

Optimizing footwear for older people at risk of falls

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Abstract—Footwear influences balance and the subsequent risk of slips, trips, and falls by altering somatosensory feedback to the foot and ankle and modifying frictional conditions at the shoe/floor interface. Walking indoors barefoot or in socks and walking indoors or outdoors in high-heel shoes have been shown to increase the risk of falls in older people. Other footwear characteristics such as heel collar height, sole hardness, and tread and heel geometry also influence measures of balance and gait. Because many older people wear suboptimal shoes, maximizing safe shoe use may offer an effective fall prevention strategy. Based on findings of a systematic literature review, older people should wear shoes with low heels and firm slip-resistant soles both inside and outside the home. Future research should investigate the potential benefits of tread sole shoes for preventing slips and whether shoes with high collars or flared soles can enhance balance when challenging tasks are undertaken.

Key words: accidental falls, aged people, balance, biomechanics, footwear, gait, heel height, insoles, rehabilitation, slips, trips.

INTRODUCTION

Many falls experienced by older people result from age-related deterioration of the balance and neuromuscular systems [1]. Most falls occur during motor tasks [2], and footwear has been identified as an environmental risk factor for both indoor and outdoor falls [3–4]. By altering

somatosensory feedback to the foot and ankle and modifying frictional conditions at the shoe-sole/floor interface, footwear influences postural stability and the subsequent risk of slips, trips, and falls. While the primary role of a shoe is to protect the foot and facilitate propulsion [5], fashion has strongly influenced the design of footwear throughout the ages, compromising the natural functioning of the foot [5–6]. As a result, little is known about what constitutes safe footwear for older people undertaking activities in and around the home [7]. Because footwear appears to be an easily modifiable risk factor for falls, identifying the specific shoe features that might facilitate or impair balance in older people is imperative for the design of targeted fall prevention interventions and provision of evidence-based recommendations.

In this systematic review, we initially describe the types of footwear commonly worn by older people. We then highlight studies in which footwear has been recognized as a risk factor for falls. Finally, we review the

Abbreviations: COF = coefficient of friction, COM = center of mass, COP = center of pressure, MTP = metatarsal-phalangeal.

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evidence pertaining to the effects of specific footwear characteristics on balance and related factors in older people.

SEARCH STRATEGY

We conducted a Medline search to identify studies on habitual footwear for older people, types and features of footwear associated with falls in older people, and effects of footwear and features of footwear that could affect balance and gait in both young and older people. The publication dates of the full-length articles were between 1985 and 2008. We conducted several general searches combining keywords “shoes or footwear” with one or more of the following: “aged or aging,” “balance” (subheadings: musculoskeletal equilibrium, muscles, or sensation disorders), “falls” (subheadings: aged and accidental falls), “gait” (all subheadings). We also searched specifically for these keywords: “high-heels,” “midsole hardness or sole hardness,” “slip resistance,” “friction,” and “high-collar.” Additionally, we searched the Health and Safety Science Abstracts of the CSA Illumina database (ProQuest, Bethesda, Maryland) using the keywords “shoes or footwear” and “balance.” We included articles that dealt with nontherapeutic footwear, features of footwear or footwear appliances in the context of falls and/or fall risks in older people, balance, postural control, gait, and slips. We also added articles on the effects of footwear on balance and gait in younger people if we thought they were relevant to fall risk in older people. Finally, we included articles on everyday footwear worn by older people. In contrast, we excluded articles on footwear used for therapeutic purposes or on the effects of footwear on the development of specific medical conditions, because we aimed to focus on the general older ambulatory population. We excluded all articles on features of shoes used for sports unless we considered the effects shown relevant to balance control during walking. Abstracts published more than 4 years ago and single-case studies were excluded. We examined the references of the selected articles from the searches including reviews and searched for any relevant article, then included it in the literature review if it satisfied the inclusion and exclusion criteria defined earlier. We assessed the level of evidence of the selected studies based on the Oxford Centre for Evidence-based Medicine Levels of Evidence [8], which ranks studies based on their methodological rigor.

SEARCH RESULTS

Our multiple Medline searches retrieved 1,185 articles, 56 of which were relevant based on title and abstract [9–64]. Based on their references, we retrieved 19 more articles [65–83]. We retrieved one additional relevant article [84] from the CSA Illumina database. One abstract presented at a recent conference [85] and two articles “in press” [86–87] were also included. We ultimately included 79 articles in this literature review (**Appendix**, available online only at <http://www.rehab.research.va.gov/jour/08/45/8/pdf/contents.pdf>). According to the Oxford Centre for Evidence-based Medicine Levels of Evidence [8], all the studies selected and involving human testing had a level of evidence of 2b because they were cohort studies, either cross-over controlled comparisons or cross-sectional studies. Two studies were nested case-control studies [26,57]. Only one article, a systematic review [22], had a level of evidence of 2a.

DISCUSSION

What Footwear Do Older People Wear?

Identifying the type of shoes usually worn in and around the home is important for determining whether the footwear worn by older people places them at an increased risk of falls. Older community-dwelling people are the most active sector of the elderly population and, as a result, are the group most exposed to environmental risk factors [2]. Furthermore, community-dwelling people are more likely to engage in outdoor activities and therefore have different footwear-wearing habits and requirements than people living in residential aged-care facilities who have limited mobility.

A survey of the footwear purchased by 128 community-dwelling people (including 60 men) aged over 65 years revealed that the majority wore slippers within their homes and that 32 percent of women and 28 percent of men usually walked barefoot or wore socks [42]. Similarly, approximately 25 percent of 312 older community-dwellers reported wearing slippers inside the house, followed by 19 percent reporting walking around without shoes [85]. Because both these studies were conducted in Australia, the warm climate might well have contributed to the high proportion of people not wearing shoes while at home. As one might expect, the probability of older people predominantly wearing slippers rises in residents

of institutions and hospital inpatients, as well as with increasing age. Accordingly, 37 percent of a sample of 606 nursing home residents (mean age 83 years) reported wearing slippers indoors [25] and 66 percent of 44 patients in a subacute aged-care hospital reported wearing slippers or moccasins [24]. Older people typically chose to wear slippers because they are usually made of soft material and their flexible structure can comfortably accommodate painful feet and foot deformities [42]. A recent study found that, in a sample of 312 older community-dwelling people, those who wore slippers indoors versus no shoes or fastened shoes reported more foot pain and had a significantly greater falls risk score as indicated by deficits in sensorimotor function tests (visual contrast sensitivity, knee extension strength, proprioception, postural sway, hand reaction time) [85].

Other studies have found that older people, irrespective of their dwelling status, wear poorly fitted shoes, which may lead to foot problems and, in turn, increase the risk of falls [88]. For example, Burns et al. noted that 72 percent of older people admitted to a rehabilitation unit ($n = 65$) were wearing ill-fitting shoes, with 90 percent of these shoes being too long or too wide [12]. Similarly, Menz and Morris found that older retirement-village residents ($n = 176$) wore ill-fitting indoor and outdoor shoes (81% and 78%) narrower than their feet [40]. While incorrect shoe length has been significantly associated with ulceration of the foot and with pain [12], overly narrow footwear has also been strongly associated with the presence of corns on the toes [40]. Larsen et al. reported similar findings, in that 43 percent and 5 percent of older community-dwelling women ($n = 2,649$) and men ($n = 1,632$), respectively, wore either socks, slippers, or improperly sized or ill-fitting shoes while indoors [27]. Of 128 patients admitted to a geriatric unit and requiring new footwear, 28 percent wore slippers often leading to heel slippage, 25 percent wore shoes with heels higher than the recommended height, 20 percent wore shoes with heels narrower than the recommended width, and 11 percent wore shoes “beyond repair,” with cut uppers or flapping soles [67].

In 44 patients from an aged-care hospital, a modified version of a footwear assessment form [89] identified that a lack of a slip-resistant sole or a fastening mechanism, as well as an excessively flexible heel counter or shank, were the most frequent detrimental shoe characteristics [24]. These shoe features likely promote slips and trips because they fail to provide foot support. A tele-

phone interview regarding shoes worn at the time of a fall in 652 community-dwellers aged 65 and over found that only 26 percent of participants were wearing “sturdy shoes” when they fell [14]. These findings, however, may be limited to participants’ varying interpretations of what constitutes a sturdy shoe.

In summary, many older people wear inappropriate footwear both inside and outside the home. Shoes are replaced infrequently, possibly because of a lack of knowledge about the importance of safe shoes and/or financial considerations [14,42]. The choice of footwear might be somewhat dictated by comfort and the need to accommodate painful feet [85], explaining the tendency for older people to wear excessively flexible and/or overly long and wide shoes. Older people might also favor shoes without fasteners for the practical reasons that they do not have to bend down to tie laces or fasten straps.

Is Footwear a Risk Factor for Falls in Older People?

Regardless of the reasons influencing older people’s choice of footwear, the types and characteristics of shoes commonly worn by older people match shoe types identified by both retrospective and prospective investigations as risk factors for falls. Investigating falls in a sample of 96 male and female community dwellers aged 60 to 80 years, Berg et al. found that participants who had falls reported wearing shoes with slippery soles or slippers as a predisposing factor (in 9% of those who fell) [3]. Gabell et al. prospectively examined risk factors associated with falls in 100 community-dwelling people aged 65 and over and identified inadequate footwear as a major contributing factor [17]. Out of 22 falls, 10 occurred while participants were wearing either heavy boots or boots with cutaway heels, slip-on shoes, or slippers. Gabell et al. also found that a history of high-heel shoe wearing in women was a predisposing factor for falling. Of the 22 falls reported, 10 occurred outdoors, which may explain why, contrary to other studies, walking barefoot did not appear to be a major falls risk factor [17].

Tencer et al. conducted a 2-year prospective investigation of falls in which they matched older community-dwelling people who fell ($n = 327$) with people with similar demographics who did not fall [57]. The researchers found that 61 percent of the falls occurred outdoors and that shoes with heels greater than 2.5 cm increased the risk of falls compared with athletic or canvas shoes (odds ratio: 1.9). They also found that the risk of falls significantly

decreased with an increase in median sole/surface area above 74 cm² (median sole/surface area for high-heel dress shoes was 49 cm²). Walking barefoot or wearing socks increased the risk of falls the most, by up to 11 times compared with walking in athletic or canvas shoes [26]. A recent prospective study conducted among 176 older retirement-village residents for whom more falls occurred indoors than outdoors ($n = 50$ vs $n = 36$) also confirmed that walking barefoot or in socks increased the risk of falls indoors (odds ratio: 13.7) [41]. Furthermore, Larsen et al. reported a strong independent association between walking indoors in socks or slippers and falls (odds ratio: 5.5) in women aged over 66 years [27].

Using a footwear assessment form that identifies shoe characteristics relevant to a loss of balance or a fall [89], another retrospective study noted that 75 percent of a sample of 95 older people (mean \pm standard deviation age 78.3 \pm 7.9 years) who had a hip fracture-related fall were wearing improper footwear at the time of the incident [52]. The largest proportion of falls occurred while the older people were walking inside their homes (48%), and slippers were the most common type of footwear worn (22% of the fall cases). The unsafe features of shoes identified in this study included a lack of fixation (63%), excessively flexible heel counter (43%), and an excessively soft sole (20%) [52]. The participants who tripped ($n = 32$) were more likely to be wearing slippers or ill-fitting shoes without proper fixation. Hourihan et al. also reported that at the time of a hip-fracture-related fall, 24 percent of 104 older people were barefoot or in socks, 33 percent were wearing slippers, and 22 percent were wearing slip-on footwear [71]. Similarly, analysis of footwear habits among nursing-home residents ($n = 606$) revealed a strong association between wearing slippers (as opposed to shoes) and fractures [25]. Furthermore, Keegan et al. found that slip-on shoes and sandals were associated with a greater risk of a foot fracture from a fall (odds ratio: 2.3 and 3.1, respectively), and that wearing medium- to high-heel shoes and narrow shoes increased the risk of fractures at five sites (foot, distal forearm, proximal humerus, pelvis, and shaft of the tibia/fibula) in people aged 45 years and over [59].

These findings suggest that suboptimal footwear, regularly worn by older people, increases the risk of falls. Older people might exacerbate their risk of slipping by walking barefoot, in socks, or in shoes without slip-resistant outer soles, or their risk of tripping by wearing ill-fitting slippers or shoes lacking fasteners. Wearing

shoes that are the wrong size might also lead to foot problems that, in turn, can place older people at an increased risk of falls [88]. Indoor footwear, or the lack of it, seems to be more implicated in the etiology of falls than outdoor shoes, possibly because more studies have been conducted among older people living in residential aged care who engage less often in outdoor activities.

What are the Effects of Specific Footwear Conditions on Stability?

Findings from experimental studies that have investigated the effects of specific characteristics of footwear on balance and gait can help determine why some shoe types are associated with a higher risk of falls in older people. These investigations might also help us identify features of footwear that may be beneficial to older people's balance and should be considered in the design of safe shoes. This section updates the literature review by Menz and Lord [38] and describes findings related to how shoe properties can facilitate or impair balance.

Barefoot Versus Wearing Shoes

One may assume that proprioception and plantar sensitivity provide optimal input to the postural control system when the wearer is barefoot versus wearing shoes. While footwear might indeed attenuate tactile sensory input to the plantar sole of the feet [51], this may not always be the case, especially for individuals who have been conditioned to wearing shoes since childhood. In a study by Robbins et al., both young and older subjects were required to estimate the amplitude and the direction of the slope of a weight-bearing surface [51]. The older subjects' joint position awareness was 162 percent lower than that of their younger counterparts when barefoot, possibly due to age-related decline in plantar tactile sensitivity. Wearing running shoes further increased mean estimate error in joint position in both groups, suggesting attenuation of the tactile sensory input through footwear. In addition, a group of community-dwelling older people made fewer errors when barefoot than when wearing shoes in estimating the maximum supination angle of the soles of their feet when they walked along a beam [49]. In contrast, Waddington and Adams reported that older community dwellers ($n = 20$) were significantly better at discriminating ankle inversion movements when shod than when barefoot [58]. However, the subjects had undergone wobble-board balance training for 5 weeks in self-selected shoes, which may in part explain these findings.

As discussed earlier, more than a quarter of older community dwellers walk in the home barefoot [42,85], which is associated with an increased risk of falling [26,41]. Therefore, addressing the effects of barefoot versus shoe-wearing conditions on balance in older people is crucial. Interestingly, being barefoot or wearing shoes did not affect standing balance (maintaining balance while standing on a firm or a compliant surface with eyes open or closed) in 30 older adults who had vestibular problems [61]. Similarly, Arnadottir and Mercer did not report any significant differences in functional reach performance in older women ($n = 35$) barefoot compared with fitted with walking shoes [9]. However, these older women took less time and achieved greater self-selected speed in the timed up and go and 10 m walk tests when wearing shoes, presumably because footwear enhanced plantar shock absorption and therefore improved comfort.

In contrast, Lord and Bashford found that older women ($n = 30$) performed worse in a test of maximal balance range but exhibited less postural sway and better scores in a leaning balance test (coordinated stability) when barefoot than when wearing standard low-heel shoes [32]. However, these contrasting findings may be explained by the subjects in the Lord and Bashford study being novice wearers of a pair of standard low-heel shoes [32] compared with subjects wearing their own flat or walking shoes as in the previous studies [9,61]. Furthermore, older community dwellers required to walk on a 7.8 cm-wide beam in various footwear conditions failed the task more frequently when barefoot than when wearing shoes [48–49], possibly because of decreased function of the toes associated with long-term wearing of shoes [48]. Despite the hypothesis that walking barefoot or in stockings over a wet or a shiny indoor surface might exacerbate the risk of slipping [41], no study to date has investigated the risk of older people slipping while walking barefoot or wearing socks over common household surfaces such as polished wooden floors. Alternatively, walking barefoot or in socks over a carpeted surface might provide excessive slip-resistance that could lead to a trip in older people; this issue also requires further investigation. Finally, Burnfield et al. reported significantly higher plantar pressures in older people walking barefoot versus shod [11], suggesting that older people should avoid walking around barefoot as it could increase the risk of foot trauma.

The conflicting findings regarding differences in joint position sense and standing balance in older people

between barefoot and shod conditions may be attributed to methodological differences. However, wearing shoes appears to enhance walking stability. Wearing shoes also protects the foot from mechanical insult and irregularities in walking surfaces and is likely to provide more grip than the plantar sole of the foot, reducing the risk of slipping, especially indoors.

Heel Height

As highlighted earlier, heel elevation is associated with an increased risk of falling in older people [17,57]. By elevating and shifting the wearer's center of mass (COM) forward, high-heel shoes affect balance control and lead to postural and kinematic adaptations [53]. The plantar-flexed ankle position adopted when wearing elevated heel shoes might contribute to larger vertical and horizontal ground reaction forces noted at heel strike [15,23,53]. In the plantar-flexed ankle, calcaneal eversion is reduced, which is often noted in high-heeled gait [15,53], and foot rollover in the shoe is absent [15]; these later adaptations might prevent the foot from pronating, affecting the foot's natural shock-absorption mechanism. Compensation strategies in response to this impaired shock absorption subsequently arise at the knee and hip as shown by altered kinematics and kinetics [13–15,44–45,53–55,69]. Age and sex interactions appear to lead to different trunk and pelvis kinematics during gait. When wearing shoes with high heels, older women and young men show a flattened lumbar lordosis [13,44] while younger women display increased trunk lordosis [44]. Studies have consistently recorded significant increases in forefoot loading during high-heeled gait [20,76], with especially greater pressures in the medial forefoot [23,54,63,65,81]. Such increased pressures might contribute to the development of plantar calluses [90]. In fact, these foot problems have been associated with wearing shoes with heels higher than 2.5 cm in older women [40].

Individuals wearing high-heel shoes compared with low-heel shoes or barefoot displayed slower walking speed [16,44–45], shorter step or stride length [15–16,45,69], and increased walking cadence [15,60,69], possibly a consequence of a more cautious walking pattern. Raising the COM increases the moment arm of the medial-lateral moment of force applied at the COM about the shoe/floor interface, resulting in a smaller medial-lateral perturbation required for a fall to occur and, thus a smaller critical tipping angle of the elevated heel shoe [57].

Despite quite different methodologies, study findings show that experience in walking with elevated heel shoes alters lower-limb muscle activity patterns. For example, men and women wearing high-heel shoes exhibited reduced gastrocnemius muscle activity [28,73], possibly because the plantar-flexed position of the ankle alters the length-tension relationship of this muscle. However, while men showed a significant increase in tibialis anterior muscle activity (possibly to counteract a feeling of instability), women who were regular high-heel shoe wearers displayed the opposite muscle activity pattern [28]. In contrast, five young healthy women did not display significantly different peak tibialis anterior muscle activity during walking in medium- and high-heel shoes compared with low-heel shoes [72]. The level of experience of these women with wearing high-heel shoes, which was not specified, and the imposed walking velocity could have contributed to the contradictory findings reported here. In another study following a fatigue exercise simulating high-heeled gait, habitual high-heel shoe wearers showed low-level endurance of the peroneus longus muscle and an imbalance in muscle activity between the lateral and medial heads of gastrocnemius [21]. This muscle imbalance might increase foot instability as suggested by abnormal lateral movements of the center of pressure (COP) under the heel and first metatarsal head observed in habitual high-heel shoe wearers [21].

Few studies have investigated the effects of wearing elevated heel shoes on stability in older people. One study showed that young women ($n = 27$) maintained significantly better balance on a moving platform when subjected to various accelerations while wearing tennis shoes compared with cowboy boots [10]. Subsequently, Lord and Bashford found that older women from a retirement village ($n = 30$) performed significantly worse in three tests of balance (postural sway, maximal balance range, and coordinated stability) in high-heel dress shoes (6 cm heel height) than when barefoot or in low-heel shoes (1.6 cm heel height) [32]. A group of 29 people aged over 70 years also showed greater postural sway when standing in elevated heel shoes (4.5 cm heel height) compared with standard shoes (2.7 cm heel height) [86]. Similarly, other researchers noted that elderly community-dwelling women ($n = 35$) performed significantly worse in the tests of functional reach, timed up and go, and 10 m walk when wearing dress shoes (5.3 cm mean heel height) compared with walking shoes (1 cm mean heel height) or being barefoot [9]. However, Lindemann

et al. did not find any differences in postural sway or walking velocity in a sample of frail older women ($n = 26$) wearing tennis shoes with either 1 or 2 cm heel height [31].

Because some types of male footwear (e.g., cowboy boots) also have an elevated heel, some investigations have included male subjects in their sample [13,36]. The variety of findings pertaining to the effects of high-heel shoes on balance and gait can be attributed to inconsistencies in the choice of footwear. While some studies have compared barefoot with high-heel dress shoe conditions [20,36,43,69], others have compared tennis shoes or flat shoes with high-heel shoes with a narrow toe-box [20,36,44–45,55,60,69,76]. Some researchers have used only a shoe heel attached to the heel of the foot of the individual [65], whereas others have used each individual's dress shoes or have provided a standard dress shoe [28,32,36,44–45,81]. Few studies have managed to isolate the effect of heel height by keeping a shoe of similar design but systematically increasing the heel height [15,23,31,53,63,66,73,86]. Thus, whether study findings reflect the true effects of heel height or are influenced by other shoe design factors is questionable. Nevertheless, the detrimental effects of elevated heel shoes are numerous and, for this reason, older people should be advised against wearing such footwear because it places them at an increased risk of falling.

Sole Cushioning Properties

Following research associated with the development of shoes with extra midsole cushioning designed to attenuate impact forces and reduce injuries during running [91–93], studies have been conducted to investigate the effects of sole and midsole thickness and hardness on stability in older people. An initial study involving 25 older men demonstrated the detrimental effect that soft and thick shoe midsoles (shore A-15 [for the studies reviewed here, shore-A hardness ranges from shore A-15 for soft soles, to shore A-58 for hard soles], 27 mm at the heel and 16 mm under the 1st metatarsal-phalangeal [MTP] joint) have on balance control, assessed by the frequency of falls from a walking beam [48]. A later study involving young men reported similar findings [50]. The older men perceived the shoes with soft thick midsoles to be the most comfortable among shoes of varying hardness (shore A-15, A-33, and A-50) and thickness (13 mm at the heel and 6.5 mm under the 1st MTP joint versus 27 mm at the heel and 16 mm under the 1st MTP joint) [48], possibly because the soft and thick midsoles enabled even

distribution of load across the plantar surface of the foot. This even distribution of load, in turn, was hypothesized to reduce plantar tactile sensory feedback and subsequently impair balance control. The authors also suggested that the midsole mechanical instability generated frontal plane movements at the ankle through material compression. A subsequent study investigating the effects of age and footwear on joint position sense clarified these proposed mechanisms, concluding that shoes with soft thick soles impair stability by reducing joint position sense [51].

This notion was subsequently tested in more dynamic conditions, in which 13 young and 13 older men who walked on a beam in shoes of varying midsole hardness and thickness were asked to estimate the maximum supination angle of the sole of their foot [49]. Position error was then calculated with rear-foot angle [49]. Foot position awareness was worse, by approximately 200 percent, in the older compared with the younger adults in any footwear condition, and the older subjects' mean position error was greatest in the shoes with the thickest and the softest midsoles. In agreement with previous findings [48], balance was worst in the thick and the soft midsole shoes, especially in the older group. Furthermore, errors in judgment of foot position were positively correlated with midsole thickness, and negatively correlated with balance and with midsole hardness.

Sekizawa et al. also reported detrimental effects of thick-sole shoes (50 mm at the heel and 30 mm under the 1st MTP joint) compared with barefoot on joint position sense in 20 young males as they stood with the foot placed in dorsiflexion [80]. Furthermore, Perry and colleagues investigated balance control in young people performing tests of rapid unplanned stopping both barefoot and when wearing midsoles of three different hardnesses (shore A-15, shore A-33, and shore A-50) fixed to their feet [46]. Compared with the hard midsoles, the soft midsoles led to a significant reduction in medial-lateral range of COM displacement, to possibly counteract the lack of mechanical support of the material. A reduction in the COM-COP distance, together with a significantly greater vertical loading rate in the softer midsoles compared with barefoot during terminal stance demonstrates how softer midsoles, may impair balance control in the sagittal plane during stopping. Perry et al. concluded that soft-sole shoes may threaten an older person's stability, because greater muscular activity is required to maintain stability during stopping in this footwear condition [46].

In an attempt to combine comfort and stability, Robbins et al. investigated the effects of a soft, low-resilience material on postural sway and perceived comfort in 30 young and 30 older adults [79]. The authors hypothesized that, in addition to providing a cushioning sensation, soft, low-resilience interfaces would remain compressed after foot strike and prevent excessive frontal plane movement of the foot, as would be expected with high-resilience materials. Results of the study confirmed that in both groups, sway velocity was significantly lower when subjects stood on the thin low-resilience interface than on the thick high-resilience interface. Overall, a trend developed, with the low-resilience material being more comfortable than the high-resilience material. In accordance with these findings, optimum comfort and stability might be obtained if the soles of the shoe are thin and hard combined with low-resilience insoles. However, no significant differences in measures of postural sway and leaning balance during standing (maximal balance range and coordinated stability) were found between a medium-hard-sole (shore A-42) and a hard-sole (shore A-58) shoe in a population of 42 older women, leading to the conclusion that the soft-soled shoes used in this study might not have been compliant enough to affect balance [33]. Accordingly, Menant et al. did not find any difference in tests of postural sway, leaning balance, and choice-stepping reaction time in older people ($n = 29$) wearing soft-sole shoes (shore A-25) or hard-sole shoes (shore A-58) versus medium-hard-sole shoes (shore A-40) [86].

In summary, variations in sole or midsole hardness do not appear to significantly alter balance during standing. However, thick- and soft-sole shoes impair stability during walking by reducing foot position awareness and mechanical stability, and may pose an even greater threat to stability during challenging tasks [46]. Despite this evidence, epidemiological studies have failed to confirm whether sole hardness or thickness are risk factors for falls in older people [57]. Because of the constrained nature of balance tests in the investigations conducted by Robbins et al. (beam walking [93], as discussed in Grabiner and Davis [94]) and the lack of evidence regarding older people's balance control during challenging tasks, further studies are required before definitive recommendations can be made regarding midsole hardness and thickness.

Collar Height

High-collar shoes were initially investigated in the context of preventing sports-related ankle sprains, by

providing extra mechanical support around the ankle. Relative to low-collar sports shoes, high-collar sports shoes offer significantly better resistance against inversion [78] and reduced ankle inversion angular velocity [82] in young adults performing various sporting tasks.

In addition to providing greater mechanical stability to the ankle joint, the extra sensory input provided by a high collar is thought to facilitate joint position sense [62] and, in turn, improve medial-lateral balance control. In fact, a tactile stimulus applied to the leg of younger, older, and neuropathic subjects has been found to reduce body sway during standing [95]. Significant improvements in postural sway and leaning balance were also noted in laced boots versus low-collar shoes in a group of 42 women aged 60 to 92 years old [33], while no difference in tests of balance and stepping were found in 29 male and female community dwellers wearing low-collar shoes versus 11 cm-high collar shoes [86]. In contrast, compared with trainers, cowboy boots were found to impair balance control in young women standing on a platform that was translated in the anterior-posterior direction [10]. However, in addition to a higher collar, the boots also had an "inverted" heel of 3.7 cm, which may have contributed to the subjects' instability. More research is therefore recommended to confirm the potential benefits of high-collar shoes on stability during challenging motor tasks, since potential aesthetic concerns of such footwear combined with their lack of suitability for hot climates might deter older people, especially women, from wearing such shoes on a regular basis.

Sole Flaring

By increasing the base of support, a flared sole might improve medial-lateral stability [38] and therefore warrants consideration when shoes are designed for older people [96]. Most published investigations have examined this shoe feature in the context of preventing running injuries [77,82]. For example, compared with standard trainers, low-cut trainers with a flared sole were found to reduce slipping of the foot within the shoe. Further, the flared sole led to a significantly lower inversion moment at the subtalar joint by increasing the lever arm in young subjects who were performing sideward cutting movements [82]. Running shoes with a heel flare were also found to significantly increase initial pronation during running in 14 male runners, but did not affect total pronation or impact force peaks [77]. Menant et al. recently investigated the effects of flared-sole shoes on

tests of balance and stepping in older people and found no differences between standard shoes and flared-sole shoes in older people ($n = 29$) [86]. However, whether shoes with a flared sole are beneficial or detrimental to balance control during gait, particularly in older people, remains to be seen.

Slip-Resistant Sole Properties

Slips and trips are the most commonly reported causes of falls in older people [3,97], with 17 percent of falls found to be due to slips in a population of healthy community-dwellers aged over 70 years [2]. Not wearing shoes indoors is suggested to contribute to indoor slips since walking barefoot or in socks increases the risk of falls in older people by more than tenfold [26,41]. Furthermore, ice- and snow-related slips contribute to a high number of injurious falls in cold climate countries. In a 1-year prospective study, 34 percent of ice and snow slip-related injuries in a Swedish town occurred in adults aged between 50 and 79 years [98], and shoes lacking slip-resistant soles likely contributed to these incidents. Because of their higher likelihood of slip-related falls due to an age-related decline in sensorimotor systems, older people may benefit from slip-resistant footwear [99].

In the context of preventing outdoor winter slips during Swedish winters, Gard and Lundborg evaluated various antiskid devices fixed to the footwear of older people who were performing simple walking tasks over five slippery surfaces (ice with sand, ice with gravel, ice with snow, ice with salt, and ice alone) [19]. An antiskid device applied to the shoe heel was rated the best in terms of walking safety and balance, time to put on, and ease of use and it did not significantly affect gait and posture compared with either whole-foot or forefoot-only devices. Using the same testing protocol, Gard and Berggard later confirmed that compared with whole-foot or toe antiskid devices, a heel device was preferred and perceived as providing the best walking safety and balance by 107 men and women aged 22 to 80 years [68]. A study conducted in North America investigated the effects of an elastometer netting ("Yaktrax Walker") worn around the sole of the shoe on outdoor slips and falls in a sample of community-dwelling fallers aged over 65 years [37]. The relative risks of outdoor slips, falls, and injurious falls for the group wearing the device versus the control group who wore their habitual winter shoes were 0.5, 0.45, and 0.13, respectively. These devices therefore may

provide a useful and inexpensive solution to the problem of outdoor falls on icy surfaces.

An early study that used a slip-resistance testing machine showed that none of several rubber-nitrile-heeled shoes tested could provide a safe friction coefficient for walking over smooth wet surfaces contaminated with detergent or oil. Roughening of the floor surfaces, however, was shown to increase safety when nitrile or polyvinyl chloride-heeled shoes were used [83]. Furthermore, Gao et al. compared the slip-resistance of four types of footwear of varying materials and sole tread, hardness, and roughness and found a significant positive correlation between sole roughness and slip-resistance [18]. Following a series of studies on the slip-resistance of various rubber soles on water-wet floors as well as on oil-contaminated surfaces and icy surfaces, Manning and Jones found that to reduce the risks of slips, one should avoid floor polish where possible and increase the roughness of new shoe soles by abrading them [35]. They also suggested that people should be informed of the hazardous slip-resistance of commercially available footwear on icy footpaths. Further testing showed that a rubber heel with a bevel of about 10° , which provides a greater contact area at heel strike than a square rubber heel, offered better slip-resistance over both dry and wet floor surfaces [75]. For the wet floor, a tread pattern reduced the lubricating effect of the water at heel contact but showed dangerously low coefficients of friction (COFs) on oily surfaces.

A study by Menz et al. using a similar methodology confirmed these findings [39]. An Oxford-type shoe (a leather shoe with lacing and a low heel) with various heel configurations was found to provide safe dynamic COFs on common dry household surfaces, the beveled heel configuration being the most slip-resistant. While dress shoes with broad heels reached a significantly greater COF than narrow-heeled ones, overall women's dress shoes could not be considered safe regarding slip-resistance. Unfortunately, none of the Oxford-type shoes or the dress shoes, even when equipped with a patterned sole, had a safe COF on wet oil-contaminated surfaces. Using a slip meter, Li and Chen demonstrated that, compared with flat footwear pads, tread grooves about 1.2 cm wide on a variety of shoe-soling materials (ethylene-vinyl acetate, leather, blown rubber, and neolite) provided greater slip-resistance on a range of surfaces (terrazzo, steel, and vinyl), wet or even water-detergent contaminated, because they allowed drainage of the contaminant between the footwear pad and the floor and decreased the contact area

between the two surfaces [29]. Tread grooves with an orientation perpendicular to the walking direction provided the highest COF [74]. However, the shoe tread grooves were not effective in providing a safe COF when the surfaces were oil-contaminated [29,74]. Subsequent experiments demonstrated the benefits of increased tread groove depth (from 1 to 5 mm) of neolite footwear pads on slip-resistance on wet and water-detergent-contaminated surfaces but not on oil-contaminated ones [30].

Conflicting views come from a study by Connell and Wolf, in which two near-fall incidents due to excessive foot-floor slip-resistance were documented [4]. In both situations, the older community dwellers were pivoting and the slip-resistance from both their shoe soles and the flooring became too high and resisted the rotation of their lower limb, resulting in a loss of balance. While the slip-resistance of the shoe soles and that of the flooring might have been acceptable if considered individually, they appeared to be too high when combined. Menz et al. also reported that during their prospective falls study in older retirement-village residents, four indoor fallers and one outdoor faller perceived their fall to be caused by their shoe getting "stuck," suggesting cases where excessive slip-resistance might have led to trips and/or loss of balance [41]. Too much friction at the shoe/walking surface interface may be hazardous to stability for older people who have a shuffling gait, such as those with Parkinson disease. For these people, a smooth surface may be desirable because shufflers tend to have a very low toe clearance, which may increase the risk of trips when they are traversing an irregular or highly slip-resistant surface.

In summary, Oxford-type shoes equipped with a tread sole and a treaded beveled heel appear to provide sufficient slip-resistance for walking over dry and water wet surfaces. However, older women should be advised to avoid wearing high-heel dress shoes because, in addition to their known detrimental effects on posture and balance, these shoes do not have a safe COF, even with a broad heel. To prevent slips, areas contaminated with detergent or oil should be avoided and frequently cleaned. Roughening these surfaces will also offer greater slip resistance. While providing useful information regarding the safety of footwear/floor interactions, mechanical friction testing has some limitations in that it cannot replicate human behavior in terms of gait biomechanics and psychophysiological factors [99]. For example, prior knowledge of a slippery surface leads to postural and temporal gait adaptations, in turn, lowering the required COF

[100]. In addition, COF measurements determined from mechanical testing should be interpreted with caution because of the variety of devices and assessments techniques that have been used. Future research should therefore focus on evaluating the effect of slip-resistant shoe soles on older people's stability and risk of slipping while performing challenging motor tasks on various (slippery and nonslippery) household and outdoor surfaces. Finally, recommendations provided to older people regarding wearing slip-resistant footwear should be adapted to each individual's level of functioning, keeping in mind the potential risks of falling associated with excessive slip-resistance.

Plantar Sensation Facilitating Insoles

The critical function that plantar cutaneous sensation has on postural control has been well established [101–103]. Skin mechanoreceptors within the plantar surface of the foot provide information to the central nervous system about body position to induce postural responses [101]. Hence, providing extra tactile sensory input to the plantar surface of the feet has the potential to improve balance control. Priplata et al. recorded postural sway in 15 young and 12 older people who were standing with their eyes closed on vibrating gel-based insoles [47]. Mechanical noise applied to the soles of the feet at a sub-sensory level led to significant reductions in postural sway, more so in older adults whose threshold of tactile sensitivity would be higher than that of their younger counterparts. Suomi and Kocaja evaluated the effects of wearing magnetic insoles on balance in 14 healthy young and older adults and reported small but significant reductions in postural sway in the older subjects wearing the magnetic insoles but no changes in young subjects [56]. However, the validity of these findings is limited because the subjects were not blinded to the insole conditions and the texture of the magnetic and nonmagnetic insoles was different. Further, Hinman did not observe any significant difference in standing or leaning balance in 56 older community-dwelling people with a history of falls or balance problems who were wearing either pairs of magnetic insoles (15 magnets with either a Gaussian rating of 3,900 or 12,000 each) or placebo insoles [64]. Considering the limited evidence of the beneficial effects of magnetic insoles on balance and that the mechanisms whereby a magnetic field applied to the plantar surface of the feet could affect postural control are unclear, magnetic insoles should not be recommended for wear in older people.

After 4 weeks of wearing textured foot orthotics in standardized shoes, 40 healthy women showed that wearing the devices had no significant effects on postural sway (anterior-posterior and medial-lateral range of COP excursions) during standing with their eyes open or eyes closed or on step width during walking at self-selected speed [87]. In contrast, when wearing textured insoles in their own athletic shoes and without any previous familiarization, young subjects exhibited similar COP area and excursion velocity during quiet standing with eyes open and closed, suggesting that extra tactile sensory input from the textured insoles has a beneficial effect on postural control when visual input is inhibited [84]. Variations in the insoles' textured patterns (1 mm-high nubs [87] vs 2.5 mm-high nubs [84]) or in the study design could account for the conflicting findings between these studies.

Hosoda et al. found that, contrary to their hypothesis, wearing "health sandals" (textured insoles with small projections) versus slippers (with smooth insoles) increased latency responses to anterior-posterior perturbations from a motorized balance platform in young adults [70]. In contrast, Maki et al. evaluated the effects of facilitating plantar sensation on balance control by providing 7 young (mean age: 26 years) and 14 older (mean age: 69 years) subjects insoles with a raised edge at the plantar surface boundaries [34]. Fewer "extra" steps and arm movement reactions were noted in older people wearing the modified insoles when stepping in response to unpredictable forward perturbations. Older people wearing the modified insoles also maintained a greater margin of stability relative to the posterior border of the base of support during continuous platform perturbations when required to resist the perturbation without stepping.

As concluded by Hijmans et al. [22], the benefits associated with wearing vibrating insoles [47] or insoles that mechanically facilitate plantar tactile sensitivity [34] are likely to be particularly useful to older people with age-related declines in plantar sensitivity or to counteract the detrimental effects on balance of thick, soft-sole shoes prescribed to people with ulcers or peripheral neuropathy [104]. However, these postural control enhancing insoles may not be easily combined with the orthotic devices that some older people wear and their long-term effects have yet to be demonstrated.

CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

The question raised by the American and British Geriatrics societies and the American Academy of Orthopaedic Surgeons in 2001 [7]—What is the safest footwear for older people who have fallen or are at risk of falling?—remains unanswered, despite substantial advances in the field of footwear and falls research. Now sufficient epidemiological evidence suggests that older people should wear appropriately fitted shoes both inside and outside the house, because walking barefoot and in socks indoors are the footwear conditions associated with the greatest risk of falling. Older people should wear low-heel shoes because the detrimental effects of high-heel shoes on posture, balance, and gait are numerous and this type of footwear is also associated with an increased risk of falls. Because shoes with a softer sole (sole hardness less than shore A-33) can alter balance control during challenging gait tasks, older people should be advised to wear thin, hard-soled shoes to optimize foot position. A tread sole and a treaded beveled heel may further prevent slips on wet and slippery surfaces. These recommended features are shown in the **Figure**.

Prevention of falls should also include education of older people and their caregivers/family (for those housebound or institutionalized) regarding these footwear recommendations, because financial and comfort aspects likely currently outweigh safety considerations when older people purchase shoes. Future directions for research should include systematic investigations on the effects of a high collar and a flared sole on stability in older people performing challenging activities. A strong emphasis should be placed on clinical studies assessing slip-resistant features of the sole that can prevent indoor

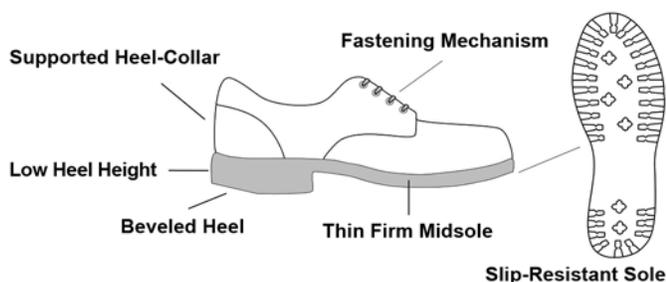


Figure.
Recommended shoe features for older people.

slipping. Finally, the potential benefits of somatosensory stimulating insoles on postural control should be further explored.

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