrain (DN: FFO vs SFO).

collectively suggest that optimizing the design and placement of tactile stimulating knobs is crucial for enhancing postural stability and gait performance.

Similar to CoP trajectory parameters, the lack of significant changes in spatiotemporal gait parameters were in line with previous research indicating that SFO typically do not alter these parameters under controlled conditions (Hartmann et al., 2010; Valizadeh et al., 2021). One possible explanation is that treadmill walking at a constant speed promotes uniform gait patterns across participants (Fukuchi et al., 2019; Hollman et al., 2016; Sloot et al., 2014). Moreover, treadmill walking is associated with lower vertical foot acceleration and improved postural control, potentially masking additional benefits of the SFO (Tong et al., 2020). Future research should therefore investigate gait and balance in more variable, real-world environments, where the effects of somatosensory stimulation may be more pronounced. Conversely, a previous study reported that SFO negatively affected stride length and gait velocity (Hatton et al., 2012). The flat configuration of foot orthoses without arch support, often reported as positive feature in SFO (Jor et al., 2025), might limit the contact surface area for tactile stimulation, thereby reducing its effectiveness.

Table 3. Mean, standard deviation, effect size, and statistical significance in pairwise comparisons of maximum plantar forces and pressure distribution during walking at varying inclined terrains.

			FFO		SFO			
Parameters (Maximum plantar forces)	Testing conditions	Norm	Mean	SD	Mean	SD	Effect size (Cohen's d)	*P* value
Toes, N/kg	Walking Level	Yes	1.62	0.51	1.72	0.67	0.2	0.288
	Walking Uphill	Yes	1.46	0.47	1.43	0.51	0.1	0.587
	Walking Downhill	Yes	1.84	0.71	1.78	0.76	0.1	0.586
Forefoot medial, N/kg	Walking Level	Yes	1.87	0.36	1.88	0.36	0.0	0.814
	Walking Uphill	Yes	1.77	0.36	1.65	0.34	0.4	**0.015**
	Walking Downhill	Yes	1.82	0.25	1.76	0.28	0.2	0.051
Forefoot inner, N/kg	Walking Level	Yes	2.71	0.40	2.72	0.48	0.0	0.908
	Walking Uphill	Yes	2.63	0.46	2.46	0.52	0.3	0.051
	Walking Downhill	Yes	2.54	0.39	2.45	0.44	0.2	0.068
Forefoot lateral, N/kg	Walking Level	Yes	1.43	0.21	1.49	0.23	0.3	**0.044**
	Walking Uphill	Yes	1.36	0.24	1.36	0.26	0.0	0.977
	Walking Downhill	Yes	1.44	0.23	1.46	0.29	0.1	0.611
Midfoot, N/kg	Walking Level	Yes	3.08	0.75	3.02	0.74	0.1	0.625
	Walking Uphill	Yes	3.07	0.49	2.98	0.66	0.2	0.434
	Walking Downhill	Yes	3.06	0.97	3.24	1.11	0.2	0.112
Rearfoot medial, N/kg	Walking Level	Yes	2.16	0.41	2.11	0.40	0.1	0.461
	Walking Uphill	Yes	2.19	0.50	2.11	0.51	0.2	0.057
	Walking Downhill	Yes	2.06	0.30	2.02	0.33	0.1	0.430
Rearfoot lateral, N/kg	Walking Level	Yes	2.19	0.45	2.21	0.40	0.0	0.796
	Walking Uphill	Yes	2.32	0.53	2.30	0.49	0.0	0.792
	Walking Downhill	Yes	1.93	0.38	1.98	0.40	0.1	0.349
Parameters (Maximum plantar pressure)								
Toes, N/cm2	Walking Level	No	11.93	1.91	11.92	2.50	0.0	0.260
	Walking Uphill	No	10.83	2.31	10.22	2.50	0.3	**0.003**
	Walking Downhill	No	12.00	2.16	11.53	1.93	0.3	**0.019**
Forefoot medial, N/cm2	Walking Level	Yes	14.00	2.44	13.85	2.35	0.1	0.107
	Walking Uphill	No	13.78	2.81	12.72	2.96	0.5	**0.000**
	Walking Downhill	No	13.09	1.90	12.54	2.05	0.3	**0.013**
Forefoot inner, N/cm2	Walking Level	No	14.72	2.46	14.59	2.85	0.1	**0.007**
	Walking Uphill	No	14.66	3.06	13.51	3.30	0.4	**0.001**
	Walking Downhill	No	13.65	2.41	13.11	2.33	0.5	**0.000**
Forefoot lateral, N/cm2	Walking Level	No	12.15	2.35	11.95	2.22	0.1	0.107
	Walking Uphill	No	12.33	3.81	11.56	2.71	0.2	0.128
	Walking Downhill	No	11.25	2.23	11.21	2.37	0.0	0.627
Midfoot, N/cm2	Walking Level	No	12.02	2.33	11.88	2.28	0.1	0.370
	Walking Uphill	No	11.85	1.62	11.94	2.22	0.1	0.761
	Walking Downhill	No	11.02	1.73	11.33	2.08	0.3	0.494
Rearfoot medial, N/cm2	Walking Level	No	10.78	1.88	10.76	2.94	0.0	**0.029**
	Walking Uphill	No	10.81	2.18	10.83	3.45	0.0	0.153
	Walking Downhill	No	10.39	1.67	10.24	2.34	0.1	**0.018**
Rearfoot lateral, N/cm2	Walking Level	No	11.41	1.66	11.46	2.69	0.0	0.274
	Walking Uphill	No	11.33	2.00	11.69	3.13	0.1	0.784
	Walking Downhill	No	10.36	1.59	10.63	2.13	0.1	1.000

FFO: flat foot orthoses; SFO: somatosensory foot orthoses; SD: standard deviation.

The observed reduction in plantar pressure, particularly in high-pressure regions such as the medial forefoot, inner forefoot, and medial rearfoot, suggests that the SFO's stimulating knobs help redistribute pressure more evenly across the foot and potentially reduce the risk of pressure-related injuries and falls (Li et al., 2019; Mickle et al., 2010; Pol et al., 2021). This redistribution could be attributed to two mechanisms: (1). a screw-like effect, where the raised heel cup and contoured medial and lateral arch supports guide and redistribute forces away from high-pressure areas; (2). a massaging effect, where the soft protruding knobs gently stimulate the sole, alleviating localized stress and promoting even pressure distribution. Additionally, the SFO's contoured structure and raised heel cup may further enhance tactile contact and support, improving both pressure distribution and postural stability (Bonanno et al., 2011).

Overall, these findings highlight the potential of SFO with tactile stimulating knobs to enhance postural stability and plantar pressure distribution, particularly on inclined terrains. These findings have significant clinical implications for older adults at risk of balance deficits and falls, who often experience declines in muscle strength and sensory function (Osoba et al., 2019). While this study focused on community-dwelling older adults, the potential benefits of SFO may be even greater for individuals with balance impairments, a history of falls, or early sensory deficits. By enhancing somatosensory feedback and promoting a more stable gait, SFO could serve as a valuable tool in rehabilitation programs, improving both mobility and confidence. Future studies should investigate the effects of varying material hardness, design specifications (e.g., shape and height) and knob placement to maximize their benefits and broaden applications for populations with balance impairments or risk of falls.

Several limitations should be acknowledged. This study included only community-dwelling older adults, limiting generalizability to those with greater balance impairments or history of falls. The SFO combined protruding knobs, arch support, and a raised heel cup, making it difficult to isolate the effects of individual components. Only a single configuration of knobs was tested, and long-term effects or adaptations to the tactile stimuli were not assessed. Future research should examine larger, more diverse populations, isolate orthosis components, test varied knob configurations, and evaluate long-term effects through randomized controlled trials.

Conclusion

SFO with tactile knobs demonstrated potential to redistribute plantar forces and pressures and improve stability during specific stance phases on inclined terrains. However, no significant differences were observed between FFO and SFO in AP/ML CoP ranges, CoP velocities, maximum vertical GRFs, and spatiotemporal parameters. These findings support the role of SFO in enhancing tactile feedback and postural control, providing a foundation for future studies. Longitudinal studies with larger samples and varied SFO characteristics are needed to further validate their benefits and assess broader clinical applications.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was supported by the Hong Kong Research Grant Council, University Grants Committee (No. PolyU15211322).

ORCID

Abu Jor MSc http://orcid.org/0000-0002-5014-8594
Toshiki Kobayashi PhD http://orcid.org/0000-0001-6158-9670
Yufan He MSc http://orcid.org/0009-0006-8047-5680
Wing-Kai Lam PhD http://orcid.org/0000-0001-8692-2206
Stanley J. Winser PhD http://orcid.org/0000-0002-8766-3688
Fan Gao PhD http://orcid.org/0000-0002-6406-9467
Ming Zhang PhD http://orcid.org/0000-0002-6027-4594

References

Aboutorabi, A., Bahramizadeh, M., Arazpour, M., Fadayevatan, R., Farahmand, F., Curran, S., & Hutchins, S. W. (2016). A systematic review of the effect of foot orthoses and shoe characteristics on balance in healthy older subjects. *Prosthetics and Orthotics International*, *40*(2), 170–181. https://doi.org/10.1177/0309364615588342

Asgari, N., Yeowell, G., & Sadeghi-Demneh, E. (2022). A comparison of the efficacy of textured insoles on balance performance in older people with versus without plantar callosities. *Gait Posture*, *94*, 217–221. https://doi.org/10.1016/j.gaitpost.2022.03.022

Bae, K.-H., Shin, J.-H., Lee, J.-S., Yang, J.-O., Lee, B.-J., & Park, S. (2016). Analyses of plantar foot pressure and static balance according to the type of insole in the elderly. *Korean Journal of Sport Biomechanics*, *26*, 115–126. https://doi.org/10.5103/KJSB.2016.26.1.115

Bonanno, D. R., Landorf, K. B., & Menz, H. B. (2011). Pressure-relieving properties of various shoe inserts in older people with plantar heel pain. *Gait & Posture*, *33*(3), 385–389. https://doi.org/10.1016/j.gaitpost.2010.12.009

Chan, H. L., Chen, R. S., Kuo, C. C., Chen, Y. T., Liaw, J. W., Liao, G. S., Lin, W. T., Chien, S. H., & Chang, Y. J. (2024). Laser-light cueing shoes with integrated foot pressure and inertial sensing for investigating the impact of visual cueing on gait characteristics in Parkinson's disease individuals. *Frontiers in Bioengineering and Biotechnology*, *12*, 1334403. https://doi.org/10.3389/fbioe.2024.1334403

Chen, B., Liu, P., Xiao, F., Liu, Z., & Wang, Y. (2021). Review of the upright balance assessment based on the force plate. *International Journal of Environmental Research and Public Health*, *18*(5), 18. https://doi.org/10.3390/ijerph18052696

Corbin, D. M., Hart, J. M., McKeon, P. O., Ingersoll, C. D., & Hertel, J. (2007). The effect of textured insoles on postural control in double and single limb stance. *Journal of Sport Rehabilitation*, *16*(4), 363–372. https://doi.org/10.1123/jsr.16.4.363

de Morais Barbosa, C., Bértolo, Gaino, J. Z., Davitt, M., Sachetto, Z., de Paiva Magalhães, E., & Barros Bértolo, M. (2018). The effect of flat and textured insoles on the balance of primary care elderly people: A randomized controlled clinical trial. *Clinical Interventions in Aging*, *13*, 277–284. https://doi.org/10.2147/CIA.S149038

Fukuchi, C. A., Fukuchi, R. K., & Duarte, M. (2019). Effects of walking speed on gait biomechanics in healthy participants: A systematic review and meta-analysis. *Systematic Reviews*, *8*(1), 153. https://doi.org/10.1186/s13643-019-1063-z

Gao, C. C., Chern, J. S., Chang, C. J., Lai, P. L., & Lung, C. W. (2019). Center of pressure progression patterns during level walking in adolescents with idiopathic scoliosis. *PLOS ONE*, *14*, e0212161. https://doi.org/10.1371/journal.pone.0212161

GmbH zM. (2013). FDM-T specifications and hardware user manual - Measuring system for gait and stance analysis.

GmbH zM. (2019). *Software manual Zebris FDM* (Version 1.16.x).

Halvarsson, A., Dohrn, I. M., & Ståhle, A. (2015). Taking balance training for older adults one step further: The rationale for and a description of a proven balance training programme. *Clinical Rehabilitation*, *29*(5), 417–425. https://doi.org/10.1177/0269215514546770

Haris, F., Jan, Y. K., Liau, B. Y., Hsieh, C. W., Shen, W. C., Tai, C. C., Shih, Y. H., & Lung, C. W. (2023). The effects of different inner pressures of air insoles and walking durations on peak plantar pressure. *Medicine (Baltimore)*, *102*, e35704. https://doi.org/10.1097/MD.0000000000035704

Hartmann, A., Murer, K., de Bie, R. A., & de Bruin, E. D. (2010). The effect of a training program combined with augmented afferent feedback from the feet using shoe insoles on gait performance and muscle power in older adults: A randomised controlled trial. *Disability and Rehabilitation*, *32*(9), 755–764. https://doi.org/10.3109/09638280903295441

Hatton, A. L., Dixon, J., Rome, K., Newton, J. L., & Martin, D. J. (2012). Altering gait by way of stimulation of the plantar surface of the foot: The immediate effect of wearing textured insoles in older fallers. *Journal of Foot and Ankle Research*, *5*(1), 11. https://doi.org/10.1186/1757-1146-5-11

He, Y., Hu, M., Jor, A., Hobara, H., Gao, F., & Kobayashi, T. (2024). Dynamics of center of pressure trajectory in gait: Unilateral transfemoral amputees versus non-disabled individuals. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *32*, 1416–1425. https://doi.org/10.1109/TNSRE.2024.3381046

Hijmans, J. M., Geertzen, J. H., Dijkstra, P. U., & Postema, K. (2007). A systematic review of the effects of shoes and other ankle or foot appliances on balance in older people and people with peripheral nervous system disorders. *Gait & Posture*, *25*(2), 316–323. https://doi.org/10.1016/j.gaitpost.2006.03.010

Hollman, J. H., Watkins, M. K., Imhoff, A. C., Braun, C. E., Akervik, K. A., & Ness, D. K. (2016). A comparison of variability in spatiotemporal gait parameters between treadmill and overground walking conditions. *Gait Posture*, *43*, 204–209. https://doi.org/10.1016/j.gaitpost.2015.09.024

Huang, M., Yick, K. L., Ng, S. P., Yip, J., & Cheung, R. T. (2020). The effect of support surface and footwear condition on postural sway and lower limb muscle action of the older women. *PLOS ONE*, *15*, e0234140. https://doi.org/10.1371/journal.pone.0234140

Jor, A., Kobayashi, T., Khan, M. J., Hosen Opu, S., Lam, W. K., Winser, S. J., Gao, F., & Zhang, M. (2025). Effects of somatosensory stimulation foot orthoses on balance and stability in older adults:

A systematic review, meta-analysis, and meta-regression. *Gait Posture*, 109974. https://doi.org/10.1016/j.gaitpost.2025.109974

Kiaghadi, A., Bahramizadeh, M., & Hadadi, M. (2020). Effect of textured and prefabricated insole use with medical or sports shoes on dynamic postural control in elderly people. *Topics in Geriatric Rehabilitation*, *36*(1), 55–59. https://doi.org/10.1097/TGR.0000000000000255

Labata-Lezaun, N., Rodríguez-Rodríguez, S., López de Celis, C., Rodríguez-Sanz, J., Canet-Vintró, M., Ro, G., González-Rueda, V., & Pérez-Bellmunt, A. (2023). Effectiveness of different training modalities on static balance in older adults: A systematic review and meta-analysis. *Life (Basel)*, *13*(5), 13. https://doi.org/10.3390/life13051193

Lajoie, Y., & Gallagher, S. P. (2004). Predicting falls within the elderly community: Comparison of postural sway, reaction time, the Berg balance scale and the activities-specific balance confidence (ABC) scale for comparing fallers and non-fallers. *Archives of Gerontology & Geriatrics*, *38*(1), 11–26. https://doi.org/10.1016/S0167-4943(03)00082-7

Li, P. L., Yick, K. L., Ng, S. P., & Yip, J. (2019). Influence of textured indoor footwear on Posture stability of older women based on center-of-pressure measurements. *Human Factors: The Journal of the Human Factors & Ergonomics Society*, *61*(8), 1247–1260. https://doi.org/10.1177/0018720819837414

Lin, H. W., & Bhattacharyya, N. (2012). Balance disorders in the elderly: Epidemiology and functional impact. *The Laryngoscope*, *122*(8), 1858–1861. https://doi.org/10.1002/lary.23376

Lugade, V., & Kaufman, K. (2014). Center of pressure trajectory during gait: A comparison of four foot positions. *Gait & Posture*, *40*(4), 719–722. https://doi.org/10.1016/j.gaitpost.2014.07.001

Ma, C. Z., Lam, W. K., Chang, B. C., & Lee, W. C. (2020). Can insoles be used to improve static and dynamic balance of community-dwelling older adults? A systematic review on recent advances and future perspectives. *Journal of Aging & Physical Activity*, *28*(6), 971–986. https://doi.org/10.1123/japa.2019-0293

Malatesta, D., Canepa, M., & Menendez Fernandez, A. (2017). The effect of treadmill and overground walking on preferred walking speed and gait kinematics in healthy, physically active older adults. *European Journal of Applied Physiology*, *117*(9), 1833–1843. https://doi.org/10.1007/s00421-017-3672-3

Mawarikado, Y., Uchihashi, Y., Inagaki, Y., Ogawa, M., Uchihara, Y., Seriu, N., Ishida, Y., Kobayashi, Y., Sakata, A., Nogami, K., Shima, M., Tanaka, Y., & Kido, A. (2025). Relationship between history of falls and foot pressure centre parameters during gait and stance in patients with lower-limb osteoarthritis. *Scientific Reports*, *15*(1), 26723. https://doi.org/10.1038/s41598-025-11684-6

Mickle, K. J., Munro, B. J., Lord, S. R., Menz, H. B., & Steele, J. R. (2010). Foot pain, plantar pressures, and falls in older people: A prospective study. *Journal of the American Geriatrics Society*, *58*(10), 1936–1940. https://doi.org/10.1111/j.1532-5415.2010.03061.x

Mueller, M. J. (1996). Identifying patients with diabetes mellitus who are at risk for lower-extremity complications: Use of Semmes-Weinstein monofilaments. *Physical Therapy*, *76*(1), 68–71. https://doi.org/10.1093/ptj/76.1.68

Nor Azhar, A., Bergin, S. M., Munteanu, S. E., & Footwear, M. H. (2024). Orthoses, and insoles and their effects on balance in older adults: A scoping review. *Gerontology*, *70*(8), 801–811. https://doi.org/10.1159/000539591

Nüesch, C., Overberg, J.-A., Schwameder, H., Pagenstert, G., & Mündermann, A. (2018). Repeatability of spatiotemporal, plantar pressure and force parameters during treadmill walking and running. *Gait & Posture*, *62*, 117–123. https://doi.org/10.1016/j.gaitpost.2018.03.017

Osoba, M. Y., Rao, A. K., Agrawal, S. K., & Lalwani, A. K. (2019). Balance and gait in the elderly: A contemporary review. *Laryngoscope Investig Otolaryngol*, *4*(1), 143–153. https://doi.org/10.1002/lio2.252

Palluel, E., Nougier, V., & Olivier, I. (2008). Do spike insoles enhance postural stability and plantar-surface cutaneous sensitivity in the elderly? *Age (Dordr)*, *30*, 53–61. https://doi.org/10.1007/s11357-008-9047-2

Peterka, R. J. (2018). Sensory integration for human balance control. Chapter 2. *Handb Clin Neurol*, *159*, 27–42. https://doi.org/10.1016/b978-0-444-63916-5.00002-1

Piri, M., Malmir, K., Otadi, K., & Shadmehr, A. (2025). Postural stability measures as diagnostic tools for chronic ankle instability: A comprehensive assessment. *BMC Sports Science, Medicine and Rehabilitation*, *17*(1), 16. https://doi.org/10.1186/s13102-025-01064-y

Pol, F., Forghany, S., Hosseini, S. M., Taheri, A., & Menz, H. B. (2021). Structural and functional foot and ankle characteristics associated with falls in older people. *Gait Posture*, *88*, 78–83. https://doi.org/10.1016/j.gaitpost.2021.05.012

Qiu, F., Cole, M. H., Davids, K. W., Hennig, E. M., Silburn, P. A., Netscher, H., & Kerr, G. K. (2012). Enhanced somatosensory information decreases postural sway in older people. *Gait & Posture*, *35*(4), 630–635. https://doi.org/10.1016/j.gaitpost.2011.12.013

Qu, X. (2015). Impacts of different types of insoles on postural stability in older adults. *Applied Ergonomics*, *46*(Pt A), 38–43. https://doi.org/10.1016/j.apergo.2014.06.005

Reed, L. F., Urry, S. R., & Wearing, S. C. (2013). Reliability of spatiotemporal and kinetic gait parameters determined by a new instrumented treadmill system. *BMC Musculoskeletal Disorders*, *14*(1), 249. https://doi.org/10.1186/1471-2474-14-249

Remaud, A., Thuong-Cong, C., & Bilodeau, M. (2016). Age-related changes in dynamic postural control and attentional demands are minimally affected by local muscle fatigue. *Frontiers in Aging Neuroscience*, *7*, 257. https://doi.org/10.3389/fnagi.2015.00257

Rhea, C. K., Kiefer, A. W., Haran, F. J., Glass, S. M., & Warren, W. H. (2014). A new measure of the CoP trajectory in postural sway: Dynamics of heading change. *Medical Engineering & Physics*, *36*(11), 1473–1479. https://doi.org/10.1016/j.medengphy.2014.07.021

Rizzato, A., Paoli, A., Andretta, M., Vidorin, F., & Marcolin, G. (2021). Are static and dynamic postural balance assessments two sides of the same coin? A cross-sectional study in the older adults. *Front Physiology*, *12*, 681370. https://doi.org/10.3389/fphys.2021.681370

Sloot, L. H., van der Krogt, M. M., & Harlaar, J. (2014). Self-paced versus fixed speed treadmill walking. *Gait & Posture*, *39*(1), 478–484. https://doi.org/10.1016/j.gaitpost.2013.08.022

Tong, J., Zhang, J., Dong, E., Liu, C., & Du, S. (2020). The influence of treadmill on postural control. *IEEE Access*, *8*, 193632–193643. https://doi.org/10.1109/ACCESS.2020.3019442

Valizadeh, A., Mokhtari Malekabadi, A., & Jafarnezhadgero, A. (2021). The acute effect of using of texture foot orthoses on ground reaction forces in older adults during walking. *Medical Journal of Tabriz University of Medical Sciences and Health Services*, *42*(6), 756–763. https://doi.org/10.34172/mj.2021.017

Van Alsenoy, K., Thomson, A., & Burnett, A. (2019). Reliability and validity of the Zebris FDM-THQ instrumented treadmill during running trials. *Sports Biomechanics*, *18*(5), 501–514. https://doi.org/10.1080/14763141.2018.1452966

Wang, J., Li, Y., Yang, G. Y., & Jin, K. (2024). Age-related dysfunction in balance: A comprehensive review of causes, consequences, and interventions. *Aging and Disease*, *16*(2), 714. https://doi.org/10.14336/AD.2024.0124-1

West, B. A., Bhat, G., Stevens, J., & Bergen, G. (2015). Assistive device use and mobility-related factors among adults aged≥65years. *The Journal of Safety Research*, *55*, 147–150. https://doi.org/10.1016/j.jsr.2015.08.010

Yoo, S. D., Kim, H. S., Lee, J. H., Yun, D. H., Kim, D. H., Chon, J., Lee, S. A., Han, Y. J., Soh, Y. S., Kim, Y., Han, S., Lee, W., & Han, Y. R. (2017). Biomechanical parameters in plantar fasciitis measured by gait analysis system with pressure sensor. *Annals of Rehabilitation Medicine*, *41*(6), 979–989. https://doi.org/10.5535/arm.2017.41.6.979