Biomechanics of the Ageing Foot and Ankle: A Mini-Review

Hylton B. Menz

Department of Podiatry and Lower Extremity and Gait Studies Program, School of Allied Health,
La Trobe University, Bundoora, Vic., Australia

Key Words

Foot · Biomechanics · Ageing

Abstract

Foot pain is highly prevalent in older people and has a significant detrimental impact on mobility and quality of life. In recent years, there has been increased interest in exploring the biomechanical factors that may contribute to the development of foot disorders and the associated impairment of mobility in this age group. Studies have shown that with advancing age, there is a general tendency for the foot to exhibit increased soft tissue stiffness, a decreased range of motion, decreased strength and a more pronated posture as well as to function in a more pronated position with reduced joint mobility and less efficient propulsion when walking. These changes may contribute to the development of foot pain, impair performance in functional weight-bearing activities and increase the risk of falls. However, plantar pressure analysis technology has considerable potential to assist in optimising the design of interventions to redistribute load away from high-pressure areas, thereby alleviating foot symptoms and improving mobility in older people.

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Introduction

Foot pain affects approximately one in four older people [1] and is associated with a decreased ability to undertake the activities of daily living [2], problems with balance and gait [3, 4] and poorer health-related quality of life [5]. The majority of older people with foot pain consider it to be disabling [1] and one in five consider it to be the primary cause of their inability to leave their home [6]. As a consequence, older people account for the largest proportion of consultations for foot problems with general practitioners [7] and podiatrists [8], with many of them eventually seeking surgical treatment for their foot condition [9].

Several potential risk factors for foot pain have been identified from cross-sectional studies, including increased age, female sex, obesity, chronic conditions, e.g. osteoarthritis and diabetes, and inappropriate footwear [10]. More recently, the contribution of biomechanical factors to the development of foot pain in older people has been explored, aided by technology which enables the accurate quantification of load distribution when walking. This review summarises the key age-related changes in foot structure and function that may contribute to the

development of foot pain in older people, and highlights the role of plantar pressure measurement in the design of orthotic interventions to alleviate foot pain in this age group.

Age-Related Changes in Skin

The plantar skin has several unique features which relate to the biomechanical demands of weight bearing. The epidermis is considerably thicker (approx. 1.5 mm, compared to 0.1 mm in other regions of the body), and demonstrates a pattern of ridges which assist in generating sufficient friction when walking. The dermis is approximately 3 mm thick, and is penetrated by adipose tissue which provides resilience to shear stresses [11]. With advancing age, there is a flattening of the dermo-epidermal junction, a reduction in the turnover rate of keratinocytes and a reduced density of sweat glands. At the level of the dermis, there is an overall loss of elastin and collagen fibres, with the collagen fibres that remain becoming thicker and stiffer [12]. These age-related changes significantly alter the mechanical properties of the plantar skin, leading to increased hardness [13], dryness and loss of elastic recoil, thereby predisposing the older person to xerosis, fissuring and the development of hyperkeratosis (corns and calluses) [14].

Hyperkeratosis is one of the most prevalent foot problems in older people. Although it is often considered to be a relatively minor complaint, it may result in considerable pain and disability. In response to repetitive friction from weight-bearing activities or occlusion from ill-fitting footwear, the stratum corneum and granulosum become hypertrophied, placing pressure on nerves in the papillary dermis. Plantar lesions are more likely to form in older people with hallux valgus or lesser toe deformity, due to elevated and abnormally distributed plantar pressures. Indeed, peak pressures under the metatarsal heads when walking have been shown to be between 9 and 12% higher in older people with calluses at these sites [15]. Clinically, these findings suggest that optimum management of hyperkeratosis in older people requires off-loading strategies to address the underlying mechanical cause. Clinical trials have shown that when used in isolation, scalpel debridement of hyperkeratosis has only a small, short-term effect on pain [16], and that the use of pressure-relieving foot orthoses in conjunction with scalpel debridement has a greater effect than scalpel debridement alone [17].

Age-Related Changes in Plantar Soft Tissues

The deeper plantar soft tissues anchor the skin to the underlying bony architecture of the foot, protect underlying blood vessels and nerves and attenuate the shear forces that are applied when walking. These tissues contain highly specialised pads of fat cells constrained by fibrous septae under the metatarsal heads and the heel. The metatarsal pads, which range in thickness from 9 to 14 mm, undergo compression of up to 46% when walking [18]. With advancing age, the pads maintain their thickness, but demonstrate greater stiffness, dissipate more energy when compressed and are slower to recover after the load is removed [19, 20]. Similarly, the heel pad retains its thickness of 18–20 mm with age, but becomes stiffer and dissipates more energy when compressed [20, 21]. On ultrasound images, the increased stiffness of the heel pad is seen to be accompanied by increased thickness and decreased echogenicity of the plantar fascia; this may be indicative of a physiological aging process of the plantar fascia itself or a secondary effect of the loss of heel-pad elasticity [22].

Over time, these changes are likely to contribute to the development of symptoms in the older foot, as the load generated during weight-bearing activities is not effectively dissipated and thus transferred to deeper tissues. A recent study has shown that in older people with forefoot pain, peak pressure under the lateral metatarsal heads is 10% higher than in individuals without forefoot pain [23]. Similarly, older people with foot pain have been shown to have higher peak pressure and pressure-time integrals (a measure of both the magnitude and duration of load) under the heel [24]. It is likely that these differences are due not only to age-related changes within the plantar soft tissues, but also to associated changes in the range of motion in the joint, foot posture and dynamic foot function.

Age-Related Changes in Joint Range of Motion

Ageing is associated with several changes in joint physiology, including a reduction in the water content of the cartilage, the synovial fluid volume and the proteoglycans. The collagen fibres in the cartilage undergo a cross-linking process, resulting in increased stiffness [25]. These changes may contribute to the reduced range of motion in lower extremity joints observed in older people. Several studies have shown that ankle dorsiflexion-plantarflexion and subtalar joint inversion-eversion

range of motion are 12–30% lower in older people [26–28]. More recently, older people were found to have 32% less dorsiflexion range of motion of the first metatarsophalangeal joint than younger people [29].

Due to the important role played by the foot in adapting to uneven terrain, a reduced range of motion in the joints of the foot and ankle is strongly associated with impaired balance and functional ability in older people [3, 30]. One prospective study has shown that decreased ankle dorsiflexion range of motion is a risk factor for falls [4]. Reduced range of motion in the rearfoot and midfoot may also influence the motion of the foot when walking, which, in turn, may affect the extent to which plantar loads can be attenuated. Indeed, a recent biomechanical study reported that the inter-segmental range of motion at the ankle, rearfoot and midfoot when walking was inversely associated with peak pressure at the corresponding plantar regions, i.e. individuals with less foot joint mobility generate significantly larger plantar loads [31].

Age-Related Changes in Foot Strength

One of the most characteristic features of advancing age is reduced muscle mass, due to a reduction in both the size and number of muscle fibres and the development of large, slow-twitch motor units as type II fibres become denervated [32]. As a consequence, decreases in strength in the order of 20–40% have been reported in individuals between the age of 30 and 80 years [33]. Age-related changes in muscle strength are particularly evident in the lower limb compared to the upper limb, and tend to progress from distal to proximal. Foot muscles are therefore highly susceptible to age-related atrophy, a process that may also be exacerbated by the long-term wearing of ill-fitting footwear. Several recent studies have confirmed that older people exhibit approximately 24–40% less strength in muscles responsible for movement of the foot and ankle than young people [34–36].

Loss of foot strength has several implications for older people. Decreased ankle plantarflexor strength is associated with difficulties in rising onto the toes [37], and toe plantarflexor weakness impairs the grasping function of the toes when performing weight-bearing activities, resulting in impaired balance and functional ability [3] and an increased risk of falls [4, 38]. Atrophy and the associated reduced strength of the toe muscles may also play a role in the development of toe deformities, as a reduced thickness of intrinsic musculature has been identified in older people with hallux valgus and lesser toe deformities

[39, 40] on ultrasound images, and older people with toe deformities exhibit reduced toe plantarflexor strength compared to those without toe deformity [38, 41].

Nevertheless, emerging evidence indicates that age-related reductions in foot and ankle range of motion and strength may be at least partly ameliorated by targeted foot and ankle exercise programs in older people [42], suggesting that exercise should be considered as part of an overall rehabilitation approach to older people with foot pain.

Age-Related Changes in Foot Posture and Dynamic Foot Function

The medial longitudinal arch of the foot plays an important role in shock attenuation and in generating sufficient power for propulsion when walking. From middle age, there is a trend towards a gradual lowering of the arch, as evidenced by greater medial contact of the midfoot, observed from footprints [43], and higher scores (indicative of a more pronated foot posture) on the triplanar Foot Posture Index measurement tool [44] (fig. 1). The reasons for this apparent lowering of the arch are not fully understood. However, tibialis posterior dysfunction, a degenerative process involving the gradual weakening, elongation and rupture of the tibialis posterior tendon, is thought to be the most common cause of acquired flat foot in older people [45]. It is therefore likely that age-related lowering of the arch is an early stage in the continuum of this physiological process.

The lowering of the medial longitudinal arch associated with ageing has implications for how the foot functions when walking. Studies of dynamic foot function using plantar pressure measurement techniques have demonstrated greater medial displacement of the centre of pressure in older people, indicative of a more pronated foot function [46, 47]. Figure 2 provides typical examples of plantar pressure outputs from a young male and an older male and demonstrates differences in the centre of pressure excursion index (CPEI). The CPEI has been shown to differentiate between foot types, although it is likely that it is also influenced by proximal structures [48]. Kinematic comparisons between young and old people indicate that, independent of walking speed, the older foot exhibits reduced midfoot and metatarsal mobility and a less plantarflexed calcaneus at toe-off [49]. These changes are indicative of a less propulsive gait pattern and suggest that older people adopt a ‘pull-off’ rather than ‘push-off’ strategy to generate forward momentum when walking.

Fig. 1. Scatter-plot of 619 Foot Posture Index (FPI) scores according to age. Higher scores represent a flatter/more pronated foot posture [from 44].

Fig. 2. Plantar pressure outputs from a 35-year-old male (**a**) and a 77-year-old male (**b**), showing the centre of the CPEI scores. Lower CPEI scores represent greater medial displacement of the centre of pressure at the distal third of the footprint and are associated with relatively pronated foot function.

There is also some evidence that reduced dynamic foot and ankle range of motion is not limited to the walking gait of older people, but that running gait exhibits similar age-related changes. A comparison of three-dimensional lower extremity running kinematics between 17 young (26–36 years of age) and 17 older (67–73 years of age) people revealed that the older group had significantly less tibial internal/external rotation, contacted the ground with their rearfoot everted, and reached maximum rear-foot eversion earlier than the younger group [50]. Taken together, these changes suggest that older people have relatively pronated dynamic foot function, but this pattern is accompanied by reduced foot mobility.

The general tendency towards flatter and more dynamically pronated feet with advancing age may partly explain the increased prevalence of foot disorders and foot symptoms in older people. Findings from two recent population-based studies (the Framingham Foot Study and the Johnston County Osteoarthritis Project), indicate that planus foot posture is associated with an increased likelihood of hammer toes and overlapping toes [47], while pronated dynamic foot function is associated with hallux valgus and overlapping toes [47, 51]. Similarly, planus foot posture and pronated foot function are associated with generalised pain in the foot as well as with heel and arch pain in older men [52]. The underlying mecha-

Fig. 3. Typical examples of plantar pressure recordings from older people with hallux rigidus (a), pes planus (b), hallux valgus (c) and pes cavus (d).

nism linking pronated foot function to foot pain is not well understood, although cadaver studies have shown that simulating a flat foot results in increased plantar fascia strain, talo-navicular joint motion and dorsal compressive forces in the midfoot, factors that could potentially lead to tissue damage and subsequent foot symptoms [52]. Clinically, these findings suggest that contoured foot orthoses designed to support the medial longitudinal arch have a role in the management of foot pain in older people [53], although care needs to be taken to not overly restrict motion in those who already exhibit limited foot flexibility.

The Role of Plantar Pressure Technology in the Assessment and Management of the Older Foot

The ability to measure loading patterns underneath the foot when walking has provided valuable insights into both the underlying mechanisms that may be responsible for the development of foot disorders and the design of mechanical interventions such as footwear and orthoses.

A range of sensor technologies has been developed for this purpose [54]. The most common are capacitance transducers (used in novel systems, Novel GmbH, Wiednitz, Germany) and force sensing resistors (used in Tekscan® systems, Tekscan, South Boston, Mass., USA). These systems enable the accurate quantification of magnitude and timing of force, pressure and contact area under specific regions of the foot. The main benefits of plantar pressure technology in older people compared to other gait analysis methods are feasibility, portability, relatively efficient data processing and the synergy between platform systems (for barefoot analysis) and in-shoe systems (for analysing the effects of interventions). Although the cost of most plantar pressure systems largely limits their use to research settings, several lower-cost options are now available for use in clinical practice.

Plantar pressure analysis has identified characteristic patterns of load distribution underneath the foot that are associated with common foot disorders in older people, such as hallux valgus, hallux rigidus and pes planus. Figure 3 shows some typical examples. However, pressure distribution under the foot is dependent on a wide array

Fig. 4. Typical example of an in-shoe plantar pressure recording of an older person with forefoot pain wearing a shoe alone (**a**) and with the addition of a metatarsal dome (**b**). Note the reduction in forefoot peak pressures.

of factors such as walking speed, step length, body weight, foot structure, range of motion and peripheral sensation; the amount of variability in pressure patterns that can be explained by these factors is relatively modest (<50%) [55]. Such findings highlight the complexity and variability of foot function when walking. Furthermore, it is important to consider that the current, commercially available systems have limited spatial resolution and only measure force perpendicular to the sensor surface, so some caution is required when interpreting pressure data from small anatomical regions (such as the toes) and data obtained from in-shoe systems where the sensor insole may become curved or distorted [54].

Despite these limitations, several studies have shown that various types of orthoses can redistribute plantar pressures away from high-pressure areas to reduce pathological loading on specific regions of the foot. Our research team recently assessed the pressure-relieving properties of a silicon heel cup, a soft-foam heel pad, a heel lift and a prefabricated foot orthosis in older people with heel pain, and found that the prefabricated orthosis was the most effective, reducing the heel pressure by 29%

[56]. This reduction was accompanied by increases in force and contact area in the midfoot, which suggests that redistributing load to the medial arch is a more effective technique for reducing heel pressure than simply cushioning the heel itself. In addition, another recently completed study of older people with forefoot pain compared the pressure reduction of four types of forefoot pads, and found that the most effective padding design (a 6-mm-thick, teardrop-shaped metatarsal dome positioned 5 mm distal to the metatarsal heads) significantly reduced pressure under the forefoot by 19% [57]. Figure 4 shows a typical example of an in-shoe plantar pressure recording of an older person with forefoot pain with and without the addition of a metatarsal dome.

These biomechanical findings suggest that foot orthoses can be designed to reduce plantar pressures under specific regions of the foot. However, in order to be therapeutically beneficial, these changes need to result in an improvement in symptoms. Preliminary evidence from two small, uncontrolled trials provides some support for this. Kang et al. [58] measured in-shoe plantar pressures and visual analogue pain scales in people aged 28–67 years with forefoot pain-prescribed metatarsal domes. Over a 2-week period, significant reductions in peak pressure and foot pain were observed, with the reduction in pain being significantly correlated with the degree of pressure reduction. More recently, Chang et al. [59] found that a full-length insole resulted in a 47% reduction in forefoot peak pressure and an 86% reduction in forefoot pain in people aged 65–84 years after 4 weeks. These early findings are promising, and demonstrate the valuable insights provided by pressure measurement technology. However, it needs to be acknowledged that the relationship between foot pressure changes and symptom relief is complex, and is influenced by a range of anthropometric factors such as body mass and foot posture [60].

Future Directions

Biomechanical analysis of the foot and ankle in older people is a relatively under-researched area with considerable future potential to improve foot health outcomes. To further our understanding of the relationship between foot and ankle biomechanics and foot pain, and optimal treatment with mechanical interventions such as footwear and orthoses, four key areas are worthy of future investigation. Firstly, although plantar pressure measurement has provided useful insights into the age-

ing foot, emerging technologies such as 3-dimensional foot scanning [61] and the measurement of shear stress [62] and in-shoe foot motion with stretch sensors [63] may enable more detailed insights into foot structure and function to be collected in a relatively efficient manner. Secondly, computer-aided design and additive manufacturing techniques have shown considerable promise for the individual optimisation of foot orthoses in people with rheumatoid arthritis [64], and may therefore be particularly helpful in the provision of orthoses for older people with foot deformity who are not adequately catered for by generic, 'off-the-shelf' devices. Thirdly, recent advances in wearable robotic technology have the potential to augment lower limb function to help older people ambulate more efficiently [65]. Finally, very few randomised trials have been conducted to evaluate the effectiveness of treatments for foot pain in older people, so there is a need for mechanical interventions developed from biomechanical studies to be rigorously evaluated in trials using foot-specific, patient-reported outcome measures.

Conclusion

Foot pain is common and disabling in older people, so there is a need to optimise treatment approaches in order to enhance mobility and improve the quality of life in this age group. This review has provided an overview of the changes in the structure and function of the foot that are associated with ageing and that have considerable implications for the well-being of the older person. With advancing age, there is a general tendency for the foot to exhibit increased soft-tissue stiffness, a decreased range of motion, decreased strength and a more pronated posture, and to function in a more pronated position with a reduced range of motion and less efficient propulsion when walking. These changes may contribute to the development of foot symptoms, impair performance in functional weight-bearing activities and increase the risk of falls. Plantar pressure measurement provides valuable insights into the underlying mechanisms that may be responsible for the development of foot disorders in older people, and has considerable potential to assist in optimising the design of mechanical interventions such as footwear and orthoses to alleviate foot pain in this age group.

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