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The effect of minimal shoes in combination with textured and supportive insoles on static and dynamic stability in older adults'

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ABSTRACT

This study investigated the effects of minimal shoes and their combination with textured and supportive insoles on spatiotemporal gait parameters, functional mobility, and static stability compared to barefoot and habitual footwear in healthy older adults. Forty participants completed a 2-min walk test, a Timed Up and Go test, and a bipedal standing test to assess dynamic and static stability. One-way repeated measures analysis of variance followed by Bonferroni post-hoc pairwise comparisons showed that all minimal shoe combinations and barefoot improved static stability compared to habitual footwear. The barefoot condition results longer TUG time, shorter stride lengths, and increased cadence during the walk test. Textured insoles improve static stability in eyes open condition, while supportive insoles in minimal shoes benefited dynamic tasks. These findings suggest that insole properties have different effects on static and dynamic stability in older adults, offering a better alternative to walking barefoot or using minimal shoes alone.

1. Introduction

Falling is one of the leading causes of injuries, hospitalisations, and injury related death in older adults. About 30–50 % of older adults fall once a year (Ambrose et al., 2013) and the long-term consequence can affect independence and quality of life (Brustio et al., 2018). The cost associated with fall related injuries is a significant burden to health care system as they often require long term treatment (Florence et al., 2018; Liu et al., 2015) and the number of older adults is increasing globally. Maintenance of postural stability and balance during locomotion is challenging, particularly for older adults because the visual, vestibular, and somatosensory systems that control stability tends to deteriorate with age (Ambrose et al., 2013; Shaffer and Harrison, 2007). The World Falls Guidelines recommend exercise interventions to prevent falls and reduce injury risk (Montero-Odasso et al., 2022). Despite their effectiveness, adherence of exercise interventions is often poor, with a tendency to discontinue after intervention. As an alternative in the current study, footwear and insole characteristics are being explored to improve stability.

It has become evident that footwear and insole characteristics can influence gait and stability positively, as well as negatively (Aboutorabi et al., 2016b; Hatton et al., 2013; Ma et al., 2020; Mulford et al., 2008; Nor Azhar et al., 2024; Qiu et al., 2012). Shoes and insoles may affect somatosensory feedback, landing pattern, comfort, support, foot muscle strength, and the natural function of the foot (Chen et al., 2016; Cudejko et al., 2020a, 2020b; Davis, 2014; Lieberman et al., 2010; Mulford et al., 2008; Qiu et al., 2012). Supportive footwear with low heel, high collar and textured insoles improve static and dynamic stability in older adults through a combination of sensorimotor and mechanical mechanisms, whereas thick and soft midsoles negatively influence stability and elevated heels are associated with greater risk of falls (Nor Azhar et al., 2024).

In recent years, minimal shoes were proposed as a means to enhance stability in older adults (Cudejko et al., 2020a). These are characterised by their lightweight design, low heel-to-toe drop, high flexibility, and absence of motion control or stability devices (Esculier et al., 2015). This type of footwear is often likened to barefoot walking or running, as it provides a similar level of flexibility while offering protection from

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environmental impact (Esculier et al., 2015). Research suggests that wearing minimal shoes can strengthen the intrinsic foot muscles over time by providing less mechanical support to the foot which positively effects the medial longitudinal arch and volume of foot muscle (Chen et al., 2016; Wei et al., 2022). Additionally, the thin outsoles enhance somatosensory feedback by stimulating more plantar cutaneous mechanoreceptors, and the wider forefoot influence pressure distribution across foot. Both these characteristics play an essential role in maintaining static and dynamic stability (Park et al., 2023; Willems et al., 2021). Most previous studies have investigated the potential benefit of minimal shoes in sport settings, particularly during running (Andreyo et al., 2022; Bonacci et al., 2020; Ekizos et al., 2017). Though some studies investigated the effects of minimal shoes on postural and dynamic stability in older adults (Azhar et al., 2023; Cudejko et al., 2020a, 2020b; Franklin et al., 2017), outcomes were inconsistent likely due to the variation in the experimental protocol. Cudejko et al. (2020a, 2020b) reported improvements in both static and dynamic stability among older adults, with and without a history of falls, when using various minimal shoe conditions compared to conventional cushioned shoes. Another study reported that older adults experience increased foot strength after using minimal shoes for four months but no significant improvements in postural stability, foot mobility, gait speed and step length (Franklin et al., 2017). However, neither of these studies compared the outcomes with participants' habitual shoes which serve as an important individual baseline for assessing real world effects.

In addition, insole characteristics such as a textured surface, arch support and heel cups positively impact postural stability (Ma et al., 2020). Textured insoles are believed to enhance tactile information and proprioception, which reduces postural sway and stability in young adults during bipedal static standing (Kenny et al., 2019). A previous study conducted by Qui et al. (2012) reported greater static stability while standing on foam surface in older adults using texture insoles. Tactile stimulation from the textured insoles reduced gait speed and stride length in older adults (Hatton et al., 2012). A review conducted by Kenny et al. (2019) also reported beneficial effects of textured insoles on static and dynamic stability with some heterogeneity in the results of different studies because of the diversity in the experimental protocol. Supportive insoles with arch support and heel cups improve balance and enhance stability during gait in older adults by maintaining the heel positioned on the insole platform and potentially enhancing somatosensory feedback via cutaneous receptors near the heel through increased lateral support (Ma et al., 2020). In a cross-sectional study conducted by Qu et al. (2015), supportive insoles were found to improv dynamic stability during walking in older adults but no beneficial effects on static stability were observed.

Despite current understanding on how footwear and insole characteristics influence static and dynamic stability in older adults, substantial uncertainty remains due to varied research methods. Therefore, further studies are necessary to identify specific footwear and insole characteristics that can enhance static and dynamic stability for this population. While various studies have demonstrated the benefits of minimal shoes and specific insole characteristics, little attention has been given to investigate how the combination of minimal shoes and insoles influences specific gait parameters and postural stability to a barefoot and habitual shoe conditions. To the best of our knowledge, no studies focused on the combined effects of minimal shoes and insoles on spatiotemporal gait parameters in older adults. Thus, in this exploratory study, we evaluated the effects of minimal shoes without insoles and in combination with textured and supportive insoles on spatiotemporal gait parameters, functional mobility, and static stability in healthy older adults compared to barefoot and habitual footwear conditions. The objective was to provide valuable insights into how the combination of footwear and insole characteristics alter stability and fall risk in older adults.

2. Methods

2.1. Participants

Aging is defined by both cultural and chronological aspects, however, in medical research, individuals aged 65 or older are generally considered older adults (Farage et al., 2012). Given that this project aims to investigate the effects of footwear on walking gait parameters, static stability and functional movement, data is collected from a sample of 40 healthy older adults (16 males and 24 females, age: 71.9 ± 4.7 years, height: 1.7 ± 0.1 m, weight: 74.8 ± 16.2 kg). To be included in this study, participants were required to be between 60 and 80 years old, independently living, absence of any deformities in feet, self-reported normal or corrected vision (with lenses) and free from lower limb pain due to osteoarthritis or musculoskeletal injury within the previous six months. The exclusion criteria were the use of walking aid, visual or gait impairment resulting from any accidental injury or surgical procedure in lower limbs (within the last six months), being prescribed ≥5 medications and taking any medication which may affect gait and stability. Ethical approval (ID 743) for the study was granted from the Human Invasive Ethics Committee of Nottingham Trent University and participants gave written consent prior to testing.

2.2. Footwear conditions

The footwear conditions examined in this study comprised: 1. minimal shoes without insoles (Fig. 1a), 2. minimal shoes with supportive insoles featuring heel cups and arch support (Figs. 1b), 3. minimal shoes with textured insoles (Figs. 1c), 4. barefoot, and 5. habitual shoes (Haowlader et al., 2024). Size EUR 37–47, unisex, Tadeevo Bliss Barefoot, minimal shoes were used as minimal shoes. Due to its highly flexible upper and thin rubber out-sole, low-weight, zero heel-to-toe drop, absence of artificial stabilization and wide forefoot region suitable for natural shape of human foot, it fits the characteristics of minimal shoes (Esculier et al., 2015). Medium density rectangular (125 cm × 78 cm) Evalite Pyramid Lightweight EVA sheet (aortha: OG1549) were cut into insole shape for different shoe sizes to use as textured insoles (Kenny et al., 2019). This sheet has evenly distributed pyramidal peaks with approximate 2 mm edge and 1 mm height on the upper surface. The thickness of the textured material and shore value were 3 mm and A40 respectively. Medium density lightweight, full length FootActive Comfort EVA insoles having shore value A35–A40 were used as supportive insoles. The medium size of this insole is suitable for 7–8.5 UK size shoes have a maximum height of 29 mm arch support in the midfoot region, 16 mm depth heel cup, 8 mm heel thickness and 5 mm forefoot thickness. Participants wore their own sneakers or trainers for the habitual shoes condition. To ensure correct fitting, participants feet was measured using the Brannock shoe measurement device (The Brannock Device Co., Syracuse, NY, USA).

2.3. Experimental protocol

All participants attended one data collection session. Dynamic tests included a 2-min walk test (2-MWT) and a Timed Up and Go (TUG) test, and the static test involved a bipedal standing task in eyes open and closed conditions. All tests were performed in the same sequence in each footwear condition, while different footwear conditions were randomized between participants. Participants were given a 5-min break between conditions to minimise fatigue. During the 2-MWT, participants walked for 2 min at their comfortable speed along a straight 12-m walkway (Chan and Pin, 2019). Following this, they completed three trials of the TUG test as fast as they could. A 3-m distance from a chair with standard height, without armrests and fixed legs was used for the TUG test. The static test involved participants performing three 30 s trials of bipedal standing with their eyes open followed by their eyes closed. Feet position was standardised by maintaining a 12 cm gap

Figure: 1. (a) Minimal shoes, (b) supportive insoles featuring heel cups and arch support and (c) textured insoles used for the experimental conditions.

between the midpoints of heels and second toes aligned along two parallel lines marked on the force plate using tape on the floor (Wilson et al., 2008). Participants were instructed to stand as still as possible with their hands on their hips during eyes open and eyes closed trials and looking at a cross placed 1.5m away at eye level during eyes open trials.

2.4. Outcome measures

As a reliable measure of gait parameters, Kinesis Gait™ and Kinesis QTUG™ IMU sensors (Kinesis Health Technologies Ltd., Dublin, Ireland) were utilised to record quantitative value of gait parameters during the 2-MWT and TUG test (Motti Ader et al., 2021; Smith et al., 2016). Kinesis QTUG™ sensors are recommended as a reliable method for quantitatively measuring the Timed Up and Go (TUG) test, while Kinesis Gait™ sensors have demonstrated excellent reliability in assessing gait parameters in community-dwelling older adults in previous studies (Motti Ader et al., 2020, 2021; Smith et al., 2016). During the test, these sensors were securely attached to the mid-point of participants' anterior shins using velcro straps and collected data at a frequency of 102.4Hz (Greene et al., 2012, 2018). In the 2-MWT, the total distance travelled, cadence (steps per minute), and percentage of swing and stance time were measured (Herssens et al., 2020). In the TUG test, the total task time i.e., time taken to complete the task, time taken to stand up from the chair, and time taken to sit back down after walking were assessed as these factors are important for evaluating fall risk and functional mobility (Makizako et al., 2017). Stride length, single support time and double support time, also the coefficient of variation in stride length and stride time in both the 2-MWT and the TUG test were recorded for better understanding of the effects of footwear on gait parameters related to stability (Ciprandi et al., 2017; Motti Ader et al., 2020). Average values of stride time, swing and stance time were used to calculate the percentage of swing and stance time. The coefficient of variation for the stride length and stride time was computed by dividing the standard deviation by the mean and multiplying by 100 (Motti Ader et al., 2020).

Centre of pressure during the bipedal standing test were recorded using a dual force plate system (AmtiGen-5, BP600900-2K-CTT), sampling at 1000Hz. Centre of pressure data was filtered using a fourth order lowpass Butterworth filter with a cutoff frequency of 10Hz (Mouzat et al., 2004). The data from the middle 20 s of the 30-s trial were used for analysis. Postural stability was evaluated by computing the standard deviation of the displacement and velocity of centre of pressure in the anterior-posterior (AP) and medial-lateral (ML) direction (Ghasemi and Anbarian, 2020). In addition, confidence ellipse was calculated by multiplying the standard deviation of the AP and ML displacement by π (Jakobsen et al., 2011). Instead of maximum and minimum values, SD of centre of pressure parameters was used to reduce variance and improve reliability (Ghasemi and Anbarian, 2020). Static parameters were computed using Visual3D v2022.09.1 (C-Motion, Inc., Rockville, MD, USA). Mean values of these parameters across the three trials in each footwear conditions were used for statistical analysis.

2.5. Statistical analysis

A one-way repeated measures analysis of variance was conducted separately for all target parameters to evaluate the influence of footwear. The impact of gender, age and body mass index (BMI), as covariates, on the measured parameters of the 2-MWT, TUG test and static test ware preliminary examined using repeated measures analysis of covariance. Body mass was also used as covariate in the analysis of standing test data, as other studies reported the significant effects of body mass on static stability (Koltermann et al., 2023). Levene's Test assessed homogeneity of variance, while Mauchly's test evaluated sphericity. In case of violation of sphericity, the Greenhouse-Geisser correction was applied (Ghasemi et al., 2020). The alpha level was set at 0.05 to account for multiple testing and control the rate of Type I errors, different correction methods, depending on the analysis level, were applied. For the ANOVAs, the False Discovery Rate (FDR) correction using the Benjamini and Hochberg (1995) procedure was applied to control for multiple comparisons while maintaining statistical power. Statistical significance was accepted if the FDR-corrected p-value was <0.05. Partial eta-squared ($\eta 2$) was used to interpretate the effect size, where a strong effect size was defined by > 0.14, moderate between 0.13 and 0.06 and low <0.01 (Cohen, 2013; Richardson, 2011). For between condition comparisons, Bonferroni comparison, post hoc test was used to control the family-wise error rate within each set of comparisons. Post hoc comparisons were considered significant for p-value below 0.05. All analyses were carried out using IBM SPSS Version 28.0.0.0 (190).

3. Result

3.1. Dynamic tests

Effect of gender, age and BMI were not significant in the observed parameters in 2-MWT and TUG test. No significant variations were found among the three minimal shoe conditions in any of the observed parameters in 2-MWT and TUG test. Significant differences were observed when minimal shoes with and without insoles were compared to the habitual shoe and barefoot condition. The effects of footwear conditions among participants in 2-MWT and TUG test are presented in Table 1, and the post-hoc test results of pairwise footwear comparisons are graphically presented in Fig. 2.

3.1.1. 2-min walk test

Footwear conditions resulted significant differences in walking gait parameters in the 2-MWT for stride length, cadence, swing time

Table 1
Spatiotemporal gait parameters (mean and standard deviation) in 2-MWT and TUG test across participants and footwear conditions.

Test name	Parameter	Footwear Condition					Within-subjects effects		
		Barefoot (BF)	Habitual shoes (HS)	Minimal shoes without insoles (MS)	Minimal shoes and textured insoles (MTI)	Minimal shoes and supportive insoles (MSI)	F value	False Discovery Rate corrected P value	Partial eta squared (η^2p)
2-MWT	Distance travelled (m)	146.4 (20.2)	147.1 (18.5)	147.7 (19.2)	148.0 (17.9)	149.3 (19.7)	0.89	0.461	0.022
	Cadence (Steps/min)	120.2 (10.2)$^{\text{HS,MS,MTI,MSI}}$	115.9 (9.9)$^{\text{BF}}$	119.0 (9.7)$^{\text{BF}}$	116.3 (8.7)$^{\text{BF}}$	116.8 (9.8)$^{\text{BF}}$	8.78	**<.001**	0.184
	Stride length (cm)	121.8 (10.7)$^{\text{HS,MS,MTI,MSI}}$	127.2 (10.7)$^{\text{BF}}$	127.4 (10.3)$^{\text{BF}}$	127.3 (10.1)$^{\text{BF}}$	128.0 (10.8)$^{\text{BF}}$	19.79	**<.001**	0.337
	Coefficient of variation in stride length (%)	9.4 (2.6)	10.4 (2.6)	9.7 (2.7)	9.8 (3.0)	9.7 (2.8)	2.11	0.118	0.051
	Coefficient of variation in stride time (%)	5.9 (2.8)	6.6 (2.8)	5.7 (2.3)	5.9 (3.3)	6.4 (3.3)	1.08	0.411	0.027
	Single support time (s)	0.45 (0.02)	0.46 (0.02)$^{\text{MS,MTI}}$	0.45 (0.02)$^{\text{HS}}$	0.45 (0.02)$^{\text{HS}}$	0.45 (0.02)	4.49	**<.01**	0.103
	Double support time (s)	0.10 (0.04)	0.10 (0.04)	0.11 (0.04)	0.11 (0.04)	0.11 (0.04)	3.74	**<.05**	0.087
	Swing time (%)	45.2 (2.1)	45.4 (2.2)$^{\text{MS}}$	44.6 (2.3)$^{\text{HS}}$	44.6 (2.2)	44.9 (2.4)	4.17	**<.01**	0.097
	Stance time (%)	54.7 (2.2)	54.5 (2.2)$^{\text{MS}}$	55.4 (2.3)$^{\text{HS}}$	55.3 (2.1)	55.1 (2.4)	4.16	**<.01**	0.096
TUG test	Time taken to complete the test (s)	8.4 (1.3)$^{\text{HS,MSI}}$	8.1 (1.2)$^{\text{BF}}$	8.3 (1.4)	8.3 (1.3)	8.2 (1.3)$^{\text{BF}}$	3.44	**<.05**	0.081
	Time taken to stand (s)	1.13 (0.21)	1.18 (0.20)	1.18 (0.22)	1.13 (0.17)	1.14 (0.23)	2.38	0.085	0.57
	Time taken to sit (s)	1.51 (0.44)	1.46 (0.41)	1.56 (0.48)	1.51 (0.39)	1.48 (0.38)	1.19	0.318	0.318
	Stride length (cm)	131.4 (11.4)$^{\text{MS,MSI}}$	135.6 (12.8)	135.6 (11.9)$^{\text{BF}}$	133.3 (13.7)	135.5 (12.3)$^{\text{BF}}$	3.71	**<.05**	0.087
	Coefficient of variation in stride length (%)	18.2 (4.3)$^{\text{MTI}}$	20.1 (5.0)	19.5 (4.9)	21.5 (4.4)$^{\text{BF}}$	19.9 (5.5)	3.77	**<.05**	0.088
	Coefficient of variation in stride time (%)	10.2 (5.8)	9.5 (4.3)	8.9 (4.7)	8.2 (3.9)	9.0 (5.3)	1.5	0.245	0.037
	Single support time (s)	0.46 (0.02)$^{\text{HS,MSI}}$	0.47 (0.03)$^{\text{BF}}$	0.47 (0.03)	0.47 (0.03)	0.47 (0.03)$^{\text{BF}}$	4.43	**<.05**	0.102
	Double support time (s)	0.10 (0.30)	0.08 (0.04)	0.09 (0.04)	0.09 (0.04)	0.09 (0.04)	2.82	0.066	0.068

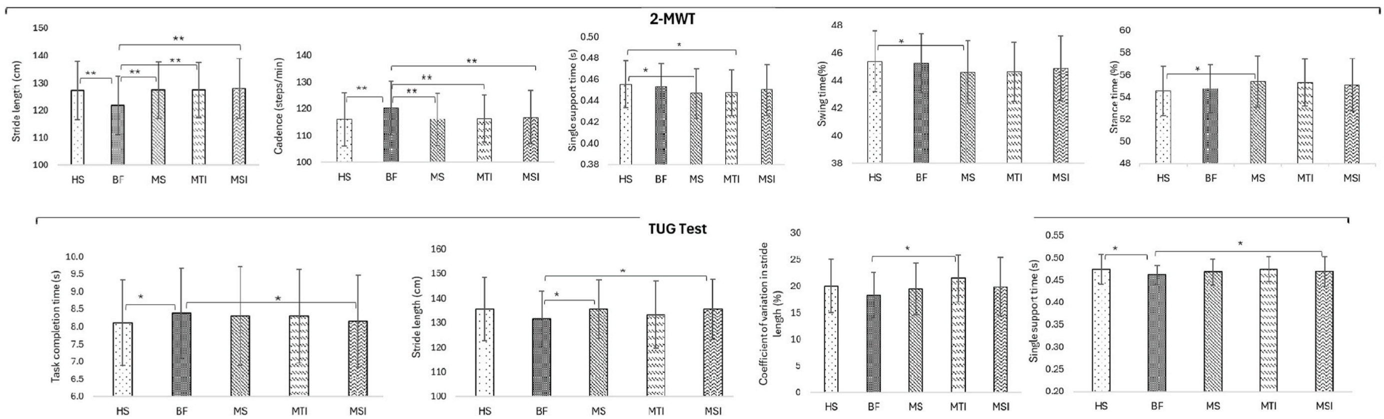

Figure: 2. Graphical presentation of post-hoc test result across footwear conditions in 2-MWT and TUG test. Notes: * indicates $0.001<p<0.05$, ** indicates $p<0.001$ Abbreviations: BF - Barefoot, HS - Habitual shoes, MS - Minimal shoes without insoles, MTI - Minimal shoes and textured insoles, MSI - Minimal shoes and supportive insoles.

percentage, stance time percentage and single support time. The post-hoc test shows that stride length significantly reduced ($p < 0.001$), and cadence significantly increased ($p < 0.001$) during barefoot walking compared to all other footwear conditions. Swing time percentage significantly decreased ($p < 0.05$) and stance time percentage significantly increased ($p < 0.05$) in minimal shoes without insoles compared to habitual shoes. In habitual shoes, single support time was significantly increased compared to minimal shoes without insoles ($p < 0.05$) and minimal shoes with textured insoles ($p < 0.05$). No significant effects of footwear were observed on total distance travelled in 2 min, coefficient of variation in stride length and stride time. Though there was a significant effect of footwear on double support time, the post hoc test revealed no significant difference between conditions after the Bonferroni correction (Table 1).

3.1.2. TUG test

The TUG test completion time significantly decreased minimal shoes with supportive insoles ($p < 0.05$) and habitual shoes ($p < 0.05$) compared to barefoot. Single support time was significantly reduced while barefoot compared to habitual shoes ($p < 0.05$) and minimal shoes with supportive insoles ($p < 0.05$). Stride length was significantly reduced when barefoot compared to minimal shoes without insoles ($p < 0.05$) and minimal shoes with supportive insoles ($p < 0.05$). Barefoot walking reduced the coefficient of variation in stride length compared to minimal shoes with textured insoles ($p < 0.05$). No other significant differences were found in the time taken to stand, sit back down after walking, coefficient of variation in stride time and double support time between footwear conditions. (Table 1).

3.2. Static test

Repeated measures analysis of covariance demonstrated no significant effects of gender, BMI, and body mass on the observed parameters in static bipedal standing test except the standard deviation of ML velocity in the eyes closed condition which was significantly higher ($p < 0.001$) in males compared to females. During eyes closed condition only, participants' age significantly effects the SD of ML displacement, confidence ellipse and SD of velocity in both AP and ML direction.

3.2.1. Eyes open condition

All parameters were significantly reduced in minimal shoes with textured insoles compared to habitual shoes. The standard deviation of AP displacement significantly increased in habitual shoes compared to barefoot ($p < 0.01$). The standard deviation of the AP velocity significantly decreased in minimal shoes without insoles compared to habitual shoes ($p < 0.001$). The confidence ellipse significantly decreased in minimal shoes ($p < 0.05$), minimal shoes with textured insoles ($p < 0.001$), minimal shoes with supportive insoles ($p < 0.01$) and barefoot ($p < 0.01$) compared to habitual shoes. The confidence ellipse significantly reduced in minimal shoes with textured insoles compared to minimal shoes without insoles ($p < 0.05$). No other differences were found among the three minimal shoes conditions (Table 2 and Fig. 3).

3.2.2. Eyes closed condition

Minimal shoes with and without insoles as well as barefoot condition significantly reduced all postural stability parameters compared to habitual shoes during the eyes close trials. In addition, standard deviation of AP velocity was significantly reduced ($p < 0.05$) while barefoot compared to the minimal shoes with supportive insoles condition. No other differences were observed in the eyes closed condition (Table 2 and Fig. 3).

4. Discussion

This study demonstrates that different footwear conditions influence spatiotemporal gait parameters, functional mobility, and static stability in healthy older adults, offering valuable insights into how minimal shoes, both with and without insoles, compare to habitual footwear and barefoot conditions in terms of stability and fall risk. Wearing textured insoles in minimal shoes improved static stability under eyes-open conditions; however, no significant differences were observed among the three minimal shoe conditions during eyes-closed trials. Supportive insoles in minimal shoes and habitual shoes resulted in faster Timed Up and Go (TUG) test completion times, suggesting potential benefits for dynamic tasks, particularly those requiring greater speed and mobility. Walking barefoot led to a shorter stride length and higher cadence, while maintaining a comparable gait speed to other conditions. This suggests that participants adopted a more cautious gait pattern, likely due to reduced perceived stability in the barefoot condition. These findings contribute to a better understanding of how footwear and insole characteristics impact stability and mobility, with potential implications for fall prevention strategies in older adults. Textured insoles in minimal shoes significantly reduced all centre of pressure parameters during the static bipedal standing task in the eyes open condition compared to habitual shoes (Table 2). This suggests that textured insoles, in combination with the minimal shoes, enhance static stability compared to the footwear habitually worn by older adults. Furthermore, this textured insole minimal shoe condition also significantly reduced the confidence ellipse compared to minimal shoes without any insoles. Additionally, the standard deviation of the medial-lateral displacement was significantly lower in minimal shoes with textured insoles compared to barefoot condition. Standing on textured surface increases proprioceptive

Table 2
Centre of pressure parameters (mean and standard deviation) in bipedal standing test across participants and footwear conditions.

Condition	Parameter	Footwear Condition					Within-subjects effects		
		Barefoot (BF)	Habitual shoes (HS)	Minimal shoes without insoles (MS)	Minimal shoes and textured insoles (MTI)	Minimal shoes and supportive insoles (MSI)	F value	FDR corrected P value	Partial eta squared (η^2p)
Eyes open	SD of AP displacement (mm)	4.8 (1.2)$^{\text{HS}}$	6.3 (2.6)$^{\text{BF, MTI}}$	5.3 (1.7)	4.8 (1.5)$^{\text{HS}}$	5.6 (2.1)	8.66	**<.001**	0.198
	SD of ML displacement (mm)	3.3 (1.0)$^{\text{MTI}}$	3.6 (1.2)$^{\text{MTI}}$	3.2 (1.2)	2.9 (0.9)$^{\text{HS,BF}}$	3.2 (1.1)	7.55	**<.001**	0.177
	SD of AP velocity (mm/s)	11.8 (4.6)$^{\text{HS}}$	13.8 (4.9)$^{\text{BF, MS,MTI}}$	12.0 (4.3)$^{\text{HS}}$	11.8 (4.4)$^{\text{HS}}$	12.9 (4.8)	8.39	**<.001**	0.193
	SD of ML velocity (mm/s)	9.7 (4.0)	10.6 (4.4)$^{\text{MTI}}$	9.5 (4.2)	9.0 (3.2)$^{\text{HS}}$	9.6 (3.8)	5.15	**<.01**	0.128
	Confidence ellipse (mm^2)	52.5 (24.6)$^{\text{HS}}$	76.6 (51.6)$^{\text{BF, MS,MTI,MSI}}$	57.1 (34.3)$^{\text{HS,MTI}}$	46.3 (22.6)$^{\text{HS,MS}}$	60.8 (38.9)$^{\text{HS}}$	11.26	**<.001**	0.243
Eyes closed	SD of AP displacement (mm)	5.6 (1.9)$^{\text{HS}}$	6.8 (2.1)$^{\text{BF,MS, MTI,MSI}}$	5.5 (1.8)$^{\text{HS}}$	5.4 (1.6)$^{\text{HS}}$	5.7 (1.8)$^{\text{HS}}$	13.28	**<.001**	0.275
	SD of ML displacement (mm)	4.6 (2.0)$^{\text{HS}}$	5.5 (2.6)$^{\text{BF,MS, MTI,MSI}}$	4.4 (2.0)$^{\text{HS}}$	4.2 (1.9)$^{\text{HS}}$	4.6 (2.3)$^{\text{HS}}$	13.63	**<.001**	0.28
	SD of AP velocity (mm/s)	17.8 (9.1)$^{\text{HS,MSI}}$	24.0 (12.6)$^{\text{BF, MS,MTI,MSI}}$	19.2 (10.2)$^{\text{HS}}$	18.2 (8.8)$^{\text{HS}}$	20.0 (10.1)$^{\text{HS,BF}}$	16.82	**<.001**	0.325
	SD of ML velocity (mm/s)	14.0 (7.7)$^{\text{HS}}$	17.3 (9.8)$^{\text{BF, MS,MTI,MSI}}$	13.3 (7.7)$^{\text{HS}}$	13.0 (7.1)$^{\text{HS}}$	13.9 (7.8)$^{\text{HS}}$	14.63	**<.001**	0.296
	Confidence ellipse (mm^2)	89.8 (86.6)$^{\text{HS}}$	132.7 (93.3)$^{\text{BF,MS, MTI,MSI}}$	84.7 (61.4)$^{\text{HS}}$	79.3 (55.5)$^{\text{HS}}$	90.5 (66.5)$^{\text{HS}}$	17.62	**<.001**	0.335

Abbreviations: AP - anterior-posterior, ML - medial-lateral, SD - standard deviation, FDR - False Discovery Rate.

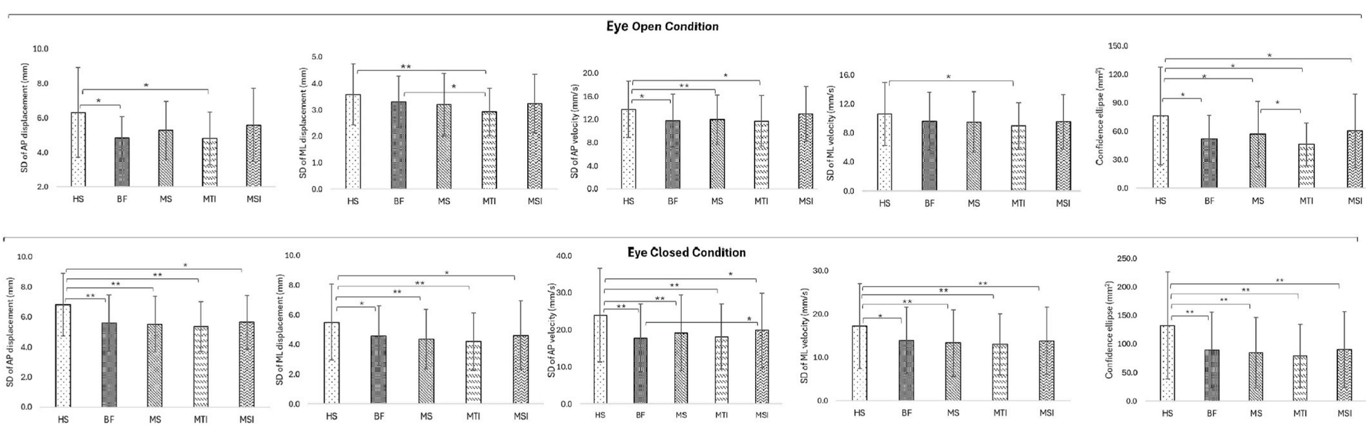

Figure: 3. Graphical presentation of post-hoc test result across footwear conditions in bipedal standing test. Notes: * indicates 0.001<p < 0.05, ** indicates p < 0.001
Abbreviations: BF - Barefoot, HS - Habitual shoes, MS - Minimal shoes without insoles, MTI - Minimal shoes and textured insoles, MSI - Minimal shoes and supportive insoles.

sensory input by stimulating the mechanoreceptors, which helps to reduce the centre of pressure parameters during bipedal standing (Qiu et al., 2012). Qiu et al. (2012) found greater static stability in older adults during standing on a foam surface after exposure to textured insole material. However, in their study, the textured material was used as a surface rather than shoe insoles. In contrast, Wilson et al. (2008) found no improvements in postural stability in middle-aged females after four weeks of textured insole use. Maintaining postural stability is more challenging for older adults due to age-related sensory decline, which may explain why healthy middle-aged participants in Wilson et al. (2008) showed no improvement, given their higher baseline stability levels. The beneficial effects of textured insoles on static stability observed in the current study could be an acute effect, requiring further longitudinal investigation to assess their long-term impact.

In eyes-closed conditions, habitual shoes resulted in reduced static stability, as indicated by the greater values of all CoP parameters (Table 2). Unlike eyes-open conditions, textured insoles in minimal shoes did not enhance static stability compared to minimal shoes alone. Static stability is more challenging in eyes-closed conditions, as it relies solely on the vestibular and proprioceptive systems, without visual feedback (Ray et al., 2008). The cushioning of the midsoles of the habitual shoes appeared to be detrimental to static stability during the more challenging eyes closed task, where vision cannot be used to aid balance. In contrast, minimal shoes and barefoot conditions, which lack extra cushioning, provided better stability. However, adding textured insoles to minimal shoes offered no additional benefit in this task. This outcome might be explained by the underlying characteristics of minimal shoes. Absence of extra cushioning and motion control devices in minimal shoes provide an increased level of stimulation to the cutaneous mechanoreceptors. It appeared the additional stimulation from the textured insoles offered no further gain to the central nervous system to influence static stability during the more challenging static stability task (i.e., eyes closed condition). These results are similar to a previous study by Cudejko et al. (2020a) who also reported no significant differences in static stability in eyes closed condition between barefoot and several minimal shoes and insoles combination in middle aged and older adults. However, they did not investigate the results in eyes open condition and supportive insoles were not included in the protocol. In the current study, during eyes closes condition, static stability was reduced in minimal shoes with supportive insoles compared to barefoot as indicated by the greater value of anterior-posterior velocity standard deviation. Overall, minimal shoes improved static stability in older adults under both eyes-open and eyes-closed conditions, with textured insoles further enhancing stability in eyes-open conditions. Since maintaining stability while standing with eyes open is more applicable to daily life, textured insoles in minimal shoes could provide a practical option for improving static stability in real-world settings.

The 2-min walk test revealed detrimental effects of barefoot walking on the spatiotemporal gait parameters, showing a significantly higher cadence and a shorter stride length compared to the other footwear conditions. This indicates that older adults are least stable when walking barefoot even when they walk at their comfortable speed without any unexpected perturbation inside the laboratory. A longer stride length aids stability by increasing the base of support, whereas a higher cadence requires greater motion strength during the initial swing phase and reduces terminal swing time, thereby increasing the risk of tripping during gait (McAndrew Young and Dingwell, 2012; Wang et al., 2018). In previous study, higher cadence and smaller step length in participants habitual shoes was observed when stability was challenged by unexpected mechanical perturbation during treadmill walking by moving the treadmill surface and speed (Madehkhaksar et al., 2018). Older adults generally walk slower with smaller stride lengths and increased cadence (Aboutorabi et al., 2016a). These changes are considered as the strategy to maintain stability during walking for this age group (Bridenbaugh and Kressig, 2011). We did not observe any significant effect of footwear in total distance covered in 2-MWT suggesting that the footwear conditions used did not affect the self-selected gait speed. Significantly greater single support time and percentage of swing time in habitual shoes could be an indicator that participants were more comfortable in their habitual shoes compared to the minimal shoe conditions. Another possible reason of this could be adaptation time, since older adults may require time to adjust to minimal shoes with and without insoles conditions. However, no significant difference in total distance covered in 2 min, stride length and cadence in habitual shoes and all minimal shoes conditions provides initial evidence that their stability is not substantially affected during walking.

Time required to complete the TUG test is commonly used for fall risk assessment in older adults (Park, 2018). Older adults were faster and had greater single support time in the TUG test whilst wearing their habitual shoes and the minimal shoes with supportive insoles compared to barefoot. This indicates that shoe stability and support under the foot is important when older adults walk faster as required during the TUG test. Fast walking speed and turning during walking in the TUG test increases the difficulty level thus to maintain stability greater control is required which was provided by the shoe cushioning. In contrast, the self-selected pace during the 2-MWT did not seem challenging enough to influence walking speed with footwear conditions. Existing research has demonstrated that the use of supportive insoles can lead to improvements in various measures, including Berg Balance Scale, TUG, along with reduced back, foot, knee, and hip pain in older adults (Mulford et al., 2008). Moreover, supportive insoles may aid stability by enhancing somatosensory stimulation over a larger contact area of the foot and provide greater sensory input to respond changes in the centre of pressure perceived through the plantar aspect of the foot (Gross et al., 2012). Yet, the textured insoles did not increase TUG task time, suggesting that it was the supportive insole design to keep the foot in-place within the minimalist shoe that may have been more important for dynamic stability.

5. Limitations

Age related physiological changes, health status, physical activity level, various footwear habits, overground surface conditions have potential influence on stability. The findings of this study are limited in its generalisability as the study population was only healthy older adults. This study focused on the impact of textured and supportive insoles, such as those with heel cups and arch support, on observed parameters. Differences in thickness, 5–8 mm in supportive insoles versus 3 mm in the textured insoles, shape geometry of the supportive insoles, and material hardness may have also effects results by influencing foot mechanics and pressure distribution. Controlling these factors in future research is necessary for better understanding about the effects of texture more precisely. The participants had little time to adapt to the minimal shoes and insole conditions during this cross-sectional study, which may have potential effects on observed parameters, but longer familiarisation period was beyond the scope of this study. Future research should include both cross-sectional and longitudinal study, a broader age range, diverse health conditions and natural environments to improve the applicability and understanding of long-term effects of minimal shoes and insoles on stability across the lifespan.

6. Conclusion

This study found that minimal shoes, whether worn with or without textured or supportive insoles, influence gait parameters differently during static and dynamic tasks in older adults. Being barefoot or wearing minimal shoes (with or without insoles) improved static stability under eyes-closed conditions compared to habitual footwear, which provides cushioning. However, findings from dynamic tests suggest that balance is compromised during barefoot walking, indicating that being completely barefoot is not ideal for maximising stability in older adults. Textured insoles in minimal shoes enhanced static stability, while supportive insoles improved functional mobility, as evidenced by better performance in the Timed Up and Go (TUG) test. Therefore, a combination of textured and supportive insoles, rather than minimal shoes alone, may be a more effective approach to improving both static and dynamic stability in older adults.

CRediT authorship contribution statement

Salahuddin Haowlader: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Charlotte Apps:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Maria Bisele:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Roberto Vagnetti:** Writing – review & editing, Visualization, Resources, Formal analysis. **Daniele Magistro:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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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.

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