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Can flexible shoes improve function in the older foot?

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Keywords
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Abstract

Older people with toe deformities have been identified as having an increased risk of falling. Little is known, however, about the biomechanical changes that might contribute to this increased risk. Therefore, the purpose of this study was to determine whether older people with hallux valgus and lesser toe deformities displayed different gait, balance and plantar pressure characteristics compared to individuals without toe deformities. The presence of hallux valgus and lesser toe deformities were assessed for 312 community-dwelling older men and women. Spatiotemporal gait parameters were measured using the GAITrite® system, postural sway was assessed on two surfaces using a sway-meter and dynamic plantar pressure distribution was measured using an Emed-AT4 pressure plate. The results indicated that, although there were no effects of toe deformities on spatiotemporal gait characteristics or postural sway, older people with hallux valgus (n=36) and lesser toe deformities (n=71) were found to display altered forefoot plantar pressure patterns. These findings suggest that toe deformities alter weight distribution under the foot when walking, but that the relationship between toe deformities and falls may be mediated by factors other than changes in spatiotemporal gait parameters or impaired postural sway.

Keywords: hallux valgus, toe deformity, foot problems, plantar pressures, gait

1. Introduction

The ability to walk safely and efficiently is vital for older people in order to reduce the risk of falling and to maintain independence [1]. Despite many age-related changes in balance and gait biomechanics being well documented [2, 3], relatively few studies have investigated the relationship between specific foot problems and foot function in the older population. The presence of lesser toe deformities and the severity of hallux valgus has been shown to have weak-to-moderate relationships with balance and functional test scores in older retirement village residents [4], suggesting that toe deformities may contribute to a decline in functional mobility. Our recent research has also found that older people with moderate-to-severe hallux valgus and lesser toe deformities were at a greater risk of falling than older people without these deformities [5]. We theorize that these toe deformities compromise foot function leading to mechanical instability. As a consequence, stability during the weight-bearing and push-off phases of gait, or when in situations requiring corrective steps to maintain balance, will be affected. This notion, however, has not been systematically investigated.

Despite the important contribution of the toes to normal foot function [5], there is a lack of literature describing the biomechanical changes to foot function that occur in older adults with toe deformities. Studies investigating hallux valgus deformity are more frequent, although inconsistent findings have been reported. Although individuals with hallux valgus deformity show altered forefoot loading, as evidenced by increased plantar pressures, debate remains as to whether these alterations occur to either the central [6], lateral [7] or the medial metatarsals [8]. The presence of claw or hammer toes has been related to lower hallux pressures but higher metatarsal pressures [9, 10]. Diabetic patients with claw or hammer toe deformities

have been found to generate higher peak pressures and pressure-time integrals under the metatarsals than age- and gender-matched diabetic patients without toe deformities [11]. Similarly, an increased metatarsophalangeal joint angle, indicative of hammer/claw toe deformity, has been significantly associated with increased plantar pressures under the hallux and metatarsal heads in a sample of 20 people with diabetes [10]. Although the previous research has been predominantly focussed on toe deformities in diabetic patients, these studies suggest that toe deformities affect loading of the foot. Therefore, it could be anticipated that gait and balance would also be affected by the presence of toe deformities.

The purpose of this study was to evaluate gait, balance and foot function in older people with hallux valgus and lesser toe deformities and determine whether these factors differ to otherwise healthy older people without toe deformities. Premised on the theory that structure influences function, it was hypothesised that older people with hallux valgus and lesser toe deformities would display altered foot function and that these changes would also be reflected in impaired gait and balance.

2. Methods

2.1 Participants

Three hundred and twelve men and women aged over 60 years were randomly selected as study participants. The sample size was determined based on data from previous population studies, whereby 300 participants would allow for a minimum of 10 outcome cases per variable to be entered into multivariate models, which were required for other aspects of this study [5]. Details regarding the recruitment procedures have been reported in detail elsewhere [5]. Briefly, all participants were living independently and ambulatory (with or without assistive devices), but were excluded if they had neurological diseases or cognitive impairment. Each participant

gave written informed consent after reading the participant information package before any testing procedures began. All recruiting and testing procedures were approved by the University of Wollongong Human Research Ethics Committee (HE05/169).

2.2 Physical assessments

Each participant attended one assessment session. These sessions were conducted at venues within the participants' local communities, such as community halls and licensed clubs. At each location a circuit of the assessment tasks was arranged based upon efficient use of the available space and the number of research assistants present. The varied order of the assessment tasks reduced any test order effects. Each participant's height was measured to the nearest 0.1 cm using a portable stadiometer and their mass was measured to the nearest 0.05 kg using electronic scales with their shoes, socks and any heavy outer clothing removed. The chief investigator [KJM] examined each participant's feet and recorded the presence of calluses, hallux valgus and lesser toe deformities, such as claw or hammer toes, using methods described elsewhere [5, 12].

2.3 Gait

Spatiotemporal gait characteristics were measured using the GAITRite® system (CIR Systems, Inc, USA; 80 Hz); a portable carpet walkway (5.1 x 0.89 m; active = 4.2 x 0.6 m) embedded with pressure sensors, that has been shown to have strong test-retest reliability in young and older adults [13]. Participants were instructed to "*walk at a comfortable pace, as if you were walking down the street*". Each subject completed 10 to 15 trials, with 4 to 9 steps taken to traverse the mat. Walking speed ($m.s^{-1}$), step and stride length (m), step width (cm), swing phase, stance phase and double support duration (% gait cycle) and angle of toe in/out (°) were registered by the GAITRite®

system. Within-subject means and standard deviations of each variable were calculated with the standard deviation used to represent gait variability.

2.4 Postural sway

Postural sway was measured using a sway-meter attached to participants at waist level [14]. The sway-meter traced any body movements onto a piece of graph paper (1 mm^2 divisions) secured to a height-adjustable table. The participant was instructed to stand as still as possible for 30 s with eyes open and then to repeat the test while standing on a 15 cm thick piece of foam. The total number of 1 mm squares traversed by the pen was counted. This test has been found to correlate well with centre-of-pressure movement measured using a force-plate [15] and has been used extensively in assessing the postural stability of older cohorts [14, 16], with reliability coefficients reported to be greater than 0.73 [14].

2.5 Plantar pressures

Barefoot plantar pressure distributions were measured by an Emed-AT4 pressure plate (Novel GmbH, Munich, Germany; 25 Hz) using the 2-step protocol and methodology described elsewhere [17]. This protocol has been found to produce the most repeatable plantar pressure measurements in people with foot complaints [18]. The dynamic plantar pressure footprints generated by each participant were divided into 10 masks (Novel-ortho Automask software, $Novel_{gmbh}$, Munich), based around the following anatomical landmarks: heel (M01), midfoot (M02), 1st metatarsal (M03), 2nd metatarsal (M04), 3rd metatarsal (M05), 4th metatarsal (M06), 5th metatarsal (M07), hallux (M08), 2nd toe (M09) and toes 3-5 (M10) (see Figure 1). These masks ensured that each major structural region of the foot was clearly identified. The mean peak pressure footprints were then analysed to determine the peak pressure (kPa; the highest pressure value recorded by a single sensor) and pressure-time integral (kPa.s;

the integral of pressure over time) across the total foot and in each of the masked areas. Peak pressure was chosen as it examines the magnitude of the pressures that were being experienced under the feet and takes into consideration both the forces generated and the contact area of each foot region. Pressure-time integrals were calculated to account for both the magnitude and time the pressures were experienced, as high pressure-time integrals have been associated with skin ulcerations, which are common in diabetic patients with toe deformities [11].

2.6 Assessment of health status

Each participant completed the 36-Item Short Form Health Survey (SF-36) [19] as an indication of health-related quality of life [20]. The answers to the 36 items were numerically coded and then added together to give a total SF-36 score out of 100, with lower scores indicating poorer health.

2.7 Statistical analysis

Variables that were not normally distributed were logarithmically transformed before analysis (postural sway, plantar pressures and SF-36 scores). Participants with moderate-to-severe hallux valgus (n = 36) and lesser toe deformities (n = 71) were compared ($p \leq 0.05$) to an equal number of gender-, age- and BMI-matched controls (see Table 1), who did not have any toe deformities, using chi-square or independent *t*-tests.

<Insert Table 1 about here>

3. Results

Compared to the controls, participants who presented with moderate-to-severe hallux valgus and lesser toe deformities displayed similar spatiotemporal gait and postural sway characteristics ($p > 0.05$; see Table 2), with the exception of an increased walking speed variability in the lesser toe deformity group ($p = 0.03$). In addition, the total SF-

36 score did not differ between the participant groups (p>0.2; Table 1), indicating similar health status.

<Insert Table 2 about here>

Despite recording similar total contact times (hallux valgus = 830.5±143.8 ms; control = 826.8±108.0 ms; p=0.9), the individuals with hallux valgus generated a significantly higher total peak pressure and total pressure-time integral compared to the control group (peak pressure = 900.9±233.7 kPa *vs* 637.8±233.9 kPa; pressure-time integral = 378.8±139.2 kPa.s vs 283.5±96.2 kPa.s; $p \leq 0.001$). More specifically, the hallux valgus group experienced significantly higher peak pressure under the 1st metatarsal and 2nd metatarsal regions (p<0.01; see Figure 2) and a significantly higher pressure-time integral at the 1st metatarsal region relative to their control group (p=0.04; see Figure 3).

Individuals with lesser toe deformities walked with similar contact times to controls (866.0±143.5 ms *vs* 842.8±96.4 ms; p=0.3). However, the individuals with lesser toe deformities generated a significantly higher total peak pressure and total pressure-time integral compared to their control group (peak pressure = 839.1±246.6 kPa *vs* 670.0±245.7 kPa; pressure-time integral = 373.8±134.5 kPa.s vs 307.4±110.2 kPa.s; $p \leq 0.001$). Additionally, those with lesser toe deformities displayed a significantly increased peak pressure and pressure-time integral under the 2nd and 3rd metatarsals, 2nd toe and toes 3-5 in comparison to the control group ($p \leq 0.37$; see Figures 2 and 3). As the toe deformity groups contained a similar proportion of participants who had plantar calluses as the control groups (see Table 1), the presence of calluses is an unlikely contributor to the higher pressures displayed by the toe deformity groups.

<insert Figure 2 and 3 about here>

4. Discussion

In general, participants with hallux valgus and lesser toe deformities did not display significantly different spatiotemporal gait characteristics, or increased gait variability, compared to those without toe deformities. The only exception was seen in the lesser toe deformity group, whereby they displayed increased walking speed variability compared to the control group. As specific spatiotemporal gait characteristics, such as slow walking speed, short step length, increased step width and increased time spent in stance and double support, have been associated with an increased risk of falling [21], it was expected that those with toe deformities may display some of these gait adaptations. Furthermore, gait variability has been suggested as a marker for poor balance control and has also been found to predict falls in older people [22, 23]. Although no study was located that had investigated whether the presence of toe deformities may be a contributing factor to increased gait variability, this study suggests that gait variability, in general, is not affected by toe deformities.

The lack of difference in spatiotemporal gait characteristics between the participant groups is consistent with the results of Deschamps et al. [24], who found that patients with hallux valgus spent a similar amount of time in the swing and stance phases of the gait cycle as those without hallux valgus. As between-group differences in plantar pressures were shown, it is proposed that kinematic variables characterising joint motion rather than spatiotemporal gait characteristics may be more relevant indicators of gait disturbance in people with toe deformities. This notion is supported by the results of Deschamps et al. [25], who found that patients with hallux valgus had decreased plantar flexion motion of the hallux during terminal stance compared to controls. Although Deschamps et al. [25] did not find any difference in sagittal plane motion at the ankle, the hallux valgus group showed a small, but statistically

significant, increase in hindfoot eversion at terminal stance, indicating a less stable foot [25]. Menz & Lord [26] found that the vertical plane acceleration of the head and pelvis was affected by hallux valgus when older individuals walked on an irregular surface, indicating decreased gait stability compared to individuals without hallux valgus. As this difference between the hallux valgus groups was only evident on the irregular surface and not on a level surface, it suggests that hallux valgus may contribute to gait instability when walking on irregular/uneven surfaces and is consistent with the lack of difference in spatiotemporal gait parameters in the current study.

It has been suggested that individuals with clawed or hammer toes may exhibit exaggerated postural sway due to reduced foot contact area, resulting in a reduced geometrical base of support [27]. In addition, the reduced ability of the toes to assist in controlling horizontal projections of the body's center of mass is thought to reduce the functional base of support in people with toe deformities [27]. In contrast, individuals with hallux valgus or lesser toe deformities in this study displayed similar postural sway scores as those without toe deformities, despite the balance test accounting for both anterior/posterior and medial/lateral projections. Similarly, Menz & Lord [28] reported no impairment of performance in the same postural sway tests in older people with lesser toe deformities or severe hallux valgus. They found that these foot problems were more likely to be detrimental on tests of co-ordinated stability and functional performances, such as stair ascent and descent, rather than static balance tests. Therefore, the presence of toe deformities does not appear to significantly affect standing balance, but may impede normal foot function during locomotion or tasks with more demanding postural requirements.

The hallux and 1st metatarsophalangeal joint play a major role in weight transference across the foot during gait [29]. Several authors have demonstrated altered plantar pressure patterns in adults with hallux valgus compared to asymptomatic individuals [6, 24, 29], but with conflicting results. For example, higher hallux peak pressure has been observed with hallux valgus deformity [9], as well as a negative correlation between increasing hallux valgus angle and peak pressure under the hallux [10]. Our findings of similar pressure patterns under the hallux in those with hallux valgus and those with no deformity are in agreement with Kernozek et al. [6], which suggests that the functional loading capacity of the hallux has not been altered during straight line walking. Depending upon the region classification, some studies suggest there is increased pressure under the 1st to 3rd metatarsals [8] whereas other studies have reported an increased load over the central [6, 24] or lateral metatarsals [7] in those with hallux valgus. Our study found that older people displaying moderate-to-severe hallux valgus generated a significantly higher peak pressure and pressure-time integral under the 1st and 2nd metatarsals compared to those without hallux valgus. This supports the results of Mueller and colleagues [10] who showed that greater hallux valgus severity was correlated with higher pressure under the 1st metatarsal [10]. The inverse relationship between soft tissue thickness and plantar pressures [30] is a likely contributor to the higher peak pressure experienced under the 1st metatarsal in those with hallux valgus.

Participants in our study with lesser toe deformities displayed a significantly higher peak pressure and pressure-time integral under the 2nd and 3rd metatarsals compared to controls. Similarly, Bus et al. [11] reported that diabetics with claw or hammer toe deformities generated significantly higher peak pressures and pressure-time integrals at the central metatarsals (2nd – 4th) than age- and gender-matched

diabetic patients without toe deformities. Bus et al. [11] suggested that distal displacement of the metatarsal fat pad was the primary mechanism behind the association between increased metatarsal pressure and toe deformity.

Interestingly, participants with lesser toe deformities in the present study generated a significantly higher peak pressure and pressure-time integral under toes 2-5 compared to their controls. Despite the toes being the affected structure, few studies have reported the pressures generated under the toes in those with toe deformities [9, 10]. Our findings suggest that when the toes are pulled back into extension, in the case of lesser toe deformities, they are unable to function in their normal weight-bearing capacity due to the reduced contact area of the toes, resulting in higher peak pressures (force/area) under the toes and excess weight borne through the metatarsals.

Individuals with hallux valgus and lesser toe deformities have reported significantly greater levels of pain during walking than those without the deformity [6, 31]. It has been suggested that mechanical stress, which can be represented by high pressures experienced over longer durations (peak pressure and pressure-time integral) is associated with the development of foot pain [29, 32]. In fact, our previous research supports this theory whereby older individuals with foot pain displayed significantly higher peak pressure and pressure-time integrals compared to those without foot pain [17].

It must be acknowledged that in order to compare the foot function of those participants in the present study with toe deformities to those without, only the right foot was used to satisfy the statistical assumption of data independence. Therefore, individuals who had unilateral left foot toe deformities were not included in the prevalence rate. It must also be noted that balance was only assessed statically and therefore it is unknown whether more demanding static or dynamic tasks would have

produced the same results. However, the strength of this study design was the matching of toe deformity groups to controls based upon age, gender and BMI. This eliminated these factors as potential confounders on the biomechanical variables, as they have been found to be associated with differences in postural sway, gait and plantar pressures [27, 33]. This may also explain the lack of differences identified for most variables between the toe deformity groups and controls.

5. Conclusions

Although older people with hallux valgus and lesser toe deformities are at an increased risk of falling, poor static balance and altered spatiotemporal gait characteristics do not seem to be factors in the causal pathway between toe deformities and increased risk of falling. However, as hypothesised, older people with hallux valgus and lesser toe deformities display altered foot loading patterns through the forefoot and lesser toes. This is likely to be due to the structural changes that are evident with the toe deformities, such as reduced soft tissue under the metatarsal heads, and may lead to pain and discomfort during walking. This altered foot loading is likely to affect foot function and mechanical stability during more challenging locomotor tasks such as recovering from a perturbation, changing direction or stair ascent and descent, although this notion warrants further investigation.

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Table 1: Descriptive characteristics for participants with hallux valgus (HV), lesser toe deformities (LTD) and matched controls.

Variable	HV (n = 36)	HV Control (n = 36)	LTD (n = 71)	LTD Control (n = 71)
Age (years)	71.9 ± 6.7	71.9 ± 6.6	73.2 ± 6.9	73.1 ± 6.9
Gender (M:F)	17:19	17:19	42:29	42:29
BMI ($kg.m^{-2}$)	27.6 ± 4.4	27.6 ± 3.7	28.8 ± 5.6	28.4 ± 5.2
Total SF-36 score	75.6 ± 16.4	74.9 ± 15.7	76.6 ± 14.0	73.9 ± 17.1
Calluses (%)	39	28	22	22

Table 2: Postural sway and spatiotemporal gait characteristics for participants with hallux valgus (HV), lesser toe deformities (LTD) and matched controls. All between group comparisons exhibited $p>0.05$, except walking speed variability between the lesser toe deformity and control groups.

Variable	HV (n = 36)	HV Control (n = 36)	LTD (n = 71)	LTD Control (n = 71)
Balance				
Floor (mm)	76.4 ± 39.0	69.8 ± 31.2	81.4 ± 33.7	77.6 ± 39.0
Foam (mm)	178.5 ± 58.2	169.2 ± 69.6	190.8 ± 75.3	184.2 ± 87.2
Gait				
Speed ($m.s^{-1}$)	1.03 ± 0.18	1.00 ± 0.17	1.01 ± 0.18	1.00 ± 0.17
Speed variability ($cm.s^{-1}$)	5.7 ± 2.0	5.2 ± 2.1	6.2 ± 2.6*	5.1 ± 2.0
Stride length (m)	1.18 ± 0.14	1.18 ± 0.16	1.17 ± 0.16	1.16 ± 0.16
Stride length variability (cm)	4.1 ± 1.7	3.9 ± 1.3	4.3 ± 1.8	4.2 ± 2.0
Step length (m)	0.59 ± 0.1	0.59 ± 0.1	0.58 ± 0.1	0.58 ± 0.1
Step length variability (cm)	2.6 ± 1.2	2.4 ± 0.9	2.8 ± 1.1	2.4 ± 1.1
Step width (cm)	10.3 ± 2.8	9.5 ± 3.1	10.6 ± 3.3	10.6 ± 3.7
Step width variability (cm)	2.1 ± 0.8	2.2 ± 0.8	2.2 ± 0.8	2.1 ± 0.7
Stance duration (% gait cycle)	61.8 ± 2.1	61.7 ± 1.8	62.0 ± 2.5	61.8 ± 1.9
Swing duration (% gait cycle)	38.2 ± 2.1	38.3 ± 1.8	38.0 ± 2.5	38.2 ±1.9
Double support (% gait cycle)	24.0 ± 3.9	23.6 ± 2.8	24.1 ± 4.9	23.9 ± 3.4
Toe out angle (°)	8.0 ± 6.1	6.5 ± 5.3	7.5 ± 6.7	8.4 ± 5.9

* indicates significant difference at $p<0.05$

Figure Captions

Figure 1. Example of a mean peak pressure picture showing the masked regions based around the heel (M01), midfoot (M02), metatarsals 1-5 (M03-M07), hallux (M08), 2nd toe (M09) and toes 3-5 (M10). The colour scale indicates the maximum pressure that was generated in each sensor.

Figure 2. Mean (± SD) peak plantar pressures generated by the hallux valgus (HV), lesser toe deformity (LTD) and control groups under each metatarsal, the hallux, 2nd toe and toes 3-5. * indicates a significant difference between the HV group and their matched controls. # indicates a significant difference between the LTD group and their matched controls.

Figure 3. Mean (± SD) pressure-time integrals generated by the hallux valgus (HV), lesser toe deformity (LTD) and control groups under each metatarsal, the hallux, 2nd toe and toes 3-5. * indicates a significant difference between the HV group and their matched controls. # indicates a significant difference between the LTD group and their matched controls.