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# Shoe design for older adults: Evidence from a systematic review on the elements of optimal footwear

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ABSTRACT

Due to changes in foot morphology and the occurrence of foot deformities and foot pain with ageing, older people frequently wear ill-fitting shoes. This can lead to discomfort and reduced mobility.

A review of the literature was performed in Medline, Scopus and Embase with three aims: (a) to evaluate the effects of shoes or shoe elements on the comfort and mobility of older adults, (b) to summarise the evidence-based elements of a safe and comfortable shoe for older adults, and (c) from that, to compile those elements into design recommendations for a safe and comfortable shoe for older adults.

Safe elements of footwear include proper anatomical fit, a well-fitting toe box, limited heel height, a broad enough heel, a firm insole and midsole, an outsole with sufficient tread, bevelled heel, firm heel counter with snug fit, and an easy and effective closing mechanism. We conclude that there is a need for shoe design specifically aimed at the foot morphology and demands of older people. The shoe market should increase the availability of well-fitting shoes designed for the older foot and person.

## 1. Introduction

The world is ageing rapidly. By 2050, the world's population aged ≥60 is expected to total 2 billion, up from 900 million in 2015, and the population aged ≥80 is projected to triple from 137 million in 2017 to 425 million in 2050 [1].

### 1.1. Morphological changes

Changes in foot morphology occur with ageing, [2–7], and might differ between men and women [5]. Older adults have a lower medial foot arch but an increased circumference of the forefoot, ankle and instep [2]. For the same foot length, older men have larger foot parameters than women, including foot width, ball girth, upper arch, and toe depth [3]. Flat feet are more common in older women [8] and the first and fifth metatarsophalangeal angles are increased, which might be due to the higher prevalence of hallux valgus in women [4]. For older women, ball width, high instep circumference, and heel instep circumference also increase with age [5].

### 1.2. Pain

Many older adults are confronted with foot pain when wearing shoes [4,3,9–11]. This may be due to an increased prevalence of foot deformities, such as hallux valgus, mallet toes, hammer toes and claw toes [8]. Hallux valgus is related to the wearing of shoes with small toe boxes at age 20–39 years [12].

### 1.3. Doffing and donning, i.e. getting in and out of shoes

Ageing frequently leads to problems with doffing and donning, i.e. getting in and out of shoes [10]. Therefore, easy and effective closing mechanisms are usually preferred.

### 1.4. Ill-fitting shoes and safety aspects

As a consequence of the afore-mentioned changes, older people often wear ill-fitting shoes [13,14] or resort to comfort shoes or slippers, especially in and around the home [9,10].

Unsafe or unsuitable shoes affect balance and gait, and might play

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an important role in increasing fall risk with ageing. Although the literature points to the risks that arise when older people wear shoes that provide little support [13,14], the shoe market has not responded with specific designs of footwear for older people, apart from usually expensive (semi-)orthopaedic shoes. As good shoe design might be a preventative factor for falls, we were interested in determining which elements of footwear, excluding (semi-)orthopaedic shoes, are important for stable balance and gait performance, and for minimising fall risk.

The aims of this review were, therefore, (a) to evaluate the effects of shoes or shoe elements on the comfort and mobility of older adults, (b) to summarise the evidence-based elements of a safe and comfortable shoe for older adults, and (c) based on that, to compile those elements into design recommendations for a safe and comfortable shoe for older adults.

## 2. Methods

A systematic review of the literature in Medline, Scopus, and Embase was performed in accordance with the PRISMA guidelines [15].

### 2.1. Eligibility criteria

All studies in the English language published in peer-reviewed journals were considered eligible for inclusion, irrespective of the year of publication. Included were original studies that assessed the effects and/or elements of footwear or footwear characteristics on aspects such as fit, comfort, foot health, foot pain, balance, gait, fall risk, quality of life and social functioning, within a population of men and women aged ≥65 years who were independently mobile, that is, were able to walk without the use of a walking aid. Only studies reporting a footwear-specific outcome were included

We excluded studies or study results on (1) orthopaedic and semi-orthopaedic shoes, (2) disease-specific study populations, such as diabetes mellitus, Parkinson's disease and other neurological disorders, musculoskeletal disorders, (3) hospital or assisted living environments, e.g. nursing/care/residential homes.

### 2.2. Search strategy

For Scopus and Embase the search query considered the title, abstract and keywords of the records. For Medline this combination was not available and therefore the query considered only the title and abstract.

The search query consisted of two parts. The first part served to identify studies of the older target population, and so included the terms "seniors" or "elderly" or a combination of a term from "senior" - "older" -" old" -" elderly" -" ageing" with a term from "people" -" adults" -" men" -" women". The second part served to identify studies on the subject of footwear, and so included the terms "footwear" or "shoes". We did not set limits on the publication date. The searches were executed on December 13, 2018 (Scopus), April 30, 2019 (Embase), and May 21, 2019 (Medline). See Fig. 1.

### 2.3. Study selection

One author screened the abstracts of the records identified by the database search for eligibility. Subsequently, the records identified as eligible were distributed among the four authors for further confirmation by reading the entire article.

## 3. Results

### 3.1. Search results

The study selection process was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) [15] (see Fig. 2). The database search identified 1761 potentially relevant records (1,048 from Scopus, 367 from Embase, and 346 from Medline). Removing duplicates and screening the titles and abstracts led to the selection of 158 potentially eligible articles (101 from Scopus, 54 from Embase, and 3 from Medline). Finally, **57** met the inclusion criteria (see Table 1).

The current review identified multiple effects of footwear on the quality of life, safety and mobility of older adults.

### 3.2. Morphological changes with ageing

Shoe manufacturers still rely on shoe lasts that are designed for the younger adult population, while the morphology of older feet is clearly different from that of young feet [4]. To improve the shoe last design, anthropometric data that reflect ethnic [3] and gender as well as age differences [3–5,8] are necessary.

Several studies found an association between ill-fitting shoes, foot pain and a possible increase in fall risk [8,10]. Ill-fitting shoes and shoes with absent or poor fixation [13] reduce balance and gait and increase fall risk and reduce quality of life and social functioning [16–20,13,14,21].

Walking barefoot has a negative effect on balance and gait [22,23,17,24,25] and so sharply increases fall risk [20]. Suboptimal footwear is associated with fall-related hip fractures [13,22]. In a study of the footwear worn at the time of a fall-related hip fracture, the majority of the participants had worn slippers [26]. Walking with open-heel shoes reduces gait quality and gait speed [19]. Athletic shoes are associated with decreased fall risk [20]. Shoes with a firm sole and enclosed heel optimise balance and gait compared with slippers [27].

### 3.3. Fit

#### 3.3.1. Fit and pain

Shoes that are too narrow or too small are likely to cause pain [3,8]. Shoes that are too loose, however, are also considered a bad fit [11,9,28,12,13] and result in lower gait speed, shorter stride length, and a less regular gait pattern. When older adults were provided with newly fitted shoes, based on digitally measured foot length and ball girth, their gait parameters improved [28].

#### 3.3.2. Fit, quality of life, foot health

A proper fit can have a positive impact on quality of life (QoL). Heel fit is correlated with exercise tolerance as measured with the shuttle walk test [29]. Subjects with properly fitting shoes experienced reduced pain, higher QoL related to foot health and general health, better foot function and better social function, as measured by the Foot Health Status Questionaire [30].

Shoe size and width selection via a Brannock device resulted in wearers' perception of improved fit and comfort [31].

Detailed fitting guidance and custom insoles resulted in improved health-related QoL, including mental and physical aspects, in elderly women [30]. Shoe fitting, though, is complicated by the fact that dimensions can differ between the left and right foot. These differences are mostly observed at the region from the ball to the mid-arch and could be accommodated by adjustable or opening upper parts of the shoes [3].

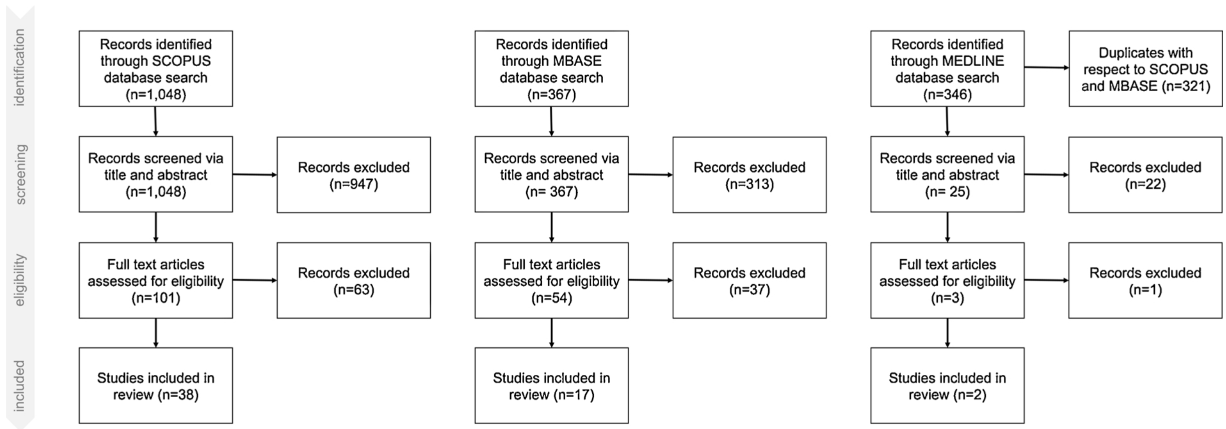


**Fig. 1.** Search strategy.

```
TITLE-ABS-KEY (
        seniors
        OR
        elderly
        OR
        (
                ( senior  OR  older  OR  old  OR  elderly  OR  ageing )
                AND
                ( people  OR  adults  OR  men  OR  women )
        )
        AND
        ( footwear  OR  shoes )
)
AND  ( LIMIT-TO ( SRCTYPE ,  "j" ) )
AND  ( LIMIT-TO ( LANGUAGE ,  "English" )
```

**Fig. 2.** Flow Chart.

### 3.4. Heel height

The pressure on the plantar forefoot increases with heel height [32], which is experienced as discomfort [33]. Shoes with high heels are associated with heel pain [9]. Wearing shoes with heel elevation greater than 2,5 cm was associated with hallux valgus and plantar calluses in women [34]. Shoes with heels of 3,8 cm significantly increase knee torque, which is a measure of the compressive forces on the knee [35]. High heels increase fall risk [36], especially when the heels exceed 2,5 cm [33]. Heel height > 4,5 cm leads to lower dynamic stability (in relation to the gait parameters step length, step width, walking speed, movements of center of mass and base of support) [33,37]. In a study that separately compared different aspects of shoes in stability experiments, the conclusion was that elevated heels decreased walking stability, athough heel height was not actually specified [38]. Gait was better with heels of 1 cm and 3 cm, compared with 5 cm, and a higher peak plantar pressure was measured with heels of 5 cm compared with 1 or 3 cm heels [32]. People adapt their walking pattern to shoes with elevated heels, and reduce their walking velocity and increase toe clearance to compensate for a decreased reaction time in case of a fall and to create a safety margin to prevent the shoe hitting irregularities on the floor [38]. Older women wearing shoes with high heels (> 5,5 cm) going upstairs showed larger trunk side flexion and hip internal rotation compared with younger people on high heels, indicating a risk of imbalance [39].

In addition to the height of the heel, the width of the heel is relevant; indeed, the ratio of heel height to width is a measure for critical tipping angle (lateral stability) [36].

Older adults are advised not to wear high heels; however, women who have been used to walking on high heels for years can have stability issues when they suddenly need to walk on shoes with lower heel [40].

### 3.5. Bevelled heel and bevelled nose of the shoe

A bevelled heel may reduce the risk of slipping, because at heel strike a flatter shoe-floor angle improves grip [38]; therefore a bevelled heel has been advised for older people [26,38,37]. A posterior 10-degree heel bevel is optimal [41]. To enhance toe clearance during the swing phase of the leg, a bevelled nose of 10–15 degrees (this is called a rocker angle) is advised [42]. See Fig. 3.

### 3.6. Sole width, hardness and sole resilience

Greater sole/surface contact area was found to be associated with a significantly lower risk of a fall [36]. Shoes with a widened base of support improve lateral stability [43].

The hardness of the sole influences sensorial awareness of foot position, which is related to stability and balance [44,45]. The use of thick, soft materials in a midsole construction may cause instability [40]. A hard shoe sole (measured as Shore density, which was A-50) provides optimal stability [38,33]. Softer soles are detrimental to balance control [46]. Wearing shoes with hard insoles or a hard sole increases balance [24,37,38,47]. Sole hardness (Shore A-25, A-40 and A-58) has been evaluated (comfort and plantar pressure) and hard soles give higher plantar pressure, but there was no difference in comfort between the degrees of hardness [48]. A sole material that retains compressed thickness between steps (low resilience) improves stability and comfort [49].

**Table 1**
Details of included studies.

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
|---|---|---|---|---|---|---|
| Ansuategui Echeita (2016) The Netherlands [5] | Cross-sectional, observational study | 168 women from 20 to over 80 years of age, divided into seven categories, with the same number of participants in each: 20–25, 30–35, 40–45, 50–55, 60–65, 70–75, and > 80. | Lab setting | Six foot-shape measurements of each foot: foot lengths, ball widths, ball circumferences, low instep circumferences, high instep circumferences, and heel instep circumference. Measurements were manually taken using a tape, a sliding caliper, and the Brannock device (The Brannock Device, Liverpool, NY, USA). The tape in the Brannock Device was replaced with a millimeter scale for this study. | To assess age related changes of foot morphology of women | Older women had significantly greater foot-shape measurements. Ball widths increased 3.1–4.0 mm per decade, ball circumferences 5.6–7.4 mm per decade, high instep circumferences 0.4–4.8 mm per decade, and heel instep circumferences 1.8–1.9 mm per decade. Ball widths, ball circumferences, and left high instep circumference plateaued in the 70–75 years-of-age category, and decreased in the oldest age category. Foot length was not associated with age. |
| Arnadottir (2000), North-Carolina [22] | Observational study | A convenience sample of 35 women, aged 65 to 93 years. 5 from assisted living facilities and 30 lived independently | Lab setting | Functional Reach Test (FRT), the Timed Up & Go Test (TUG), and measures of self-selected gait speed in 10-Meter Walk Test (TMW) are tested with walking shoes, dress shoes, barefoot | FRT, TUG and TMW outcomes are compared to shoe type | Best balance (FRT) in walking shoes. Fastest gait (TUG and TMW) in walking ahoes, slowest in dress shoes. |
| Bih-Jen Hsue (2009) Taiwan [39] | Experiment | Sixteen healthy young females aged 28.7 ± 5.6 years old, and eleven elder females above 70.4 ± 4.4 years old | Lab setting | Kinematic and kinetic data were collected with cameras when the subjects ascended stairs (5 step wood staircase with built in force plates) with their preferred speed in two conditions: wearing low-heeled (< 2 cm) shoes (LHS), and high-heeled (> 5,5 cm) shoes (HHS). | Younger and elderly women adapt their gait and postural control differently during stair ascent (SA) while wearing HHS. | Elderly showed larger trunk side flexion and hip internal rotation due to high heeled shoes during stair ascent. |
| Broscheid (2016), Germany [23] | RCT | Twenty-eight healthy, community-dwelling, physically active adults (mean age 66 ± 6.4, range 52–76) | Lab setting | Balance test (Balance Error Scoring System = BESS). Gait analysis: mean data and variability coefficients (%) of maximum vertical impact and propulsive ground reaction forces (GRFs), step length, step time, stance phase and cadence of all gait cycles during a 30 second treadmill walkning trial. | Balance and gait in standard shoes vs minimalist vs barefoot (one time use) were analysed. to investigate the effects of minimalist shoes on walking gait patterns and balance in older adults. | Balance control was significantly (P < .001) poorer during minimalist shoe and barefoot conditions than with standard shoes. When walking barefoot, participants had a significantly (P < .001) shorter step length, step time, and stance phase and a higher cadence than with standard shoes. The minimalist shoe condition significantly reduced step time, stance phase (P < .001) and increased cadence (P = .01) but had no influence on step length. Walking with minimalist shoes also significantly increased variability in step time (P < .001), cadence (P < .001), and stance phase (P = .007). |
| Büyükturan (2018) Turkey [54] | Experiment | 56 individuals (n = 30 females) aged 65 and over, independently living, having falling down during the year prior to enrollment for the study, and no neurological or musculoskeletal diagnosis that could account for possible imbalance and falls. | Lab setting | Postural stability (PS), risk of falling (RoF). Assessments were perfomed under five different conditions: 1) barefoot, 2) only shoes, 3) with 5 mm insole, 4) with 10 mm insole, 5) with 15 mm insole. | Evaluated both statically and dynamically using Biodex Balance System. | For older population, 10-mm-thick insoles made of medium- density plastozote can be recommended to help them with a better PS and a reduced RoF; 50% of women and 34.3% of men wore narrow shoes. About 22% of the subjects (35.5% of women) who used small footwear reported foot pain |

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**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
|---|---|---|---|---|---|---|
| | | | | | | compared to 9.5% of subjects who used appropriate sizes. This reflected the ethnic differences and confirmed the importance of using the proper anthropometric data for shoe making. |
| Chaiwanichsiri (2008) Thailand [3] | Cross-sectional study | 108 men and 105 women, healthy, independent in self-care and walking, mean age 68.7 ± 5.4 years | Lab setting | Anthropometric data of the feet: dimensions in the weight bearing position by using the Chula foot caliper and standard tape measure. Foot length, foot width, arch length, toe depth, heel width, upper ball, upper arch, ball girth, waist girth, instep girth, short heel girth, ankle circumference, and ankle height were recorded in centimeters (cm). Current footwear used was also measured for internal dimensions using Chula shoe caliper and tape measure. The internal shoe length, shoe width, and toe box were compared with the corresponding foot dimensions. | Mismatching of foot–shoe size was defined if any of those three main dimensions was different more than 5 mm. | All variables increased with foot length, except toe depth. As toe depth provides for all toes which often become deformed with aging, it is crucial to make sure that there is enough room. This result is important in designing shoes with adequate toe depth rather than making the same proportion for each shoe size. |
| Chaiwanichsiri (2009), Thailand [8] | Cross-sectional study | 213 healthy volunteers (108 men, 105 women) with a mean age of 68.6 ± 5.4 years, independent in self-care and walking. | Lab setting | Physical examination for general health status and foot-toe deformities, callus formation, and characteristic of plantar arch (pes planus, pes cavus, normal arch) were recorded. Pinprick sensation, proprioceptive sense, and protective sensation tested by 10 g Semmes-Weinstein monofilament.<br>Footwear size related to foot size, pain according to orthotist's evaluation.<br>'Timed Get Up & Go' test and 6-m walking speed. | To study foot musculoskeletal disorders, falls and associated factors in healthy elderly subjects. Fall history in past 6 months was asked in interview. | Foot pain was found in 14% with a male:female sex ratio of 1:4. The causes of pain were plantar fasciitis, hallux valgus, callus, metatarsalgia, and inappropriate footwear. > 30% of footwear sizes and subjects' feet were mismatched; Variables associated with foot pain were severity of hallux valgus and the footwear used.<br>Foot pain, especially from plantar fasciitis, increased risk of falls in healthy older persons.<br>Foot pain doubles the risk of falls in healthy elderly people without a significant effect on walking performance.<br>Aging foot assessment, foot pain management, and proper footwear play important roles in fall prevention. |
| Chen (2014) Taiwan [59] | RCT | 45 subjects (age = 71.29 ± 6.12 y) from outpatient clinic, without abnormal gait patterns, lower limb deformities, or foot pain. | Lab setting | Stability Index (SI) was measured with Biodex Balance System (static balance test) before and after 8 weeks. Insoles with a heel cup and arch support in own shoes for 8 weeks. | 25 participants were divided in good stability group, 20 in the poor stability group. SI was evaluated in and between these groups, before and after. | The differences in SI before and after the intervention both in the good-stability group (2.764 ± 0.546 versus 2.592 ± 0.538) and the poor-stability group (3.845 ± 0.188 versus 3.655 ± 0.128) were statistically significant ($P < 0.001$) due to the insole with heel cup and arch support. |
| Cronckright (2011) Australia [56] | Experiment | Thirty-one adults (10 males, 21 females) aged over 65 years (mean 75.4, SD 5.2) | Lab setting | Plantar pressure data were collected under the rearfoot, midfoot and forefoot | Pedar 1 in-shoe system while participants walked along an 8 m walkway wearing shoes only, new orthoses and old orthoses (12 months or older) to evaluate durability | Compared to the shoe-only condition, both the new and old orthoses produced significant reductions in peak pressure and maximum force in the rearfoot with corresponding increases in force and contact area in the midfoot. Compared to the new orthoses, the old orthoses exhibited small but significant increases in peak |

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**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
|---|---|---|---|---|---|---|
| | | | | | | pressure in the rearfoot (6%, p = 0.001) and maximum force in the rearfoot (5%, p < 0.001) and forefoot (2%, p = 0.032). These findings indicate that the prefabricated orthoses evaluated in this study are only slightly less effective at redistributing plantar pressure after at least 12 months of wear. |
| Cruz (2014) USA [53] | Experiment | 61 (38 females and 23 males) the mean age was 74.5 ± 6.6 years. | Lab setting | Cutaneous tactile perception was assessed at four sites on the plantar surface of each foot using a Semmes–Weinstein 5.07 (10 g) monofilament. The great toe (GT), first metatarsal head (MT1), fifth metatarsal head (MT5) and heel (H). Balance was tested with a Berg Balance Scale (BBS), a 14-item performance assessment of balance related tasks, and walking tests (measurement of usual and maximal speed). | The extent to which tactile perception at the four different sites related to mobility was evaluated with regard to balance (BBS) and walking tests. | Tactile perception at each site was significantly associated with performance on the BBS. Tactile perception at MT1 was the only site found to be significantly associated with usual and maximal walking speed. The results also show that the strength of the association between MT1 and BBS score was stronger than the association between MT1 and usual walking speed and maximal speed. Compared to participants with no impairment at MT1, those with mild impairment at MT1 had lower scores for the BBS score, usual walking, and a trend for lower maximal walking speed. This supports the design of footwear that is used to augment somatosensation. |
| Davis (2016) Australia [21] | Observational study | 30 community dwelling females aged between 60 - 80 y mean 69.1 SD 5.1 | Lab setting | 10 m walkway, Gaitrite system. Footwear with dorsal fixation (laces), compared to slippers with closed heel and bare feet. | Effect of footwear on minimum foot clearance, heel slippage and spatiotemporal variables of gait | Participants walked with a 4 mm higher minimum foot clearance when wearing the well-fitted footwear compared to bare feet and slippers. When wearing the well-fitted footwear, participants walked faster and with a longer step length, a narrower step width, a shorter step duration and greater minimum foot clearance and less heel slippage compared to walking barefoot or with slippers. |
| De Castro (2010) Brazil [4] | Cross sectional study | 399 older adults (227 women and 172 men) age 60 to 90 y | Lab setting | Shoe fit and foot anthropometry | Questionnaire about the presence of diabetes, pain in the lower limbs and back, and pain when wearing shoes. Width, perimeter, height, length, first metatarsophalangeal angle, the Arch Index, and the Foot Posture Index. | The percentage of the participants wearing shoe sizes bigger than their foot length was 48.5% for the women and 69.2% for the men. Only 1 man was wearing a shoe size smaller than his foot length. The older adults wearing the incorrect shoe size presented larger values for foot width, perimeter, and height than those wearing the correct size, but there were no significant differences between the groups with respect to the Arch Index and the Foot Posture Index. Men were more likely to wear incorrectly fitting shoes. |
| Doi (2010) Japan [28] | Intervention study | 85 community- dwelling older adults (48 males | Lab setting | Habitual shoes were classified in well-fit and | Association of shoe fit with gait parameters (speed, | Subjects wearing ill-fitting shoes had a tendency to walk |

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**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
|---|---|---|---|---|---|---|
| | | and 37 females aged 60–78 years) | | poorly-fit. The sizes of their feet were measured using an optical laser scanning system to provide newly-fitted shoes. Gait was evaluated on a 25 m walkway with an accelerometer | stride duration, stride length, regularity.) | slower, had shorter stride lengths and lower regularity in the vertical direction than those wearing well-fitting shoes. Habitual shoes were too loose in 86%; around the toe of hallux (forefoot region), around the center, the inside and the outside of the metatarsophalangeal joints (midfoot region), and around the heel (rearfoot region). |
| Elhadi (2018) China [55] | Experiment | 15 community dwelling elderly age > 65y | Lab setting | Long distance walking on a treadmill with silicon insoles with heel lift versus original insoles. Between the treadmill walks, gait tests were done on a 8 m walkway with force plates and a motion analysis system. Subjective evaluation using visual analog and Borg's CR10 scales. | Assess with kinetic and kinematic parameters if silicone insoles with heel lifts facilitate long-distance walking | Heel lifts and silicon insoles facilitated long-distance walking of older adults. |
| Horgan (2009) Ireland [25] | Crossover trial | One hundred elderly females with a mean age of 82 (range 61–95) years; community-dwelling women | A day hospital | Information on demographics and falls history were noted. Footwear assessment (shoe style, heel height, fixation, heel counter stiffness, longitudinal sole rigidity, sole flexion point, tread pattern and sole hardness). Berg Balance Scale (BBS) was used to assess balance. | Subjects were tested with shoes on and shoes off. | Wearing their own shoes, compared to going barefoot, was associated with a significant improvement in balance. |
| Hourihan (2000) Australia [14] | Cohort study | 107 community dwelling people mean age 77 who were admitted to a hospital with hip fracture during a 13 month study | In private homes or hostel | Questionnaire to collect data on foot problems, falls history, use of footwear worn at the time of hip fracture. A standardised approach was used to physically examine features of footwear worn at the time of fracture. | To describe features of footwear worn at the time of hip fracture-related falls | Most subjects (33%) wore slippers or were not wearing any footwear (24%) at time of a fall-related hip fracture, Most people choose footwear for comfort reasons, not safety. |
| Kerrigan (2005) USA [35] | RCT | Twenty-nine healthy young women (age 26.7 ± 5.0y) and 20 healthy elderly adult women (age, 75.3 ± 6.5y). | Lab setting | To determine if women's dress shoes with heels of just 3,8 cm in height increases knee joint torques. Measurements in two conditions: shoes with heels (3,8 cm) and shoes without additional heels. Ground reaction forces and 3D movement of markers on knee (Vicon system) | Peak external varus knee torque (a measure for compressive force on medial aspect of the knee) in early and late stance and prolongation of flexor knee torque in early stance, | Shoes with moderately high heels (3,8 cm) significantly increase knee torques, thought to be relevant in the development and/or progression of knee OA (Osteo Arthritis). |
| Kim (2012) Korea [32] | RCT | 14 older women age 71.7 ± 4.4 | Lab setting | Heel heights of 1 cm, 3 cm, and 5 cm. Plantar foot pressure was recorded using the F-scan system (Tekscan Inc, Boston, USA). | To evaluate changes in plantar foot pressure distribution during walking in shoes with different heel heights | Improved gait for low heel heights. Gait was more stable and more likely to prevent fall events when older women wore 1 or 3 cm heels, compared to 5 cm. Peak plantar pressures of the dominant lower limb during the stance phase increased in the T2-5 region and heel region when 5 cm heels were worn, and were considerably lower when 3-cm heels were worn. |
| Koepsell (2004) USA [20] | Nested case-control study. | | In and outside private homes | A two-person field team visited the faller by | | Athletic and canvas shoes (sneakers) were the styles of |

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**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
|---|---|---|---|---|---|---|
| | | 1.371 community dwelling people aged 65 and older | | appointment at the location of the fall, if feasible, or at the faller's home. Interviews about fall risk factors after the fall occurred, and direct examination of footwear were conducted. Shoe characteristics in relation to fall risk; Athletic shoes; canvas shoes (sneakers); barefoot; stockings | How the risk of a fall varies in relation to style of footwear worn. | footwear associated with lowest risk of a fall. Going barefoot or in stocking feet was associated with sharply increased risk. |
| Kusumoto (2008) Japan [60] | RCT | 79 women > 65 years: 40 controls (75.0 ± 5.1 years) and 39 interventions (75.5 ± 6.0 years) | Daily life | Effect of custom made insoles and shoe fitting on quality of life after one month usage. | Medical Outcomes Study Short Form 36; frequency of going out; frequency of wearing custom insole | Wearing shoes with CMI adjusted to individual feet significantly improves the health- related QOL, including both physical and mental aspects in community-living elderly women. Improvements in five domains and two summary scores, i.e., vitality and mental component summary ($p < 0.05$), role physical, general health per- ceptions, role emotional and physical component summary ($p < 0.01$), and mental health ($p = 0.0003$). |
| Lane (2014) Australia [48] | Experiment | 29 women and 6 men, community-dwelling, aged > 65 (mean 73.2, SD 4.5 years) with current or previous forefoot pain. | Laboratory test | Plantar pressure and comfort scores for three shoe conditions: (i) Soft-soled shoe (sole hardness – Shore A25). (ii) Medium-soled shoe (sole hardness – Shore A40). (iii) Hard-soled shoe (sole hardness – Shore A58). | Peak plantar pressure (pedar-X analysis system); shoe comfort VAS scale. | The hard-soled shoe registered the highest peak pressures and the soft-soled shoe the lowest peak pressures. However, no differences in comfort scores across the three shoe conditions were observed. |
| López-López (2016) Spain [30] | Cohort study | 29 men and women aged between 65 and 96 years | Lab setting | Effects of shoe fit (length and width) on quality of life. | Foot Health Status Questionnaire (FHSQ); length and width of the feet and shoe using the Brannock device. | Reduced pain; higher quality of life related to foot health and general health, better foot function; better social function |
| Lord (1999) Australia | A randomized order, cross-over, controlled comparison | 42 women aged 60 to 92 years (76 ± 9.03): 15 hostel residents, 11 in retirement village, and 16 independently living | Lab setting | Postural sway, maximal balance range and coordinated stability for (1) soft-soled (A42) bowls shoes, (2) hard-soled (A58) bowls shoes, (3) college-style shoes (6.5cm collar), (4) college-style shoes with a high (boot) collar (15cm), and (5) barefoot. | 60 minute balance assessment: body sway test, maximal balance range test, and coordinated stability task | Subjects were more stable when wearing the high collar shoes than when wearing the college shoes ($P < .001$) or when barefoot ($P < .05$). In contrast, subjects performed similarly in the balance tests in the soft and hard- soled shoes ($P = .30$) and no better than when barefoot ($P = .12$ and $P = .93$, respectively). |
| Losa Iglesias (2012) Spain [47] | Experiment | 16 healthy women and 6 healthy men aged 77 to 91 years (85 ± 3 years). | Lab setting | Effect of gel soft insole, hard insole, sock, and barefoot on balance (postural sway and coordinated stability). | Force plate (EPS-Platform; Loran Engineering,) measurements: center of pressure, sway area, distance of sway area, sway velocity, excursions, and their Romberg indices | Excursion distances and sway areas were reduced, and sway velocity was decreased when wearing insoles. The hard insole was also effective when visual feedback was removed, suggesting that the more rigid an insole, the greater potential reduction in fall risk. Shoe insoles may be a cost-effective, clinical intervention that is easy to implement to reduce the risk of falling. |
| Ma (2018) China [61] | Repeated-measures study design | 14 elderly subjects: 4 females and 10 males, aged 70.2 ± 3.4 years, height 162.8 ± 7.9 cm, | Lab setting | Balance was tested for three conditions: (1) without socks or insoles, (2) with socks but without insoles, and (3) with both | Romberg test for static balance; Postural balance assessed by center of pressure movement during standing; Monofilament test | Thick socks significantly decreased the monofilament score ($p < 0.001$), suggesting reduction in ability to detect external |

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**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
|---|---|---|---|---|---|---|
| | | and weight 63.6 ± 10.0 kg | | socks and insoles. Socks had 4.5mm thick bottom. Insoles were medium firm (A30–A35) EVA with medial longitudinal arch supports and heel cups. | to evaluate foot plantar sensation | forces. All center of pressure parameters increased significantly while wearing thick socks ($p < 0.017$), implying reduction of postural stability. They then decreased significantly with the additional use of insoles ($p < 0.017$). |
| Maki (1999) Canada [44] | Cohort (young vs old) | 7 young adults (2 men and 5 women; average age 26, range 23-31) and 14 older adults (8 men and 6 women; average age 69, range 65-73) with measurable loss of plantar sensitivity. | Lab setting | Effect of mechanical facilitation, via flexible tube attached to plantar surface, on control of rapid stepping reactions evoked by unpredictable postural perturbation. | Posural behaviour monitored with cameras; Force plate measurements on perturbation platform: step timing, rate of limb loading, and center of mass. | Plantar facilitation reduced the incidence of "extra" limb movements, beyond the initial step, during forward-step reactions in the older adults; an improved ability to control feet-in-place reactions: young subjects were better able to recover balance without stepping when falling backward (given instructions to "try not to step"), and both young and older subjects reduced the extent to which the center of foot pressure approached the posterior foot boundary during continuous anteroposterior platform motion. |
| McRitchie (2018) UK [6] | Cross sectional study | 67 community dwelling female participants > 40 who routinely received podiatric treatment. | Podiatric practice | Length and width of dominant foot and footwear. Short questionnaire to rate the shoe characteristics, emotions whilst wearing and reasons for the purchase. Comparison between age groups 40-60 and > 61 | Foot and footwear measurements and questionnaire analysis | High prevalence of structural foot pathology for those over 61 who preferred slip on shoes. This group also wore shoes that were significantly narrower than their feet with width difference correlating to the presence of Hallux Abductovarus (HAV). This study emphasises that the width of the shoe is an important part of fit, highlighting the need for patient specific footwear assessment and education for behaviour changes. Individual education of the choices made and how that influences foot pain and pathology could improve the foot health of patients as well as influence fashion and image. |
| Menant (2008) Australia [37] | Experiment | 29 community-dwelling volunteers aged ≥70 years (mean (SD) age, 79.1 (3.7) years, n = 15 females) | Lab setting | Shoe conditions compared to standard shoe by balance tests: body sway and maximal balance range (measured in square mm with a swaymeter), coordinated stability (error score) and choice-stepping reaction time (ms). Standard shoe compared with 7 different shoes: elevated heels (4,5 cm), soft sole (A-25), hard sole (A-58), flared sole, bevelled heel, raised collar height (11 cm) and tread sole. | Index score: based on the sum of z- scores across three tests (sway, coordinated stability and choice-stepping reaction) time) normalized to the standard condition | The footwear performance index score indicated that the elevated heel was most detrimental to balance ($p < 0.05$) whereas a high collar and a hard sole showed trends towards being beneficial. An elevated heel of only 4.5 cm height significantly impairs balance in older people. |
| Menant (2008) Australia [33] | Experiment | 11 Young adults (7 women, mean age 22.5 SD ± 2.5 years and 15 older adults (7 women; | Lab setting | Shoe conditions compared to standard shoe (with A-40 sole hardness) by walking trials on level | Values for gait pattern were calcuated, Center of Mass (COM) related to Base of Support (BOS) in Antero- | Both young and older subjects adopted a conservative walking pattern in the elevated heel shoes. |

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**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
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| | | mean age 73.7 SD ± 4.2 years) | | linoleum floor and uneven walkway.<br>3D kinematic data were collected for 5 sec. Ground reaction forces were measured. Subjective ratings of perceived stability and comfort were assessed at the end of each shoe condition by using a 5 point scale.<br>Participants were tested on visual contrast sensitivity, hand reaction time, and knee extension strength.<br>Shoe characterisitcs: elevated heel (4,5 cm), a high collar (11 cm), a tread sole, a smooth soft sole (A-25), a smooth hard sole (A-58). | Posterior (AP) and Medio Lateral (ML) direction, and Loading Rate Variables were evaluated with regard to Age-Group and Surface. | Both young and older subjects had impaired mediolateral balance control in the soft-sole shoes.<br>Increased sole hardness (above that found in a standard shoe), a tread sole, and a raised collar height did not improve walking stability in either group. |
| Menant (2009) Australia [46] | Experiment | Ten healthy young adults (age: 27.4 ± 2.5 years, 6 females) and 26 healthy older adults (age: 78.5 ± 4.2 years, 12 females) | Lab setting | Reaction time (rapid gait termination) was measured during the different circumstances.<br>Coefficient of friction was determined with mechanical traction method.<br>Floor: dry linoleum floor, irregular surface and wet linoleum floor.<br>The shoe conditions: standard laced Oxford-type shoe and seven modified pairs of shoes differing from the standard shoe by one feature: elevated heel, soft sole, hard sole, flared sole, bevelled heel, high-collar and tread sole. | They performed eight walking trials on 7 m walkway in each footwear / surface condition. Subjects were required to stop as soon as possible in response to an auditory cue (presented at a random time point during the trial) and to remain still until told to move again. | Soft sole shoes might be detrimental to balance control during gait termination, as they elicited a longer total stopping time compared to the standard shoes. In contrast, the high-collar shoes improved total stopping time on the wet surface. |
| Menant (2009) Australia [38] | Observational study | Ten healthy young adults (age: 27.4 ± 2.5 years; 6 females) and 26 healthy older adults (age: 78.5 ± 4.2 years; 12 females) | Lab setting | The timing of heel strike and toe-off, walking velocity, step length, step width, horizontal velocity of the heel marker at heel strike, sagittal shoe-floor angle.<br>Shoe and floor characteristics: walking along 7 m walkway with three surfaces: level (control), irregular, and wet in eight randomised shoe conditions (standard, elevated heel, soft sole, hard sole, high-collar, flared sole, bevelled heel and tread sole). A scanner and 2 markers on the shoes to track motion of the feet. | A reduction in step length and walking velocity and an increase in double-support time and step width would indicate adaptations aimed at improving walking stability. Minimum toe/ floor clearance at mid-swing indicates the potential risk of tripping. A reduced toe-floor clearance on the irregular surface compared to the control surface would indicate a greater likelihood of tripping. On the wet versus the control surface, increased heel horizontal velocity and foot/floor angle at heel strike might predispose an individual to slip. | Less walking stability for shoes with elevated heels or soft soles, especially on wet floors. When walking on the wet surface, the subjects displayed small but significant reductions in walking velocity, step length and shoe-floor angle at heel strike . These strategies are likely intended to decrease the risk of initiating a slip by lowering the required coefficient of friction.<br>High-collar shoes of medium sole hardness (A-40) provide optimal stability on level (dry), irregular and wet floors. |
| Menz (2001) Australia [41] | Experiment | No testpersons involved | Lab setting | 4 different flat heels (mens' shoes) 'normal heel', '30° sole flare to the back heel', 'bevelled heel', normal heel with textured slip resistant sole*. And 4 different 4,5 cm high heels (womens' shoes) varied in surface (small 3 cm2 and 16 cm2, with and without textured slip resistant sole* | Dynamic friction testing device | On dry surfaces, the shoe with the 30° sole flare showed the least slip resistance.<br>A trend towards improved slip resistance of the shoe with the 10° posterior heel bevel.<br>None of the women's fashion shoes could be considered safe. |

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**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
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| | | | | on different floor surfaces (dry and wet tiles, vinyl, terra cotta, concrete). * texture specified as “tread pattern smoother than the deep tread patterns commonly used in safety footwear” | | |
| Menz (2005) Australia [34] | Cross-sectional | 176 people (56 men, 120 women) aged 62–96 years (mean 80.09, SD 6.42) who were residing in a retirement village. 155 in independent units and 21 in serviced appartments | Lab setting | To examine the relationship between footwear characteristics (fit, high heel) and the prevalence of common forefoot problems in older people (pain and deformity). | Hallux valgus severity using Manchester scale; presence of lesser digital deformities, corns and calluses. Reported pain. Length, maximum width, and area for foot sole and shoe sole based on pen trace on paper. Measured heel raise of current shoe and reported use of this style of shoes. | Most subjects wore shoes narrower than their feet. Women wore shoes that were shorter, narrower and had a reduced total area compared to their feet than men. Wearing shoes substantially narrower than the foot was associated with corns on the toes, hallux valgus deformity and foot pain, whereas wearing shoes shorter than the foot was associated with lesser toe deformity. Wearing shoes with heel elevation greater than 25 mm was associated with hallux valgus and plantar calluses in women. |
| Menz (2006) Australia [24] | Observational study | 176 people (56 men and 120 women) aged 62–96 years (mean 80.1, SD = 6.4) who were residing in a retirement village. | Indoors and outdoors | Shoe type, heel height, heel counter height, heel width, critical tipping angle, method of fixation, heel counter stiffness, sole rigidity and flexion point, tread pattern and sole hardness; The presence and severity of hallux valgus was determined using the Manchester scale. Participants were followed for 1 year to determine the incidence of falls. | To evaluate shoe fit, the difference between the length, width and surface area of the shoe compared to the foot was calculated as a percentage. | Shoe characteristics not significantly associated with fall risk either inside or outside the home. Those who fell indoors were more likely to go barefoot or wear socks inside the home (OR = 13.74; 95% CI 3.88-48.61, $p < 0.01$) |
| Menz (2014) Australia [31] | Experiment | 56 participants, 82,2 y SD 8.0, 22 females | Lab setting | 3D footscanner (weightbearing) to obtain foot dimensions and Brannock device to determine shoe sizes. Participants were provided with a pair of shoes, available in three different widths. 100 mm visual analogue scales (VAS) for comfort evaluation. | Evaluation of Brannock device for selection of footwear. Shoe sizes, foot dimensions, and comfort levels were compared. | The use of Brannock device used in the study resulted in the selection of appropriately fitting shoes, as evidenced by the shoes being slightly longer than the foot and having equivalent ball width and ball girth measurements. Participants’ overall perceptions of shoe fit and comfort were also very high, providing subjective confirmation of the objective measurements. |
| Menz (2015) Australia [7] | Randomized trial | Community-dwelling older people with disabling foot pain (72 men and 48 women aged 65 to 96 years; mean age 82 [SD 8]) were randomly allocated to an intervention group (n = 59) or control group (n = 61). | Podiatric practice | The intervention group was provided with off-the-shelf, extra-depth footwear. Participants in the control group received their footwear at the completion of the study at 16 weeks. Both groups continued to receive usual podiatry care for the study period. | Foot Health Status Questionnaire (FHSQ), measured at baseline and 16 weeks | The findings indicate that wearing appropriately-fitting, off-the-shelf, extra-depth footwear significantly reduces foot pain, improves foot function, and is associated with the development of fewer keratotic lesions over a 16 week period compared to usual podiatry care. |
| Menz (2016) Australia [12] | Cohort study | Women aged 50-89 years (n = 2,627) | Questionnaire | Footwear characteristics of shoes previously worn from age 20: toe box shape and heel heights. | | Foot pain lasting over12 months at older age not related with high heels or small toeboxes at age 20-39y Hallux valgus was related with previous wearing of |

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**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
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| | | | | | | shoes with small toe boxes at age 20-39y |
| Menz (2017) Australia [26] | Experiment | Older women (n = 30) aged 65– 83 years (mean 74.4, SD 5.6) | Lab setting | Balance ability (postural sway, limits of stability, and tandem walking, measured with the NeuroCom Balance Master) and gait patterns (walking speed, cadence, and step length, measured with the GAITRite walkway). Comparison of a backless slipper and an enclosed slipper; firm sole. | To evaluate the effect of backless slipper compared to enclosed slipper on stability. | Indoor footwear with an enclosed heel, Velcro fastening, and a firm sole optimises balance and gait compared to backless slippers. |
| Menz (2017) Australia [27] | Experiment | Older women (n = 30) aged 65 - 83 years (mean 74.4, SD 5.6) | Lab setting | Balance ability (postural sway on a foam rubber mat, limits of stability and tandem walking, measured with the Neurocom Balance Master) and gait patterns (walking speed, cadence, step length and step width at preferred speed, measured with the GAITRite walkway) Different shoes: flexible footwear, own footwear, prototype that is designed for outdoor use with all design aspects that are considered to be good and safe, replica of dr. Comfort footwear). | To evaluate the effect of prototype shoe on stability compared with own shoes and minimal shoes. | Significantly reduced step width when doing tandem walking with prototype shoe. Aesthetics are also important when people are asked if they would buy these shoes. |
| Mickle (2011) Australia [9] | Cross-sectional | 312 community-dwelling men and women aged between 60 and 90 years. | Indoors and outdoors | Shoe type categorised as good (athletic or fastened, closed-toe shoe), average (slip-on, work-boot or ugg-boot) or poor (high-heel, sandal or slipper); Reported for indoor and outdoor. | Self reported shoe fit and foot pain. | Individuals with toe and hindfoot pain were more likely to wear poor shoes around the home. Poor indoor footwear was highly represented by slippers. Poor outdoor shoes mainly consisted of sandals and high-heeled shoes, which typically do not provide heel cushioning or support, and therefore may contribute to heel pain. |
| Morais Barbosa (2018) Brazil [52] | Prospective, parallel, randomized, and single-blind trial | 42 makes and 49 females > 65 years (70.0 ± 4.7 years) | Lab setting | Flat versus textured insoles versus control group. | Berg Balance Scale and Timed-Up and Go test after 4 weeks of usage. | Improvements in the Berg Balance Scale and the Timed Up and Go test were noted only in intervention groups with insoles but not in control group. No significant difference was found between flat and textured insoles. Minor adverse effects were noted only in the group with textured insoles |
| Mulford (2008) USA [57] | Experiment | 23 males and 44 females aged between 60y and 87y with mean age 69.9y | Lab setting | Effects of arch supports on balance, functional mobility, and pain in the back and lower extremity joints, immediately after the intervention and after six weeks. | Berg Balance Scale for balance and Timed-Up and Go test for functional mobility. Pain was assessed through questionnaire using Numeric Pain Distress Scale. | The results of this study show statistically significant improvement with arch support ($p < 0.05$) in scores for balance (BBS), functional mobility (TUG), pain, and self-reported benefits from the use of arch supports. There was no statistically significant change in ankle pain ($p > 0.05$). |
| Munro (1999) Australia [16] | Mail survey | 60 men and 68 women > 65 (72.0 ± 5.9 years) | In and around the home | Footwear around the home and outside the home: shoes, slippers, barefoot, socks or nylons. | Questionnaire on general characteristics (health status, foot problems, falls), footwear-wearing habits, | All respondents considered their household shoes comfortable because of good fit, shoe softness, ease of |

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**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
|---|---|---|---|---|---|---|
| | | | | | and footwear-pur- chasing habits. | donning the shoe, and light weight. |
| Perry (2008) Canada [62] | RCT | Test group of 11 men en 9 women with mean age of 69y (SD 3.6y) and control group of 10 men and 10 women with mean age of 69y (SD 3.1y). All had moderate insensitivity of the foot sole. | Lab setting simulating uneven terrain that varied through trials | Differences in kinematic data for standard insole vs insole with ridge along perimeter was collected to evaluate stability, at the start of the test and after 12 weeks. | Optotrak 3020 motion analysis system to calculate body center of mass (COM) through walking trials. Stability was measured as minimum distance between COM and base of support (BOS) during single support phase. | The facilitatory insole improved lateral stability during gait for two out of four platform slope orientations, and this benefit did not habituate after 12 weeks of wearing the insole in daily life. For the lateral orientation, the mean lateral stability margin increased when wearing the facilitatory insoles, in comparison to the conventional insoles (6.0 vs 5.4 cm; $F1 = 7.92$, $p = .007$). For the anterior platform orientation, the facilitatory insole caused the stability margin to increase to a similar degree (6.3 vs 5.8 cm; $F1, = 4.81$, $p = .035$). |
| Qu (2015) China [58] | Experiment | 13 Healthy older adults (5 males and 8 Females, age: 69.2 ± 7.2 y. | Lab setting | Static stance trials on force platform, 4,5 min walking trials on a treadmill at comfortable speed (26 reflective markers were recorded) dynamic postural stability with cupped insole (raise edge around heel), textured, rigid and soft insoles. | Calculations of Center of Pressure (static test) and Magin of Stability (MOS) (dynamic postural stability) | Cupped insoles improved dynamic postural stability (MOS in AP direction increased $P < 0.001$) Rigid insoles lead to greater dynamic postural stability than soft insoles (MOS in AP direction increased $P = 0{,}035$). |
| Robbins (1997) Canada [45] | Randomized-order, cross-over, controlled comparison. | 13 males with mean age 72.6y (SD 4.5y) from internal medicine clinic versus 13 males with mean age 28.1y (SD 4.0y) from general population, all in good health, no condition affecting walking or balancing, and no history of frequent falls (> 2 past 12 months) | Lab setting | Advancement of foot position awareness and its relation with balance and shoe sole hardness. Six custom fabricated athletic shoes with different sole thicknesses: (1) 13mm at heel and 6.5mm at forefoot and (2) 26mm at heel and 16mm at forefoot; Different sole hardness: A15, A33, and A50. | Balance failure frequency, defined as falls per 100 meters of beam walking; rearfoot angle in degrees, measured via an optical position measurement system; perceived maximum supination when walking, in degrees, estimated by subjects using a ratio scale; foot position error, in degrees, was defined as the rearfoot angle minus perceived maximum supination. | Foot position error during walking (1) increases with advancing years; (2) is positively related to stability; (3) is positively related to midsole thickness; (4) is negatively related to midsole hardness; and (5) correlates best with perceived maximum supination. In other words, shoes with thin, hard soles provide better stability for men than those with thick, soft midsoles. |
| Robbins (1998) Canada [49] | Randomized-order, cross-over, controlled comparison. | 30 older (mean age 66 years, SD 3), and 30 younger (mean age 34 years, SD 6) healthy men | Lab setting | Stability was inferred by sway measures: sway velocity, X-Y area and radial area, measured with a force-moment platform. Comfort was measured by direct scaling and magnitude. Shoe characteristics: a sole material that retains compressed thickness between steps (low resiliency) and shoes with high resilience sole material | Subjects were tested with barefoot standing on one leg on the force-moment platform, covered with 4 diferent materials (3 high resilience and 1 low resilience) in 2 different thickness (7 and 14 mm) | Interface with resilience strongly reduces stability. 7 mm-thick interfaces provided better stability than 14-mm interfaces. Elimination of high resilience sole materials from footwear and use of low resilience technology will result in footwear that provides high stability and comfort. The greatest beneficiaries are likely to be frail older people. |
| Roman De Mettelinge (2015) Belgium [17] | Observational study | 57 community-dwelling women (68.0 ± 4.6 years) | Lab setting | Spatiotemporal gait analysis using the GAITRite walkway. 4 Footwear conditions: barefoot, slippers, high heels, and standard shoes and 3 task conditions (single-task, motor dual task, and cognitive dual-task). | Influence of footwear on velocity, cadence, stride time, stride length, and stride length variability. | Gait performance decreased significantly when walking barefoot compared to standard shoes; these significant gait alterations were also observed when adding a cognitive task to normal walking. |

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**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
|---|---|---|---|---|---|---|
| Sherrington (2003) Australia [13] | Retrospective study | 95 older people (average age 78.3 years, SD 7.9, range 57.5–92.8) who had suffered a fall-related hip fracture were included in this study. There were 72 women and 23 men. 11 subjects were residents of aged care facilities and the remainder were community-dwellers. | Community dwelling | Interview after the fall. Worn footwear at time of hip#-fall was assessed by physiotherapists. Slippers (22%), walking shoes (17%), sandals (8%), high heels (2%). The majority of subjects (75%) wore shoes with at least one theoretically sub-optimal feature, such as absent fixation (63%), excessively flexible heel counters (43%) and excessively flexible soles (43%). | Evaluated the characteristics of footwear worn at the time of fall-related hip fracture and establish whether the features of the shoe influenced the type of fall associated with the fracture. | The most commonly reported type of fall was a trip (n = 32) followed by loss of balance (n = 24), slip (n = 14), felt dizzy (n = 4), legs gave way (n = 2) and faint (n = 1). The majority of subjects (n = 38) fell while walking on one level inside their own home. Ten subjects fell while walking in their own garden and 31 fell in other outdoor locations. Hip fracture falls also occurred in other indoor locations (n = 7), own front or back stairs (n = 5), getting out of bed (n = 3) and climbing on a chair or ladder (n = 1). The wearing of slippers or shoes without fixation may be associated with increased risk of tripping. Suboptimal footwear worn at time of fall-related hip fracture by 75% of subjects; absent fixation (63%), excessively flexible heel counters (43%), excessively flexible soles (43%). |
| Tanigawa (2015) Japan [29] | RCT | 155 community dwelling elderly people, age 73,6 ± 4,4. Female: 81 | Lab setting | Exercise tolerance (Shuttle Walk Test [SWT]), 10-m walking time (10mWT), and forced expiratory volume in 1 second (FEV1) were measured. A shoe fit checklist was used (particpants were asked to wear common shoes on the day of the test) | Heel-fit, toe space, Width-fit (Width), Sole stiffness, heel counter yes/no, lace, Velcro, zip fastening, adjusting yes/no. Exclusion criteria: high heels, not covered upper, high-cut shoes, sandals and boots. | Adequate heel fit enhances walking. |
| Tencer (2004) USA [36] | Nested case-control study | A cohort of 1.371 people > 65y was followed for occurrence of falls over a 2-year period. About 60% of the group, both cases and controls, ranged in age from 70 to 79, 33% were 80 and older, and 6% were aged 65 and 69. The group included 68% women and 32% men. | Community dwelling | Shoe measurements related to lateral stability (heel height and width, ratio = critical tipping angle); **foresole material,** | Comparing biomechanical measurements of shoes worn by fallers vs. non-fallers | Increased fall risk with greater heel height > 2,5 cm, P for trend = 0,03. Fall risk decreased with greater sole/surface contact area P = 0,03 with confounders and P = 0,005 without confounders. |
| Thies (2015) UK [42] | Experiment | 4 men and 8 women, aged > 65, community-dwelling and able to walk comunity distsnces. | Laboratory with custom built ramp reflecting real world environment | Toe clearance and walking stability for three pairs of shoes with rocker angles of 10, 15 and 20 degrees | 3D motion tracking with Qualisys Proreflex | Toe clearance increased substantially from the 10 to the 15 degrees rocker angle (p = 0.003) without compromising measures of walking stability (p > 0.05). A further increase in rocker angle to 20 degrees resulted in less substantial enhancement of toe clearance and came at the cost of a decrease in gait speed on the decline. The novelty of this investigation lies in the exploration of the trade-off between reduction of trip-risk through footwear design and adverse effects on walking stability on real-life relevant surfaces. |
| Tomassoni (2014) Italy [2] | | 577 male and 528 female volunteers (aged | Lab setting | Anatomical parameters: foot length, circumference | To assess age related changes of foot morphology | In old individuals, no differences between men and |

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**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
|---|---|---|---|---|---|---|
| | Cross-sectional, observational study | between 20 and 25 years; n = 130 males and 128 females), adult (aged between 35 and 55 years; n = 283 males and 260 females) and old (aged between 65 and 70 years; n = 164 males and 140 females). | | and height, ankle length, circumference and height. With a millimetric table and tape measure prepared for anthropometric measurements. | | women were found after normalization for foot length. In old vs adult individuals, foot circumference (increased) showed the most relevant age-related differences. |
| Van der Cammen (2016) The Netherlands [19] | Observational study | 25 community-dwelling independent older persons (14 women and 11 men), aged 59-85 years (mean age 68.5 years, SD ± 6.9 | Lab setting | Comfort shoes, indoor footwear: three different shoe models frequently worn at home, open heel vs high collar (soft sole and hard sole version, both with velcro fastening). Spatial-temporal gait analysis with GAITRite walkway, while wearing three different shoe models. Post test questionnaire about comfort and stability. | Spatial gait parameters used: stride length, and heel-to-heel base of support. Temporal parameters: cadence (steps/minute), step time, velocity, swing time, stance, and double support time. | Reduced gait performance with open heel versus high collar. Higher fall risk with open heel. High collar shoe with soft sole is qualified as most comfortable. |
| White (1989) UK [10] | Cross-sectional | 25 males (average age 83.9 years, range 80-96), and 71 females (average age 84 years, range 80-97). | Home environment | Shoe usage and age, level of mobility, and assessment of shoe (materials, alterations, heel height, fastening) | Visit to subjects home to assess patterns of footwear usage and difficulties associated with buying and wearing shoes. | Of the 96 people, 55 spent most of the day wearing shoes and 41 usually wore slippers. Of 20 housebound subjects, 16 wore slippers for most of the day. 5/96 Participants complained of discomfort from their shoes, while 6/96 had difficulty putting their shoes on; 12/96 used some form of aid when putting on shoes. Of those confined to their home, only 4/20 wore shoes for most of the day; 71/96 participants said they were able to go to the shop in person to choose their footwear, though 9 of these would rely on a friend or relative to take them. |
| Yamaguchi (2015) Japan [43] | Experiment | Sixteen healthy, ambulatory, community-dwelling older adults (aged 65–78) | Lab setting | With normal shoes and widened shoes (20mm medially plus 20mm laterally) base-of-support on shoes. GAITRite mat, tests of preferred- and maximum-speed gait, tandem gait, Timed-Up-and-Go, and 180°-turn. Balance: video recordings to determine respons to stability perturbation on a motion platform. | To determine whether a small increase in footwear width can improve ability of older adults to regain lateral stability after experiencing a balance perturbation. | Improved ability to stabilize the body without stepping ($p = 0.002$), with the size of effect depending on perturbation magnitude (footwear-by-magnitude interaction: $p = 0.057$). The widened base-of support shoe did not compromise mobility and agility. |
| Yamaguchi (2019) Japan [51] | Experiment | Three groups: young group (n = 56; age range, 20–34 years), middle-aged group (n = 50; age range, 35–64 years), and old group (n = 82; age range, 65–77 years) | Lab setting | Analysis of kinetic and kinematic data from gait database (with data from gait trials walking barefoot on 10 m walkway: Required coefficient of Friction (RCOF) during breaiking (RCOFres), in Anterior Posterior (AP) and Medio Lateral (ML) direction. | RCOF variables | The RCOFres and RCOFAP were lower in the old group than in the other groups, indicating a lower slip risk in this group. However, the RCOFML was higher and the step width was greater in the old group than in the other groups. The higher RCOFML and lower RCOFAP in the old group might be associated with slips in a more lateral direction. Older adults have a high risk of slipping in a more lateral direction. Shoes with high-slip resistance in the |

(continued on next page)

**Table 1** (*continued*)

| Author (year), country, [ref] | Study type | Participants (n) | Setting (home environment, lab) | Measurements | Evaluation Method | Main findings |
|---|---|---|---|---|---|---|
| | | | | | | lateral direction are recommended to prevent hazardous lateral slips among older adults. |

### 3.7. Collar height

Sway measurements (displacements of the body while standing still), balance range (how far participants can lean forward or backward from the ankles) and coordinated balance (steady and co-ordinated sway while placing participants near or at the limits of their equilibrium) were improved with a high heel collar (collar height 15 cm) [50]. For static balance and stepping, shoes with a high collar (collar height 11 cm) are beneficial compared with normal shoes with a low collar [37]. Shoes with collar height 11 cm gave improved balance but had no beneficial effects for walking in everyday circumstances [33,38], although they were beneficial for walking on level, irregular and wet surfaces, which are typical outdoor circumstances [38].

### 3.8. Tread

There is no evidence that a greater than normal shoe tread is beneficial on even or uneven surfaces [33], or irregular or wet surfaces [38]. The tread needs to provide friction in the antero-posterior direction as well in the medio-lateral direction, because older adults have a high risk of slipping in the lateral direction [51].

### 3.9. Insoles

Insoles enhance somatosensory function, due to better alignment of the joints in the feet, potentially improving muscular contributions to stability [47]. Step width when doing a tandem walk was significantly narrower in shoes with textured insoles [27]. Balance improved with flat and textured insoles [52]. This texture could be positioned at metatarsus 1 (close to the great toe) because sensitive input from this specific location is related to improved balance [53]. Rigid insoles lead to greater dynamic postural stability than soft insoles. Medium-density insoles (10 mm thick) give better postural stability and decrease the risk of falling [54]. Heel-lift and silicon insoles facilitated long-distance walking in elderly people [55]. Insoles enhance plantar pressure distribution [56]. Significant improvements ($p < 0.05$) in scores for balance (BBS), functional mobility (TUG), pain, and self-reported benefits were obtained from the use of arch supports [57].

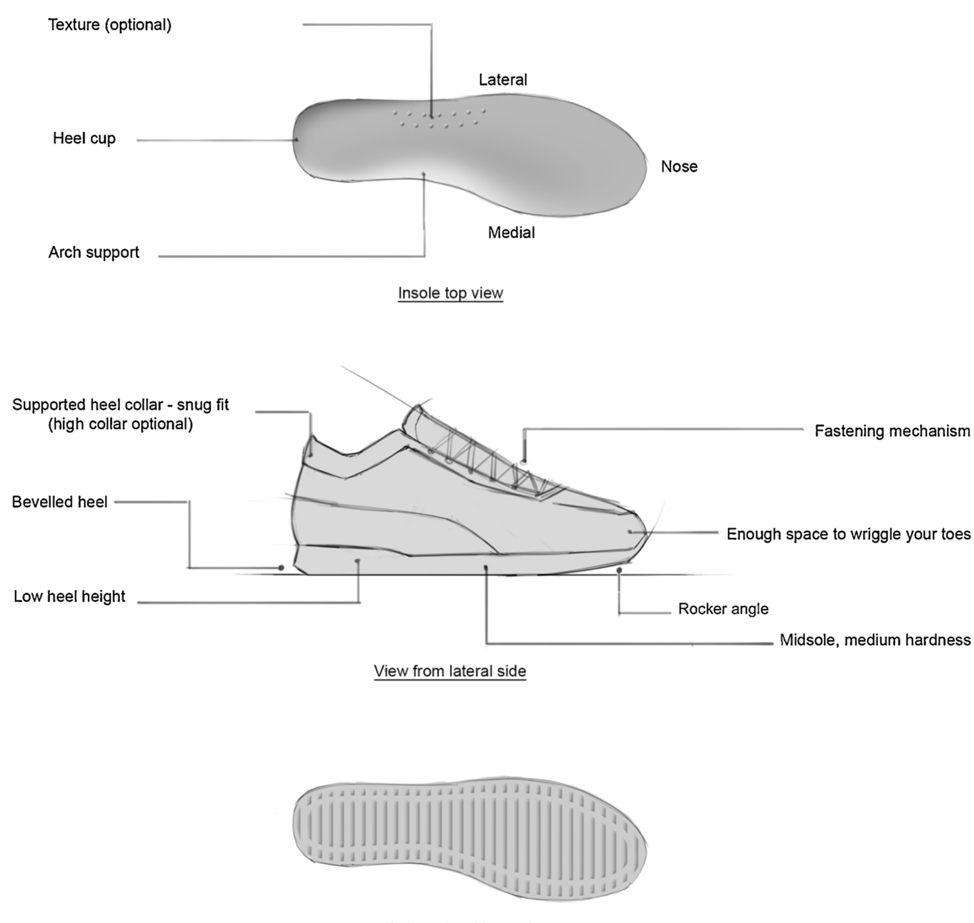


**Fig. 3.** Evidence on safe and comfortable shoe elements compiled in a shoe design for older adults.

Cupped insoles, for better fit of the heel, improved dynamic postural stability [58] and standing balance [59]. Custom-made insoles and shoe fitting resulted in better physical and mental health in older Japanese people [60]. Wearing thick socks reduces plantar pressure sensitivity and increases postural sway, which can be compensated by the use of insoles [61]. An insole with a ridge along the perimeter improved lateral stability during walking [62].

### 3.10. Opening and closing mechanisms, doffing and donning

Despite the fact that doffing and donning problems [16] increase with ageing, we identified no studies reporting on innovative opening and closing mechanisms.

### 3.11. Education/knowledge of older people and professionals about footwear

It is important to educate older adults on choosing proper footwear [6]. Most people choose their footwear for comfort, without considering their safety and increased fall risk [14]. Older people believe they are doing well by buying light-weight, soft shoes which are easy to put on and take off [16]. People described soft shoes as comfortable [19]. People with toe and hindfoot pain preferred to wear slippers [9].

## 4. Shoe design for older people based on the evidence collected in this review

Based on the evidence collected in this review we are able to make design recommendations for the shoe elements required for a comfortable and safe shoe for older adults (see Fig. 3).

An optimal shoe for older adults should include the following elements: a proper anatomical fit, a well-fitting toe box, a limited heel height, a broad enough heel, a firm insole and midsole, an outsole with sufficient tread and width, a bevelled heel, a bevelled shoe nose, a firm heel counter with snug fit, and an easy and effective closing mechanism.

## 5. Discussion

In the current review, the effects of footwear and footwear elements on aspects of comfort, mobility and quality of life in older independently mobile people aged ≥65 are summarised. The data presented demonstrate that well-fitting footwear can improve balance and gait, quality of life and social functioning in older adults, and can reduce fall risk.

A shoe that fits the individual's foot shape well is essential for functioning and comfort. We included studies in independently mobile people, and took into account the usual daily life activities of this age group. In specific circumstances, such as slippery surfaces, elderly people adapt their gait. This lowers the necessary coefficient for friction, and shoes with a tread sole perform well in these circumstances [38]. However, when people do not realise that they are on a slippery floor, greater friction between sole and floor becomes crucial. The design of such a tread sole for use on wet floors is described by Liu et al [63], and also for icy road conditions by Menant et al [64] when special adaptations to footwear are required. As these conditions are exceptional and not common in older people's daily lives, we did not include these features in our recommended shoe design.

Safe elements of footwear for older people include a proper anatomical fit, a well-fitting toe box, a limited heel height, a broad enough heel, a firm insole and midsole, an outsole with sufficient tread and width, a bevelled heel and shoe nose, a firm heel counter with snug fit, and an easy and effective closing mechanism.

It was surprising to find a lack of knowledge and education of both older people and professionals on the importance of optimal, well-fitting footwear for mobility, comfort and QoL of older adults. Older people reported poor aesthetics of the better-fitting footwear as a reason to resort to less well-fitting shoes.

While the morphology of the older foot is clearly different from that of the young foot, shoe manufacturers still rely on shoe lasts [4] that are designed for the younger adult population.

There is a need to educate the general public as well as professionals on the importance of optimal, well-fitting footwear for mobility, comfort and QoL of older adults.

Anthropometric data should be translated into shoe lasts specific to older people. New technologies such as 3D scanning are currently used to gather these data and might lead to customised designs of shoes for older people.

We conclude that there is a need for shoe design specifically aimed at the foot morphology and demands of older people and propose a design for a shoe for older adults based on the evidence collected in this review (Fig. 3). The shoe market should make well-fitting shoes designed specifically for the older foot and person more readily available, especially because well-fitting shoes might be a reversible risk factor for falls in older people.

## 6. Conclusions

Foot morphology changes and foot deformities increase with ageing. The importance of careful selection of a well-fitting shoe should not be overlooked. We conclude that there is a need for shoe design specifically aimed at the foot morphology and demands of older people, including aesthetics. Shoes need to provide stability, also in the lateral direction. The current shoe market should provide better availability of well-fitting shoes designed for the older foot and person. Innovation is needed with regard to a closing mechanism that makes doffing and donning easier for elderly people.

### Contributors

Anton Jellema conceived this study, contributed to the systematic review and wrote the initial draft of the manuscript.

Toon Huysmans contributed to the systematic review and wrote the initial draft of the manuscript.

Klaas Hartholt contributed to the systematic review.

Tischa van der Cammen conceived this study, provided supervision, contributed to the systematic review and wrote the initial draft of the manuscript.

All authors were involved in the critical revision of the manuscript, and saw and approved the final version.

## Provenance and peer review

This article has undergone peer review.

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