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Minimal footwear improves stability and physical function in middle-aged and older people compared to conventional shoes

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ABSTRACT

Background: Effects of minimal shoes on stability and physical function in older people are under-researched. No studies have systematically explored effects of a range of minimal footwear features on these factors in older people.

Methods: A within-participant repeated-measures design was used. Participants were subjected to thirteen footwear conditions: (i) barefoot, (ii) a conventional shoe, (iii) a control minimal shoe, (iv-xiii) minimal shoes differing from the control minimal shoe by one design feature. The outcomes were: (i) postural stability expressed with movement of the center of pressure (CoP) during standing (ii) dynamic stability expressed with the CoP movement during walking, (iv) physical function assessed with the Timed Up and Go test (TUG), and (iv) perceptions of footwear assessed with the Monitor Orthopaedic Shoes questionnaire. Linear Mixed Models were applied for statistical analyses.

Findings: Twenty-two people participated in the study. Compared to the conventional shoe, participants: (i) were more stable during standing and walking in the majority of minimal shoes, and (ii) completed the TUG test faster when wearing the minimal shoe with wider sole. Compared to the control minimal shoe, participants: (i) completed the TUG test faster when wearing the minimal shoe with wider sole; and (ii) perceived features such as a split toe and a higher ankle collar as less fashionable and wearable.

Interpretation: Wearing minimal shoes might be more beneficial for stability and physical function in older adults than wearing conventional shoes. The results will be highly valuable for the design of minimal footwear for older adults.

1. Introduction

Falls occur in 30–60% of older adults each year, and 10–20% of these result in injury, hospitalisation and/or death (Rubenstein, 2006). Costs resulting from falls in 2009 alone ranged between 0.85 and 1.5% of the total healthcare expenditure within the United States of America and the European Union (Heinrich et al., 2010). Postural and dynamic (gait) instabilities have been recognized as major risk factors for frequent falls among older people (Rubenstein, 2006). Although the causes of falls are complex and multifactorial, footwear, being at the interface between the body and the surface, influences stability and, subsequently, the risk of falling (Gabell et al., 1985).

Footwear plays an important role in postural and dynamic stability by facilitating somatosensory feedback to the foot, via the tactile and proprioceptive systems. Changes in foot pressures are often related to changes in human erect posture (Kavounoudias et al., 1998). It has been shown that when plantar surface afferents are anaesthetised, the maintenance of stability in quiet stance is impaired (Meyer et al., 2004). Due to their design features i.e. cushioning and higher heels, use of conventional shoes is thought to lead to a diminished capacity to detect information from the soles of the feet during interactions with external environments (Ridge et al., 2018). In contrast, research suggests that minimal footwear might improve stimulation of plantar mechanoreceptors compared to conventional shoes (Franklin et al., 2018), enhancing postural responses. Studies comparing minimal shoes with conventional shoes in older people are limited (Broscheid and Zech, 2016). In addition, although often referred as “barefoot” shoes, little is known how minimal shoes compare to actual barefoot in contributing

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to human stability and physical performance.

Numerous features of shoe design have been suggested to have an impact on stability and physical performance (Aboutorabi et al., 2016). These include heel height, heel-collar height, sole hardness, heel and midsole geometry and slip resistance of the outer sole. Minimal footwear attempts to minimise the influence of such features as it is a "footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices" (Esculier et al., 2015). To our knowledge, the stability and physical performance-related effects of minimal footwear features have not been studied yet in older people. Furthermore, peoples' perception of the design of minimal footwear is rarely considered. To be regarded a practical intervention, minimal footwear needs to be acceptable to older people from the perspective of comfort, ease of use and aesthetics (Davis et al., 2013).

The primary aim of the study was to investigate the effects of minimal shoes on postural and dynamic stability, and physical function in older people compared to conventional shoes. The secondary aims were: (i) to systematically explore the effects of a range of minimal footwear features on these factors and on perceptions, and (ii) to compare minimal shoes to barefoot.

2. Methods

2.1. Trial design

A within-subject repeated-measures design was used. Participants were subjected to thirteen footwear conditions in a randomized order i.e. (i) barefoot, (ii) a standardized conventional shoe, (iii) a control minimal shoe, (iv–xiii) minimal shoes differing from the control minimal shoe by one design feature (Fig. 1). Simple randomisation with a computer system (www.randomizer.org) was used.

2.2. Participants

Participants were recruited via posters and adverts in the University of Liverpool's staff intranet between December 2018 and February 2019. Inclusion criteria were (i) age: ≥45 years old, and (ii) foot length 22.2–24.2 cm or 25.2–27.2 cm (due to availability of prototypes of the minimal shoes). Exclusion criteria were: (i) presence of a macro-vascular condition (angina, stroke, peripheral vascular disease or diabetes) or a neuromuscular disease (Multiple Sclerosis, Alzheimer's disease or Parkinson's disease), (ii) use of a walking aid (cane or walker), (iii) ankle, knee or hip surgery ≤3 months, and/or (iv) pain of ≥8 on the Numeric Rating Scale (0 – not pain at all, 10 – worst pain imaginable). Inclusion and exclusion criteria were self-reported by participants and/or managed objectively by the study coordinator (TC).

All participants provided written informed consent according to the Declaration of Helsinki. Ethics approval was obtained from the Research Ethics Committee of the University of Liverpool.

Fig. 2. A. Conventional shoe for women (Go Walk 4.0-Pursuit, Skechers USA, Inc.); B. Conventional shoe for men (Superior 2.0-Jeveno shoe, Skechers USA, Inc.); C. Control minimal shoe (Vivobarefoot ltd., London, UK).

2.3. Footwear conditions

2.3.1. Barefoot

Participants undertook assessments barefoot.

2.3.2. Standardized conventional shoe

The Go Walk 4.0-Pursuit for women (Skechers USA, Inc.; Fig. 2A) and the Superior 2.0-Jeveno shoe for men (Skechers USA, Inc.; Fig. 2B) were used.

2.3.3. Minimal shoe

A range of prototypes of the Vivobarefoot Ltd. (London, UK) minimal shoe (Fig. 2 C) were evaluated. Size 4 (EU 37) for women and 8

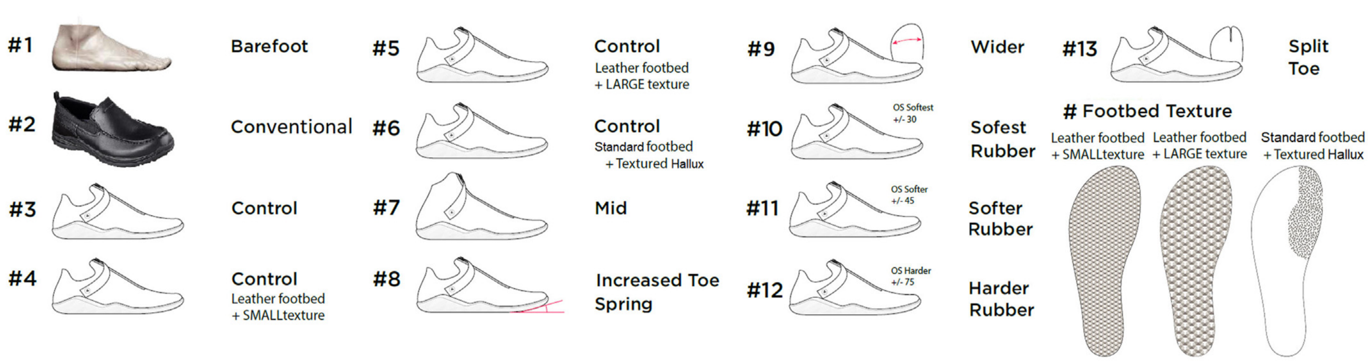

Fig. 1. List of footwear conditions. Abbreviations: Mid – minimal shoe with a higher ankle collar; OS – Shore O hardness scale.

(EU 42) for men were used.

To diminish participants' bias, we did not inform participants about the characteristics of the shoes and the study hypothesis. The study coordinator (TC) fitted each participant with the shoes by palpating the participant's hallux during standing to ensure that there was approximately 0.5–2 cm between the hallux and shoe end. Participants were asked if they were comfortable in the shoe and if the shoe felt that it was appropriately fitted to ensure correct fitting.

2.4. Outcome measures

2.4.1. Postural stability

Postural stability was expressed with movement of the center of pressure (CoP) during standing. CoP movement was measured using a pressure plate (FootWork Pro, AM CUBE, Berkshire, UK) with 4096 sensors, dimensions 490 × 490 × 7.6 mm and a sampling frequency 20 Hz. Participants were required to stand still on both feet with eyes closed. Three trials of 30 s were performed for each footwear condition. Intra-tester and inter-tester reliability for this method have been reported as high in older people (Ruhe et al., 2010). Postural stability was quantified by computing the mean velocity (mm/stance duration) and the maximum range (mm) of the CoP movement in anterior-posterior (AP) and medial-lateral (ML) directions. Smaller values were considered as indicative of better postural stability. The mean values from the three trials were used for further statistical analyses (Ruhe et al., 2010).

2.4.2. Dynamic stability

Dynamic stability was expressed with movement of the CoP during walking. CoP movement was measured using a pressure plate (FootWork Pro, AM CUBE, Berkshire, UK). Participants were required to walk over the pressure plate at their self-selected walking velocity. Dynamic stability was quantified by computing the mean velocity (mm/stance duration) and the maximum range (mm) of the COP displacement in the ML direction. Smaller values were considered indicative of better dynamic stability. The displacement of the CoP in ML direction was defined with respect to the x-axis, perpendicular to the longitudinal foot axis. The longitudinal foot axis was defined as the regression line fitted against all non-zero cells. A mean value from three trials for each foot was used for further statistical analysis.

2.4.3. Physical function

Physical function was assessed with the Timed up and Go (TUG) test. The TUG test is typically used to evaluate basic physical function in older people (Podsiadlo and Richardson, 1991). The TUG test was timed with a stopwatch and a continuous form, in seconds, was used in the statistical analyses. A longer time to complete the test was considered as worse physical function. Intra-tester and inter-tester reliability for the TUG test have been reported as high in older people (Steffen et al., 2002).

2.4.4. Perceptions of footwear

Perceptions of the minimal footwear were assessed using questions selected from the Monitor Orthopaedic Shoes questionnaire (van Netten et al., 2009) and scored on a 100-mm visual analogue scale (VAS). The selected questions were related to: (i) attractiveness (0 mm - extremely unattractive, 100 mm - extremely attractive); (ii) attractiveness for others (0 mm - extremely unattractive, 100 mm - extremely attractive); (iii) comfort (0 mm - extremely uncomfortable, 100 mm - extremely comfortable); (iv) fit (0 mm – worst fit possible, 100 mm – best fit possible); (v) ease of use (0 mm – extremely difficult to put on and off, 100 mm - extremely easy to put on and off); (vi) weight (0 mm - extremely light, 100 mm - extremely heavy). The remaining questions from the Monitor Orthopaedic Shoes questionnaire were not administered, as they relate to the perceived effectiveness of footwear in the treatment of foot pain, wounds, and sprains. The rating scale has been previously validated and is reported to be a reliable measure of perceptions of footwear (Mills et al., 2010; van Netten et al., 2009). An additional question regarding stability of the footwear was also administered using the VAS (0 mm - extremely unstable, 100 mm - extremely stable). The VAS is a tool with high sensitivity and low bias tendency and has been previously used to assess the stability of footwear (Leong et al., 2018). The conventional shoes were shoes that are currently available on the market. Conversely, minimal shoes are prototype versions not ready for market sale, and therefore they were not intended to be attractive nor have a perfect fit/comfort yet. For this reason, we assessed perceptions of footwear only for the comparison between the control minimal shoe and other minimal shoes. We did not evaluate perceptions of footwear for barefoot and the conventional shoes.

2.5. Other measures

Participants' physical characteristics were recorded prior to testing and included: age, sex, weight, height, body-mass index (BMI), foot length. BMI was calculated as body mass in kilograms divided by height in meters squared. Foot length, in centimetres, was measured with a tape from back of the heel until top of the hallux.

2.6. Procedure

Participants attended a single testing session at the Gait Laboratory, Faculty of Health & Life Sciences, University of Liverpool. Prior to data collection, the procedures were described in detail for the participants and each participant read and signed a consent form. Participants had a familiarization session for each of the assessments, before data collection started.

Following recording of participants' physical characteristics, participants were fitted with the first footwear condition and commenced the assessments of postural stability. Participants were required to stand still on both feet with eyes closed for 30 s. The position of the feet was marked on the pressure plate to ensure the same foot placement for all conditions and to eliminate confounding effects of altered foot position between trials. Explicit instruction was given to participants i.e. “When I say ‘go’ I want you to close your eyes and to stand as still as possible until you hear the instruction to rest. Keep your arms relaxed by your sides but do not rest your hands on your body” (Ruhe et al., 2010). A test was invalidated and repeated if the participant: (i) moved their foot position during the test; (ii) changed their arm starting position or (iii) opened their eyes.

Following the assessment of postural stability, we evaluated participants' dynamic stability. The 5-step mid-gait protocol was used, which is a reliable standardized protocol previously reported by Burns et al. (Burns et al., 2005), in which the participant strikes the pressure platform on the fifth step as he or she walks along an 8-m walkway. To ensure a natural gait, cadence and gait speed were not controlled and each participant had a practice session walking across the pressure plate. Participants were positioned at the start line and given the following standardized instructions: “Please start walking at your usual speed towards the end of the walkway, now”. Participants were instructed not to look down at the pressure plate in order to prevent targeting. Data collection was considered valid when the following criteria were met: (i) at least three complete footprints from each foot, (ii) no visible adjustment in gait pattern when crossing the plate, (iii) total stance duration was within 10% of the individual average value.

Next, participants completed the TUG test. Participants began the test sitting correctly (hips all the way to the back of the seat) in a chair with arm rests. The chair was stable and positioned such that it did not move when the participant moved from sit to stand. The participants were allowed to use the arm rests during the sit-stand and stand-sit movements. Explicit instruction was given to participants i.e.: “On the word ‘go’ you will stand up, walk to the line on the floor, turn around and walk back to the chair and sit down. Walk at your regular pace." Timing started on the word "go" and stopped when the participant was seated again correctly in the chair with their back resting on the back of the chair.

Following the TUG test, participants completed the questionnaire related to the perceptions of footwear. After completing the questionnaire, participants had a 5 min break during which: (i) they were seated, allowing them to rest to prevent fatigue, (ii) they were asked to become accustomed to the new footwear condition by performing a ten-metre walk ten times (Melvin et al., 2014). The whole testing session lasted from 1.5 to 2 h and was non-strenuous to participants.

2.7. Data processing

The CoP data were filtered using a 4th-order zero-lag Butterworth low-pass filter with a 2 Hz cutoff frequency, and processed using custom Matlab routines (R2014a, The Mathworks, Inc., Natick, Massachusetts, USA).

2.8. Statistical analysis

Descriptive statistics were used to characterize the study population. Numbers (percentages) were used for categorical variables and means (SD) for continuous variables. Prior to the statistical analysis, outcome measures were checked for normality with Shapiro–Wilk and Kolmogorov-Smirnov tests. Because data on postural and dynamic stability were positively skewed, statistical analyses were conducted on log10-transformed data (Tabachnick and Fidell, 2007). Linear mixed-effects model analysis with Bonferroni corrections was used for statistical analyses. The following comparisons were made: (i) the conventional shoe versus minimal shoes, (ii) the control minimal shoe versus other minimal shoes, and (iii) barefoot versus minimal shoes and the conventional shoe. Statistical significance was accepted at $p < 0.05$. All analyses were performed using SPSS software, version 24.0 (IBM, Armonk, NY, USA).

3. Results

3.1. Descriptive

Twenty-two people participated in the study. The participants had a mean age of 55.4 years (SD 7.8), a mean BMI of 26.7 kg/m^2 (SD 4.9) and 11 (50.0%) were women. Participants using shoe size 4 had a mean foot length 23.2 cm (SD 0.33), and participants using size 8 had a mean foot length of 26.3 (SD 0.30).

3.2. Postural stability

Participants were more stable during standing when wearing each of the minimal shoes than when wearing conventional shoes (except two cases). There were no differences between the control minimal shoe and other minimal shoes, nor between barefoot and all minimal shoes. Full results are presented in the Table 1.

3.3. Dynamic stability

Compared to wearing the conventional shoe, participants were more stable during walking when wearing the minimal shoe with wider sole, the minimal shoe with higher ankle collar, the minimal shoe with softer rubber and the minimal shoe with harder rubber. We found no differences between the control minimal shoe and other minimal shoes, nor between barefoot and all minimal shoes. Full results are presented in the Table 1.

3.4. TUG test

When wearing the minimal shoe with a wider sole, participants completed the TUG test in a faster time compared to when wearing the conventional shoe (mean difference (md) −0.45 s.; standard error (std. error md) 0.12; 95% Confidence Intervals (CI) −0.85–0.01), and compared to when wearing the control minimal shoe (md −0.46 s.; std. error md 0.12; 95% CI −0.86–0.01). Full results are presented in Fig. 3 A.

3.5. Perceptions of footwear

Compared to the control minimal shoe, participants perceived the minimal shoe with a split toe as: less attractive (md −24.3 mm, std. error md 3.1; 95% CI -34.6 -14.0; Fig. 3 B), less attractive for others (md −24.4 mm, std. error md 3.3; 95% CI -35.4 -13.4; Fig. 3 C), less comfortable (md −29.8 mm, std. error md 4.3; 95% CI -44.5 -15.1; Fig. 3 D) and as more difficult to put on and off (md −27.2 mm, std. error md 4.1; 95% CI -41.1 -14.0; Fig. 3 F). Compared to the control minimal shoe, participants perceived the minimal shoe with a higher ankle collar as: more difficult to put on and off (md −16.0 mm, std. error md 4.1; 95% CI -29.9 -2.0; Fig. 3 F) and heavier (md 9.8 mm, std. error md 2.6; 95% CI 1.0 18.5; Fig. 3 G). Full results are presented in the Fig. 3 B–H.

Because it has been shown that adjusting the *p*-value for multiple comparisons might lead to an increased risk of type II error (Perneger, 1998), the statistical analyses were repeated without the Bonferroni corrections. The conclusions were the same (data not shown).

4. Discussion

4.1. Conventional shoe versus minimal shoes

To our knowledge, this is the first study that shows that wearing minimal shoes is more beneficial for postural and dynamic stability in older people than wearing conventional shoes.

We observed that wearing minimal shoes consistently improved all CoP metrics of anterior-posterior and almost all metrics of medio-lateral postural stability. A likely explanation is that heel elevation present in the conventional shoe might have shifted the total body center of mass anteriorly, modifying posture and plantar pressure distribution (Snow and Williams, 1994). In addition, shoes with higher heel may lead to lateral instability as they present a higher tipping angle compared to lower heel shoes (Tencer et al., 2004). We also showed that some of the minimal shoes were more beneficial for dynamic stability compared to the conventional shoe. The plausible reason behind why all minimal shoes were superior to the conventional shoes in improving postural stability and only several were found to be superior in improving dynamic stability may lay in the methodology. Postural stability was assessed with participant's eyes closed, while dynamic stability was assessed with eyes open. It is known that human postural control system relies more heavily on the somatosensory system for proprioceptive feedback to maintain balance when vision is compromised (Simoneau et al., 1999). Our findings are in contrast to previous study (Broscheid and Zech, 2016) which showed that one-time use of minimal footwear reduced balance control compared to conventional shoes. This discrepancy might be explained by different methods used in both studies. We expressed postural stability by movement of the center of pressure in both anterior-posterior and medio-lateral directions. Broscheid & Zech used the Balance Error Scoring System, involving a performance-based physical test in which an examiner counts errors, or deviations from the proper stance, accumulated by the subject.

Furthermore, we observed that participants completed the TUG test 0.45 s. faster when wearing the minimal shoe with a wider sole than when wearing the conventional shoe. This effect might be explained by a more stable base of support and enhanced somatosensory information from the skin receptors in the foot sole. Kennedy and Inglis (Kennedy

Table 1
Footwear effects on metrics of postural and dynamic stability (means and SD).

	Postural stability				Dynamic stability	
	AP Velocity (mm/st. dur.)	AP range (mm)	ML velocity (mm/ st. dur.)	ML range (mm)	ML velocity (mm/ st. dur.)	ML range (mm)
Barefoot	13.38 (4.6)[a]	3.62 (1.2)	6.43 (2.8)[a]	1.67 (0.7) [a]	14.53 (4.6)[a]	5.28 (1.4)
Conventional	19.03 (5.8) [b,c]	4.27 (1.4) [b]	10.05 (4.2) [b,c]	2.33 (1.2) [c]	18.12 (4.5) [c]	6.76 (2.5) [b]
Control	12.95 (4.1)[a]	3.29 (1.1)[a]	7.09 (3.1) [a]	1.86 (0.9)	16.15 (4.3)	5.17 (1.4) [a]
Control + ST	12.78 (4.9)[a]	3.16 (1.1)[a]	6.68 (2.4) [a]	1.67 (0.7) [a]	16.95 (5.6)	5.36 (1.6)
Control + LT	12.51 (4.0)[a]	2.85 (0.8) [a,c]	7.39 (2.5) [a]	1.73 (0.5) [a]	17.73 (6.6)	5.83 (2.6)
Control + TH	12.99 (4.9)[a]	3.27 (1.4) [a]	7.26 (2.9) [a]	1.70 (0.7) [a]	15.16 (4.8) [a]	5.13 (1.6) [a]
Mid	13.27 (4.2)[a]	3.11 (0.9) [a]	6.99 (2.3) [a]	1.65 (0.5) [a]	15.18 (4.9) [a]	4.80 (1.4) [a]
↑Toe Spring	13.59 (3.9)[a]	3.32 (1.0) [a]	7.20 (2.4) [a]	1.81 (0.6) [a]	16.67 (5.7)	5.36 (1.9)
Wider sole	12.84 (4.2)[a]	3.39 (1.2) [a]	7.14 (2.7) [a]	1.70 (0.6) [a]	16.02 (4.8) [a]	4.42 (1.7) [a]
Softest rubber	13.93 (4.8)[a]	3.24 (1.1) [a]	7.31 (3.0) [a]	1.78 (0.7) [a]	16.43 (6.2)	5.80 (2.1)
Softer rubber	13.37 (4.1)[a]	3.42 (0.8) [a]	6.47 (2.3) [a]	1.53 (0.5) [a]	14.43 (3.8) [a]	4.66 (1.2) [a]
Harder rubber	12.78 (4.1)[a]	3.20 (1.2) [a]	7.12 (2.1) [a]	1.71 (0.5) [a]	14.92 (4.1) [a]	4.83 (1.5) [a]
Split Toe	12.57 (4.2)[a]	3.24 (1.2) [a]	7.16 (2.6) [a]	1.87 (0.8)	16.36 (4.5)	5.63 (1.7)

Abbreviations: AP – anterior-posterior, ML – medial-lateral; mm/st. dur – millimetres/stance duration; ST – leather footbed with a small texture; LT – leather footbed with a large texture; TH – standard footbed with textured hallux; ↑ - increased; Mid – higher ankle collar.

[a] Significantly different from the conventional shoe.

[b] Significantly different from the control minimal shoe.

[c] Significantly different from barefoot.

and Inglis, 2002) observed increased concentration of cutaneous mechanoreceptors in the forefoot of the human sole and its lateral borders. These receptors are sensitive to contact pressures (Magnusson et al., 1990) and may be sensitive to potential changes in the distribution of pressure (Kavounoudias et al., 1998). The wider sole might have allowed the pressures to be distributed more evenly across the foot, potentially leading to stimulation of plantar mechanoreceptors located in the regions that are not normally stimulated in a conventional shoe with a narrower sole. It is plausible that the central nervous system could have used this additional sensory information to elaborate on descending motor strategies (i.e. improved muscle activity and/or gait stability), resulting in an ability to complete the TUG test in a faster time.

Although footwear effects on performance-based physical function has been studied before in older people (Aboutorabi et al., 2016), the results seems conflicting and direct comparison are difficult due to the variability of the footwear used. The clinical significance of this effect should be viewed in the light of this being a laboratory study among healthy older adults, and the short duration of use of the footwear.

4.1. Control minimal shoe versus other minimal shoes

This is the first study that systematically explored the effects of minimal footwear features on postural and dynamic stability, physical function, and perceptions of footwear in older people.

We did not find any advantages or disadvantages of other features of minimal footwear on postural and dynamic stability. A likely explanation could be that the assessments might not have been sensitive enough to detect differences between other features of the minimal shoes. Future studies should employ more extensive testing, such as surface electromyography, proprioceptive testing or kinematic analysis, during more challenging dynamic motor tasks, for example, when walking on varying surfaces or during stepping over obstacles.

We showed that when wearing the minimal shoe with a wider sole, participants completed the TUG test 0.46 s. faster than when wearing the control minimal shoe. As discussed earlier, greater contact area may reflect a more stable base of support and a greater transmission of tactile information about surface to the foot (Kennedy and Inglis, 2002), which might have helped participants to complete the TUG test in a faster time. Poor performance on the TUG test has been associated with increased risk of falls (Beauchet et al., 2011; Kang et al., 2017). Thus, our study endorses previous literature indicating the importance of a footwear with a wide sole for fall prevention (Tencer et al., 2004).

Finally, we observed that certain features of minimal shoes, i.e. a split toe and a higher ankle collar, were not deemed wearable and/or fashionable by older people. The mean overall attractiveness score for each of the minimal shoes failed to reach half way of the scale. This, however, was to be expected, as these were prototype versions of the minimal shoe not intended to have an attractive style. More importantly, participants viewed all minimal shoes, except the prototypes with a split toe and a higher ankle collar, as comfortable and easy to use, demonstrating the potential feasibility of this type of footwear in older people.

4.2. Barefoot versus minimal shoes and conventional shoes

We did not find any differences in postural and dynamic stability nor in physical function between barefoot and minimal shoes. Previous research has shown that minimal footwear is similar to barefoot in kinematics and kinetics (Wirth et al., 2011; Wolf et al., 2008) and in lower-leg muscle activity during walking (Franklin et al., 2018). Our findings further strengthen the claim that minimal footwear is similar to barefoot by showing no differences in movement of the CoP during standing and walking, nor in performance-based physical function.

The results of the study showed that when being barefoot, participants were more stable during standing and walking than when wearing the conventional shoes.

Although being barefoot has also been previously associated with good postural stability performance in the laboratory (Lord and Bashford, 1996), evidence from prospective observational studies (Koepsell et al., 2004; Menz et al., 2006) show that being barefoot or wearing socks indoor increases the risk of falls. A likely explanation of this discrepancy is that without shoes, the foot is more vulnerable to pain if an unexpected obstacle is encountered or to slips on certain surfaces, potentially leading to an increased chance of a fall in an indoor environment.

4.3. Significance

We showed that wearing minimal footwear improves biomechanical measures of postural and dynamic stability. Loss of stability is an important factor in increasing the risk of falling in older people. Thus, this study might assist clinicians in making recommendations to their patients about safer footwear.

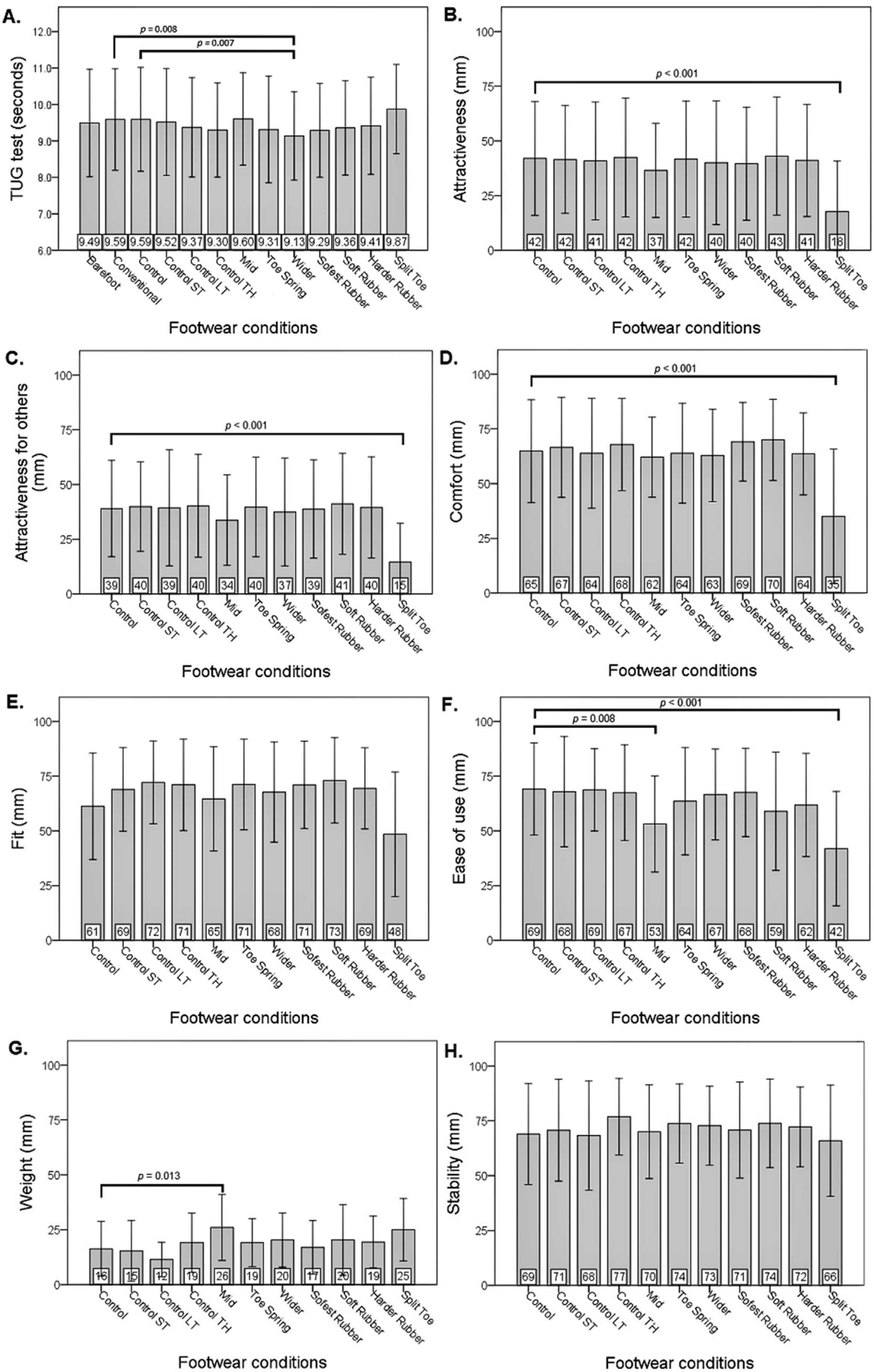

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Fig. 3. Effects of the footwear on the TUG test and perceptions (means and SD). Abbreviations: ST – footbed with a small texture; LT – footbed with a large texture; TH – standard footbed with textured hallux.

This study might have important implications for the design and manufacturing of minimal shoes. Based on the results, minimal shoes for older people should include a wide sole to maximize effects on physical function. To improve adherence and satisfaction, minimal shoes should not have the following features: a split toe and/or a higher ankle collar.

4.4. Limitations

First, participants were not tested while wearing their own shoes which might reduce the generalizability of the results. In addition, testing participants in new shoes may influence postural and dynamic responses to footwear. However, we allowed participants sufficient time to become accustomed to the new footwear (Melvin et al., 2014).

Moreover, while the metrics of postural and dynamic stability we used may not provide a full insight into human stability, previous research has shown that they are reliable measures (Ruhe et al., 2010) and are associated with falls in older people (Piirtola and Era, 2006). In addition, CoP describes the neuromuscular response to shifts of center of mass and measures of CoP have been previously used as an indicator of dynamic stability (Reid et al., 2011; Sims and Brauer, 2000).

Finally, the findings should be treated with caution when applied to real-life situations, since the testing was conducted in a safe laboratory environment which might not translate to performance in the activities of everyday life of older people.

5. Conclusions

This study suggests that wearing minimal shoes may be more beneficial for postural and dynamic stability in older people than wearing conventional shoes. In addition, wearing minimal shoes with a wider sole might translate to improved physical function in older people. Finally, minimal shoes with a split toe or with a higher ankle collar are not deemed fashionable and/or wearable by older people. This information may help older adults, clinicians who care for them, and shoe designers to make better-informed choices regarding footwear for fall prevention.

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Declaration of competing interest

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