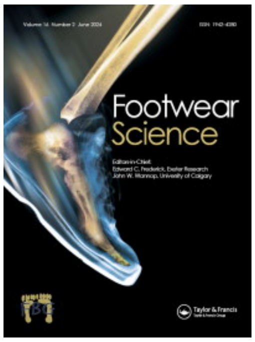

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RESEARCH ARTICLE

The effects of minimal shoes in combination with textured and supportive insoles on spatiotemporal walking gait parameters in healthy young adults

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ABSTRACT
Spatiotemporal parameters, such as speed, cadence, stride length are often adjusted to enhance stability during walking. Minimal shoes and insoles are known to impact dynamic stability, however their combined effect on such gait parameters in healthy young adults remains unexplored. This cross-sectional study assessed the effects of a minimal shoes, the combination of a minimal shoes with a textured insoles, a minimal shoes with a supportive insoles, barefoot walking and habitual shoes on stability-related spatiotemporal walking gait parameters. Sixty-two healthy young adults (41 males and 21 females, age: 24.6 ± 5.5 years, height: 1.73 ± 0.01 m, weight: 73.8 ± 14.2 kg) were assessed using a 2-minute walk test (2-MWT), and a Timed up and Go (TUG) test in a randomized order of five different footwear conditions. Measurements were made using Kinesis Gait™ and QTUG™ sensors. Repeated measures analyses of covariance were conducted to examine the effect of footwear with gender and BMI as covariates. Results revealed improvement in observed gait parameters during the 2-MWT in minimal shoes, minimal shoes with a textured insoles and minimal shoes with a supportive insoles compared to barefoot and habitual footwear. Participants covered a significantly greater distance ($p < 0.05$) during the 2-MWT at a self-selected speed in all three minimal shoes conditions with larger stride length and improved cadence. Significant variations ($p < 0.05$) were found between barefoot walking and minimal shoes conditions while participants being least stable during the barefoot walking. The use of textured or supportive insoles within the minimal shoes did not provide any additional benefits nor did it have any detrimental effect on the spatiotemporal parameters. Nevertheless, minimal shoes with or without insoles have the potential to enhance stability during walking as speed, cadence, and stride length are improved.

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Minimal shoe; insoles; dynamic stability; spatiotemporal parameters; walking gait

1. Introduction

Maintaining postural stability during locomotion is a complex task that involves rapid responses to both external and internal perturbations for maintaining upright balance and preventing falls (Lord et al., 2021). To maintain stability, the sensorimotor control system coordinates the movement of body segments on input from the somatosensory, vestibular, and visual systems (Zampogna et al., 2020). Adjusting spatiotemporal gait parameters under various circumstances is a common phenomenon during locomotion. As an external factor, design of footwear may influence spatiotemporal gait parameters and either aid or attenuate somatosensory feedback between the human foot and external environment, which in turn influences stability during dynamic activities (Huber et al., 2022; Menant et al., 2008a).

Dynamic stability is crucial for preventing falls and maintaining balance during movement, as it allows the body to adapt to sudden changes and perturbations effectively (Hak et al., 2013; Hof, 2008). Enhancing dynamic stability can significantly reduce the risk of injuries and improve overall mobility and functional performance in daily activities (Lencioni et al., 2020; McAndrew Young & Dingwell, 2012). Margin of stability, defined as the distance between the base of support and the extrapolated centre of mass has been proposed (Hof, 2008) and practiced in literature (Fallahtafti et al., 2021; McAndrew Young & Dingwell, 2012) as a measure of dynamic stability. Spatiotemporal gait parameters such as, gait speed, stride length, cadence, step time, single and double support time are corelated with margin of stability (Hak et al., 2013; Herssens et al., 2020; Lencioni et al., 2020). Greater variability in these parameters especially, stride-to-stride variability in stride length is considered an independent predictor of unstable gait during walking (Beauchet et al., 2009). Compared to healthy young adults, older individuals exhibit slower walking speed, shorter stride length, prolonged double support time and higher cadence, indicating either a deterioration of stability

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control system or a strategic adjustment for safer gait (Bridenbaugh & Kressig, 2011). Young adults also took shorter, wider and faster steps to increase dynamic stability when encounter unexpected perturbations (Madehkhaksar et al., 2018; Sivakumaran et al., 2018). Due to age related decrements in balance control system, dynamic stability becomes challenging with age which increases the risk of fall in older adults (Ungar et al., 2013; Woollacott & Shumway-Cook, 2002). Moreover, dynamic stability is potentially important for both young and older adults, as instability is linked with falls which is identified as third cause of accidental injuries across all ages (Heijnen & Rietdyk, 2016). Spatiotemporal parameters have been studied under different circumstances for having insight about the effects of these parameters on dynamic stability. However, further research is required to understand how different footwear characteristics affects these parameters in healthy young adults.

The purpose of footwear is to protect the feet from the environmental impact and hazards (Davis, 2014). While this remains a key function, footwear has evolved to serve additional roles in modern society, including cultural expression, fashion and supporting foot and comfort (Wilcox, 2008). Some footwear characteristics can negatively influence postural stability and long-term foot health (Neville et al., 2020). For instance, cushioning in the sole reduces the demand on foot muscles during locomotion, which can result in weaker intrinsic foot muscles over time (Miller et al., 2014). Cushioning from thick, soft midsoles also limits proprioception by attenuating the cutaneous signals from the ground (Squadrone & Gallozzi, 2011). Alternatively, high ankle collars, wider soles, cupped and textured insoles enhance neural feedback from cutaneous receptors to the central nervous system which is important for activating reflexes and maintaining postural stability (Cudejko et al., 2020; Kenny et al., 2019a; Qiu et al., 2012). In addition ankle collars provide greater mechanical support around the ankle, improve proprioception and reduce ankle inversion (Menant et al., 2008b), whilst, wider soles provide a larger more stable base of support (Cudejko et al., 2020). Nevertheless, the fittings of the footwear is also important as incorrectly fitted footwear may leads to foot pain, laser toe deformity, corns and calluses in older adults, risk of foot ulceration in diabetic people and overall poorer foot health (Buldt & Menz, 2018).

Minimal shoes are promoted for both sportive and recreational activities and are characterized with high flexibility, a low heel to toe drop, and the absence of motion control and stability devices such as a heel counter and arch support (Esculier et al., 2015). These unique design characteristics do not interfere with the natural function of the foot during locomotion and can enhance sensory perception (Esculier et al., 2015). Numerous minimal footwear studies have been published but most focus on athletic groups rather than the general population (Andreyo et al., 2022; Bergstra et al., 2015; Chen et al., 2016; Davis et al., 2021; Moore et al., 2015; Rixe et al., 2012). One study did report improvement in osteoarthritis pain in older adults with minimal footwear use (Trombini-Souza et al., 2020). However, limited research has addressed the effects of minimal shoes on gait and stability and there are contradictory results reported, potentially due to differences in the experimental design. For instance, no significant differences in postural sway, foot mobility, gait timing variability, gait speed, step length, step width was observed in active older adults after using minimal shoes for four months (Franklin et al., 2017). In contrast, compared to a conventional shoe, better static and dynamic stability, as well as, greater functional ability in minimal footwear has been reported in a cross-sectional study in middle age and older adults (Cudejko et al., 2020). In addition, minimal shoes have shown both positive and negative outcome in stability measures in healthy young adults (Chander et al., 2016; Huber et al., 2022; Park et al., 2023; Petersen et al., 2020). Petersen et al., reported improved local dynamic stability in minimal shoes compared to barefoot walking (Petersen et al., 2020). Chander et al., also observed improved postural stability in minimal shoes compared to flip flops and Crocs (Chander et al., 2016). However, Park et al., did not found any significant improvement in either static or dynamic balance score after using minimal shoes in young adults over regular athletic shoes and textured insoles (Park et al., 2023). Therefore, further studies are required to understand the effect of minimal shoes on spatiotemporal gait parameters and stability.

Besides the basic structure, one important element of footwear is insoles, which are conventionally suggested as an easy way to correct foot deformity (Takata et al., 2013) reduce pain (Cho & Yoon, 2015) and enhancing postural stability (Ma et al., 2020). Textured insoles feature a textured top surface, which enhances tactile information, improves proprioception and reduces centre of pressure sway which in turn improves stability among different age groups (Kenny et al., 2019a, 2019b; Qiu et al., 2012). However, the effectiveness of textured insoles varies in recent studies (Hatton et al., 2012; Ma et al., 2016; Wilson et al., 2008). Supportive insole features, such as arch supports and heel cups, impact distinct underlying mechanisms linked to stable gait (de Morais Barbosa et al., 2013; Ma et al., 2020). They were found to improve ankle stability and to reduce back, knee and foot pain in older adults (Mulford et al., 2008).

Though the potential of minimal shoes and insoles characteristics to improve stability is present in literature, only a few studies investigated the combined effects of minimal shoes and insoles on static and dynamic stability in middle age and older adults (Cudejko et al., 2019, 2020). However, the effect of minimal shoes and insoles on specific gait parameters, particularly in comparison to being barefoot and wearing habitual shoes, are still scarce and not well-understood. Therefore, this current study focused on the effects of minimal shoes and combination of minimal shoes with two different kinds of insoles on spatiotemporal gait parameters related to stability. Outcome of these three conditions were compared with barefoot walking and participants' habitual shoes. Ageing is associated with several physiological changes which affects postural stability and balance negatively. Consequently, when studying the effects of any external factors on stability, having the data from healthy individuals could provide valuable insight about the factor itself, which is footwear in the current study. Therefore, only healthy young adults were included in this study.

The aim of this study was to assess the effects of five different footwear conditions on stability-related spatiotemporal walking gait parameters in healthy young adults.

These conditions include a minimal shoes, a combination of a minimal shoes with textured insoles, a minimal shoes with supportive insoles featuring a heel cup and arch support, barefoot and habitual shoes. Size 37–47, Tadeevo Bliss minimal shoes was used in this study as it meets the characteristics of minimal shoes (Esculier et al., 2015). Textured insoles were made from 3 mm thick, medium density EVA sheet with a shore value A40, featuring evenly distributed pyramidal peaks on the upper surface. Commercially available medium density, lightweight EVA FootActive Comfort insoles featuring with arch support and heel cup made from a material with shore value A35–A40 were used as supportive insoles. We hypothesized that walking barefoot will reveal similar results to the minimal shoe and using texture and supportive insoles with minimal shoes will improve stability related walking gait parameters.

2. Methods

2.1. Participants

A sample of 62 healthy young adults (41 males and 21 females, age: 24.6 ± 5.5 years, height: 1.73 ± 0.01 m, body mass: 73.8 ± 14.2 kg) participated in this study. Individuals with impaired vision, neuromuscular disorder, and musculoskeletal injury in six months prior to data collection were excluded from the study. Other exclusion criteria were the use of walking aid, current medical condition that may affect gait and/or balance (e.g. Ménière's disease, neuropathy, pregnancy, prescribed ≥5 medications at the time of the data collection and on any medication which clearly state side effects that affect gait and stability). Ethical approval was granted by the Human Invasive Ethics Committee (ID 743), from Nottingham Trent University and all participants provided their written informed consent prior to data collection.

2.2. Experimental design

This study was conducted in a cross-sectional design with a within-participant repeated measures approach to analyze the effects of minimal shoes and insoles on spatiotemporal walking gait parameters. Each participant attended one data collection session.

2.3. Experimental protocol

Participants' shoe size was measured using the Brannock shoe measurement device (The Brannock Device Co., Syracuse, NY, USA), to ensure correct fitting of the footwear. Then IMU sensors were attached to the mid-point of their anterior shin using velcro straps (Figure 1(a)). During the 2-MWT, the Kinesis Gait™ sensors (Kinesis Health Technologies Ltd., Dublin, Ireland) were used, which were swapped for the Kinesis QTUG™ sensors (Kinesis Health Technologies Ltd., Dublin, Ireland) during the TUG test. Both sensors collected data at 102.4 Hz, and their reliability was established in previous research (Greene et al., 2018; Motti Ader et al., 2020).

In the 2-MWT participants were instructed to start walking at their comfortable walking speed and continue to walk for 2 minutes in a loop between two plastic soccer cones placed at 12-meter gap inside the laboratory. This task was chosen because natural overground walk at a self-selected speed is one of the most common daily activities and ecologically valid for the analysis of walking biomechanics. Following the 2-MWT, participants complete three trials of the TUG test in each footwear condition (Greene et al., 2010). At the beginning of the TUG test, participants sat on a chair without armrests and with fixed legs, their back touching the backrest of the chair. During the trial, they stood up from the chair and walked as quickly as possible along a 3-meter walkway, turned, before returning to the chair and sitting back down.

2.4. Measurements

The Kinesis Gait™ and QTUG™ sensors provided the mean values of the following gait parameters for the 2-MWT and TUG test, respectively: mean stride length, stride length variability, swing time, step time, single support time and double support time. For the 2-MWT, mean value for cadence, i.e. number of steps per minute and total distance covered during the test period were also computed. Additionally, for the TUG test, mean value of the total time taken to complete the test, time taken to stand up from the chair, and time taken to sit back down after walking, calculated from three trials were included in the analysis due to their significance in the assessment of dynamic stability and functional mobility. Values of stride length, cadence, single support time and double support time were averaged across multiple gait cycles, swing time and step time were averaged across both legs. Stride length variability was calculated by the sensor software as standard deviation of the stride length divided by mean stride length across multiple gait cycle and presented in percentage. All the parameters were collected in real-time by the sensors and sent to a handheld tablet device via Bluetooth.

2.5. Footwear conditions

Each participant performed a 2-minute walk test (2-MWT) and three trials of the Timed up and Go (TUG) test in five footwear conditions: 1. minimal shoes (Figure 1(b)), 2. minimal shoes with textured insoles (Figure 1(c)), 3. minimal shoes with supportive insoles featuring a heel cup and arch support (Figure 1(d)), 4. barefoot and 5. habitual shoes. Footwear conditions were randomized for each participant and five-minute breaks were provided between each condition to avoid fatigue. For the three minimal shoes conditions, commercially available size EUR 37–47, unisex, Tadeevo Bliss minimal shoes were used. This shoes are highly flexible and lightweight, shape is comparable to a natural human foot, with a zero heel-to-toe drop and no artificial stabilization, fitting the description of minimal shoes (Esculier et al., 2015). The textured insoles were made from 3 mm thick, medium density rectangular (125 cm x 78 cm) Evalite Pyramid Lightweight EVA sheet with a shore value A40, (aortha: OG1549), featuring evenly distributed pyramidal peaks spaced 2 mm centre-to-centre on the upper surface. A similar material with shore value A50 was reported to be beneficial for enhancing bipedal static stability in healthy young adults (Kenny et al., 2019b). For the condition with

Figure 1. (a) Sensors position, (b) minimal shoes, (c) textured insoles and (d) supportive insoles.

supportive insoles, commercially available full length FootActive Comfort insoles manufactured from a medium density lightweight EVA material with shore value A35–A40 were used. The medium size of this insoles (UK size 7–8.5) has a 29 mm high arch support in the midfoot region, 16 mm depth heel cup, 8 mm heel thickness and 5 mm forefoot thickness. In the habitual shoe condition, participants wore their own comfortable sneakers or trainers. In the barefoot condition, participants walked barefoot without socks, while constant floor temperature was maintained using a central heating system and portable radiator.

2.6. Statistical analysis

Repeated measures analyses of covariance (ANCOVA) were conducted for each parameter separately for the 2-MWT and TUG test to assess the effects of the footwear conditions. Gender and BMI were used as covariates. Levene's Test was used to assess homogeneity of variance, and sphericity was assessed using Mauchly's test. If sphericity was violated the Greenhouse–Geisser correction was applied. Based on the significant main effect on estimated marginal mean, effects of footwear were followed up with pairwise post-hoc comparisons with Bonferroni corrections. The alpha level was set at 0.05. All analyses were performed using IBM, SPSS Version: 28.0.0.0 (190).

3. Result

ANCOVA analyses demonstrated significant differences in all observer parameters except stride length variability in 2-MWT (Table 1). Post-hoc test revealed that, during the 2-MWT, participants covered significantly more distance in all minimal shoes conditions compared to the barefoot and habitual shoes ($p < 0.05$). Stride length was significantly reduced ($p < 0.001$) in barefoot compared to all other conditions. Swing and step time were significantly greater ($p < 0.05$ and $p < 0.001$, respectively) in habitual shoes compared to all other footwear conditions. Cadence was significantly reduced ($p < 0.001$) in habitual shoes compared to rest of the conditions. In barefoot cadence significantly increased compared to habitual shoes ($p < 0.001$), MS ($p < 0.05$), minimal shoes with textured insoles ($p < 0.001$), and minimal shoes with supportive insoles ($p < 0.001$). Stride length variability did not vary significantly among footwear conditions in 2-MWT. Between minimal shoes conditions, double support time was significantly increased, and single support time reduced in minimal shoes with a supportive insole compared to minimal shoes. No other significant differences were found between the minimal shoe conditions. Using gender and BMI as covariates, no significant difference was found in any of the observed gait parameters in 2MWT. Variations of gait parameters with footwear conditions in 2-MWT is graphically presented in Figure 2(a,b).

In the TUG test, ANCOVAs did not reveal any significant differences among footwear conditions in time taken to complete the task, time taken to stand up from the chair, and time taken to sit back after walking, single support time, double support time, stride length and stride length variability (Table 2). However, swing time significantly varies in habitual shoes and barefoot compared to all minimal shoes conditions and step time significantly varies in barefoot compared to all other conditions during this test. Post-hoc test results of pairwise footwear comparisons for swing time and step time in TUG test is graphically presented in Figure 3. Using gender and BMI as covariate, no significant difference was found in any of the observed gait parameters in TUG test.

4. Discussion

The aim of this study was to investigate the effects of minimal shoes, combination of a minimal shoes with textured insoles, a minimal shoes with supportive insoles, walking barefoot and habitual shoes on stability related spatiotemporal walking gait parameters in healthy young adults.

The first hypothesis, that walking barefoot would reveal similar results to minimal shoes. This was rejected as most of the observed gait parameters in the 2-minute walk test (2-MWT) varied significantly in barefoot walking compared to minimal shoes. The minimal shoe used in the current study meets all the characteristics of minimal shoes, i.e. low weight, highly flexible, low heel to toe drop, low stack height and absence of motion control/stability devices

Table 1. Spatiotemporal gait parameters (mean (SD)) for the 2-MWT across participants and footwear conditions.

	Shoes conditions					Within-subjects effects		Post hoc test									
Parameter	Habitual shoes mean (SD)	Barefoot mean (SD)	Minimal shoes mean (SD)	Minimal shoes with textured insoles MEAN (SD)	Minimal shoes with supportive insoles mean (SD)	F value	*p* value	H1	H2	H3	H4	B1	B2	B3	M1	M2	M3
Distance travelled in 2 minutes (m)	150.11 (17.59)	147.14 (17.24)	155.56 (16.04)	156.19 (17.18)	156.62 (17.23)	3.501	0.012	–	*	**	*	**	**	**	–	–	–
Cadence (steps/min)	108.98 (7.49)	114.95 (8.28)	113.04 (7.24)	112.55 (8.04)	112.18 (7.34)	4.693	0.002	**	**	**	**	*	**	**	–	–	–
Stride length (m)	1.38 (0.10)	1.28 (0.10)	1.38 (0.10)	1.39 (0.10)	1.40 (0.10)	7.139	<0.001	**	–	–	–	**	**	**	–	–	–
Stride length variability (%)	10.42 (2.89)	10.52 (2.91)	10.63 (3.22)	10.04 (2.84)	10.67 (3.10)	0.343	0.834	–	–	–	–	–	–	–	–	–	–
Single support time (s)	0.45 (0.02)	0.46 (0.02)	0.45 (0.02)	0.44 (0.02)	0.44 (0.02)	2.597	0.046	**	–	–	–	**	**	**	–	*	–
Double support time (s)	0.12 (0.04)	0.10 (0.04)	0.11 (0.03)	0.12 (0.03)	0.12 (0.03)	2.676	0.04	**	–	–	–	**	**	**	–	*	–
Swing time (s)	0.49 (0.04)	0.48 (0.04)	0.48 (0.03)	0.48 (0.03)	0.47 (0.03)	3.837	0.008	**	**	**	**	–	–	–	–	–	–
Step time (s)	0.55 (0.04)	0.52 (0.04)	0.53 (0.03)	0.54 (0.04)	0.54 (0.04)	6.072	<0.001	**	**	**	**	*	**	**	–	–	–

Notes. *indicates $0.001 < p < 0.05$. **indicates $p < 0.001$.

Abbreviations: SD, standard deviation; H1, habitual shoes with barefoot; H2, habitual shoes with minimal shoes; H3, habitual shoes with minimal shoes and textured insoles; H4, habitual shoes with minimal shoes and supportive insoles; B1, barefoot with minimal shoes; B2, barefoot with minimal shoes and textured insoles; B3, barefoot with minimal shoes and supportive insoles; M1, minimal shoes with minimal shoes and textured insoles; M2, minimal shoes with minimal shoes and supportive insoles; M3, minimal shoes with textured insoles and minimal shoes with supportive insoles.

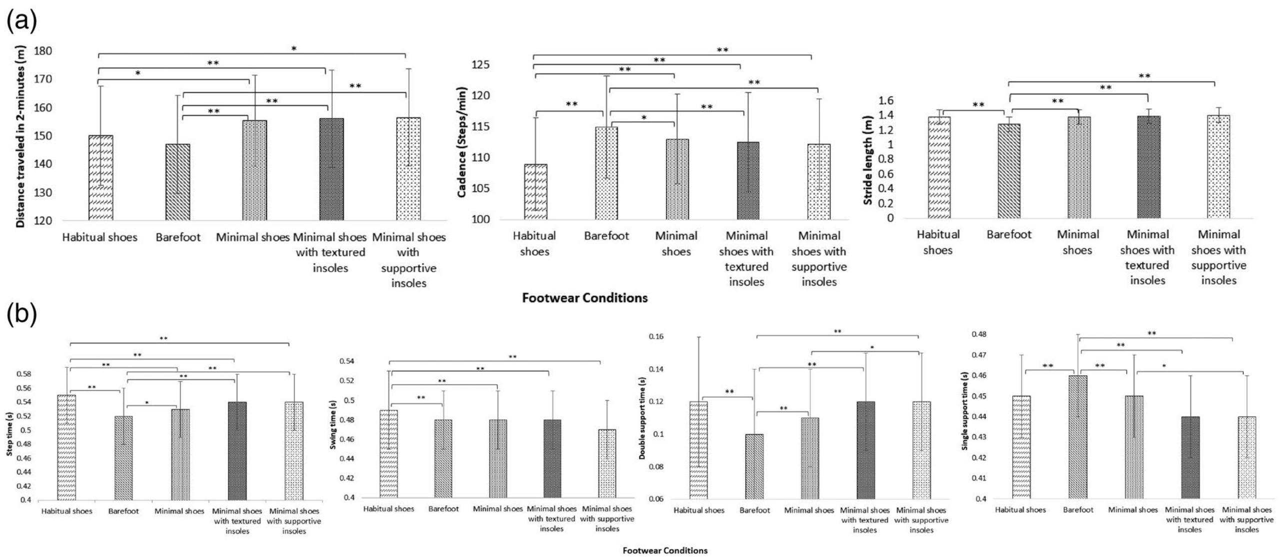

Figure 2. (a) Variations of distance travelled, cadence, and stride length with footwear conditions observed in 2-MWT. Notes: * indicates $0.001<p<0.05$, ** indicates $p<0.001$. (b) Variations of step time, swing time, double support time and single support time with footwear conditions observed in 2-MWT. Notes: * indicates $0.001<p<0.05$, ** indicates $p<0.001$.

Table 2. Spatiotemporal parameters (mean (SD)) for the TUG test across participants and footwear conditions.

	Footwear conditions					Within subjects effects	
Parameter	Habitual shoes mean (SD)	Barefoot mean (SD)	Minimal shoes mean (SD)	Minimal shoes with textured insoles mean (SD)	Minimal shoes with supportive insoles mean (SD)	F value	*p* value
Time taken to complete the task (s)	6.37 (0.81)	6.54 (0.84)	6.47 (0.78)	6.43 (0.84)	6.47 (0.80)	0.375	0.802
Time taken to stand (s)	1.03 (0.21)	1.05 (0.21)	1.05 (0.18)	1.04 (0.20)	1.06 (0.18)	0.744	0.552
Time taken to sit back after walking (s)	1.25 (0.29)	1.21 (0.26)	1.20 (0.24)	1.17 (0.26)	1.21 (0.27)	0.889	0.46
Stride length (m)	1.55 (0.13)	1.49 (0.13)	1.54 (0.12)	1.52 (0.12)	1.52 (0.12)	2.044	0.103
Stride length variability (%)	23.88 (6.83)	22.56 (4.63)	22.42 (5.18)	22.59 (5.57)	23.81 (6.26)	0.76	0.528
Single support time (s)	0.49 (0.03)	0.48 (0.02)	0.48 (0.02)	0.48 (0.06)	0.48 (0.06)	1.069	0.333
Double support time (s)	0.08 (0.02)	0.07 (0.02)	0.08 (0.06)	0.08 (0.03)	0.09 (0.04)	1.134	0.326
Swing time (s)	0.47 (0.04)	0.44 (0.04)	0.46 (0.04)	0.46 (0.04)	0.46 (0.04)	4.716	0.002
Step time (s)	0.48 (0.04)	0.46 (0.04)	0.47 (0.04)	0.47 (0.04)	0.47 (0.04)	3.081	0.02

(Esculier et al., 2015). Though minimal shoes is designed to provide minimum interference to the natural function of the foot, outcome of the current study shows that walking in minimal shoes is biomechanically different to walking barefoot. In line with current study, higher cadence and lower step length in barefoot also observed in other studies (Huber et al., 2022; Wirth et al., 2011). Huber et al. (2022) compared gait parameters based on the data collected from treadmill walk at constant speed, whereas Wirth et al., 2011 used self-selected gait speed on 12-meter long GAITRite walkway mat (Huber et al., 2022; Wirth et al., 2011). As gait parameters has direct influence on walking speed and characteristics of footwear, instead of controlled walking speed and short duration, 2-MWT at self-selected speed was used in the current study for having more reliable outcome. Covering significantly greater distance in minimal shoes compared to barefoot walking within same time means gait speed was higher in minimal-shoes. This indicates, under safe environmental conditions inside the laboratory, participants reduced their gait speed for maintaining stability during barefoot walking, as this strategy is also observed when stability were challenged by inducing unexpected perturbation (Madehkhaksar et al., 2018). Better dynamic stability and gait variability in minimal shoes are also reported in another study compared to barefoot (Petersen et al., 2020).

The second hypothesis of the study, i.e. use of textured and supportive insoles with minimal shoes will improve gait parameters compared to minimal shoes was drawn based on the previous positive effects of textured and supportive insoles on gait and stability, especially in older adults (Ma et al., 2020; Qu, 2015). Contrary to the second hypothesis, no significant difference was found in observed gait parameters between minimal shoes, minimal shoes with a textured insoles and minimal shoes with a supportive insoles in 2-MWT and TUG test, except for single and double support time in 2-MWT. Significantly increased single support time and reduced double support time in minimal shoes compared to minimal shoes with supportive insoles implies additional insole features of the supportive insole did not provide positive effects on these parameters. Another study comparing the effects of minimal shoes and various combinations of textured insoles with minimal shoes on postural and dynamic stability in healthy middle-aged and older adults also reported no significant difference among various combinations of minimal shoes and textured insoles (Cudejko et al., 2020). However, they measured stability based on centre of pressure data and a

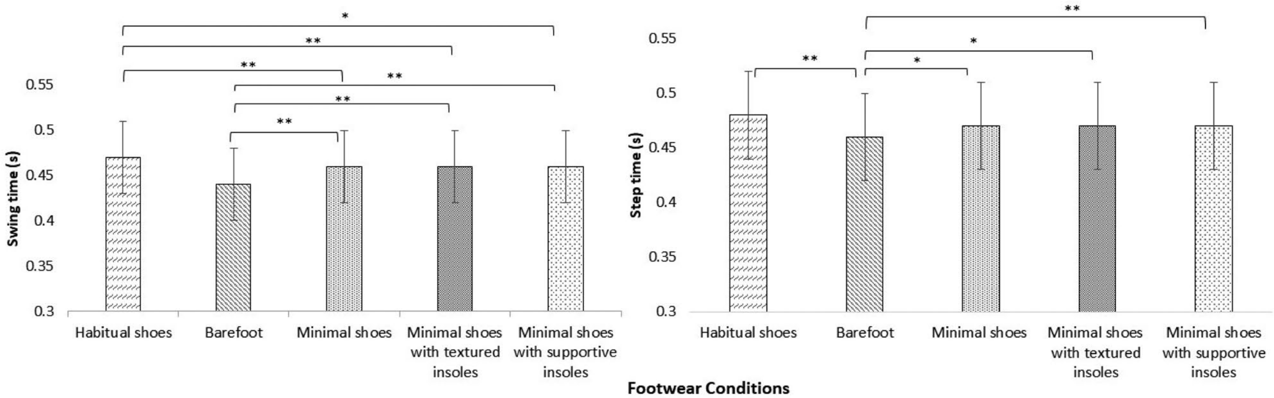

Figure 3. Variations of swing time and step time with footwear conditions observed in TUG test. Notes: * indicates $0.001<p<0.05$, ** indicates $p<0.001$.

supportive insoles was not included in that study as was done in the current study.

Increased gait speed and cadence, along with longer step length, are considered as stable gait parameters (Verghese, 2006). Pairwise comparisons of footwear conditions revealed that participants covered a significantly greater distance during the 2-MWT at self-selected speed in minimal shoes, in minimal shoes with textured insoles, and in minimal shoes with supportive insoles compared to barefoot and habitual shoes with larger stride length and improved cadence. This implies that, irrespective to the insole used, minimal shoes improved gait parameters when compared to barefoot walking or walking in habitual shoes, i.e. sneakers or trainers. Habitual shoes used in the study were representative of cushioned shoes with rigid outsole. Similar result in all minimal shoes conditions as well as improved gait parameters over habitual shoes and barefoot implies that flexibility, weight, overall shape, and heel height of the footwear play significant role in altering gait parameters rather than only cushioning.

Time required to complete the Timed up and Go (TUG) test is commonly used for fall risk assessment for older adults (Park, 2018). In the current study, except increased step and swing time in habitual shoes compared to other conditions none of the observed parameters showed significant difference between footwear conditions in this test. Which indicates the TUG test appears less sensitive in detecting the effects of footwear characteristics on spatio-temporal parameters in healthy young adults.

In a study by Bhatt et al., a strong correlation was observed between gait speed and stability at slip onset (Bhatt et al., 2005). Participants altered their gait by increasing step frequency, step width and decreasing stride length when encountering unexpected perturbation or when stability is compromised by increasing perturbation intensity (Hak et al., 2013; Madehkhaksar et al., 2018). These alteration aid stability as it shows improvement in the measure of margin of stability (Hak et al., 2013). Despite the controlled laboratory environment and the absence of perturbations in the current study, walking barefoot appeared to be least stable condition, with participants covering the least distance, higher cadence, and smaller stride length. In habitual shoes, despite the presence of greater stride length, gait speed was slower compared to walking in various minimal shoes conditions, primarily due to the lowest cadence, increased swing and step time. Stride length variability, another indicator of gait instability (Beauchet et al., 2009) did not show significant variation among footwear conditions in current study.

Existing research has demonstrated that the use of supportive insoles can lead to improvements in various measures, including Berg Balance Scale, TUG score, 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). Use of textured and supportive insoles with the minimal shoes in the current study did not yield discernible advantages over minimal shoes. Whereas supportive insoles provided comfort and support to the foot structure without compromising the gait parameters. Therefore, the inclusion of supportive insoles with minimal shoes could be a favourable approach for individuals transitioning from habituated cushioned shoes to minimal shoes. This strategy could facilitate a gradual adaptation to minimal shoes from cushioned shoes, thereby reducing the risk of injury related to stress fracture and tendonitis due to the removal of arch support and cushioning in minimal shoes (Salzler et al., 2012). However, longitudinal studies are required to confirm these outcomes.

5. Limitations

Outcomes of this cross-sectional study are based on a sample of healthy young adults. Age-related physiological changes, different health status, physical activity levels, and diverse range of habitual footwear were not considered in the study design. Therefore, findings of this study have lack of generalisability and may not be applicable to other age groups or those having physiological aspects such as vestibular disorders, neurological conditions, or musculoskeletal issues affecting dynamic and static stability. Future research should include a broader age range and individuals with varying health conditions to enhance the generalisability of the findings. Longitudinal studies are needed to improve the applicability of the results as it will provide more comprehensive understanding about the long-term effect of using minimal shoes and insole characteristics on stability. Instead of safe laboratory conditions, natural environment where irregularities and unpredictable changes are present can also be used as walking trail. Moreover, other daily activities such as stair gait may be included in future studies to enhance the reliability of the outcome in various real-life situations.

6. Conclusion

The outcome of the current study highlights that irrespective to various insole characteristics, all minimal shoes conditions improved stability-related spatiotemporal walking gait parameters compared to being barefoot walking or walking in habitual sneakers or trainers, indicated by the increased distances covered with greater stride lengths. Few differences were found among three minimal shoes conditions in the observed gait parameters, suggesting that textured and supportive insoles in minimal shoes do not provide any additional benefit to enhance stability in young healthy adults during walking.

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