Title Page

Title: Enhancing footwear safety for fall prevention in older adults: A comprehensive review of design features

Running Title: Enhancing footwear design for elderly fall prevention

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Enhancing footwear safety for fall prevention in older adults: A comprehensive review of design features

Abstract

Background: Falls are a global concern affecting people of all ages; however, older adults are particularly vulnerable to age-related factors and foot-related issues. Footwear is critical for preventing falls, as it provides stability and protection against slips and falls (STFs). However, a significant gap exists in the systematic exploration of the safety aspects of footwear design for fall prevention in older adults.

Methods: This comprehensive review applied a meticulous search strategy encompassing prominent databases, including Google Scholar, ScienceDirect, SCOPUS, MEDLINE, ResearchGate, and PubMed. This review synthesized and analyzed existing research to bridge knowledge gaps and provide insights into optimal footwear choices for older adults in terms of design features such as fit, fixation, heel height, collar height, slip resistance, and sole/insole hardness.

Results: The results underscore the importance of specific design features for preventing falls among older adults. A proper fit, secure fixation, appropriate heel and collar heights, slip resistance, and...
sole/insole hardness significantly contributed to fall prevention. These findings offer valuable guidance for optimizing footwear designs to enhance comfort, stability, and safety in the daily lives of older individuals.

**Conclusion:** This comprehensive review fills a critical knowledge gap regarding the safety of footwear designs for fall prevention in older adults. The identified design features play a vital role in reducing the risk of falls and offer practical recommendations for the development of safer footwear. Ultimately, this study contributes to the existing knowledge base and supports efforts to prevent STFs in older adults through improved footwear design.

**Keywords:** Falls in older adults; Footwear safety; Footwear fit; Safe footwear design; Slip resistance.

**INTRODUCTION**

A profound demographic shift is underway as the global population ages, driven by increasing life expectancy. Projections indicate that individuals aged 65 years and older will comprise 12% of the world's population by 2030 and 16.7% by 2050. An aging workforce across diverse industries mirrors this demographic transformation, a trend anticipated to persist in coming years. Along with these changes, the societal and healthcare ramifications of falls among older adults have become increasingly apparent.

Approximately 37.3 million fall incidents necessitating medical attention are reported annually globally. According to the World Health Organization (2022), falls will be the second-leading cause of unintentional injury deaths, trailing only road traffic injuries. Although falls can affect individuals of all age groups, older people are particularly vulnerable and face the highest risk of sustaining severe injuries and fatalities. Alarming, over 30% of adults aged ≥65 years experience a fall each year, with 50% of these cases experiencing recurrences. The surge in fall-related hospitalizations not only escalates the economic burden on patients, caregivers, and healthcare systems but also affects the psychological well-being of older adults. Strikingly, 60% of older individuals with a fall history report a fear of falling, which can subsequently have deleterious effects on their overall functionality and quality of life.
Given these pressing challenges, this comprehensive review aimed to delve into the multifaceted problem of falls among older adults. By synthesizing existing research and insights, this study sought to address critical questions concerning the role of footwear design in mitigating the risk of falls by examining key features of footwear such as fit, fixation, heel height, collar height, slip resistance, and sole/insole hardness. Through a meticulous analysis of the literature, the findings from this review may contribute to the current knowledge base, offering valuable recommendations for optimizing footwear choices to enhance comfort, stability, and safety for older adults in their daily lives. This review further aimed to shed light on the complexities of fall prevention among older adults and provide guidance for researchers, healthcare practitioners, and policymakers to reduce the burden of falls in an aging world.

BACKGROUND INFORMATION

Physical factors - frailty and aging

Frailty among individuals aged ≥65 years is a prevalent concern, with estimates ranging between 6.9% and 8.4% and a clear upward trend with increasing age. Older adults often have musculoskeletal disorders that diminish their functionality and mobility. These individuals may exhibit reduced foot sensitivity, weakness, limited range of motion, increased soft tissue stiffness, and postural pronation. Improper gait patterns, attributed to various medical conditions, are also common among older adults. Combined with their slower response time to sudden situations, these factors can impair balance control in this population and increase the risk of slip, trip, and fall (STF) incidents. Moreover, chronic illnesses and persistent pains are strongly associated with fall incidents, with many older adults concurrently managing multiple diseases and taking various medications, amplifying the risk of STFs.

Footwear - role of footwear in fall prevention

Most of the literature available on STF incidents affecting older adults primarily focuses on intrinsic risk factors such as activity levels; functional and cognitive disabilities; ambulatory status; chronic diseases; use of walking aids; medication use; and sociodemographic and socioeconomic factors such as sex, marital status, employment status, living conditions, and education. In contrast,
evaluations of extrinsic risk factors often underestimate or overlook the impact of footwear features on safe ambulation and STF prevention. However, emerging evidence has highlighted the significant impact of footwear interventions on the static and dynamic stability and gait patterns of older adults. Footwear choices are crucial in fall prevention, influencing an individual's balance and overall stability. As footwear modifications may be a relatively simple, efficient, and cost-effective means of enhancing safety, understanding the specific footwear characteristics that promote or compromise balance in older adults is essential. The key footwear features that have been studied for fall prevention include:

1) **Fit:** Properly fitting shoes are crucial. Loose or tight footwear can cause instability and discomfort.
2) **Fixation:** Shoes should provide adequate support and focus to prevent the foot from sliding within them, which can affect balance.
3) **Heel height:** Heel height can affect gait and balance. Higher heels may also increase the risk of falls.
4) **Collar height:** The shoe collar height around the ankle can influence ankle stability.
5) **Slip resistance:** The shoe outsole should have adequate slip resistance to prevent slipping on various surfaces.
6) **Sole/insole hardness:** The hardness of the sole or insole can affect shock absorption and comfort, which in turn can affect balance.

Understanding the interplay between footwear characteristics and the unique needs of older adults is crucial for developing strategies to reduce the incidence of footwear-related STF incidents. Footwear interventions can range from selecting appropriate off-the-shelf shoes to customizing orthopedic shoes depending on an individual's needs. By investigating how footwear features can promote or compromise balance in older adults, researchers and healthcare practitioners can contribute more effective fall prevention strategies and improve the safety and well-being of the aging population. Fig. 1 illustrates the main features of shoe design that affect balance control and falls.

(Figure 1 about here)
Objectives

The primary aim of this study was to comprehensively review the recent literature on footwear-related issues among older adults, with a specific focus on footwear fit, fixation, heel height, collar height, slip resistance, and sole/insole hardness. To achieve this aim, this study formulated the following research questions:

1) Objective 1: To conduct a comprehensive review of recent literature to determine the prevalence and availability of specific footwear features including fit, fixation, heel height, collar height, slip resistance, and sole/insole hardness in footwear designed for older adults.

2) Objective 2: To assess the prevalence of footwear features in older adults, based on existing research and data.

3) Objective 3: To analyze the impact of selected footwear features on various aspects of older adults' well-being, including comfort, balance, gait, and slip resistance based on the findings of recent studies and publications.

4) Objective 4: To investigate the relationship between footwear features and the occurrence of STF incidents among older adults.

5) Objective 5: To synthesize the reviewed literature and provide evidence-based recommendations for optimal footwear features to enhance safety and reduce the risk of STF incidents among older adults, thereby contributing to the development of footwear design guidelines.

The above refined objectives and questions provide a clear and focused framework for this review, helping to systematically explore the relevant literature and providing valuable insights into the role of footwear in fall prevention among older adults.
MATERIALS AND METHODS

Literature search strategy

This review employed a meticulous and systematic search strategy to comprehensively address the primary research questions. We used the following five primary search keywords: “footwear properties”, “older adults”, “slips”, “trips”, and “falls”. These keywords were selected to capture relevant literature surrounding footwear issues in older adults and their relationship with STF incidents. We conducted this search across a carefully curated selection of well-established and respected academic databases; namely, Google Scholar, ScienceDirect, SCOPUS, MEDLINE, ResearchGate, and PubMed, to ensure the comprehensive retrieval of pertinent literature from various sources.

Inclusion criteria

The following stringent inclusion criteria were applied to determine the quality and relevance of the studies included in this review.

1) Language: We considered only studies published in English. This criterion was chosen to ensure the accessibility and understanding of a broad readership.

2) Publication date: This review focused on studies published from 2011 onwards. This timeframe was chosen to prioritize the incorporation of the most current research findings and practices in the field. This approach allowed us to build on prior knowledge while keeping our review contemporary.

3) Study participants: To maintain consistency and relevance, the included studies featured adults aged ≥60 years as the primary participants. We adopted this age criterion to align with the target older adult population at a higher risk of STF.

4) Study outcomes: The selected studies investigated and reported at least one of the following aspects:
   - Prevalence of specific footwear properties.
   - Influence of footwear-related factors on comfort, balance, gait, and slip resistance.
   - Associated risks of STF incidents among older adults attributed to footwear characteristics.
Study selection process

The process of selecting eligible studies adhered to well-established systematic review guidelines to ensure rigor and objectivity. This process comprised several sequential stages.

1) Initial database search: We searched the designated databases using predefined search keywords.
2) Title and abstract screening: We systematically screened the titles and abstracts of the retrieved studies for relevance to our research questions and adherence to the inclusion criteria.
3) Full-text review: Studies that passed the initial screening underwent a thorough full-text review. This step was essential to ascertain their alignment with the inclusion criteria.

Data extraction and synthesis

This review extracted vital information from the selected studies, including the study design, sample characteristics, methodological approach, and footwear-related variables. We meticulously compiled and analyzed these data to facilitate a comprehensive understanding of the outcomes reported in the literature. Fig. 2 illustrates the selection procedure for research papers included in this review.

(Figure 2 about here)

RESULTS AND DISCUSSION

Shoe fit (SFT)

Shoe fit is a critical aspect of footwear that significantly affects comfort and functionality. While some older adults make appropriate choices regarding well-fitted footwear, ill-fitting shoes appear to be more common among this demographic. A descriptive observational study involving 100 older adults at an outpatient clinic reported that 83% wore improperly fitted footwear on at least one foot.
Furthermore, a case-control study assessing fall risk factors in 333 older adults revealed that 34% of men and 50% of women wore excessively narrow footwear, leading to discomfort and foot-related issues.\textsuperscript{20}

This proclivity toward ill-fitting footwear selection among older adults can be attributed to several factors. One contributing factor is the reduced sensitivity of the feet of older individuals.\textsuperscript{19} Moreover, many older adults do not routinely check their feet, lack awareness of their correct shoe size, or have difficulties in selecting footwear that accommodates variations in foot morphology.\textsuperscript{21} O'Rourke et al.\textsuperscript{22} revealed parallel findings, indicating that 72% of older adults wore ill-fitting shoes. Notably, the percentage of those who experienced a fall in the previous six months was higher among individuals wearing ill-fitting footwear (56%) than among those wearing correctly fitting shoes on at least one foot (39%). However, this difference was not statistically significant.

Furthermore, a recent comparative study involving 153 older adult participants found that 60% wore ill-fitting footwear. In this group, 26% had experienced a fall in the past year, in contrast to only 15% of those who wore correctly fitted footwear. Those wearing ill-fitted shoes also exhibited lower scores on the Berg Balance Scale (BBS) and reported higher levels of fear of falling, as measured by the Activities-Specific Balance Confidence Scale (ABC).\textsuperscript{23} Well-fitted footwear can enhance the stability, gait, and social engagement of older adults while reducing their fear of falling.\textsuperscript{17,23} This underscores the importance of recommending properly fitting footwear as a viable strategy for mitigating the risk of STF incidents.

**Shoe fixation (SFX)**

Shoe fit is a critical aspect of footwear that significantly affects comfort and functionality.\textsuperscript{17} Proper shoe fixation ensures that the foot remains securely positioned within the footwear, allowing for better control over potential trip hazards.\textsuperscript{24}

A study investigating the gait of 20 older women, both barefoot and wearing various types of footwear, highlighted the importance of fixation. The participants wore backless slippers, less-fixed shoes with a nylon mesh upper and lenient heel counter, and well-fixed shoes with dorsal fixation, a belt, and a
stiff heel counter. The results revealed notable alterations in the knee and ankle joint angles when walking in slippers and less-fixated shoes. These alterations indicated adjustments made to keep the footwear in place, potentially increasing the risk of trips and falls.\textsuperscript{25}

Further evidence comes from an analysis of 70,196 fall incidents among older adults conducted by Büchele et al.\textsuperscript{26}, in which the use of open slippers significantly predicted falls, resulting in hospital transfers for older women. The design of open slippers can impede the stepping motion, potentially contributing to falls. Additionally, gait assessments of 30 older women highlighted the benefits of shoes with lace fixation.\textsuperscript{24} The use of such shoes resulted in increased walking speed, step length, and minimum foot clearance while reducing step width, step duration, and heel slippage compared to enclosed slippers lacking dorsal fixation. O'Rourke et al.\textsuperscript{22} assessed the common daily footwear choices of older adults, observing that 26% lacked proper fixation. However, Vass et al.\textsuperscript{18} reported a higher percentage, with 60% of footwear lacking adequate fixation. This variance may be attributed to differences in the sample size and types of footwear considered, encompassing indoor and outdoor options.

In conclusion, recommending footwear with adequate fixation is crucial for enhancing foot clearance, gait, and stability in older adults.\textsuperscript{24} This measure helps mitigate the risk of trips and falls, thus contributing to fall prevention.\textsuperscript{24,25}

**Shoe heel height (SHH)**

The height of the shoe heel is a critical factor to consider when assessing its effect on the biomechanics and stability of older adults during walking. This particular footwear characteristic can induce substantial alterations in various key parameters, including the trajectory of the center of pressure (COP), the area of contact between the foot and ground, and the peak plantar pressure.\textsuperscript{27} Consequently, high-heeled shoes are associated with hallux valgus, musculoskeletal pain, and first-party injury.\textsuperscript{28}

Furthermore, a heel height exceeding approximately 2.5 cm can elevate and shift the body's center of mass (COM), leading to consequential adjustments in posture and kinematics, which can significantly affect overall stability.\textsuperscript{29} Given its profound influence on lower extremity function and
balance, heel height is a pivotal consideration in footwear design for older adults.\textsuperscript{30} Moreover, an excessively high heel is a potential risk factor for falls.\textsuperscript{27,31}

A study assessed the effects of varying heel heights on plantar foot pressure in a cohort of older women.\textsuperscript{26} The participants wore shoes featuring heel elevations of 1 cm, 3 cm, and 5 cm. The findings revealed a relationship between heel height and gait stability. Specifically, individuals who wore shoes with 1 cm or 3 cm heel elevations exhibited improved gait stability compared to those wearing 5 cm heels. Thus, the lower elevations substantially reduced the fall risk.\textsuperscript{27}

High heels are unlikely to be the most common type of footwear worn by older women when they experience falls.\textsuperscript{32} This observation can be attributed to the decreasing prevalence of high-heeled footwear as women age. An examination of the most commonly worn outdoor footwear revealed that only 3.3\% of older women wore high heels, consistent with the notion that the practice of wearing high heels with a very narrow toe box declines to <10\% in women aged \geq 40 years.\textsuperscript{33}

These findings underscore the importance of considering heel height when designing safe footwear for older adults. Recommendations within established guidelines emphasize the prudence of restricting heel heights, focusing on limiting the elevation to ensure optimal balance and mitigate fall risks.\textsuperscript{17,30,34} A heel height of \leq 4 cm is a reasonable threshold for maintaining balance and stability, thereby mitigating the associated risk of falls.\textsuperscript{35}

In summary, the multifaceted interplay between heel height, gait stability, and fall risk in older adults underscores the paramount importance of heeding recommendations for heel height limitations in footwear selection. Such considerations are a cornerstone of the broader strategy for mitigating the profound impact of STFs in the older adult population.

**Shoe collar height (SCH)**

The consensus in the literature is that shoes with a high collar height and top line play a crucial role in enhancing the balance of older adults, making SCH a vital consideration in the design of safe footwear.\textsuperscript{17,36,37} The underlying rationale is that materials covering all sides of the ankle provide mechanical
stability to the ankle and subtalar joints in the coronal plane. Additionally, elevated collar height may enhance proprioceptive feedback, a vital sensory component for balance, compared to regular footwear.\textsuperscript{36}

These factors align with those of an experimental study that assessed the impact of three different footwear styles on gait parameters associated with falls among older adults. The three footwear styles included soft open-heel shoes with no collar or fastening and two closed-heel shoes with varying material hardness featuring a high collar and Velcro fastening. The results revealed significant improvements in walking speed, stride length, and step time for closed-heel shoes with high collars. The participants also rated these shoes as more comfortable and stable.\textsuperscript{38} Thus, incorporating high collar height and top-line designs into footwear design for older adults is a promising strategy for enhancing balance and stability, contributing to reduced fall risk. These findings underscore the importance of integrating high collar height into footwear design for older adults to improve their proprioceptive feedback, mechanical stability, and overall balance, thereby reducing the risk of falls.

**Shoe slip resistance (SSR)**

Slips leading to falls often result from the delicate balance between a traction force and a vertical force applied to the ground, which ultimately determines the coefficient of friction (COF) between the footwear and the walking surface.\textsuperscript{39} Footwear lacking adequate slip-resistant properties can significantly contribute to falls among older adults, thus emphasizing the importance of addressing this aspect in footwear design and selection.\textsuperscript{40,41}

**Heel/sole tread**

The tread pattern on the soles of shoes plays a pivotal role in enhancing slip resistance. Effective channeling and dispersion of fluid pressure during ground contact mitigate the detrimental effects of liquid-induced reductions in the COF.\textsuperscript{42} Older adults tend to take broader steps during walking, increasing the demand for mediolateral (ML) and anteroposterior (AP) COF. Consequently, sole tread
patterns should be designed to offer superior slip resistance in both the ML and AP directions to minimize the risk of sideways slips, which are common in older adults.39)

Although slip tests involving older adults are infrequent because of their hazardous nature, insights gleaned from experiments conducted in young adults suggest a treaded sole coupled with increased tread depth significantly enhances friction at the shoe-floor interface, thereby reducing the likelihood and severity of slip and fall incidents.42,43) Studies have consistently recommended incorporating an appropriate tread pattern in footwear design to enhance the safety of older adults.17,34,44)

Another critical factor to consider in sole profile design is wear caused by repeated use, as worn soles are frequently observed when evaluating older adults' indoor and outdoor footwear. O'Rourke et al.22) reported wear in 90% of older adults' footwear, whereas Vass et al.18) reported that 60% of older adults' footwear had been owned for >1 year, with 48% showing partially to excessively worn soles. As the worn area of the shoe sole increases, the peak fluid pressure under the shoe increases, leading to a decrease in the available COF and an aggravated risk of slipping.45)

**Heel/sole material**

The choice of heel and sole materials in footwear design is important, particularly when addressing slip resistance and overall safety, especially for older adults. Rubber, a versatile and widely used material, has become the preferred option owing to its proven slip-resistant properties. However, other factors should be considered when evaluating the suitability of heel/sole materials for fall prevention in older adults.

1) Slip resistance: Rubber's intrinsic characteristics make it a natural choice for enhancing traction and reducing the risk of slips and falls. Its high slip resistance on various surfaces, including wet or slippery surfaces, contributes significantly to its efficacy in preventing slip and fall incidents.40,41) The use of rubber in shoe heels/soles and, more recently, in anti-slip socks, underscores its role in providing stability and reducing the likelihood of accidents.16) Nevertheless, the nuances surrounding
the effectiveness of anti-slip socks must be acknowledged. Hartung and Lalonde\textsuperscript{46} reported inconclusive evidence regarding the efficacy of anti-slip socks in averting falls, especially in hospitalized older adults. This ambiguity underscores the importance of discerning the precise conditions under which anti-slip socks are most efficacious. Moreover, concerns regarding the potential transmission of infections through shared hospital-provided anti-slip socks have been raised, necessitating a careful approach to their implementation. Furthermore, anti-slip socks provided by hospitals may not provide the requisite support to the heel, forefoot, or sole necessary to cultivate ideal gait and balance characteristics in older adults.\textsuperscript{18}

2) Material durability: Beyond slip resistance, material durability is paramount, especially for older adults who may wear footwear for extended periods. The resilience of rubber to wear and tear ensures that it maintains its slip-resistance properties over time. However, the initial slip resistance of the sole material and its ability to withstand prolonged use (wear and tear) without losing its effectiveness must be assessed.\textsuperscript{40,41,45}

3) Evaluating alternative materials: While rubber is a frontrunner, alternative materials with slip-resistant qualities must also be explored. Advances in material science and technology have led to the development of innovative sole materials with exceptional traction on various surfaces.\textsuperscript{41} These materials may present new possibilities for enhancing the safety and comfort of footwear in older adults.

4) Customization for specific settings: The heel and sole material choice should also consider the specific settings in which older adults wear their footwear. For instance, hospital environments may require different material characteristics due to hygiene concerns and the nature of hospital floors. Customized solutions such as slip-resistant coatings or hybrid materials may be required to satisfy the unique demands of healthcare settings.\textsuperscript{46}

5) User comfort: Achieving slip resistance must not compromise user comfort. Footwear with excessively rigid or uncomfortable heels and soles may discourage older adults from consistently
wearing them. Striking a balance between slip resistance and comfort is a delicate but essential consideration in footwear design.\(^{47}\)

6) Future directions: Research on novel materials and technologies for enhancing footwear slip resistance and user comfort is ongoing. Collaborative efforts between material scientists, footwear designers, engineers, and healthcare professionals can yield innovative solutions tailored to the specific needs of older adults.

In conclusion, while rubber remains a steadfast choice for slip-resistant heel and sole materials, ongoing research and innovation can expand the array of materials available to enhance footwear safety and comfort for older adults. A holistic understanding of user needs, durability, and the unique demands of different settings should guide heel/sole material selection.

**Anti-slip devices**

Older adults are advised to use slip-resistant footwear to mitigate fall risk. For example, the use of anti-slip devices represents a practical and effective strategy for alleviating fall risk in this population, especially in icy or slippery environments.\(^{48,49}\) These devices, such as studded footwear and ice cleats, enhance traction on challenging surfaces and provide users with a safer walking experience. By actively engaging older adults in the design and testing phases, anti-slip devices can be developed to meet their functional requirements and provide high user satisfaction and usability. This user-centered approach contributes to the overall effectiveness and acceptance of anti-slip solutions for older individuals. The following critical issues must be considered:

1) Multi-environment compatibility: This requires the design of anti-slip devices that perform exceptionally well on various surfaces commonly encountered by older adults, including wet floors, icy sidewalks, and uneven terrain. Thus, research should focus on developing materials and tread patterns that can adapt to different surface conditions to provide consistent slip resistance. Studies on
surface interactions and material compatibility can provide insights into the optimization of anti-slip devices for multiple environments.\textsuperscript{40,41} Extensive testing on various surfaces, including laboratory-controlled conditions and real-world scenarios, is needed to ensure effectiveness.

2) Material selection: The slip resistance properties of shoe materials should be investigated by considering high-quality rubber, silicone, or thermoplastic elastomers to determine which materials offer the best grip on different surfaces. Comprehensive material testing is needed to understand friction coefficients and surface adhesion properties. Material science research on these factors can provide in-depth knowledge regarding the suitability of different materials.\textsuperscript{44} Detailed material testing involving tribology studies and surface characterization can help identify the most effective materials for slip resistance.\textsuperscript{40,41}

3) Customization and adjustability: Anti-slip devices should have adjustable features such as strap length and tightness to accommodate various shoe sizes and styles. Customization should enhance user comfort and usability. Thus, human factors and ergonomic research can guide the design of adjustable features that cater to the diverse footwear preferences of older adults.\textsuperscript{50} Detailed studies on foot anatomy and sizing should inform adjustable mechanisms to ensure a secure fit.

4) Ergonomic design: The design of slip-resistant footwear must incorporate ergonomic concepts considering elastic materials, adjustable straps, and user-friendly fasteners to ensure a secure and comfortable fit. The design should minimize pressure points or discomfort. Ergonomic studies provide insights into wearable device design, including considerations for pressure distribution and comfort.\textsuperscript{51} Detailed biomechanical research can help identify areas where pressure or discomfort may occur and guide design adjustments.

5) Tread patterns: Various tread patterns should be identified to optimize traction and stability during forward and lateral movements. Extensive research must be conducted using channels or grooves in the tread to effectively disperse liquids and debris. Tribology research has explored shoe surface texture and friction enhancement.\textsuperscript{40,41,52} Detailed studies should assess the performance of different tread patterns under various conditions to identify the most effective designs for better slip resistance.
6) Durability and longevity: Anti-slip devices prone to wear and tear must be reinforced to extend their lifespan. Materials and construction techniques that can withstand frequent usage must also be evaluated. Material engineering and product durability studies offer insights into the design of anti-slip devices that can withstand the rigor of daily use.\textsuperscript{40,41,53} Detailed testing should include accelerated wear tests and real-world simulations.

7) Compact and portable: Anti-slip devices must be compact and easily portable, allowing older adults to conveniently carry them in bags or pockets when not in use. A compact design should not compromise performance. Product design principles for portability and compactness can guide the development of compact anti-slip devices.\textsuperscript{54} Detailed engineering studies require the optimization of device size and weight without sacrificing effectiveness.

8) Non-intrusive profile: Anti-slip devices must not significantly alter the user's gait or comfort. Biomechanical and gait analysis studies can provide insight into the impact of wearable devices on gait.\textsuperscript{55,56} Detailed testing involving older adults can assess the impact of these devices on their gait parameters.

9) Easy maintenance: Providing clear maintenance instructions and selecting materials that are resistant to degradation over time must also be considered. Anti-slip devices should be easy to clean and maintain. Older users should be able to maintain their slip-resistant properties. Material science research on aging and degradation resistance can inform material choices that resist wear and tear.\textsuperscript{57} Detailed maintenance guidelines should be developed based on user feedback and testing.

10) Accessibility and inclusivity: Anti-slip devices must be designed for accessibility that considers the needs of older adults with mobility challenges or specific health conditions. Devices should be inclusive and user-friendly for a diverse user base. Inclusive design principles for wearable assistive devices offer guidance for creating products that cater to this wide range of users.\textsuperscript{58} User testing involving older individuals with diverse abilities and needs should be conducted to assess accessibility.

11) User feedback and testing:
a) The real-world usability issues and preferences of older adults must be addressed during the design process through user testing and feedback. Engaging users from the target demographic is needed to ensure that anti-slip devices are tailored to their specific needs. We suggest the implementation of the following strategies for feedback and testing in older adults:

- User-centered design workshops: Workshops or focus groups with older adults should be organized to gather insights into the daily challenges related to slipping and falling. Older participants should be encouraged to share their experiences, needs, and expectations regarding anti-slip devices.

- Prototype testing: Prototypes of anti-slip devices should be constructed based on the initial designs. Older adults should be invited to evaluate these prototypes in controlled environments to simulate real-world conditions. Feedback on comfort, ease of use, and effectiveness in preventing slips and falls must also be collected.

- Field trials: Field trials are needed, in which older adults use anti-slip devices in their natural living environments. Their experiences should be monitored over an extended period to assess the durability of the devices, as well as their long-term comfort, and overall user satisfaction.

- Feedback loops: Continuous feedback loops with older adult participants should be established, in which the participants are encouraged to report issues, concerns, or suggestions during real-world use. This feedback should be regularly incorporated to refine and improve the design.

- Usability testing: Formal usability testing sessions with older adults are needed to evaluate specific aspects of anti-slip devices, such as fastening mechanisms, adjustability, and maintenance, using established usability metrics to assess user interactions.

b) Involving older adults in the design process ensures that anti-slip devices align with their preferences and requirements. This helps to identify potential usability issues early in the development cycle, leading to more user-friendly and effective products. User feedback and
testing also enhance user acceptance and satisfaction, thereby increasing the likelihood of widespread adoption.

**Shoe hardness (SHD)**

*Sole hardness*

The concept of rugged soles in footwear has garnered attention as a potential tool for reducing the risks associated with STF incidents among older adults.\(^{17,47}\) Previous studies have shown improved balance and gait when rugged soles are incorporated into footwear design.\(^{12,59}\) However, more studies are needed to explicitly examine the role of sole hardness in fall prevention among older people. This scarcity can be attributed to the widely accepted validity of the recommendations. Furthermore, when advocating the use of footwear with stiff soles, it is imperative to consider the expected benefits of wearing such shoes. A study assessing the effects of wearing three identical shoes with varying sole hardness (Shore A25, A40, and A58) on forefoot pain in older adults surprisingly observed that while plantar pressure increased proportionally with hardness alone, the comfort scores did not differ significantly across the range of hardness levels.\(^{47}\)

**Insole hardness**

Incorporating insoles into footwear design serves a multifaceted purpose, including providing cushioning, facilitating uniform pressure distribution, and maintaining proper alignment of the lower extremities.\(^{60}\) Unlike soft insoles, which conform to the foot's position, more rigid insoles may exert a corrective influence, aiding in the maintenance of a neutral foot position and, consequently, enhancing postural stability.\(^ {61}\) Iglesias et al. (2012)\(^{61}\) investigated the impact of insole hardness on the static balance of older subjects with eyes open and closed. Soft gel and rigid insoles (Shore A50) were assessed. The results indicated that the rigid insole improved postural sway when visual feedback was eliminated compared with the soft gel insole. Additionally, Qu (2015)\(^{62}\) explored the effects of different insole designs and materials on the static and dynamic balance of older adults and found that hard insoles made of polyurethane and ethylene-vinyl acetate (EVA) significantly increased the anteroposterior margin of
stability (MOS), suggesting that stiffer insoles may enhance dynamic balance in the anteroposterior direction.

However, a study examining the effects of soft-textured (270-density EVA) and hard-textured (320-density EVA) insoles on postural sway in younger and older adults on foam and firm surfaces reported contradictory findings. Although the young participants generally performed better with hard insoles, the older participants did not evidence similar benefits. Moreover, older participants standing on hard insoles for extended durations reported discomfort. Although increased sole and insole hardness may improve stability, the optimal materials and degree of hardness required to maintain the comfort of wear must be identified.

**Optimal footwear design**

Numerous studies have sought to incorporate specific features in the selection, design, and testing of footwear intended for safety to enhance balance, gait, slip resistance, and overall comfort in older individuals. The following important features were collectively integrated into this footwear.

*Spatiotemporal gait analysis and standard footwear*

A study conducted a spatiotemporal gait analysis of 57 older women performing various walking tasks, including single and double motor and cognitive tasks. During these assessments, the participants were observed barefoot and wearing three distinct types of footwear: backless slippers, high-heeled footwear (heels ≥3.5 cm), and a standard footwear option provided for the study. The traditional footwear was characterized by lace fixation, a mildly rounded low heel (<2.5 cm), an EVA foam midsole, a solid 6.5 cm heel collar, and a treaded sole. The results revealed that standard shoes consistently and significantly increased participants' gait speed and stride length regardless of the conditions. These findings suggest that everyday footwear is the optimal choice for enhancing gait performance in older individuals.34)

*Effects of different footwear types on gait and balance*
A study investigated the effects of three distinct footwear types—regular socks, backless slippers, and enclosed slippers—on gait and balance control in older women. The backless slippers, characterized by a lack of fixation, featured a soft foam (Shore A15) sole with a uniform thickness of 25 mm. In contrast, the enclosed slippers included Velcro fixation, a hard rubber (Shore A50) sole 15 mm below the forefoot and 32 mm below the heel, and a solid heel counter. The results of the study demonstrated that enclosed footwear provided the most substantial support for gait and balance, leading to improved directional control and reduced postural sway, step width, and end sway. Furthermore, the participants consistently reported higher comfort, fit, and overall satisfaction with the enclosed slippers.

**Prototype footwear for enhanced performance**

Another study assessed the balance and gait performance of older women wearing three different types of footwear: outdoor footwear, flexible footwear (control), and prototype footwear designed to optimize performance. The prototype footwear featured a rubber sole with Shore A55 hardness and forefoot sole and heel thicknesses of 18 mm and 25 mm, respectively, and also incorporated both lace and Velcro fixation mechanisms. The design enhancements included a high collar, a firm heel counter, a 10-degree bevel in the heel area to improve slip resistance, and specific tread patterns. Additionally, a textured EVA insole with unique characteristics was designed. The results of these assessments demonstrated consistently better performance when the participants wore the prototype footwear, including a narrower step width and reduced end-postural sway. These improvements in lateral stability are particularly significant in mitigating the risk of STFs among older adults.

**Balance shoes for enhanced stability**

Other studies have explored the effects of balance shoes designed for stability, contrasting them with regular outdoor shoes. The balance-specific shoes featured a longitudinal track under the heel and a protective space within the midsole, strategically designed to mitigate potential balance disturbances caused by pebbles. The midsole further incorporated bands elevated 2 mm on both sides to improve
balance. A metal shank was integrated into the sole to enhance rigidity, and a circular arc tread was bolstered to improve slip resistance. The findings consistently demonstrated that balance-specific shoes significantly enhanced leg stability, especially with the eyes closed. Moreover, the participants reported an increased sense of steadiness and security when wearing these specialized shoes. These studies collectively emphasize the importance of integrating specific footwear features to enhance balance, gait, and overall safety in older individuals. Thus, optimal footwear design considers factors such as fixation, sole properties, and tread patterns to reduce the risk of STFs in this vulnerable population.

Table 1 and Fig. 3 provide a comprehensive overview of the results of this review, summarizing the findings from published studies related to footwear features and their associations with fall risk, as discussed in the Results and Discussion. Fig. 3 shows the significant increase in research on shoe slip resistance (SSR) over the past 12 years. However, as highlighted by Kim, the challenges of addressing wear and tear on shoe heel/sole surfaces due to friction remain an important concern that necessitates innovative engineering solutions. Therefore, we strongly recommend that future research aimed at developing safer footwear designs to prevent falls among older adults should adopt a holistic approach involving collaboration between clinicians, researchers, and engineers.

(Table 1 about here)

(Figure 3 about here)

CONCLUSION

The results of this comprehensive review highlight the central role of footwear in preventing falls in older adults. Addressing this multifaceted challenge requires a thorough approach involving education, awareness, assessment, and innovation. Integrating these recommendations into clinical practice and public health initiatives can invigorate efforts to reduce the burden of STFs among older individuals, ultimately creating a safer and more secure environment for vulnerable populations.