2010

Do foot pathologies increase the risk of falling in older people? A biomechanical perspective

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University of Wollongong

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Do foot pathologies increase the risk of falling in older people? A biomechanical perspective.

A thesis submitted in fulfilment of the requirements for the award of the degree

Doctor of Philosophy

from

University of Wollongong

by

Karen J Mickle
BSc (Hons)

School of Health Sciences
2010
Dedication

I would like to dedicate this thesis to my Dad, who instilled the traits of hard work and determination into me, and to my sister Cara, who has always kept me grounded. Your unconditional love and support has got me where I am today.
Declaration

I, Karen Julie Mickle, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Health Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged in this thesis. This document has not been submitted for qualifications at any other academic institution.

Karen J Mickle
Publications

This thesis includes chapters that have been written as the following journal articles:


**Chapter 4:** Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. Foot shape of older people: Implications for shoe design. *Footwear Science*. 2010; 2:131-139.

**Chapter 5:** Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. Soft tissue thickness under the metatarsal heads is reduced in older people with toe deformities. *Journal of Orthopaedic Research*. Accepted November 2010.

**Chapter 6:** Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. Gait, balance and plantar pressures in older people with toe deformities. *Gait and Posture*. Submitted October 2010.

**Chapter 7:** Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. Foot characteristics, functional ability and health-related quality of life in older people with disabling foot pain. *Journal of the American Geriatrics Society*. Submitted November 2010.

As the primary supervisor, I, Professor Julie Steele, declare that the greater part of the work in each article listed above is attributed to the candidate, Karen Mickle. In each of the above manuscripts, Karen contributed to the study design, recruited participants, was primarily responsible for data collection and data analysis, and was largely responsible for statistical analysis and data interpretation. The first draft of each manuscript was written by the candidate and Karen was then responsible for responding to the editing suggestions of her co-authors. The co-authors, Bridget Munro, Stephen Lord, Hylton Menz and Julie Steele were responsible for assisting in study design, data interpretation and editing the manuscripts. Karen has been solely responsible for submitting each manuscript for publication to the relevant journals, and she has been primarily in charge of responding to reviewer’s comments, with assistance from her co-authors.

Karen J Mickle  
Candidate  
19 November, 2010

Professor Julie R Steele  
Primary Supervisor  
19 November, 2010
Acknowledgements

This thesis would not have been possible without the help and contributions made by many. My sincerest thanks to:

- Professor Julie Steele, my primary supervisor, whose encouragement, guidance and belief in me, has transformed me into the researcher I am today.
- Dr Bridget Munro, my co-supervisor, who encouraged me to take on such a big project and supported me when things didn’t always go to plan.
- Professor Stephen Lord and Associate Professor Hylton Menz, whose expansive wealth of knowledge has given added depth to my thesis.
- All members of the Biomechanics Research Laboratory, whose support and friendships over the last 6 years has made the experience ‘enjoyable’.
- My testing team, including Jess Allen, Krystal Burnie, Simone Chambers, Shelley Collier, Tim Fitzgerald, Victoria Head, Margo Marshall, Jasmine Menant, Leann McMillan, Natasha O'Regan, Denise Schmid, Mitch Scully, Aimee Smith, Lisa Swift, Jenny White, John Whitting, Catherine Wild and Paul Zamudio; data collection would not have been possible without their help.
- My 312 participants; this study would not have been possible without their donation of time.
- National Health and Medical Research Council, Australia, and the Australian Podiatry Education and Research Foundation for their financial support.
- My friends and family, who travelled the journey with me and kept me in touch with the ‘real world’.
Abstract

One in three people aged 65 years and above fall at least once every year and this rate increases with age. With the proportion of older people increasing, falls are a devastating health, social and economic problem in Australia and worldwide. Effective evidence-based falls prevention interventions are therefore urgently required to reduce the risk of falling in older people and, in turn, reduce the burden of falls on society. However, modifiable risk factors must first be identified in order to better target these interventions.

During normal gait, the foot is the only source of direct contact with the ground. Therefore, factors that disrupt normal foot structure and function are likely to impair stability and balance and, in turn, increase the risk of falls. Therefore, the primary purpose of this thesis was to determine whether foot pathologies, specifically toe deformities and foot pain, increase the risk of falls in independently-living older people. If the hypotheses held true, the secondary aim was then to explore these foot pathologies to better understand the mechanisms that may contribute to an increased risk of falls in this population.

Three hundred and twelve community-dwelling older men and women aged between 60 and 90 years were randomly recruited to participate in the study. Participants initially underwent a comprehensive baseline assessment that included foot anthropometrics and plantar soft tissue thickness to characterise foot structure. Dynamic plantar pressure, ankle dorsiflexion strength, ankle dorsiflexion flexibility, foot reaction time, hallux and lesser toe flexor strength, postural sway and spatiotemporal gait parameters were measured to characterise foot function. Each participant also had their feet assessed for the presence of foot problems, including...
lesser toe deformities, hallux valgus and peripheral neuropathy. Disabling foot pain and health-related quality of life were assessed with validated questionnaires. Participants were then followed prospectively, via monthly diaries, to determine their falls incidence over 12 months.

The presence of hallux valgus, lesser toe deformities and foot pain are common foot pathologies that significantly increase the risk of falling in community-dwelling older people. Older people with toe deformities display altered foot structure, whereby the foot anthropometrics significantly differ and soft tissue thickness under the metatarsal heads is significantly reduced compared to those without toe deformities. Although static balance and spatiotemporal gait characteristics do not seem to be affected by these deformities ($p > 0.05$), load distribution under the forefoot is altered during ambulation. Foot function is further impaired in older people with toe deformities whereby toe flexor strength is significantly reduced and is a possible contributor to their increased risk of falling ($p < 0.01$). Similarly, individuals with disabling foot pain reported statistically significantly reduced functional ability, reduced health-related quality of life and displayed altered foot function, in particular foot and ankle muscle weakness, also a possible mechanism associated with an increased risk of falling. Therefore, providing older people with interventions that treat foot problems, foot pain and improve foot function may play a role in reducing falls risk and improving quality of life.
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Chapter 1
The problem

INTRODUCTION

Falls are the leading cause of injury, disability, hospitalisation and death for people aged over 65 years, and the rate of deaths due to falling increases with increasing age.\(^1\) The cost of falls is enormous, both personally and economically.\(^1\) with falls often being the cause for nursing home admission.\(^2\) The total cost of health care associated with injurious falls in older people in New South Wales, Australia, is estimated to be over $550 million per annum, with community-dwelling older people accounting for most of these costs (85%).\(^3\) The average fall-related cost of care has been estimated at $4,722 for each community-dwelling faller in New South Wales.\(^3\) No other single injury cause, including road trauma, costs the healthcare system more than injury associated with falls in older people.

The incidence of falls in community-dwelling adults aged over 65 years has remained consistent at approximately 31-39%.\(^4-8\) Furthermore, once a person has fallen, there is a high chance that they will fall again.\(^7, 9, 10\) Reports suggest that up to 30% of falls result in a serious injury, which includes fractures or soft-tissue injuries that require medical attention.\(^1, 3, 6, 9, 11\) In an Australian study of community injuries resulting in hospitalisation, approximately 75% of admissions were a result of accidental falls in adults aged 65 years and older.\(^12\) From 85 years onwards, the proportion of falls as a cause of hospitalisation rises to 87%.\(^12\) Also of concern, over half of all falls result in at least some minor soft tissue damage (such as bruise, abrasion, or sprain)\(^6, 9, 11, 13\) with an additional 4-11% of falls resulting in fractures.\(^6, 11, 13\) Almost two-thirds of people aged over 65 years who are hospitalised due to a fall-related injury
sustain at least one fracture.\textsuperscript{14} Falls, particularly injurious falls, are also associated with a functional decline in the ability to carry out activities of daily living through restricted mobility\textsuperscript{9, 15, 16} and the fear of falling again,\textsuperscript{6, 9} all contributing to a reduced quality of life. Despite the increasing research devoted to falls epidemiology and mechanisms surrounding falls, little impact has been made in reducing the incidence of falls in older people. In fact, the age-standardised rates of hospitalised fall-related injuries have increased throughout the last decade.\textsuperscript{14}

Most falls occur while an individual is ambulatory. For example, in a study of 327 falls in older people, only 18\% occurred when the individuals were not in motion.\textsuperscript{17} During normal gait, the foot is the only source of direct contact with the ground. Therefore, the foot plays a substantial role in maintaining stability and balance during locomotion. Despite this, little is known about how foot structure and function contribute to falls in older people. Given their role, foot and ankle characteristics have been found to significantly affect balance and functional ability in older people. For example, plantar sensitivity, ankle flexibility and toe strength have all been correlated with performance during postural sway and leaning tests in retirement home residents.\textsuperscript{18} In addition, Menz and Lord\textsuperscript{19} reported a detrimental effect of foot problems on balance when older adults were required to cope with large excursions of their total body centre of gravity. Several studies have also suggested that the presence of foot problems may increase the risk of falling in older people.\textsuperscript{6, 20-24} For example, Dolinis et al.\textsuperscript{20} found that the presence of a corn or bunion was an independent risk factor for retrospective falls, whereas Blake et al.\textsuperscript{25} reported that foot problems were associated with falls in 1,042 older adults aged 65 years in a 12 month period. In a prospective study of 336 people over 75 years, serious foot problems and lower extremity disability were found to be significantly associated with falling.\textsuperscript{6} Serious foot problems were defined as moderate-
to-severe bunions, toe deformity, ulcers or deformed nails, whereas problems with strength, sensation or balance were defined as as lower extremity disorders.\textsuperscript{6} A limitation of these previous studies, however, is that they have grouped foot problems as a single variable and failed to report the definition or severity. Therefore, it is unknown whether one specific foot problem was more strongly related to falls incidence than others. More recently, Menz et al.\textsuperscript{26} found that fallers in a retirement village exhibited more severe hallux valgus deformity than non-fallers, although this association has not been investigated in community-dwelling older people. Toe deformities are much more prevalent in the older population\textsuperscript{27} and have been suggested to be caused by a reduction in the strength of the toe flexor muscles.\textsuperscript{28-31} As the toes are in contact with the ground for 75\% of the stance phase of gait,\textsuperscript{32} they are vital to provide both stability and efficient propulsion. Given the important roles that toes play during gait, it is plausible that altered structure (e.g. deformity) and function (e.g. weakness) affect gait patterns of older people in a manner that increases the risk of falling.

Despite its associations with impaired balance and walking ability, only a few studies have investigated the relationship between foot pain and fall risk. Foot pain has been associated with an increased risk of falling in disabled women aged over 65 years\textsuperscript{7} and in men and women aged over 62 years residing in a retirement village.\textsuperscript{26} It is currently unknown, however, whether foot pain is a risk factor for falling in community-dwelling older men and women. Furthermore, the mechanisms contributing to relationships between foot pain, foot problems and falls are poorly understood.
STATEMENT OF THE PROBLEM

The primary aim of this thesis was to determine whether foot pathologies, specifically, toe deformities and foot pain, increase the risk of falls in independently-living older people. As the foot, in particular the toes, play such a vital role in safe and efficient ambulation, it was hypothesised that these foot pathologies would be associated with a greater risk of falling. If true, the secondary aim was then to explore these foot pathologies to better understand the mechanisms that may contribute to an increased risk of falls in this population. To achieve these aims, the foot structure and function of independently-living, randomly-recruited, consenting older men and women were comprehensively assessed. These individuals were then prospectively followed for 12 months to monitor their falls incidence to determine whether toe deformities and foot pain were predictive factors of falls.

The findings from this thesis are presented as a series of studies, divided into two sections. Section A determines whether individuals with toe deformities and foot pain are at a greater risk of falling than those without these foot pathologies (Chapters 2 and 3). Section B then explores and characterises the unique structural (Chapters 4 and 5) and functional (Chapters 6 and 7) features of older people with toe deformities and foot pain. The findings of Section A can be used to identify older individuals at risk of falling and, by exploring the mechanisms that may be contributing to an increased risk of falls in Section B, appropriate and targeted falls prevention interventions can be recommended (Chapter 8). A summary of the thesis structure and the series of studies that addressed the thesis aims are outlined in Figure 1.
Chapter 1

**Thesis question:** Are older people with foot pathologies at an increased risk of falling and, if so, why?

**SECTION A: Are toe deformities and foot pain risk factors for falls?**

Chapter 2: Do toe deformities increase the risk of falling in independently-living older people?

Chapter 3: Does foot pain increase the risk of falling in independently-living older people?

**Section B: What are the unique structural and functional features of older people with toe deformities and foot pain?**

Chapter 4: Do older people with foot problems have altered foot morphology?

Chapter 5: Is soft tissue thickness under the metatarsal heads reduced in older people with toe deformities?

Chapter 6: Are gait, balance and plantar pressure characteristics altered in older people with toe deformities?

Chapter 7: Is foot function impaired in older people with foot pain?

**Thesis outcomes:** Identification of foot pathologies that place older people at an increased risk of falling and recommendations for interventions aimed at preventing falls in older people based upon foot structure and function.

Figure 1: Schematic representation of the thesis structure and the purpose of each study, designed to systematically address the overall thesis question.

**SIGNIFICANCE OF THE THESIS**

At 81.4 years, Australians have one of the world’s longest life expectancies. By 2060, an Australian woman can expect on average to reach the age of 90.\textsuperscript{33} In fact, currently, there are 2.8 million Australians (13% of the population) aged over 65 years and this number is expected to triple in the next 40 years.\textsuperscript{33} This expected change in demographics will result in an escalation in the number of falls and fall-related injuries.
unless prevention strategies are implemented. If successful, this thesis will enable strategies which can allow older people to maintain their ability to walk pain-free and with a reduced fall risk. The investment into falls prevention will not only benefit the health care system, but will improve the quality of life of older people by reducing their pain and fear, and increasing their mobility and independence.

REFERENCES


SECTION A:

Are toe deformities and foot pain risk factors for falls?
Chapter 2

Toe weakness and deformity increase the risk of falls in older people

This chapter is an amended version of the manuscript: Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. ISB Clinical Biomechanics Award 2009. Toe weakness and deformity increase the risk of falls in older people. Clinical Biomechanics. 2009; 24:787-791.

ABSTRACT

Background: Hallux valgus and lesser toe deformities are highly prevalent foot problems in older people. One factor contributing to the development of these toe deformities is reduced toe flexor strength. As adequate toe flexor strength is also crucial in maintaining balance, it was hypothesised that poor toe flexor strength and toe deformities would increase the risk of falls in community-dwelling older people.

Method: The feet of 312 men and women aged 60 – 90 years were assessed for the presence of lesser toe deformities and hallux valgus. Hallux and lesser toe flexor strength were assessed using an emed AT-4 pressure platform and novel test protocol. Participants were then followed prospectively to determine their falls incidence over 12 months.

Findings: During the 12-month follow-up, 107 (35%) participants experienced a fall. Compared to non-fallers, fallers displayed significantly less strength of the hallux (11.6 ± 6.9 vs. 14.8 ± 7.8% body weight (BW), p < 0.01) and lesser toes (8.7 ± 4.7 vs. 10.8 ± 4.5% BW, p < 0.01), and were more likely to have hallux valgus (relative risk [RR] = 2.36; 95% CI = 1.03 – 5.45; p < 0.01) and lesser toe deformity (RR = 1.32; 95% CI = 1.04 – 1.69; p < 0.01).
Interpretation: Reduced toe flexor strength and the presence of toe deformities increase the risk of falling in older people. To reduce this risk, interventions designed to increase strength of the toe flexor muscles combined with treatment of those older individuals with toe deformities may be beneficial.

INTRODUCTION

Hallux valgus, a lateral deviation of the big toe away from the midline of the body, is one of the most prevalent toe deformities suffered by older individuals. In fact, 35–74% of older men and women have some degree of hallux valgus, with approximately 30–48% being classified as moderate-to-severe. Similarly, older people have a higher prevalence of lesser toe deformities than younger people, with approximately 60% of older people displaying deformities of toes 2–5.

Common lesser toe deformities include hammer and claw toes. Hammer toe is characterised by a hyperextended metatarsophalangeal joint combined with a flexed proximal interphalangeal joint and a neutral or hyperextended distal interphalangeal joint. Claw toe differs from hammer toe whereby flexion of both the distal and proximal interphalangeal joints is evident. Irrespective of subtle between disorder characteristics, lesser toe deformities typically lead to the development of calluses over the interphalangeal joints or apex of the toe due to friction from footwear and can result in aesthetic concerns and physical discomfort. These foot problems can also have functional implications, as the presence of hallux valgus and lesser toe deformities has been associated with poorer performance in balance and functional tests, and older retirement home residents who fall exhibit more severe hallux valgus than non-fallers.

One suggested cause of the toe deformities described above is inadequate strength of the intrinsic flexor muscles of the toes. Adequate toe flexor strength is
also essential to control shifts of body weight, propel the body during gait and assist in shock absorption.\textsuperscript{15, 16} Conversely, loss of strength of the intrinsic toe muscles can lead to both structural and functional toe abnormalities.\textsuperscript{16, 17} Interestingly, a previous study using a qualitative measure of toe flexor strength (the paper grip test) revealed associations between poor toe flexor strength and poor performance in balance and functional tests in elderly people.\textsuperscript{10} Furthermore, the paper grip test of the lesser toes was found to be an independent predictor of falls in a sample of men and women residing in a retirement village.\textsuperscript{11} However, the association between toe strength and falls has not been investigated using a quantitative method of toe flexor strength, nor has this association been explored in older people residing outside of a retirement village environment. Therefore, the purpose of this study was to determine whether toe deformities and toe flexor strength increase the risk of falling in community-dwelling older people. It was hypothesised that the presence of toe deformities and poor toe flexor strength would increase the risk of falling. A secondary aim of the study was to determine whether individuals with toe deformities had decreased toe flexor strength compared to those without these foot problems.

**METHODS**

*Participants*

Volunteers aged over 60 years, were recruited from 16 randomly selected federal electorates that make up the Sydney and Illawarra statistical regions of New South Wales, Australia. After randomly selecting contact details for potential participants from the electoral roll, each potential participant was sent a letter outlining the proposed study and inviting them to participate (n = 1926). Participants were then contacted via telephone by the chief investigator [KJM] to ascertain their willingness to be involved
in the study and to be screened according to the subject selection criteria. Fifty-five percent of invited individuals declined to participate in the study and 29% could not be contacted, resulting in 312 community-dwelling older individuals forming the study cohort (158 men and 154 women; age range: 60 – 90 years).

Male and female participants were included in the study if they were aged over 60 years, living independently in the community, passed the Short Portable Mental Status Questionnaire (score ≥ 7), able to ambulate for at least 10 m with or without an aid, free from neurological diseases and could arrange their own transport to a testing venue located within each participant’s local community. Each participant gave written informed consent after reading the participant information package before any testing procedures began. All recruiting and testing procedures were approved by the University of Wollongong Human Research Ethics Committee (HE05/169).

Toe strength assessment

Toe flexor strength was quantified using our previously developed novel and reliable (ICC > 0.92) protocol that was suitable to use in the field. While each subject stood with their feet hip-width apart, with the test foot centred on an emed AT-4 pressure platform (25 Hz; Novel gmbh, Munich, Germany), they were instructed to push down on the platform as hard as possible under two conditions: (i) using their hallux and lesser toes, or (ii) using only their hallux. Three trials were completed on both the left and right feet for each condition. The data were then analysed using Novel-ortho automask software (Version 13.3.42), whereby either the hallux or lesser toes were masked on the peak force footprint of the respective trial. Peak force (N) was then determined for the mask of interest under each condition using Novel-win multimask evaluation software (Version 13.3.42) and normalised to body weight (% BW) to represent maximum hallux flexor strength and lesser toe flexor strength for each foot.
The only other study to investigate the relationship between toe flexor strength and falls used a qualitative paper grip test, whereby the subject recorded either a pass or fail when trying to resist a piece of paper being pulled out from underneath their toes. Other studies have measured surrogates of toe flexor strength, such as the resultant moments arising from the ground reaction forces generated on a force plate or using a dynamometer. However, as a portable quantitative measure of toe flexor strength was required for the present study, the novel method of using a pressure platform was developed.

Assessment of foot problems

The presence and severity of hallux valgus was assessed for each participant by the chief investigator [KJM] using the Manchester Scale, a clinical tool consisting of photographs of feet with four levels of hallux valgus: none, mild, moderate and severe. Classifications using this scale have been shown to be reliable and significantly associated with angular measurements obtained from X-rays. The chief investigator [KJM] also examined each participant’s feet and noted the presence of any lesser toe deformities (e.g. claw or hammer toes; see Figure 1).

Figure 1: Examples of participants who presented with toe deformities. Severe hallux valgus is present in A, whereby there is lateral deviation of the big toe. Deformity of the lesser toes is present in B whereby the metatarsophalangeal joints of toes 2-5 are hyperextended and the interphalangeal joints are flexed.
Physiological fall risk

The short form Physiological Profile Assessment (PPA) was used to assess the predicted fall risk for each participant. The short form PPA consists of five tests that have been found to be the most important in predicting fallers and non-fallers in both community and institutional settings. The five tests include edge contrast sensitivity, proprioception, quadriceps muscle strength, hand-reaction time and balance. Based on performance in these tests, the PPA computes an overall fall risk score, which has 75% predictive accuracy for falls in older people. Scores below 0 indicate a low risk of falling, scores between 0 and 1 indicate a mild risk of falling, scores between 1 and 2 indicate a moderate risk of falling, and scores above 2 indicate a high risk of falling. Details regarding each of the tests included in the PPA are described in detail elsewhere.23

Falls incidence

All participants were provided with a 12-month calendar and were instructed to document any falls they experienced during a given month by circling the day on which the fall occurred. A fall was defined as “unintentionally coming to rest on the ground or at some other lower level, not as a result of a major intrinsic event (e.g. stroke) or overwhelming hazard”.23, 24 At the end of each calendar month, the participants were required to return the page for that month. The calendar pages were stamped with reply-paid postal details to facilitate compliance.

Of the 312 subjects tested at baseline, 303 subjects completed the 12-month follow-up fall incidence calendars. Only nine subjects were lost at follow-up, due to a lack of interest (n = 6), illness (n = 2) or death (n = 1), resulting in a 97% study retention rate. During the 12-month follow-up period, 107 participants (35%) suffered at least one fall and were classified as fallers, while 196 participants (65%) were
classified as non-fallers. Age, gender, height and body mass index (BMI) did not statistically differ between the fallers and non-fallers (see Table 1). Of the fallers, 36 participants (12%) sustained two or more falls during the follow-up period. Of the 178 falls, 55% resulted in some form of injury, with 30% of these injurious falls requiring the participant to seek medical attention. Nine participants (5%) were hospitalised as a result of their fall.

**Table 1:** Descriptive characteristics and Physiological Profile Assessment (PPA) fall risk score of the fallers (n = 107) and non-fallers (n = 196).

<table>
<thead>
<tr>
<th></th>
<th>Fallers mean ± SD</th>
<th>Non-fallers mean ± SD</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>71.6 ± 6.6</td>
<td>71.2 ± 6.7</td>
<td>0.60</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.66 ± 0.11</td>
<td>1.66 ± 0.09</td>
<td>0.58</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>28.5 ± 5.3</td>
<td>28.5 ± 4.9</td>
<td>0.94</td>
</tr>
<tr>
<td>Men:women (n)</td>
<td>49:58</td>
<td>105:91</td>
<td>0.12</td>
</tr>
<tr>
<td>PPA</td>
<td>0.56 ± 0.92</td>
<td>0.61 ± 0.99</td>
<td>0.71</td>
</tr>
</tbody>
</table>

**Statistical analysis**

Independent *t*-tests were used to identify any significant differences in hallux and lesser toe flexor strength between those participants who fell during the 12-month prospective follow-up period compared to non-fallers. Chi-square tests were also computed to determine whether the prevalence of foot problems differed significantly between the two groups. The toe strength and deformity variables, with the addition of the physiological fall risk score, were entered into a stepwise discriminant function analysis to determine which variables were independent predictors of falls. A forward stepwise linear regression was then used to quantify these predictor variables. To determine whether there were any associations between toe deformities and toe weakness, the hallux strength of participants with moderate-to-severe hallux valgus and the lesser toe strength of those with lesser toe deformities were compared to those without these foot
problems using independent *t*-tests. An alpha of $p < 0.05$ was established for all statistical analyses, which were conducted using SPSS software (SPSS 15 for Windows).

**RESULTS**

Fallers displayed significantly less strength of the hallux and lesser toes (see Figure 2) and were more likely to have severe hallux valgus (relative risk [RR] = 2.36; 95% CI = 1.03 – 5.45; $p < 0.01$) and lesser toe deformity (RR = 1.32; 95% CI = 1.04 – 1.69; $p < 0.01$) than non-fallers. The PPA fall risk score, however, did not significantly differ between the two subject groups (see Table 1). The inability of the PPA fall risk score to predict falls in this study was likely due to sample differences in comparison to previous studies whereby the participants in the current study were slightly younger and had a lower proportion of recurrent fallers (12%). When data from the two subject groups were pooled, participants who displayed moderate-to-severe hallux valgus ($n = 36$) or a lesser toe deformity ($n = 74$) had significantly reduced strength of the hallux and lesser toes, respectively, compared to those without these foot problems ($p < 0.01$; see Figure 3).

The discriminant function analysis identified hallux strength and the presence of lesser toe deformities as the most important factors in predicting falls (Wilks’ $\Lambda = 0.926; p < 0.001$), whereby 64% of individuals could be correctly identified as a faller or non-faller based on these two variables alone. A forward stepwise linear regression indicated that for every 1% body weight increase in hallux strength, the odds of sustaining a fall decreased by 6.7% ($p < 0.001$) and that those with a lesser toe deformity were 2.1 times more likely to fall ($p = 0.01$).
Figure 2: Flexor strength of the hallux and lesser toes for older fallers and non-fallers (* indicates a significant difference between fallers and non-fallers at \( p < 0.01 \)).

Figure 3: Flexor strength of the hallux and lesser toes for older people with or without hallux valgus or deformity of the lesser toes (* indicates a significant difference between individuals with the toe deformity compared to those without at \( p < 0.01 \)).
DISCUSSION

The aim of this study was to determine whether toe deformities and toe flexor strength increase the risk of falling in community-dwelling older people. The findings indicate that both reduced toe flexor strength and the presence of toe deformities increase the risk of falls. However, although the discriminant function analysis revealed hallux strength and lesser toe deformities to be predictors of falls, not all participants were correctly identified. In these cases, other factors, particularly environmental factors which were not assessed in this study, may have been important in determining the likelihood of suffering a fall. This highlights the multifactorial nature of falls. However, as the main purpose of this study was to determine whether strength and deformity of the toes were associated with the risk of falling, possible mechanisms for these associations are discussed below.

Toe deformities

In this cohort of community-dwelling older people, individuals with severe hallux valgus had a significantly greater risk of falling than those with no hallux valgus. Therefore, our results support the findings of Menz et al.\textsuperscript{11} who found that fallers in a retirement home village exhibited more severe hallux valgus deformity than non-fallers. Similarly, the presence of a “bunion” has been found to be associated with an increased risk of falling in other studies of community-dwelling older people,\textsuperscript{24, 25} although these studies failed to report the definition or severity of this foot problem.

Given the important role that the hallux and first metatarsophalangeal joint play in gait, it is plausible that the presence of severe hallux valgus would alter gait patterns in older people in a manner that may place them at a greater risk of falling. Older subjects with moderate-to-severe hallux valgus have been found to walk at a slower velocity, have a reduced step length and have increased gait instability when walking on
an irregular surface compared to their counterparts with no or mild deformity.\textsuperscript{3} Similarly, hallux valgus has been associated with reduced force generation through the hallux in older people during walking.\textsuperscript{26} Taken together, these results suggest that hallux valgus deformity reduces the effectiveness of the big toe to propel the body forward during gait, and it is also possible that hallux valgus deformity may reduce the effectiveness of corrective steps taken in response to postural perturbation.

This is the first study to show that the presence of lesser toe deformity may be an independent risk factor for falling in older people. Whilst previous researchers have incorporated observations of lesser toe deformity as part of a composite measure of “serious foot problems”\textsuperscript{24} and an overall “foot problem score”,\textsuperscript{7} both of which were found to be risk factors for falls, lesser toe deformities in isolation have not previously been identified as a fall risk factor. Although Menz et al.\textsuperscript{11} reported that lesser toe deformity was not associated with a greater risk of falling, the analysis was based on the total number of lesser toe deformities an individual presented with, whereby fallers had on average 3.1 $\pm$ 2.7 toes with signs of deformity compared to 2.4 $\pm$ 2.3 for non-fallers. In the current study, the presence of at least one lesser toe deformity was found to be a significant independent predictor of falling.

Although there are structural differences between types of lesser toe deformities (e.g. claw toes, hammer toes), all deformities alter the weight bearing function of the toes. The toes assist to maintain balance by applying pressure to the ground to correct for any postural disturbances.\textsuperscript{27} If the toes are clawed or retracted, they cannot effectively exert pressure to the ground.\textsuperscript{28} Therefore, reduced sensory input from deformed toes may lead to reduced mechanical stability, in turn, affecting stability during the weight bearing and push off phases of gait or when attempting to take corrective steps to maintain balance in a near-fall situation.
**Toe strength**

Fallers displayed reduced plantar flexion strength of both the hallux and lesser toes compared to non-fallers. To our knowledge, no other study has previously quantified this relationship between toe strength and prospectively monitored falls. Menz and colleagues\(^1\) found that fallers were more likely to fail the paper grip test of the lesser toes than non-fallers, however the strength of the hallux was not associated with falls. Interestingly, in the present study, strength of the lesser toe flexors did not emerge as an independent predictor, whereas hallux strength was a stronger predictor of falls, whereby each 1% body weight increase in hallux strength decreased the odds of sustaining a fall by 6.7%. As quadriceps strength did not differ between fallers (25.5 ± 10.4 kg) and non-fallers (27.0 ± 10.1 kg), the reduced hallux strength recorded for fallers is unlikely to be a marker of generalised lower limb muscle weakness.

The toes play an important functional role during gait and balance. For example, people with transmetatarsal amputations perform poorer in tasks such as the functional reach test, which assesses balance, when compared to aged-matched controls.\(^2\) The authors suggested that the loss of the toes lead to impaired function due to the loss of intrinsic muscles and toe proprioceptors. During the stance phase of gait, the extrinsic toe flexors (i.e. flexor hallucis longus and flexor digitorum longus) control forward progression of the tibia over the foot and hold the toes flat on the ground as weight is transferred from the heel to the forefoot, while the intrinsic toe muscles stabilise the medial longitudinal arch and toes.\(^3\) Weakness of the toe flexor muscles will reduce the capacity of the toes to carry out their normal functions during walking and activities that require balance. This may be particularly evident in activities that are more challenging than level ground walking, such as walking on uneven terrain and when turning. Reduced toe flexor strength is therefore a plausible risk factor for falling.
in older people, and as such, strengthening exercises may be of benefit in reducing the risk of falls. Indeed, a clinical trial which incorporates toe strengthening exercises is currently underway.\textsuperscript{30}

\textit{Relationship between toe strength and toe deformities}

Despite the well documented hypotheses that weak toe flexor muscles are associated with the formation of toe deformities,\textsuperscript{8,12-14} to our knowledge, no studies have directly compared the toe flexor strength of individuals with toe deformities to those without. The greater the severity of the hallux valgus angle, particularly in cases where the hallux straddles the second toe, the greater the shift of the extensor hallucis longus tendon towards the fibula.\textsuperscript{31} This results in the tendon becoming taut, holding the hallux in extension and, in turn, reducing the capacity of the hallux to push down on the floor. This supports the findings of the present study, whereby older people with moderate-to-severe hallux valgus had significantly less hallux flexor strength than those without hallux valgus. Similarly, when lesser toe deformities are present, subluxation of the proximal phalangeal joint occurs and the axis of the intrinsic flexors change, making them less biomechanically efficient.\textsuperscript{8,13} This is likely to aggravate the deformity further. Although a relationship between reduced toe flexor strength and the presence of toe deformities was found in this study, we can not determine whether weaker toe flexors have contributed to the development of toe deformities or whether the toe deformity resulted in reduced toe flexor strength. However, our results suggest that it is worthwhile investigating whether strengthening of the intrinsic toe muscles could reduce the incidence and severity of toe deformities.
CLINICAL RELEVANCE

The hallux and lesser toes are vital structures that assist with stability during gait and balance tasks. This study has shown that the presence of hallux valgus, lesser toe deformity and reduced plantar flexion strength of the hallux and lesser toes increase the risk of falling in older people. In particular, hallux strength and the presence of lesser toe deformities were independent predictors of falls. Furthermore, individuals with hallux valgus and lesser toe deformities had weaker flexor muscles of the associated toes. Interventions designed to increase strength of the toe flexor muscles combined with treatment of those older individuals with toe deformities may be beneficial, and a clinical trial that determines whether these interventions can reduce the risk of falling is recommended.

REFERENCES


Chapter 3

Foot pain, plantar pressures, and falls in older people:

A prospective study

This chapter is an amended version of the manuscript: Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. Foot pain, plantar pressures, and falls in older people: A prospective study. *Journal of the American Geriatrics Society.* 2010; 58:1936-1940.

ABSTRACT

**Objectives:** To determine whether foot pain and plantar pressure are associated with falls in community-dwelling older adults.

**Design:** Community-based cohort study with 12-month prospective falls follow-up.

**Setting:** Sydney and Illawarra statistical regions of New South Wales, Australia.

**Participants:** Randomly recruited, community-dwelling adults (158 men and 154 women) aged 60 and older.

**Measurements:** Manchester Foot Pain and Disability Index to establish baseline foot pain and dynamic plantar pressures. Participants were then classified as fallers (n = 107) or non-fallers (n = 196) based on their falls incidence over the following 12 months.

**Results:** Fallers had a significantly higher prevalence of foot pain than non-fallers (57.9% vs. 42.1%; chi-square = 4.0; *p* = 0.04). Fallers also generated a significantly higher peak pressure and pressure-time integral under the foot than non-fallers. In addition, individuals with foot pain had a significantly higher peak pressure and pressure-time integral under the foot than those without foot pain.
Conclusion: High plantar pressures generated during gait may contribute to foot pain and discomfort, contributing to risk of falls. Providing interventions to older people with foot pain and high plantar pressures may play a role in reducing their fall risk.

INTRODUCTION

Falls, the leading cause of injuries sustained by older adults, typically occur during ambulation. Gait and balance abnormalities have consistently been associated with falls in older people, with gait disturbances having been identified as an independent risk factor for injurious falls in older men and women. During normal gait, the foot is the only source of direct contact with the ground. Therefore, any factor that can disrupt normal foot function during ambulation is likely to impair stability and balance and, in turn, increase the risk of falls. One foot-related factor that has been found to affect balance, gait, and functional ability in older adults is foot pain. For example, people aged 75 and older with foot pain were found to perform poorly on a task assessing coordinated stability and took 18% to 36% longer to ascend and descend stairs, perform alternate step-ups, and complete a 6 m walk than their pain-free counterparts. Several studies have found that older people with foot pain walk more slowly than those without foot pain, and chronic and severe foot pain has been reported to be independently associated with risk of walking difficulty.

Despite its associations with impaired balance and walking ability, only a few studies have investigated the relationship between foot pain and fall risk. Foot pain has been associated with risk of falling in disabled women aged 65 and older and in men and women aged 62 and older residing in a retirement village, but it is unknown whether foot pain is a risk factor for falling in community-dwelling older men and women. Because foot pain has been found to be present in 20% to 54% of community-
dwelling older people,\textsuperscript{3,8-11} it is important to determine whether it is a risk factor for falls.

Recent studies have established that foot pain during walking is associated with high plantar pressures generated during gait. For example, one study\textsuperscript{12} reported a significant correlation (correlation coefficient ($r = 0.562$)) between ratings of pain and average pressure generated beneath the second metatarsal head in 12 people with rheumatoid arthritis. In a sample of 70 adults (40 with a pes cavus foot type), pressure-time integrals were found to be significantly correlated with foot pain ($r = 0.486$), and those with foot pain displayed significantly higher pressure-time integrals for the whole foot than participants without foot pain.\textsuperscript{13} Similarly, another study\textsuperscript{14} reported that in 77 patients with degenerative disorders of the foot, custom-made orthopaedic shoes significantly decreased perceived foot pain at least 23% while significantly reducing the plantar pressures generated under all regions of the foot at least 9%. Furthermore, the pain that these patients experienced during walking was significantly, albeit moderately, correlated ($r = 0.521$) with the average pressure generated beneath the second and third metatarsal heads, with higher foot pain associated with higher plantar pressures.

Despite studies linking foot pain and dynamic plantar pressures, no previous research has systematically investigated whether high plantar pressures are associated with foot pain in older community-dwelling adults or, more importantly, whether foot pain or dynamic plantar pressures are a fall risk factor in this population. Therefore, the purpose of this study was to determine whether foot pain or plantar pressures generated during ambulation were associated with falls in community-dwelling older adults.
METHODS

Participants

Three hundred and twelve community-dwelling older people (154 female) were recruited from 16 randomly selected federal electorates that make up the Sydney and Illawarra statistical regions of New South Wales, Australia, using methods described in detail elsewhere. Sample size calculations were based on data from previous population studies. It was estimated that a sample size of 300 would allow for a minimum of 10 outcome cases (fallers) per variable entered into multivariate models, which were required for other aspects of this study, and be adequate for determining significant differences between fallers and non-fallers with respect to the quantitative measures of foot pain and plantar pressures used. Participants were included in the study if they were aged 60 and older and living independently in the community, passed the Short Portable Mental Status Questionnaire, were able to ambulate for at least 10 m with or without an aid, were free from neurological diseases, and could arrange their own transport to a testing venue in their community. Each participant gave written informed consent to participate in the study after reading the participant information package before any testing procedures began. The University of Wollongong Human Research Ethics Committee approved all recruiting and testing procedures (HE05/169).

Falls incidence

All participants were provided with a 12-month calendar and were instructed to document any falls they experienced during a given month by circling the day on which the fall occurred. A fall was defined as “unintentionally coming to rest on the ground or at some other lower level, not as a result of a major intrinsic event (e.g. stroke) or overwhelming hazard.” At the end of each calendar month, the participants were
required to remove the page and return it to the chief investigator [KJM]. The calendar pages were stamped with reply-paid postal details to facilitate return. At the conclusion of the prospective 12-month follow-up period, participants were classified as non-fallers (no falls experienced during the 12 months) or fallers (experienced 1 or more falls during the 12 months).

*Foot pain*

Foot pain was assessed using the Manchester Foot Pain and Disability Index (MFPDI),\(^{21}\) which consisted of 19 statements starting with the phase ‘‘Because of pain in my feet…’’. Ten items focused on functional limitations, five on pain intensity, and two on personal appearance. The MFPDI has been found to be a suitable instrument for assessing the effect of foot pain in community and clinical populations, including older community-dwelling adults.\(^{8}\) The sum of the answers provided a total MFPDI score, with a higher score indicating more-debilitating foot pain and 0 indicating no foot pain. The last two items relating to difficulties performing work activities were omitted because the participants were of retirement age. Participants were defined as having foot pain if their MFPDI was 1 or greater. Participants were additionally asked to describe the location of their foot pain and typical shoe-wearing habits.

*Dynamic plantar pressures*

The plantar pressures generated underneath each participant’s feet while they walked over an emed AT-4 pressure platform (Novel GmbH, Munich, Germany; 25 Hz; 4 sensors/cm\(^2\); 415 x 255 mm) were assessed to represent barefoot dynamic foot function. The calibrated platform was placed on a firm, level surface, with a custom-designed dense foam walkway surrounding the plate to provide a level walking surface.

The two-step method was used to minimise fatigue and limit participant burden.\(^{22, \ 23}\) That is, participants stood two steps behind the platform and started
walking so that their second step contacted the centre of the platform and then continued to walk for approximately four steps after contacting the platform. Although still in the acceleration phase of gait, the two-step method has been found to produce measurements similar to those of the mid-gait and three-step methods.22 23 Furthermore, the two-step method has been found to be a more-reproducible and efficient protocol in terms of quantifying plantar pressures than the one- or three-step method in patients with foot complaints.23 Participants were required to look straight ahead, so that they did not target the pressure platform, and to walk at a self-selected comfortable speed. Five successful trials each were collected for the right and left foot of each participant, because plantar pressure data averaged across multiple trials have been shown to be more reliable and representative of true plantar pressures than using only a single trial.22 Collecting three to five trials has also been shown to be necessary for reliable pressure measurements in populations with and without diabetes mellitus or arthritis.22-24 Trials were discarded if there were obvious gait deviations or targeting of the pressure platform.22

All files were stored in the Novel Database Medical (Version 13.3.42). The mean peak pressure footprints were then analysed using Novel-win multimask software (Version 13.3.42) to determine the peak pressure (kilopascals; kPa) and pressure-time integral (kilopascal seconds; kPa.s) generated under the whole plantar surface of the foot and averaged across the five trials.

Statistical analysis

Chi-square values were calculated to determine whether the prevalence of foot pain significantly differed between fallers and non-fallers. Because the plantar pressure variables were not normally distributed, they were logarithmically transformed before analysis. Although data were collected bilaterally, only data for each participant’s right
foot were analysed, to ensure that the assumption of data independence was met, although the same statistical results were obtained when the data were analysed grouped according to foot dominance (choice limb for single-leg balance task). Independent $t$-tests were used to determine whether there were any significant differences in the peak pressure or pressure-time integral data derived for the two faller groups. A one-way analysis of covariance was also conducted to determine whether there was any significant difference in the peak plantar pressure or pressure-time integral data generated by participants reporting foot pain and those without foot pain. Because a higher body mass index (BMI) has been shown to be associated with the presence of foot pain and plantar pressures, BMI was included as a covariate. An alpha of $p \leq 0.05$ was established for all statistical analyses, which were conducted using SPSS software (SPSS 15 for Windows, SPSS, Inc., Chicago, IL).

RESULTS

Of the 312 participants tested at baseline, 303 (97%) completed the 12-month follow-up falls incidence calendars. Reasons for loss to follow up were a loss of interest ($n = 6$), illness ($n = 2$), and death ($n = 1$).

Falls incidence

During the 12-month prospective follow-up period, 107 participants (35%) suffered at least one fall and were classified as fallers, and 196 participants (65%) were classified as non-fallers. Age, sex, height, and BMI did not differ statistically between the fallers and non-fallers (see Table 1). Of the 180 falls, 56% resulted in an injury, with 30% of these injurious falls requiring medical attention. Nine participants (5%) were hospitalised as a result of a fall.
Foot pain

Foot pain, classified using the MFPDI (score ≥ 1), was prevalent in 50% of the participants. Fallers had a significantly higher prevalence of foot pain (57.9%) than non-fallers (42.1%; chi-square = 4.0; p = 0.04).

Dynamic plantar pressures

When walking across the pressure platform, despite recording similar total contact times (fallers mean 857.7 ms, 95% CI = 834.6 – 880.8 ms; non-fallers mean 844.9 ms, 95% CI = 825.9 – 863.8 ms), the fallers generated significantly higher total peak pressure and total pressure-time integral values than the non-fallers (see Table 1). Regional pressure differences at the heel, fifth metatarsal, second toe, and third to fifth toes were also significantly associated with falls (data not shown). Participants who experienced foot pain generated a significantly higher total peak pressure (mean 767.2 kPa, 95% CI = 724.8 – 809.7 kPa vs. 683.7 kPa, 95% CI = 648.5 – 718.9 kPa) and total pressure-time integral (mean 347.2 kPa.s, 95% CI = 325.8 – 368.7 kPa.s vs. 300.7 kPa.s, 95% CI = 285.2 – 316.3 kPa.s) under the foot than those who did not experience foot pain. Individuals with foot pain also had significantly higher peak pressures and pressure-time integrals at the heel and first metatarsal (data not shown).

Table 1: Comparison of descriptive characteristics and pressure variables of the fallers (n = 107) and non-fallers (n = 196).

<table>
<thead>
<tr>
<th></th>
<th>Fallers mean (95% CI)</th>
<th>Non-fallers mean (95% CI)</th>
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<tr>
<td>Men:women (n)</td>
<td>49:58</td>
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<td>0.12</td>
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<td>Age (y)</td>
<td>71.6 (70.4-72.9)</td>
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<td>Height (m)</td>
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<td>BMI (kg.m$^2$)</td>
<td>28.5 (27.4-29.5)</td>
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<td>Peak pressure (kPa)</td>
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<td>PTI (kPa.s)</td>
<td>349.0 (324.9-373.0)*</td>
<td>311.0 (294.5-327.5)</td>
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<tr>
<td>Foot pain (%)</td>
<td>57.9*</td>
<td>42.1</td>
<td>0.04</td>
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</tbody>
</table>

PTI = pressure-time integral
* indicates a significant difference between the fallers and non-fallers.
DISCUSSION

Falls incidence

The 35% of participants in the present study who suffered at least one fall within 12 months is similar to results from previous studies of community-dwelling adults aged 65 and older, in which single fall rates of 32% to 39% have been reported. Of further concern, more than half of falls reported in this study resulted in an injury, a finding also in line with previous studies. This once again confirms the need to identify effective strategies to reduce the rate of falls in older people.

Foot pain

The overall prevalence of foot pain in this cohort (50%) was similar to the 54% reported previously but higher than in the North West Adelaide Health Study (26%) of community-dwelling people of a similar age. These between-study differences can be attributed to variations in the definitions of foot pain used in each of the studies. The higher prevalence of foot pain reported by fallers than non-fallers confirmed the notion that foot pain is a risk factor for falling in community-dwelling older men and women. This result is in agreement with recent studies of older disabled women and retirement village populations. Although the cause of foot pain is often multifactorial in this population, the significant association between foot pain and falls highlights the importance of recognising and treating foot pain that older people experience through podiatric or footwear interventions or both.

The most common location of pain reported by the participants was in the toe region (33%). Similarly, the toe region was the most common location of foot pain in two other studies of community-dwelling people aged 65 and older (36 – 53%). It is possible that toe pain may be associated with toe deformities, such as claw or hammer
toes, which are common in older adults and were present in 46% of participants in the current study.

*Dynamic plantar pressures*

This is the first study to identify that older fallers generate higher plantar pressures during gait than non-fallers. It may be that higher plantar pressures generated while walking by older fallers contribute to their foot pain, which in turn, may cause gait and balance disturbances, predisposing these individuals to falls.

Many factors, including foot structure, walking speed, and body weight, influence plantar pressures in older people. Because there were no significant between-subject group differences in body weight or BMI, it is unlikely that these factors contributed to the higher plantar pressures that the fallers generated. Similarly, fallers have been shown to walk more slowly than nonfallers, and in the present study, fallers recorded longer contact times than the nonfallers, which is characteristic of a slower average walking speed. Therefore, the significantly greater plantar pressures that the fallers displayed cannot be because of faster walking speed.

Although the link between plantar pressures, comfort, and foot pain is often speculated, few studies have systematically investigated this association. That participants who suffered foot pain in the current study generated higher plantar pressures supports the association between foot pain and plantar pressures in studies involving patients with rheumatoid arthritis and people with pes cavus feet. The greater duration and magnitude of pressure generated under the plantar surface will increase loading on anatomical structures of the foot, which may, in turn, result in foot pain. Footwear interventions, such as better cushioning under areas of high pressure, may make ambulation more comfortable and safer for older adults. Conservative measures, including podiatric treatment, such as lesion debridement or orthotic
treatment, can also remedy foot pain and reduce high plantar pressures at specific locations under the foot. Providing interventions for older individuals with foot pain and high plantar pressures may also result in reducing their risk of future falls.

The findings of this study need to be interpreted in the context of its limitations. First, plantar pressure variables were measured only barefoot. Barefoot walking has been shown to generate higher plantar pressures under the heel and central metatarsals than shod gait in older adults. Although 19% of the participants reported not wearing shoes around the home, the plantar pressures would probably be different in different footwear worn habitually by the participants. Second, although it was possible to account for the potential contribution of body weight and walking speed to plantar pressures, several other variables (e.g. foot structure) may have played a role. Finally, the link between foot pain, plantar pressures, and falls is admittedly speculative and requires further research to clarify the underlying biomechanical or physiological mechanisms that may be responsible for the pressures experienced by the fallers.

**CONCLUSIONS**

This study has shown that community-dwelling fallers display significantly higher plantar pressures and are more likely to report foot pain. Higher plantar pressures generated during gait may contribute to foot pain and discomfort, contributing to risk of falls. Identifying older individuals who experience high plantar pressures and foot pain, and assessing and treating the cause of these factors, may provide an opportunity for these individuals not only to ambulate pain free, but also to reduce their risk of falls.
REFERENCES


SECTION B:

What are the unique structural and functional features of older people with toe deformities and foot pain?
Chapter 4

Foot shape of older people: Implications for shoe design

This chapter is an amended version of the manuscript: Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. Foot shape of older people: Implications for shoe design. Footwear Science. 2010; 2(3):131-139.

ABSTRACT

Foot problems and deformities, which are highly prevalent in older people, may affect foot anthropometrics and result in older people having difficulty finding shoes that fit. This study aimed to characterise the dimensions and shape of the feet of older people and to determine whether foot anthropometrics were influenced by gender and/or the presence of foot problems in older people. Foot anthropometrics and foot problems were assessed in 312 community-dwelling older men and women. Men had significantly higher normalised first and fifth toe heights and a greater fifth toe angle, whereas women had a significantly longer normalised medial ball length and greater first toe and heel bone angles (p < 0.05). Older people who had moderate-to-severe hallux valgus, lesser toe deformities, swollen or flat feet exhibited different foot anthropometrics to those without foot problems. Consequently, footwear for older people should be designed to cater for the altered morphology of older feet.
INTRODUCTION

For shoes to fit properly, their design must match the shape and dimensions of the feet of the intended wearer. Despite the importance of foot morphology to shoe design, anthropometric data characterising the feet of older people are not well documented in the literature, with most published data derived from younger military populations. One of the few studies that have reported foot anthropometrics for the elderly found that although foot length matched well with the size of commercially available footwear, more than two-thirds of the measured feet were considerably wider than the available footwear. Similarly, other studies have suggested that up to 80% of older men and women wear shoes that are too narrow and too short for their feet. Furthermore, the incidence of foot pain, particularly in the toe region, has been shown to increase in older women when they are wearing shoes.

It has been suggested that inadequately fitting footwear, specifically inadequate fit in the width and depth of shoes, may be responsible for acquired foot deformities such as hallux valgus, hammer toes, claw toes and corns. Menz and Morris found that older adults with moderate-to-severe hallux valgus were three times more likely to be wearing shoes that were too narrow for their feet compared to those with no or mild hallux valgus. They also found the presence of lesser toe deformity was associated with wearing shoes that were too short for the foot. In a study of 103 patients requiring corrective surgery for hallux valgus deformity, 29% of the patients implicated ill-fitting shoes as the cause of their deformity.

Swollen feet are typically caused by venous insufficiency and may be present in people with diabetes, obesity, pulmonary hypertension, or increased plasma volume as a consequence of heart or renal failure, protein loss or lymphoedema. Swollen feet are therefore a common foot problem suffered by older people. Another structural foot
abnormality common in older people is pes planus (flat feet). The pes planus foot is often hypermobile, which requires greater muscular effort and can interfere with normal foot function as its ability to supinate and form a rigid lever for propulsion during gait is reduced.\textsuperscript{11} Although older people have been shown to have flatter feet than younger adults\textsuperscript{12} and pes planus has been found to be associated with foot pain in older adults,\textsuperscript{13} no studies have examined this deformity with respect to the design of shoes for older individuals.

While foot problems are often attributed to ill-fitting footwear,\textsuperscript{3, 14, 15} many foot deformities affect foot anthropometrics and, in turn, lead to further shoe fit problems. In order to design comfortable, well-fitting shoes for older people, we must first have a better understanding of the shape of the older foot, as well as factors that can influence older foot morphology. Therefore, the purpose of this study was to characterise the dimensions and shape of the feet of older people and to determine whether foot anthropometrics were influenced by gender and/or the presence of foot problems.

**METHODS**

*Participants*

Three hundred and twelve community-dwelling older people were randomly recruited from the Sydney and Illawarra statistical regions of New South Wales, Australia, using methods previously described in detail.\textsuperscript{16} Participants were included in the study if they were aged over 60 years, were living independently in the community, passed the Short Portable Mental Status Questionnaire,\textsuperscript{17} were able to ambulate for at least 10 m with or without an aid, were free from neurological diseases and could arrange their own transport to a testing venue located in their community. The sample included 158 men (age: 71.1 ± 6.3 years; height: 1.73 ± 0.1 m; mass: 84.2 ± 13.8 kg; BMI: 28.2 ± 3.6
kg/m²) and 154 women (age: 71.7 ± 7.0 years; height: 1.59 ± 0.1 m; mass: 72.4 ± 16.3 kg; BMI: 28.6 ± 6.1 kg/m²). Although the men were significantly taller and heavier than the women, BMI and age did not differ between the two genders. Each participant gave written informed consent after reading the participant information package before any testing procedures began. All recruiting and testing procedures were approved by the University of Wollongong Human Research Ethics Committee (HE05/169).

**Shoe size**

The Brannock® foot-measuring device was used to determine each participant’s shoe size. Participants stood in an even weight-bearing position with one foot placed in the Brannock® device. Heel-to-toe shoe length was measured by the size corresponding with the participant’s longest toe, while arch shoe length was read by placing the device’s pointer at the first metatarsophalangeal joint. The larger of the two sizes was recorded as the participant’s shoe size (US). To measure foot width the sliding bar of the Brannock® device was placed firmly on the lateral side of the participant’s forefoot. The width that corresponded with the shoe size was then recorded (from AAA to E). This process was repeated twice on each foot, and a third time if the two measurements differed from each other. The larger shoe size measurement of either the left or right foot was recorded as the participant’s shoe size.

**External foot anthropometrics**

Foot anthropometrics were measured using a calibrated three-dimensional foot scanner (IFU-S-01, I-Ware Laboratory Co, Ltd, Japan; scanning volume 685 x 340 x 310 mm; accuracy = 0.5 x 0.5 x 1 mm) while participants stood with their weight evenly distributed across both feet. Fifteen felt stickers (5 mm diameter) were placed on specified anatomical landmarks on each foot so the landmarks were visible to the scanner’s laser (see Figure 1). These landmarks were used to calculate 17
anthropometrical measurements per foot to characterise the external shape of each participant’s feet (see Table 1). For each calculation, the foot axis was defined as the line from the centre of heel (pternion) to the second metatarsal head.\textsuperscript{18-20} An average of three scans was used to characterise the foot dimensions of each participant’s right and left foot. Foot anthropometrics (excluding angles) were also normalised to foot length to allow later comparisons between feet of different lengths.

\textbf{Figure 1}: Placement of markers on the anatomical landmarks in preparation for scanning of each participant’s feet and a participant having their foot scanned.

\textit{Assessment of foot problems}

The presence and severity of hallux valgus was assessed for each participant by the chief investigator [KJM] using the Manchester Scale.\textsuperscript{21} Each foot was compared to a set of standardised photographs and assigned a hallux valgus rating of none, mild, moderate or severe. Grading of hallux valgus severity using this tool is based primarily upon visual inspection of the degree of abduction of the hallux relative to the first metatarsal, and scores using this tool have been shown to correlate with hallux abductus angle measurements obtained from radiographs.\textsuperscript{22} For the purpose of this analysis, hallux valgus severity was collapsed into two groups: none-to-mild and moderate-to-
Table 1: The 17 foot dimensions derived from the foot scanner to characterise the shape of each participant’s foot.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lengths (mm)</strong></td>
<td></td>
</tr>
<tr>
<td>Foot</td>
<td>The distance between the pternion and the longest toe, measured along the foot axis.</td>
</tr>
<tr>
<td>Medial ball</td>
<td>The distance between the pternion and the 1&lt;sup&gt;st&lt;/sup&gt; metatarsal head, measured along the foot axis.</td>
</tr>
<tr>
<td>Lateral ball</td>
<td>The distance between the pternion and the 5&lt;sup&gt;th&lt;/sup&gt; metatarsal head, measured along the foot axis.</td>
</tr>
<tr>
<td><strong>Widths (mm)</strong></td>
<td></td>
</tr>
<tr>
<td>Ball</td>
<td>The width of the foot at the 1&lt;sup&gt;st&lt;/sup&gt; and 5&lt;sup&gt;th&lt;/sup&gt; metatarsal heads.</td>
</tr>
<tr>
<td>Heel</td>
<td>The distance between the outer edges of the foot at 16% of foot length, perpendicular to the foot axis.</td>
</tr>
<tr>
<td><strong>Circumferences (mm)</strong></td>
<td></td>
</tr>
<tr>
<td>Ball</td>
<td>Measured around the outside of the foot, passing across the 1&lt;sup&gt;st&lt;/sup&gt; and 5&lt;sup&gt;th&lt;/sup&gt; metatarsal heads.</td>
</tr>
<tr>
<td>Instep</td>
<td>Measured around the outside of the foot at 50% of foot length, perpendicular to the foot axis.</td>
</tr>
<tr>
<td><strong>Heights (mm)</strong></td>
<td></td>
</tr>
<tr>
<td>Ball</td>
<td>The distance between the highest point on the ball of foot circumference and the floor.</td>
</tr>
<tr>
<td>Navicular</td>
<td>The distance between navicular tuberosity and the floor.</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; toe</td>
<td>The distance between the 1&lt;sup&gt;st&lt;/sup&gt; interphalangeal joint and the floor.</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; toe</td>
<td>The distance between the 5&lt;sup&gt;th&lt;/sup&gt; distal interphalangeal joint and the floor.</td>
</tr>
<tr>
<td>Instep</td>
<td>The distance between the highest point on the instep circumference and the floor.</td>
</tr>
<tr>
<td>Lateral malleolus</td>
<td>The distance between lateral malleolus and the floor.</td>
</tr>
<tr>
<td>Medial malleolus</td>
<td>The distance between medial malleolus and the floor.</td>
</tr>
<tr>
<td><strong>Angles (°)</strong></td>
<td></td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; toe</td>
<td>A base line is drawn from the medial heel width point to the widest point of the 1&lt;sup&gt;st&lt;/sup&gt; metatarsal head and extends past the foot. Another line is drawn between the widest point of the 1&lt;sup&gt;st&lt;/sup&gt; metatarsal head and the outer edge of the 1&lt;sup&gt;st&lt;/sup&gt; toe joint. The angle between these two lines is calculated.</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; toe</td>
<td>A base line is drawn from the lateral heel width point to the widest point of the 5&lt;sup&gt;th&lt;/sup&gt; metatarsal head and extends past the foot. Another line is drawn between the widest point of the 5&lt;sup&gt;th&lt;/sup&gt; metatarsal head and the outer edge of the 5&lt;sup&gt;th&lt;/sup&gt; toe joint. The angle between these two lines is calculated.</td>
</tr>
<tr>
<td>Heel bone</td>
<td>A cross section of the scan is taken at 7% of the foot length. P1 is drawn at the centre of heel at a height of 28% of the foot length. P2 is drawn at the centre of heel at a height of 4% of the foot length. A line is drawn between P1 and P2 and the angle between this line and the vertical is calculated (see Figure 2).</td>
</tr>
</tbody>
</table>
severe. The chief investigator also examined each participant’s feet and noted the presence of any lesser toe deformities, such as claw or hammer toes, dorsal calluses, and participants were asked whether they suffered from, or had been diagnosed with, swollen or flat feet.

**Figure 2:** Calculation of heel bone inclination angle (adapted from manufacturer’s User Manual). The red dots are actual markers, while the green and blue dots are calculated locations. P1 and P2 are defined in Table 1.

**Statistical analysis**

Statistical analysis was conducted on data obtained for the right foot of each participant to ensure the assumption of data independence was met. Independent *t*-tests were used to assess for any differences in absolute or normalised foot anthropometrics between men and women. Normalised foot anthropometrics were then entered into a stepwise discriminant function analysis to determine which variables were the most important in discriminating between the two genders. Independent *t*-tests were also used to determine any differences in normalised foot anthropometrics in those participants with specific foot problems (hallux valgus, toe deformities, swollen feet and flat feet) by comparing each of these four groups to those participants without any of the above mentioned foot problems. In order to establish whether the prevalence of any of these foot problems differed according to gender, a series of chi-square analyses were
conducted. An alpha of 0.05 was selected as the level of significance for all statistical analyses, which were conducted using SPSS 15 for Windows (SPSS Inc., USA).

RESULTS

Shoe size

The distribution of shoe sizes for the men and women is illustrated in Figure 3. Shoe size for the women ranged from a US 4.5C to 13B, whereas the men ranged from an 8.5D to larger than a 14.5. The largest size that could be measured with the Brannock device was a man’s 14.5, with five of the men’s feet exceeding this value.

![Figure 3: Distribution of shoe sizes for men (n = 158) and women (n = 154).](image)

Absolute foot measurements

Each of the 17 measured foot dimensions significantly differed between the two genders. Men recorded significantly larger values than the women for all dimensions with the exception of first toe and heel bone angles, whereby women had significantly larger angles (increased by 21.6% and 46.5%, respectively). As male participants had significantly longer feet (268.3 ± 13.1 mm) than their female counterparts (245.7 ± 13.5 mm; \( p < 0.001 \)), direct comparison of the absolute foot measurements were conducted for men and women whose foot length measured between 250 – 256 and 257 – 262 mm (see Table 2). These two foot length categories corresponded with European shoe sizes 38 and 39, respectively,\(^{24}\) and were the only two foot length categories with sufficient
men and women to enable a valid statistical between-gender comparison. For the given foot length categories, men typically displayed great widths, heights and circumferences than the women, although the length measures did not differ between the genders (see Table 2).

**Table 2:** Mean (± SD) absolute foot anthropometrics (mm) for males and females whose foot length measured within two common foot length categories.

<table>
<thead>
<tr>
<th>Foot dimension</th>
<th>Foot length: 250-256 mm Males (n = 15)</th>
<th>Females (n = 22)</th>
<th>Foot length: 257-262 mm Males (n = 20)</th>
<th>Females (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball girth</td>
<td>249.4 ± 11.3</td>
<td>239.0 ± 12.6*</td>
<td>256.1 ± 10.9</td>
<td>238.9 ± 13.7*</td>
</tr>
<tr>
<td>Instep circumference</td>
<td>248 ± 9.0</td>
<td>237.7 ± 12.3*</td>
<td>255.3 ± 13.8</td>
<td>240.7 ± 15.1*</td>
</tr>
<tr>
<td>Ball width</td>
<td>102.5 ± 5.4</td>
<td>98.5 ± 4.7*</td>
<td>105.9 ± 4.7</td>
<td>98.3 ± 5.7*</td>
</tr>
<tr>
<td>Ball height</td>
<td>43.7 ± 3.4</td>
<td>41.5 ± 3.7</td>
<td>44.0 ± 3.0</td>
<td>41.0 ± 4.0*</td>
</tr>
<tr>
<td>Heel width</td>
<td>66.6 ± 3.0</td>
<td>65.8 ± 4.6</td>
<td>68.4 ± 2.8</td>
<td>62.2 ± 5.5*</td>
</tr>
<tr>
<td>Navicular height</td>
<td>44.8 ± 5.0</td>
<td>40.8 ± 5.3*</td>
<td>47.8 ± 7.2</td>
<td>42.3 ± 7.2*</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; toe height</td>
<td>24.0 ± 2.9</td>
<td>22.2 ± 2.4*</td>
<td>24.7 ± 3.6</td>
<td>22.9 ± 3.3</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; toe height</td>
<td>20.1 ± 2.7</td>
<td>18.4 ± 2.4</td>
<td>20.1 ± 3.0</td>
<td>17.9 ± 2.8</td>
</tr>
<tr>
<td>Instep height</td>
<td>69.4 ± 4.0</td>
<td>65.3 ± 4.6*</td>
<td>71.9 ± 5.0</td>
<td>67.0 ± 7.2*</td>
</tr>
<tr>
<td>Medial ball length</td>
<td>182.1 ± 3.1</td>
<td>184.1 ± 6.6</td>
<td>188.8 ± 5.7</td>
<td>193.8 ± 7.9</td>
</tr>
<tr>
<td>Lateral ball length</td>
<td>159.8 ± 4.3</td>
<td>156.8 ± 3.7</td>
<td>164.0 ± 7.6</td>
<td>160.7 ± 9.0</td>
</tr>
<tr>
<td>Lateral malleolus ht</td>
<td>75.5 ± 5.7</td>
<td>71.4 ± 3.1*</td>
<td>76.6 ± 5.1</td>
<td>71.2 ± 4.3*</td>
</tr>
<tr>
<td>Medial malleolus ht</td>
<td>88.0 ± 6.6</td>
<td>77.0 ± 7.5*</td>
<td>87.3 ± 7.4</td>
<td>77.0 ± 8.6*</td>
</tr>
</tbody>
</table>

<sup>ht = height</sup>
<sup>* indicates a significant difference between males and females.</sup>

**Foot measurements normalised to foot length**

When foot dimensions, excluding angles, were normalised to foot length and averaged across all foot sizes, women had significantly lower 1<sup>st</sup> and 5<sup>th</sup> toe heights (7.4% and 5.5%, respectively) and a significantly longer medial ball length (1%; p < 0.05) than their male counterparts. The stepwise discriminant function analysis identified first toe height, first toe angle, fifth toe angle, ball of foot height, medial ball length and instep circumference (in order of importance) to be associated with gender (Λ = 0.771; p < 0.001).
Foot problems

Fourteen percent (n = 43) of the participants reported that they suffered from swollen feet and 9% (n = 28) indicated that they had flat feet. Assessment of the participants’ feet revealed that 12% (n = 37) had moderate-to-severe hallux valgus and 25% (n = 78) had a lesser toe deformity. Fifty-four percent of the participants (n = 162) did not display any of these four foot problems and were therefore used as the comparison group. The only foot problem associated with gender was the presence of lesser toe deformity, whereby men had a higher incidence (30%) than women (19.5%; \( \chi^2 = 4.4; p = 0.02 \)). When the foot dimensions were pooled for gender, older individuals who were identified as having moderate-to-severe hallux valgus, lesser toe deformities, swollen or flat feet had significantly different foot anthropometrics compared to those without any foot problems (see Table 3).

Table 3: Foot anthropometrics of the participants with moderate-to-severe hallux valgus (12% of sample), lesser toe deformities (23%), swollen (14%) or flat feet (9%) compared to those without any foot problems.

<table>
<thead>
<tr>
<th>Normalised foot dimension</th>
<th>Hallux valgus</th>
<th>Toe deformity</th>
<th>Swollen feet</th>
<th>Flat feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball girth</td>
<td>↑ 3.4%</td>
<td>0</td>
<td>↑ 2.3%</td>
<td>0</td>
</tr>
<tr>
<td>Instep circumference</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ball width</td>
<td>↑ 6.2%</td>
<td>0</td>
<td>↑ 2.3%</td>
<td>0</td>
</tr>
<tr>
<td>Ball height</td>
<td>↓ 6.0%</td>
<td>↓ 4.9%</td>
<td>0</td>
<td>↓ 6.3%</td>
</tr>
<tr>
<td>Heel width</td>
<td>0</td>
<td>0</td>
<td>↑ 4.6%</td>
<td>0</td>
</tr>
<tr>
<td>Navicular height</td>
<td>↓ 11.4%</td>
<td>↓ 5.1%</td>
<td>↓ 7.7%</td>
<td>↓ 14.1%</td>
</tr>
<tr>
<td>1st toe height</td>
<td>0</td>
<td>↑ 5.2%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5th toe height</td>
<td>0</td>
<td>↑ 6.5%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Instep height</td>
<td>↓ 3.6%</td>
<td>↓ 3.2%</td>
<td>0</td>
<td>↓ 8.5%</td>
</tr>
<tr>
<td>Medial ball length</td>
<td>↑ 1.4%</td>
<td>↑ 1.2%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lateral ball length</td>
<td>↑ 1.8%</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lateral malleolus height</td>
<td>0</td>
<td>0</td>
<td>↓ 4.1%</td>
<td>↓ 4.1%</td>
</tr>
<tr>
<td>Medial malleolus height</td>
<td>0</td>
<td>↓ 4.1%</td>
<td>↓ 6.2%</td>
<td>↓ 8.5%</td>
</tr>
<tr>
<td>1st toe angle</td>
<td>↑ 192%</td>
<td>↑ 60%</td>
<td>↑ 41.6%</td>
<td>↑ 81.8</td>
</tr>
<tr>
<td>5th toe angle</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Heel bone angle</td>
<td>↑ 71.0%</td>
<td>0</td>
<td>0</td>
<td>↑ 92.5%</td>
</tr>
</tbody>
</table>

↑ indicates significantly greater value; ↓ indicates significantly lower value; 0 indicates no significant difference in the values, relative to participants without any foot problems; # absolute angle.
DISCUSSION

Despite the world’s population ageing, this is the first study to comprehensively evaluate the foot shape of older adults living in Australia. Furthermore, it represents one of the largest databases of foot anthropometrics for people aged over 60 years. Although similar measurements have been conducted on 213 Thai men and women aged 60 – 80 years\textsuperscript{2} and 268 Japanese men and women aged 56 – 81 years,\textsuperscript{25} other reported studies investigating foot dimensions of older individuals are scarce. Typically, anthropometric studies have only reported a limited number of dimensions (e.g. length and width), however, many more dimensions are required to accurately describe the three dimensional characteristics of the foot.

Gender differences

Mean foot length of the participants (men = 268.3 ± 13.1 mm; women = 245.7 ± 13.5 mm) were almost identical to those reported by King et al.\textsuperscript{26} for their sample of 90 American adults aged over 60 years (men = 269 ± 13 mm; women = 246 ± 11 mm). The older men in the present study had significantly larger absolute foot dimensions than the older women for all 17 dimensions, with the exception of first toe and heel bone angles. This indicates that the older female foot is generally smaller than her male counterpart, but with increased pronation and hallux valgus angles. Similarly, young men have been found to have greater absolute foot dimensions compared to women for at least 25 different foot measurements characterising the shape of the arch, toes, heel and total foot volume.\textsuperscript{27, 28}

When comparing absolute foot measurements within a common foot length category, females typically displayed smaller width, height and girth measurements, but similar lengths to males, findings that are consistent with gender differences described by Krauss et al.\textsuperscript{24} Similarly, Thai older men have been reported to have a larger foot
width, ball girth, upper ball height, upper arch height, toe depth and ankle height compared to Thai older women of the same foot length. Interestingly, all length, width and girth measurements within the two foot length categories were larger in the men than the women with the exception of the medial ball length. Although not statistically significant, it approached significance in the 257 – 262 mm group ($p = 0.055$) with a mean difference between the genders of 5 mm.

When normalised to foot length and averaged across all foot sizes, men in the present study had significantly higher first and fifth toe heights, whereas women had a significantly longer medial ball length. Similarly, in younger adults, when foot dimensions were normalised to foot length, women have been found to differ in a number of shape characteristics, particularly at the arch, lateral side of the foot, the first toe and ball of the foot. It can be seen that when the foot measurements were normalised and averaged across all the foot sizes it resulted in an alternate indication of gender-related differences in foot shape. This mechanism is known as allometry, whereby foot proportions change according to size.

Medial and lateral ball lengths, as well as foot breadth, are essential in locating the metatarsal joint axis and are therefore important to good shoe fit. The ball lengths determine the ‘flex angle’ across the ball of the foot and should be matched to the ‘flex angle’ of the shoe to allow for maximum foot flexion. Hence, the longer medial ball length exhibited by the older women in this study indicates that the medial side of a women’s shoe should expand for the first metatarsal head at a more distal location than on a men’s shoe of the same length.

**Foot problems**

Individuals in the present study who exhibited moderate-to-severe hallux valgus had a significantly increased ball girth, ball width, medial and lateral ball lengths, heel bone
angle and first toe angle. An increased first toe angle indicates a more lateral deviation of the hallux, which simply confirms the presence of hallux valgus in these older people. Although our finding that older adults with hallux valgus had a broader foot provides further evidence that wearing shoes that are too narrow for the foot may contribute to the development of hallux valgus, the multifactorial aetiology of hallux valgus and the cross-sectional design of the present study limits the conclusion that ill-fitting footwear contributes to the development of the condition. As expected, most of the differences in foot shape were evident in the forefoot region, around the location of the deformity. Therefore, when designing shoes for older individuals with hallux valgus, adjustments should be made to match to the ‘flex angle’ of the forefoot with that of the shoe and to accommodate the extra girth of the forefoot.

Older people in the present study displaying hallux valgus also had a significantly lower ball height, instep height and navicular height than those without hallux valgus. The lower instep and navicular height, as well as the increased heel bone angle, are all indicators of a flatter/pronated foot type. The association between hallux valgus and pes planus has been argued by many authors with some studies showing a relationship between the presence of pes planus and hallux valgus whereas others have reported no significant correlation between these conditions. Our results suggest that a flatter foot type may be associated with moderate-to-severe hallux valgus.

Individuals with lesser toe deformities displayed an increased first and fifth toe height, first toe angle and medial ball length in addition to a decreased ball height, medial malleoli height, navicular height and instep height compared to those without lesser toe deformities. The increased fifth toe height, which was measured at the interphalangeal joint, would be expected in those with a hyperextended metatarsophalangeal joint combined with a flexed proximal interphalangeal joint,
characteristic of lesser toe deformities such as hammer or claw toes. Therefore, footwear for older adults with lesser toe deformities should include increased depth within the toe box to allow room for the increased heights of the first and fifth toes found in these individuals. Increased depth of the toe box could prevent the deformed toes rubbing against the top of the shoe, which is a common cause of callus formation on the top of the interphalangeal joints. In fact, individuals with lesser toe deformities had a significantly higher incidence of dorsal calluses (33%) than those without lesser toe deformities (9%; \( p < 0.001 \)).

The participants who indicated that they suffered from flat feet displayed a significantly lower ball height, navicular height, instep height, lateral and medial malleoli heights, and a significantly larger heel bone and first toe angle compared to those without foot problems. Both the navicular height and instep height (often termed dorsal arch height) have been used to describe the posture of the medial longitudinal arch.\(^ {33} \) Furthermore, the ratio of navicular height-to-foot length has been found to have the highest correlation with radiographic indices of medial longitudinal arch structure.\(^ {34} \) Therefore, the lower navicular and instep heights, normalised to foot length, as measured by the foot scanner, correspond with the diagnosis of flat feet in the individuals in the present study. In addition, the larger heel bone angle indicates a greater medial inclination (pronation) of the calcaneus. Footwear with a firm heel counter may provide greater support and stability for these individuals. Interestingly, it appears that those with flat feet have lower foot structures over the whole sagittal plane of the foot, with the ball and malleoli heights also being significantly lower than those without flat feet.

The reported prevalence of swollen feet ranges from approximately 12% in the general population\(^ {35} \) to 18% in an older population,\(^ {10} \) a similar proportion to that
reported in the current study (14%). Participants in the present study who reported suffering from swollen feet had a different foot shape to those without foot problems. As may be expected, these individuals had a significantly increased ball girth, ball width and heel width, likely due to the excess fluid present in the foot region. These individuals also had significantly lower navicular and malleoli heights than those without swelling. Interestingly, the individuals with swelling also appeared to have a flatter foot (decreased navicular height) and a greater severity of hallux valgus (increased first toe angle).

The larger foot of individuals with swollen feet may result in these individuals being unable to don a shoe, particularly if the swelling is severe. Alternatively, they may be forced to squeeze their foot into a shoe that is too small or wear unstructured, ‘sloppy’ footwear, which may not be safe for older people. Manufacturing shoes using compliant materials is recommended for this group of older individuals as such shoes would be able to stretch around the foot when the foot swells. Furthermore, shoes with a soft sole have been shown to reduce the effects of oedema during prolonged standing and walking. Providing comfortable shoes to older people who suffer from swollen feet may encourage more ambulation which, in turn, would assist with circulation and may be beneficial in reducing the amount of swelling.

It is acknowledged that the present study is cross-sectional in design and the presence of swollen and flat fleet were self-reported. Therefore, we cannot determine whether specific foot shapes have contributed to the development of particular foot problems. Longitudinal studies are therefore recommended to ascertain whether certain foot shapes or the habitual wearing of ill-fitting footwear contributes to the development of foot problems.
CONCLUSIONS

It is evident from the results of the present study that older people with foot problems such as moderate-to-severe hallux valgus, lesser toe deformities and swollen or flat feet exhibit different foot anthropometrics relative to their counterparts without these conditions. As comfortable footwear is vital to protect the older foot and to allow older individuals to ambulate without pain, footwear for older people should be designed to cater for their altered foot morphology, particularly those older individuals with foot problems. Furthermore, the shape of the feet of older men and women differ, with these differences most apparent in the toe region. Shoes for older women and men need to be designed to account for these gender differences in foot shape, particularly with respect to the toe box region of the shoe, which should accommodate the greater first and fifth toe heights and greater fifth toe angle characteristic of men’s feet and the greater first toe angle displayed by women. Characterising the shape of the older foot, as well as factors that can influence older foot morphology, will allow the design of comfortable, well-fitting shoes for older individuals.

REFERENCES


Chapter 5
Soft tissue thickness under the metatarsal heads is reduced in older people with toe deformities

This chapter is an amended version of the manuscript: Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. Soft tissue thickness under the metatarsal heads is reduced in older people with toe deformities. *Journal of Orthopaedic Research.* Accepted November 2010.

**ABSTRACT**

The purpose of this study was to determine whether thickness of the plantar soft tissue under the metatarsal heads differs between older individuals with and without toe deformities. Non-weightbearing total soft tissue and fat pad thickness at the heel, 1<sup>st</sup> metatarsal head (1MTH) and 5<sup>th</sup> metatarsal head (5MTH) were measured using ultrasound in 312 men and women aged over 60 years. Each participant had their feet assessed for the presence of hallux valgus or lesser toe deformities. Total soft tissue and fat pad thicknesses in those with hallux valgus (n = 36) or lesser toe deformities (n = 72) were compared to gender-, age- and BMI-matched controls using independent *t*-tests. Individuals with hallux valgus had significantly reduced total soft tissue thickness under 1MTH compared to controls (7.4 ± 1.6 mm vs. 8.5 ± 1.5 mm; *p* = 0.002). Similarly, individuals with lesser toe deformities displayed significantly reduced total soft tissue thickness under 5MTH compared to controls (5.1 ± 1.0 mm vs. 5.5 ± 1.3 mm; *p* = 0.01). As fat pad thickness did not differ between cases and controls, we speculate that the musculotendinous complex is compromised, and may result in reduced toe function in those with toe deformities.
INTRODUCTION

Atrophy of the plantar soft tissue has been observed in individuals with conditions such as peripheral neuropathy, lesser toe deformity, diabetes, dysvascular feet, pes cavus feet and rheumatoid arthritis.\(^1\)\(^-\)\(^7\) Although many conditions associated with soft tissue atrophy are more prevalent in older adults, it is unknown whether degeneration of the plantar soft tissue is a normal part of the aging process or whether it indicates pathology. For example, the plantar soft tissue of elderly patients with diabetes mellitus has been found to be significantly thinner and stiffer than healthy young adults at the heel, hallux, 1\(^{\text{st}}\) and 2\(^{\text{nd}}\) metatarsal heads.\(^1\) This study, however, included only four participants per subject group, and it is unknown whether the decreased soft tissue was associated with aging, diabetes or both. In one histological study conducted on three young and five elderly cadaveric feet, a thinner fat pad was present in the elderly feet compared to their younger counterparts.\(^3\) However, the older feet were from elderly patients with vascular impairment; therefore, the reduction in fat pad thickness was unlikely to be primarily due to normal aging.

Although the cause of soft tissue atrophy is unclear, alterations in the neurovascular supply to the foot or abnormal foot mechanics have been suggested.\(^3\) It has also been postulated that claw or hammer toes in people with diabetes are associated with a distal displacement of the sub-metatarsal head fat pads.\(^8\)\(^-\)\(^9\) Neuropathic patients with hammer or claw toe deformities have been found to have significantly thinner metatarsal fat pads and thicker phalangeal fat pads than those without toe deformities,\(^2\) suggesting that the metatarsal fat pad is distally displaced in those with toe deformity.\(^2\) Furthermore, these authors found a strong correlation between phalangeal angle and metatarsal fat pad thickness (\(r = 0.85\)), whereby those with severe toe deformity had a thinner or almost absent fat pad below the metatarsal head of the affected toe. As this
study assessed individuals under the age of 65 years, it is unknown whether a similar relationship exists in an older population where toe deformities are more prevalent.\textsuperscript{10}

Despite many anecdotal reports suggesting atrophy of the soft tissue structures under the metatarsal heads in those with toe deformities, there are few quantitative \textit{in vivo} studies to support this notion. Furthermore, particular focus has been directed to those patients also suffering from diabetes\textsuperscript{2, 7, 8, 11} rather than otherwise healthy older adults. In addition, no studies have examined soft tissue thickness in older people with hallux valgus. Therefore, the purpose of this study was to determine whether thickness of the plantar soft tissues in individuals with toe deformities differs from a representative sample of otherwise healthy older adults. It was hypothesised that individuals with hallux valgus and lesser toe deformities would have reduced soft tissue thickness in the medial and lateral plantar regions of the forefoot, respectively. A better understanding of the internal foot structures in those with toe deformities is important to improve interventions for the prevention and treatment of these foot problems in order to reduce the risk of further complications.

METHODS

Participants

One hundred and fifty-eight men and 154 women aged over 60 years, living independently in the community, were randomly recruited from New South Wales, Australia, using methods previously described in detail.\textsuperscript{12} Each participant gave written informed consent after reading the participant information package before any testing commenced. All recruiting and testing procedures were approved by the University of Wollongong Human Research Ethics Committee (HE05/169). A structured questionnaire was used to document the prevalence of medical conditions, foot
problems and foot pain (presence and location). As participants were not recruited on the basis of any pre-existing medical condition or foot problem, this sample was representative of older people living in the community.

**Plantar soft tissue and fat pad thickness**

A portable SonoSite® 180PLUS (Washington, USA) ultrasound system with a 38 mm broadband linear array transducer (10 - 5 MHz, maximum depth 7 cm) was used to measure the thicknesses of the total soft tissue and the plantar fat pad under the heel and the 1st (1MTH) and 5th metatarsal heads (5MTH) of each participant’s foot. Ultrasound has been demonstrated to be a valid method of measuring soft tissue thickness\(^1\), \(^13\) and compared to other imaging techniques, such as radiography and magnetic resonance imaging (MRI), ultrasound was chosen for use in the present investigation due to its non-invasive, non-radiating properties and its portability for use in the field.

Each non-weight bearing ultrasound image was collected with the participant sitting on a chair with their leg extended and foot resting on the lap of the chief investigator [KJM], who took all measurements. This method has been shown to produce reliable measurements\(^14\), \(^15\) and, although ankle angle was not measured, changing ankle angle has not been shown to significantly alter tissue thickness in young or old subjects.\(^1\) A 1 cm thick transparent hydrated polyacrylamide-agar Sonar-Aid® ultrasound coupling pad was placed between the skin and the linear array transducer to optimise image resolution.

A standardised method was then used to measure two thickness values (total soft tissue thickness and fat pad thickness) at three sites (the heel, 1MTH and 5MTH; see Figure 1). Total soft tissue and fat pad thicknesses were measured to characterise the cushioning properties of the heel and the medial and lateral forefoot regions. For the heel site, the transducer was placed longitudinally along a line connecting the 2nd toe.
and the mid heel. Total soft tissue thickness was then measured perpendicularly from the calcaneal tuberosity to the outer layer of skin. The fat pad portion at the same location was also directly measured. For the 1MTH and 5MTH sites, the metatarsal head was identified via the ultrasound image by placing the probe along the longitudinal axis of the 1st and 5th metatarsals, respectively. Plantar soft tissue thickness was then measured between the most prominent part of the relevant metatarsal head and the outer layer of the skin. Thickness of the fat pad was also directly measured, along the same line, perpendicular to the skin. When a clear image was attained, the ultrasound system was paused and thicknesses of the total soft tissue and fat pad were quantified using digital callipers (cm; accuracy = 0.01 cm; see Figure 1). Three measurements were taken for each site and the mean value calculated.

**Figure 1**: Ultrasound image showing total soft tissue (ST) and fat pad (FP) thickness measurements relative to the 1st metatarsal head (MTH).

**Assessment of toe deformities and peripheral neuropathy status**

The presence and severity of hallux valgus was assessed for each participant by the chief investigator [KJM] using the Manchester Scale. Each foot was compared to a set of standardised photographs and assigned a hallux valgus rating of none, mild, moderate or severe. Grading of hallux valgus deformity using the Manchester Scale is
highly correlated with hallux abductus angle, sesamoid position and presence of osteoarthritis obtained from radiographs.\textsuperscript{21, 22} For the purpose of this analysis, hallux valgus severity was collapsed into two groups: none-to-mild (no hallux valgus) and moderate-to-severe (hallux valgus present). The chief investigator also examined each participant’s feet and noted whether any lesser toe deformities, such as claw or hammer toes, were present or absent. Flexor strength of the hallux and lesser toes were also measured using methods described in detail elsewhere.\textsuperscript{12}

Due to the potential confounding effect of peripheral neuropathy, pressure threshold sensation on the plantar surface of the foot was assessed on all participants using five Semmes-Weinstein monofilaments (Sorri-Bauru, Brazil) in a modified single-step algorithm, which incorporated three turnabouts.\textsuperscript{23} This procedure was implemented at the heel, midfoot, 1MTH, 5MTH, hallux and the lateral malleolus of each participant. The number of sites on the foot that could correctly identify the 5.07 monofilament were summed to determine peripheral neuropathy status. Participants who scored $\leq 3$ were classified as having peripheral neuropathy.\textsuperscript{24}

Statistical analysis

Prior to data collection, a power analysis was conducted to determine the appropriate sample size for the study. Based on data from previous population studies,\textsuperscript{25-29} we estimated that a sample size of 300 would allow for a minimum of 10 outcome cases per variable entered into the multivariate models,\textsuperscript{30} which were required for other aspects of this study. Participants with moderate-to-severe hallux valgus ($n = 36$) and lesser toe deformities ($n = 72$) were compared to an equal number of (in order of importance) gender-, age- and BMI-matched controls (see Table 1), who did not have any toe deformities, using independent $t$-tests in order to determine whether tissue thickness
differed as a function of toe deformities. An alpha level of \( p < 0.05 \) was established for all statistical analyses.

**Table 1:** Characteristics of participants with moderate-to-severe hallux valgus, lesser toe deformities and controls.

<table>
<thead>
<tr>
<th></th>
<th>Hallux valgus ( (n = 36) )</th>
<th>Control ( (n = 36) )</th>
<th>Lesser toe deformity ( (n = 72) )</th>
<th>Control ( (n = 72) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>71.9 ± 6.7</td>
<td>71.9 ± 6.6</td>
<td>73.2 ± 6.9</td>
<td>73.1 ± 6.9</td>
</tr>
<tr>
<td>Gender (M:F)</td>
<td>17:19</td>
<td>17:19</td>
<td>42:30</td>
<td>42:30</td>
</tr>
<tr>
<td>BMI (kg.m(^{-2}))</td>
<td>27.6 ± 4.4</td>
<td>27.6 ± 3.7</td>
<td>28.8 ± 5.7</td>
<td>28.4 ± 5.2</td>
</tr>
<tr>
<td>Foot pain (%)</td>
<td>42</td>
<td>44</td>
<td>60</td>
<td>47</td>
</tr>
<tr>
<td>Plantar calluses (%)</td>
<td>39</td>
<td>28</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>PN (n)</td>
<td>8</td>
<td>9</td>
<td>25</td>
<td>21</td>
</tr>
<tr>
<td>Diabetes (n)</td>
<td>3</td>
<td>4</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>RA (n)</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

PN = peripheral neuropathy; RA = rheumatoid arthritis

**RESULTS**

Medical conditions that may have influenced soft tissue properties such as diabetes, rheumatoid arthritis and peripheral neuropathy were slightly more common in the lesser toe deformity group, but the prevalence did not significantly differ to the control group \( (p > 0.05) \); see Table 1). Individuals with moderate-to-severe hallux valgus had significantly reduced total soft tissue thickness under 1MTH compared to controls \( (p = 0.002) \); see Figure 2). Similarly, individuals with lesser toe deformities displayed significantly reduced soft tissue thickness under 5MTH compared to controls \( (p = 0.01) \); see Figure 3). However, there were no differences in fat pad thicknesses between individuals with hallux valgus or lesser toe deformities and controls at either 1MTH or 5MTH \( (p > 0.05) \). Similarly, no differences in total soft tissue or fat pad thicknesses were noted at the heel between any of the participant groups \( (p > 0.05) \).

Foot pain was reported by 50% of the total sample \( (n = 312) \), with the forefoot/toe region being the most reported location of this foot pain (42%). Compared
to those who did not suffer forefoot pain, forefoot pain was associated with reduced total soft tissue thickness under the 1MTH \( (p = 0.004) \). This association was not evident at any other location under the foot. In addition, a significant correlation was found between hallux strength and total soft tissue thickness at the 1MTH \( (r = 0.26; p < 0.001) \) and lesser toe flexor strength and total soft tissue thickness at the 5MTH \( (r = 0.18; p < 0.001) \) in the total sample.

**Figure 2:** Total soft tissue (ST) and fat pad (FP) thickness across the plantar surface of the foot in those with moderate-to-severe hallux valgus compared to age-, gender- and BMI-matched controls. (* indicates a significant difference between the two groups. 1MTH = 1st metatarsal head; 5MTH = 5th metatarsal head).

**Figure 3:** Total soft tissue (ST) and fat pad (FP) thickness across the plantar surface of the foot in those with lesser toe deformities compared to age-, gender- and BMI-matched controls. (* indicates a significant difference between the two groups. 1MTH = 1st metatarsal head; 5MTH = 5th metatarsal head).
DISCUSSION

This is the first population-based study to measure plantar soft tissue thickness in older individuals. The average total soft tissue thickness at the heel (12.4 ± 3.0 mm) for the older men and women in this study was similar to heel pad thickness values reported for young healthy adults (between 13 and 18 mm).\textsuperscript{1, 4, 31-33} The average total soft tissue thickness at the 1MTH (8.3 ± 1.7 mm) and 5MTH (5.3 ± 1.1 mm) were also comparable to the ranges reported in previous studies (1MTH = 6.5 – 14.5 mm; 5MTH = 5.1 – 11.5)\textsuperscript{4, 7, 19, 34, 35} for the soft tissue under the metatarsal heads of healthy adults and people with diabetes. The wide range of values reflects differences in methodologies between studies, in particular, the weight-bearing status at the time of measurement, whereby the soft tissue is compressed during weight-bearing. The toe deformity groups contained a similar proportion of participants who had plantar calluses as the controls (see Table 1); therefore the presence of calluses is an unlikely contributor to the decreased total soft tissue displayed by the toe deformity groups.

As hypothesised, individuals with hallux valgus and lesser toe deformities displayed reduced total soft tissue thickness under 1MTH and 5MTH, respectively. Interestingly, the total soft tissue thickness was reduced and not the thickness of the fat pad layer. These findings are in contrast to those reported by Bus et al.\textsuperscript{2} who reported that individuals with diabetic neuropathy and lesser toe deformities had reduced fat pad thickness under the 2\textsuperscript{nd} and 3\textsuperscript{rd} metatarsal heads compared to healthy controls without toe deformities (2.5 ± 1.3 mm vs. 6.0 ± 1.3 mm). However, Bus et al.\textsuperscript{2} only examined 13 individuals in each participant group and did not include individuals with lesser toe deformities without diabetic neuropathy, and no measurement was taken of the thickness of the fat pad on the lateral plantar region of the forefoot. Therefore, it is difficult to conclude whether lesser toe deformities alone were the mechanism behind
distal displacement of the metatarsal fat pads, or whether the combination of toe deformity and diabetes/neuropathy altered the plantar tissue properties. The study cohort was also younger than that in the present study (mean age = 56.2 years; age > 65 years excluded), and therefore the effects of ageing on the plantar tissues may also influence between-study differences. Furthermore, individuals with toe deformities in the current study were similar to controls in relation to the prevalence of major medical conditions (see Table 1). However, it must also be acknowledged that major methodological differences exist between these two studies, whereby fat pad thickness was measured from MRI in the Bus et al. study.

Although not specifically investigating toe deformities, Robertson et al.\textsuperscript{34} correlated metatarsophalangeal joint angle (an indication of severity of toe deformity) and soft tissue thickness beneath the metatarsal heads, reporting no relationship between these two variables (r = 0.05). However, this study included only 32 subjects, half of whom reported a history of plantar ulceration, which is likely to compromise soft tissue properties. Interestingly, when Robertson et al.\textsuperscript{34} conducted a sub-analysis of the control subjects, a stronger correlation (r = -0.24) was found whereby an increased joint angle was weakly associated with decreased soft tissue thickness under the metatarsal heads. Although a possible lack of statistical power due to low subject numbers (n = 16) may have prevented a statistically significant correlation, it supports the findings of the present study. It is acknowledged that, while the dichotomous classification of lesser toe deformity used in our study may oversimplify the pathology, this method allowed us to assess the prevalence of toe deformities in a large cohort of older people, as measuring the severity of the deformity via x-ray or MRI was not appropriate due to radiation exposure and cost of the procedure, respectively. Another limitation of previous research in this field is that investigators typically only report a single tissue
thickness value, and have not clarified which component of the soft tissue they have measured under the metatarsal heads. Our study has addressed this limitation by measuring both the total soft tissue and fat pad components under the metatarsal heads of older individuals and no participant had a history of plantar ulceration. We acknowledge that a limitation of this study is that the soft tissue under the 2nd, 3rd and 4th metatarsal heads was not measured in order to minimise subject burden. Quantification of the total soft tissue and fat pad thickness under all metatarsal heads in older adults with and without foot pathologies is therefore warranted.

Individuals with moderate-to-severe hallux valgus and lesser toe deformities in the present study had significantly less soft tissue under the 1MTH and 5MTH, respectively, compared to those without toe deformities. Reduced tissue thickness is likely to lead to increased plantar pressures and foot pain, due to a loss of the foot’s cushioning properties. Indeed, reduced soft tissue under the metatarsal heads has previously been reported to be associated with increased peak plantar pressures. Furthermore, given the association between reduced total soft tissue thickness under the 1MTH and forefoot pain found in this study, measurement of the total soft tissue thickness underneath the metatarsal heads may be useful when designing custom-made orthotics or insoles for patients with toe deformities or foot pain, by highlighting those regions of the foot that require additional cushioning.

As the thickness of the fat pad layer did not differ between the participant groups, the decrease in total soft tissue thickness may be due to atrophy of the toe flexors resulting in a reduction in the tendinous component of the tissue. Although the muscle bellies of the primary lesser toe flexors, flexor digitorum longus and quadratus plantae, are just proximal to the metatarsal heads, the tendons of flexor digitorum longus cross the metatarsophalangeal joints. In addition, the plantar aponeurosis,
which assists in the mechanical pull of the hallux and toes, spans the length of the plantar surface of the foot, crossing the metatarsophalangeal joints before inserting into the base of the proximal phalanges. The tendon of the abductor hallucis, which assists in hallux flexion, passes over the 1MTH to insert into the base of the proximal phalanx of the hallux. Also attaching at the base of the proximal phalanx are the two bellies of the flexor hallucis brevis and the adductor hallucis muscle tendons. The thickness of the tendinous component of the soft tissue may therefore be a reflection of how ‘healthy’ these structures are. For example, the physical properties of the proteoglycans within the tendons are dictated by their ability to attract water molecules in the tissue, which in turn, contributes to the tissue’s compressive properties and viscoelastic behavior. The amount of proteoglycan in tendons are affected by factors such as age and history of mechanical loading. As the tissues under the metatarsal heads undergo high frictional and compressive forces, the proteoglycan component of the tendons that cross the metatarsal heads would be important to maintain tendon integrity. Therefore, reduced thickness of the tendon under the metatarsal heads may be an indication of altered tendon properties such as a reduction in proteoglycan content, which would make the tendon appear less full and rounded in form. It is therefore possible that structural alterations of the tendons that cross the metatarsal heads reduce their functional ability to transmit muscle forces to the toes.

This speculation may explain previous findings in which older people with hallux valgus and lesser toe deformities displayed significantly reduced toe flexor strength of the hallux and lesser toes, respectively, compared to those without these foot deformities. This suggestion is supported by the significant, albeit weak-to-moderate, correlation found between hallux strength and total soft tissue thickness at the 1MTH and lesser toe flexor strength and total soft tissue thickness at the 5MTH in the complete
sample. This may have important consequences, as weakness of the toe flexor muscles will reduce the capacity of the toes to perform their normal function and potentially interfere with walking ability and balance. Indeed, we have shown that that older people who fall are more likely to have hallux valgus, lesser toe deformity and reduced toe flexor strength than non-fallers, and a more recent study reported that fallers (self-reported fall in previous year) with diabetes mellitus had a higher prevalence of prominent metatarsal heads than non-fallers. Further research is therefore warranted to determine whether atrophy/health of the soft tissue under the metatarsal heads can be reversed, perhaps through physical training of the toe muscles.

In conclusion, individuals with hallux valgus and lesser toe deformities display reduced soft tissue under 1MTH and 5MTH, respectively. As the thickness of the fat pad was not affected, we speculate that the thinner soft tissue represents atrophy of the musculotendinous structures of the forefoot, in particular the intrinsic toe flexor muscles. These findings may partly explain why individuals with hallux valgus and lesser toe deformities have decreased strength of the hallux and lesser toe flexor muscles, respectively. Therefore, interventions designed to increase toe flexor muscle strength may benefit older people with toe deformities.

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Chapter 6

Gait, balance and plantar pressures in older people with toe deformities

This chapter is an amended version of the manuscript: Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. Gait, balance and plantar pressures in older people with toe deformities. Gait and Posture. Submitted October 2010.

ABSTRACT

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

The ability to walk safely and efficiently is vital for older people in order to reduce the risk of falling and to maintain independence.\textsuperscript{1} Despite many age-related changes in gait biomechanics being well documented,\textsuperscript{2, 3} few studies have investigated the relationship between foot problems and foot function. The presence of lesser toe deformities and the severity of hallux valgus has been shown to have weak-to-moderate relationships with balance and functional test scores in older retirement village residents,\textsuperscript{4} suggesting that toe deformities may contribute to a decline in functional mobility. Our recent research has also found that older people with moderate-to-severe hallux valgus and lesser toe deformities were at a greater risk of falling than older people without these deformities.\textsuperscript{5}

We speculate that these toe deformities compromise foot function and reduce sensory input, leading to mechanical instability which, in turn, affects stability during the weight-bearing and push-off phases of gait, or when in situations requiring corrective steps to maintain balance. This notion, however, has not been systematically investigated.

Despite the important contribution of the toes to normal foot function, there is a lack of literature describing the biomechanical changes to foot function that occur in older adults with toe deformities. Studies investigating hallux valgus deformity are more frequent, although inconsistent findings have been reported. Individuals with hallux valgus deformity generate less force under their hallux\textsuperscript{6} and transfer load, as evidenced by increased plantar pressures, to either the central,\textsuperscript{6} lateral\textsuperscript{7} or the 1\textsuperscript{st} to 3\textsuperscript{rd} metatarsals.\textsuperscript{8} The presence of hammer or claw toes has been related to lower hallux pressures but higher metatarsal pressures.\textsuperscript{9, 10} Diabetic patients with claw or hammer toe deformities have been found to generate higher peak pressures and pressure-time integrals under the metatarsals than age- and gender-matched diabetic patients without
toe deformities. Similarly, an increased metatarsophalangeal joint angle, indicative of hammer/claw toe deformity, has been significantly associated with increased plantar pressures under the hallux and metatarsal heads in a sample of 20 people with diabetes. Although the previous research has been predominantly focussed on toe deformities in diabetic patients, these studies suggest that toe deformities affect loading of the foot. Therefore, it could be anticipated that gait and balance would also be affected by the presence of toe deformities.

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

METHODS

Participants

Three hundred and twelve men and women aged over 60 years were randomly selected as study participants. Details regarding the recruitment procedures have been reported in detail elsewhere. Briefly, all participants were independently living and ambulatory (with or without assistive devices), but were excluded if they had neurological diseases or cognitive impairment. Each participant gave written informed consent after reading the participant information package before any testing procedures began. All recruiting and testing procedures were approved by the University of Wollongong Human Research Ethics Committee (HE05/169).
Physical assessments

Each participant’s height was measured to the nearest 0.1 cm using a portable stadiometer and their mass was measured to the nearest 0.05 kg using electronic scales with their shoes, socks and any heavy outer clothing removed. The chief investigator [KJM] examined each participant’s feet and recorded the presence of calluses, hallux valgus and lesser toe deformities, such as claw or hammer toes, using methods described elsewhere.5,12

Gait

Spatiotemporal gait characteristics were measured using the GAITRite® system (CIR Systems, Inc, USA; 80 Hz), a portable carpet walkway (5.1 x 0.89 m; active = 4.2 x 0.6 m) embedded with pressure sensors. Participants were instructed to “walk at a comfortable pace, as if you were walking down the street”. Each subject completed 10 to 15 trials, with 4 to 9 steps taken to traverse the mat. Walking speed (m.s⁻¹), step and stride length (m), step width (cm), swing phase, stance phase and double support duration (% gait cycle) and angle of toe in/out (°) were registered by the GAITRite® system. Within-subject means and standard deviations of each variable were calculated.

Postural sway

Postural sway was measured using a sway meter attached to participants at waist level.13 The sway meter traced any body movements onto a piece of graph paper (1 mm² divisions) secured to a height-adjustable table. The participant was instructed to stand as still as possible for 30 s with eyes open, then closed and to repeat the tests while standing on a 15 cm thick piece of foam. Not all participants were able to complete 30 s on the foam with their eyes closed, therefore only the eyes open conditions were analysed. The total number of 1 mm squares traversed by the pen was counted. This
test has been found to correlate well with centre-of-pressure movement measured using a force-plate.\textsuperscript{14}

\textit{Plantar pressures}

Barefoot plantar pressure distributions were measured by an emed-AT4 pressure plate (Novel\textsubscript{GmbH}, Munich, Germany; 25 Hz) using the 2-step protocol and methodology described elsewhere.\textsuperscript{15} The dynamic plantar pressure footprints generated by each participant were divided into 10 masks (Novel-ortho Automask software, Novel\textsubscript{gmbh}, Munich), based around the following anatomical landmarks: heel (M01), midfoot (M02), 1\textsuperscript{st} metatarsal (M03), 2\textsuperscript{nd} metatarsal (M04), 3\textsuperscript{rd} metatarsal (M05), 4\textsuperscript{th} metatarsal (M06), 5\textsuperscript{th} metatarsal (M07), hallux (M08), 2\textsuperscript{nd} toe (M09) and toes 3-5 (M10) (see Figure 1). The mean peak pressure footprints were then analysed to determine the peak pressure (kPa) and pressure-time integral (kPa.s) across the total foot and in each of the masked areas.

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

Each participant completed the 36-Item Short Form Health Survey (SF-36)\(^{16}\) as an indication of health-related quality of life.\(^{17}\) The answers to the 36 items were numerically coded and then added together to give a total SF-36 score out of 100, with lower scores indicating poorer health.

Statistical analysis

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

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

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

RESULTS

Compared to the controls, participants who presented with moderate-to-severe hallux valgus and lesser toe deformities displayed similar spatiotemporal gait and postural sway characteristics (\(p > 0.05\); see Table 2), with the exception of an increased walking speed variability in the lesser toe deformity group (\(p = 0.03\)). In addition, the total SF-
36 score did not differ between the participant groups ($p > 0.2$; see Table 1), indicating similar health status.

**Table 2:** Biomechanical foot function variables for participants with hallux valgus (HV), lesser toe deformities (LTD) and controls. All between group comparisons exhibited $p > 0.05$, except walking speed variability between the lesser toe deformity and control groups.

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

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

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

**Figure 3:** Mean (± SD) pressure-time integrals generated by the hallux valgus (HV), lesser toe deformity (LTD) and control groups under each metatarsal, the hallux, 2nd toe and toes 3-5. (* indicates a significant difference between the HV group and their matched controls. # indicates a significant difference between the LTD group and their matched controls).
Individuals with lesser toe deformities walked with similar contact times to controls (866.0 ± 143.5 ms vs. 842.8 ± 96.4 ms; \( p = 0.3 \)). However, the individuals with lesser toe deformities generated a significantly higher total peak pressure and total pressure-time integral compared to their control group (peak pressure = 839.1 ± 246.6 kPa vs. 670.0 ± 245.7 kPa; pressure-time integral = 373.8 ± 134.5 kPa.s vs. 307.4 ± 110.2 kPa.s; \( p \leq 0.001 \)). Additionally, those with lesser toe deformities displayed a significantly increased peak pressure and pressure-time integral under the 2\textsuperscript{nd} and 3\textsuperscript{rd} metatarsals, 2\textsuperscript{nd} toe and toes 3-5 in comparison to the control group (\( p \leq 0.037 \); see Figures 2 and 3). As the toe deformity groups contained a similar proportion of participants who had plantar calluses as the control groups (see Table 1), the presence of calluses is an unlikely contributor to the higher pressures displayed by the toe deformity groups.

**DISCUSSION**

In general, participants with hallux valgus and lesser toe deformities did not display significantly different spatiotemporal gait characteristics, or increased gait variability, compared to those without toe deformities. The only exception was seen in the lesser toe deformity group, whereby they displayed increased walking speed variability compared to the control group. As specific spatiotemporal gait characteristics, such as slow walking speed, short step length, increased step width and increased time spent in stance and double support, have been associated with increased risk of falling,\(^{18}\) it was expected that those with toe deformities may display some of these gait adaptations. Furthermore, gait variability has been suggested as a marker for poor balance control and has also been found to predict falls in older people.\(^{19,20}\) Although no study was located that had investigated whether the presence of toe deformities may be a
contributing factor to increased gait variability, this study suggests that gait variability, in general, is not affected by toe deformities.

The lack of difference in spatiotemporal gait characteristics between the participant groups is consistent with the results of Deschamps et al.,\textsuperscript{21} who found that patients with hallux valgus spent a similar amount of time in the swing and stance phases of the gait cycle as those without hallux valgus. As between-group differences in plantar pressures were shown, it is proposed that kinematic variables characterising joint motion rather than spatiotemporal gait characteristics may be more relevant indicators of gait disturbance in people with toe deformities. This notion is supported by the results of Deschamps et al.,\textsuperscript{22} who found that patients with hallux valgus had decreased plantar flexion motion of the hallux during terminal stance compared to controls. Although Deschamps et al.\textsuperscript{22} did not find any difference in sagittal plane motion at the ankle, the hallux valgus group showed a small, but statistically significant, increase in hindfoot eversion at terminal stance, indicating a less stable foot.\textsuperscript{22} Menz and Lord\textsuperscript{23} found that the vertical plane acceleration of the head and pelvis was affected by hallux valgus when participants walked on an irregular surface, indicating decreased gait stability compared to individuals without hallux valgus. As this difference between the hallux valgus groups was only evident on the irregular surface and not on a level surface, it suggests that hallux valgus may contribute to gait instability when walking on irregular/uneven surfaces and is consistent with the lack of difference in spatiotemporal gait parameters in the current study.

It has been suggested that individuals with claw or hammer toes may exhibit exaggerated postural sway due to reduced foot contact area, resulting in a reduced geometrical base of support.\textsuperscript{24} In addition, the reduced ability of the toes to assist in controlling horizontal projections of the body’s centre of mass is thought to reduce the
functional base of support in people with toe deformities. 24 In contrast, individuals with hallux valgus or lesser toe deformities in this study displayed similar postural sway scores as those without toe deformities. Menz and Lord 25 also reported no impairment of performance in the same postural sway tests in older people with lesser toe deformities or severe hallux valgus. They found that these foot problems were more likely to be detrimental on tests of co-ordinated stability and functional performances such as stair ascent and descent rather than static balance tests. Therefore, the presence of toe deformities does not appear to significantly affect standing balance, but may impede normal foot function during locomotion or tasks with more demanding postural requirements.

The hallux and 1st metatarsophalangeal joint play a major role in weight transference across the foot during gait. 26 Several authors have demonstrated altered plantar pressure patterns in adults with hallux valgus compared to asymptomatic individuals, 6, 21, 26 but with conflicting results. For example, higher hallux peak pressure has been observed with hallux valgus deformity 9, as well as a negative correlation between increasing hallux valgus angle and peak pressure under the hallux. 10 Our findings of similar pressure patterns under the hallux in those with hallux valgus and those with no deformity are in agreement with Kernozek et al. 6 who suggested that the functional loading capacity of the hallux has not been altered during straight line walking. Depending upon the region classification, it has been suggested that there is increased pressure under the 1st to 3rd metatarsals 8 whereas other studies have reported an increased load over the central 6, 21 or lateral metatarsals 7 in those with hallux valgus. Our study found that older people displaying moderate-to-severe hallux valgus generated a significantly higher peak pressure and pressure-time integral under the 1st and 2nd metatarsals compared to those without hallux valgus. This supports the results
of Mueller and colleagues\textsuperscript{10} who showed that greater hallux valgus severity was correlated with higher pressure under the 1\textsuperscript{st} metatarsal.\textsuperscript{10} The inverse relationship between soft tissue thickness and plantar pressures\textsuperscript{27} is a likely contributor to the higher peak pressure experienced under the 1\textsuperscript{st} metatarsal in those with hallux valgus.

Participants in our study with lesser toe deformities displayed a significantly higher peak pressure and pressure-time integral under the 2\textsuperscript{nd} and 3\textsuperscript{rd} metatarsals compared to controls. Similarly, Bus et al.\textsuperscript{11} reported that diabetics with claw or hammer toe deformities generated significantly higher peak pressures and pressure-time integrals at the central metatarsals (2\textsuperscript{nd}, 3\textsuperscript{rd} and 4\textsuperscript{th}) than age- and gender-matched diabetic patients without toe deformities. Bus et al.\textsuperscript{11} suggested that distal displacement of the metatarsal fat pad was the primary mechanism behind the association between increased metatarsal pressure and toe deformity.

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

Individuals with hallux valgus and lesser toe deformities have reported significantly greater levels of pain during walking than those without the deformity.\textsuperscript{6, 28} It has been suggested that mechanical stress, which can be represented by high pressures experienced over longer durations (peak pressure and pressure-time integral) is associated with the development of foot pain.\textsuperscript{26, 29} In fact, our previous research
supports this theory whereby older individuals with foot pain displayed significantly higher peak pressure and pressure-time integrals compared to those without foot pain.\textsuperscript{15}

It must be acknowledged that in order to compare the foot function of those participants in the present study with toe deformities to those without, only the right foot was used to satisfy the statistical assumption of data independence. Therefore, individuals who had unilateral left foot toe deformities were not included in the prevalence rate. However, the strength of this study design was the matching of toe deformity groups to controls based upon age, gender and BMI. This eliminated these factors as potential confounders on the biomechanical variables, as they have been found to be associated with differences in postural sway, gait and plantar pressures.\textsuperscript{24, 30} This may also explain the lack of differences identified for most variables between the toe deformity groups and controls.

**CONCLUSIONS**

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


Chapter 7

Foot characteristics, functional ability and health-related quality of life in older people with disabling foot pain

This chapter is an amended version of the manuscript: Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. Foot characteristics, functional ability and health-related quality of life in older people with disabling foot pain. *Journal of the American Geriatrics Society*. Submitted November 2010.

ABSTRACT

**Objectives:** To evaluate foot characteristics, functional ability and health-related quality of life in older people with disabling foot pain.

**Design:** Community-based survey.

**Setting:** Sydney and Illawarra statistical regions of New South Wales, Australia.

**Participants:** Randomly recruited, community-dwelling older adults (158 men and 154 women) aged over 60 years.

**Measurements:** Manchester Foot Pain and Disability Index to establish presence of foot pain; SF-36 as a measure of health-related quality of life (HRQoL); postural sway on a firm and compliant surface; and ankle dorsiflexion strength, ankle dorsiflexion flexibility, foot reaction time, hallux and lesser toe flexor strength and spatiotemporal gait parameters to characterise foot function. Participants with disabling foot pain were then compared to those without pain, controlling for gender and body mass index.

**Results:** Participants with foot pain scored significantly lower on the total SF-36 and all sub-components. Ankle dorsiflexion strength, hallux strength, stride length, step length and walking speed were significantly reduced in those with foot pain. After applying a
more conservative cut-off for disabling foot pain, reduced toe flexor strength, increased foot reaction time, increased postural sway and reduced time spent in single support during walking, emerged as additional characteristics of those with disabling foot pain.

**Conclusions:** Older people with disabling foot pain exhibit reduced HRQoL, functional impairment and alterations to foot characteristics that may contribute to an increased risk of falling. Providing interventions to older people that treat foot pain and improve foot function may play a role in reducing fall risk and improving quality of life.

**INTRODUCTION**

Foot pain has been defined as an unpleasant sensory and emotional experience preceding perceived damage to the area distal to the tibia and fibula, and has been attributed to direct trauma, musculoskeletal overload, infection or systematic or proximal pathology. Foot pain has been found to be present in up to 60% of the older population with the prevalence of foot/ankle pain increasing with age, reaching a peak in those aged 75 years and over. Factors associated with foot pain include being female, obesity, pes planus foot type, wearing ill-fitting shoes, sensory impairment, pain in the back, hips, knees and hands or wrists and depression. For those who suffer foot pain, it has been most frequently reported to occur when walking, with studies reporting that up to 80% of people with foot pain have walking difficulty. Furthermore, older adults with foot pain have a higher prevalence of reported inability to carry out activities of daily living than those without foot pain and hence, have a reduced health-related quality of life.

Reduced functional capacity can be observed in the gait characteristics of individuals with foot pain, whereby they typically reduce their walking speed and...
take more steps to complete a walking task than those without foot pain. Of greater consequence, our recent research identified that community-dwelling older adults with foot pain are at a greater risk of falling, substantiating foot pain as a fall risk factor as previously reported in older disabled women and older retirement village residents. Despite the growing evidence that foot pain is a fall risk factor for older people, the mechanisms behind the association between foot pain and falls are poorly understood.

One of the major barriers to investigating factors associated with foot pain has been the lack of validated foot-specific outcome measures to assess self-reported foot pain and related disability. The Manchester Foot Pain and Disability Index has been validated as a suitable instrument for assessing the impact of painful foot conditions in both clinical and community populations and, as such, is becoming a widely used tool for epidemiological studies. However, classifying individuals with disabling foot pain using the criteria of a minimum of one item experienced only on ‘some days’ has the potential to include people with relatively mild symptoms and may not be able to discriminate beyond the presence of foot pain in older people where foot pain is highly prevalent and symptoms vary considerably. This consideration has recently prompted the suggestion of using an alternate definition of disabling foot pain, where at least one item of the Manchester Foot Pain and Disability Index is scored as ‘most/every day(s)’.

To date, no study has investigated whether the two above definitions of disabling foot pain are associated with objective measures of foot function and functional ability. Therefore, the purpose of this study was to determine whether disabling foot pain, using two different definitions, is associated with changes in foot characteristics, which may impair functional ability and health-related quality of life in older adults. Examining foot characteristics, gait and balance in these individuals will
improve our understanding of movement control in this group and assist in better targeting of falls prevention interventions.

METHODS

Participants
One hundred and fifty-eight men and 154 women aged over 60 years, living independently in the community, were randomly recruited from New South Wales, Australia, using methods previously described in detail. Each participant gave written informed consent after reading the participant information package before any testing commenced. All recruiting and testing procedures were approved by the University of Wollongong Human Research Ethics Committee (HE05/169).

Foot pain and health status
Foot pain was assessed using the 19-item Manchester Foot Pain and Disability Index (MFPDI). The questionnaire assesses foot-related problems across four constructs: functional limitation (10 items), pain intensity (5 items), personal appearance (2 items) and limitation in work or leisure activities (2 items). The last two items were omitted from this study as the participants were of retirement age. Participants responded to each item as occurring ‘none of the time’, ‘on some days’ or ‘on most days’. Two definitions were then used to classify participants with foot pain throughout the analyses: Definition A – at least one item scored at ‘some days’ or ‘most/every day(s)’; Definition B – at least one item scored at ‘most/every day(s)’. Each participant also completed the 36-Item Short Form Health Survey (SF-36), which consists of 36 closed questions comprising eight health concepts (physical functioning, role - physical, social functioning, mental health, role - mental, general health perceptions, body pain and vitality). Health-related quality of life is an
important measure of how an individual is impacted by disease or abnormality. The answers to the 36 items were numerically coded and combined to give scores for each concept and a total SF-36 score out of 100, with a lower score indicating poorer health.

*Postural sway*

Postural sway was measured using a sway meter attached at waist level on each of the participants.\(^\text{27}\) The sway meter traced any body movements onto a piece of graph paper (divided into 1 mm squares) secured to a height-adjustable table. The participant was instructed to stand as still as possible for 30 s (with eyes open) while standing on the floor and then standing on a standardised piece of 15 cm thick foam and the total number of 1 mm squares traversed by the pen was counted. This test has been found to strongly correlate with centre of pressure movement measured on a force platform.\(^\text{28}\)

*Foot function characteristics*

Isometric ankle dorsiflexion strength and ankle dorsiflexion flexibility were measured using a pivoted metal platform with a spring balance attached and a modified lunge test, respectively. Both tests have been found to be reliable for use in older adults.\(^\text{29}\) The maximum force generated over three trials was recorded as the measure of dorsiflexion strength, whereas the minimum angle (i.e. the greatest range) measured by the goniometer of three trials was used to represent ankle dorsiflexion flexibility.\(^\text{30}\) Hallux and lesser toe flexor strength were assessed using an emed AT-4 pressure platform and novel test protocol that we developed, which is described in detail elsewhere.\(^\text{24}\)

Reaction time (ms) was assessed using a hand-held electronic timer (Balance Systems, Australia) with a light as the stimulus and depression of a pedal by the foot as the response.\(^\text{28}\) The supra-threshold light stimulus was located on the foot pedal and the timer had a variable delay of 1 - 5 s to remove any cues that could be gained from the
test administrator commencing each trial by pressing the “start” button. Five practice trials were undertaken followed by 10 experimental trials.

The spatial and temporal characteristics of each participant’s gait were measured using a GAITRite® mat (CIR Systems, Inc, USA; 80 Hz), a portable carpet walkway (5.1 x 0.89 m; active = 4.2 x 0.6 m) embedded with pressure sensors (16,128 x 1 cm² sensors). The GAITRite® system has been shown to have concurrent validity relative to other gait systems³¹-³³ and have strong test-retest reliability in adults.³¹ Participants were instructed to “walk along the mat at a comfortable pace, as if you were walking down the street”. Each subject completed 10 - 15 walking trials, with 4 - 9 steps taken to traverse the mat. Walking speed (m.s⁻¹), step and stride length (m), step width (cm), swing phase, stance phase and double support duration (% gait cycle) and angle of toe in/out (°) were registered by the GAITRite system®. Within-subject means and standard deviations of each variable were calculated.

Statistical analysis

Analysis of covariance tests were used to determine whether there were any significant differences in the SF-36 scores, foot function or postural sway variables in those participants reporting foot pain compared to those without foot pain, with gender and body mass index (BMI; kg.m⁻²) entered as covariates. A series of chi-square tests were also conducted on each item on the MFPDI to compare the frequency of responses between the two foot pain definitions. An alpha of $p \leq 0.05$ was established for all statistical analyses, which were conducted using SPSS software (SPSS 17 for Windows).
RESULTS

Foot pain was present in 49.7% of participants using Definition A and 26% of participants using Definition B. Regardless of definition, women had a significantly higher prevalence of foot pain than men (58.7% and 59.3% using Definition A and B respectively), and participants with foot pain had a significantly higher BMI (see Table 1), justifying including gender and BMI as covariates in further analyses. Using Definition A, obese participants (BMI > 30) were more likely to report foot pain (63%) than those who were overweight (43%) or in the normal weight range (43%; $p < 0.01$). Among those with foot pain, only 68% had visited a health professional about their feet. Those indicating disabling foot pain using Definition B were more likely to have visited a health professional about their feet (79%).

Participants with foot pain, using both definitions, scored significantly lower on the total SF-36 and all sub-components (see Table 2). Participants with foot pain using Definition A had significantly reduced ankle dorsiflexion and hallux flexor strength ($p < 0.02$; see Table 1). Ankle flexibility and foot reaction time did not differ between those who had foot pain and those who did not. Standing balance on either the floor or foam surface did not differ between the two subject groups, however, stride length, step length and walking speed were significantly reduced in those with foot pain. Other gait variables such as step width and time spent in the different gait phases did not differ significantly between the foot pain groups. Gait variability, defined as the within-subject standard deviation, did not differ between the participant groups for any of the gait variables (all $p > 0.05$).
### Table 1: Descriptive characteristics, foot function and postural sway for foot pain and no-pain groups.

<table>
<thead>
<tr>
<th>Variable</th>
<th>No foot pain</th>
<th>Foot pain Definition A</th>
<th>Foot pain Definition B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Descriptive</strong></td>
<td>mean ± SD</td>
<td>mean ± SD</td>
<td>mean ± SD</td>
</tr>
<tr>
<td>Age (years)</td>
<td>71.1 ± 7.0</td>
<td>71.7 ± 6.2</td>
<td>72.6 ± 6.3</td>
</tr>
<tr>
<td>BMI (kg.m(^{-2}))</td>
<td>27.6 ± 4.5</td>
<td>29.3 ± 5.3(^*)</td>
<td>30.5 ± 5.3(^1)</td>
</tr>
<tr>
<td><strong>Foot function</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hallux strength (%BW)</td>
<td>14.6 (13.4 – 15.8)</td>
<td>12.6 (11.4 – 13.8)(^*)</td>
<td>11.7 (10.0 – 13.4)(^1)</td>
</tr>
<tr>
<td>Lesser toe strength (%BW)</td>
<td>10.5 (9.8 – 11.3)</td>
<td>9.6 (8.9 – 10.4)</td>
<td>8.8 (7.7 – 9.8)(^1)</td>
</tr>
<tr>
<td>Ankle DF strength (kg)</td>
<td>10.7 (10.1 – 11.3)</td>
<td>9.5 (8.9 – 10.3)</td>
<td>9.1 (8.2 – 9.9)(^1)</td>
</tr>
<tr>
<td>Ankle DF flexibility (kg)</td>
<td>49.2 (48.0 – 50.4)</td>
<td>49.8 (48.6 – 50.0)</td>
<td>49.5 (47.8 – 51.3)</td>
</tr>
<tr>
<td>Foot reaction time (ms)</td>
<td>301 (291 – 311)</td>
<td>312 (301 – 322)</td>
<td>323 (308 – 337)</td>
</tr>
<tr>
<td>Walking speed (m.s(^{-1}))</td>
<td>1.03 (1.0 – 1.06)</td>
<td>0.98 (0.95 – 1.05)(^*)</td>
<td>0.94 (0.9 – 0.98)(^1)</td>
</tr>
<tr>
<td>Stride length (m)</td>
<td>1.19 (1.16 – 1.21)</td>
<td>1.14 (1.12 – 1.17)(^*)</td>
<td>1.11 (1.08 – 1.15)(^1)</td>
</tr>
<tr>
<td>Step length (cm)</td>
<td>59.5 (58.3 – 60.7)</td>
<td>57.1 (56.0 – 58.3)(^*)</td>
<td>55.6 (53.9 – 57.3)(^1)</td>
</tr>
<tr>
<td>Base of support (cm)</td>
<td>10.1 (9.6 – 10.6)</td>
<td>10.3 (9.8 – 10.7)</td>
<td>10.7 (10.0 – 11.3)</td>
</tr>
<tr>
<td>Stance time (%GC)</td>
<td>61.7 (61.5 – 62.0)</td>
<td>61.8 (61.5 – 62.0)</td>
<td>62.0 (61.6 – 62.4)</td>
</tr>
<tr>
<td>Swing time (%GC)</td>
<td>38.3 (38.0 – 38.6)</td>
<td>38.3 (38.0 – 38.5)</td>
<td>38.0 (37.6 – 38.4)</td>
</tr>
<tr>
<td>Double support time (%GC)</td>
<td>23.5 (23.0 – 24.0)</td>
<td>23.9 (23.4 – 24.4)</td>
<td>24.3 (23.6 – 25.0)(^1)</td>
</tr>
<tr>
<td>Single support time (%GC)</td>
<td>38.3 (38.0 – 38.6)</td>
<td>38.0 (37.7 – 38.3)</td>
<td>37.8(37.4 – 38.2)(^1)</td>
</tr>
<tr>
<td><strong>Postural sway (mm)</strong></td>
<td>mean (95% CI)</td>
<td>mean (95% CI)</td>
<td>mean (95% CI)</td>
</tr>
<tr>
<td>Balance on floor</td>
<td>71.4 (65.4 – 77.5)</td>
<td>78.1 (72.1 – 84.2)</td>
<td>83.9 (75.4 – 92.3)(^1)</td>
</tr>
<tr>
<td>Balance on foam</td>
<td>180 (168 – 193)</td>
<td>186 (173 – 198)</td>
<td>204 (187 – 221)</td>
</tr>
</tbody>
</table>

BMI = body mass index; BW = body weight; DF = dorsiflexion; GC = gait cycle
\(^*\) significant difference between Definition A (n = 154) vs. no pain groups (n = 158); p < 0.05
\(^†\) significant difference between Definition B (n = 81) vs. remaining participants (n = 231); p < 0.05
\(^‡\) adjusted for gender and BMI

Interestingly, when using the more conservative cut-off for categorising disabling foot pain (Definition B), the same variables remained significantly different between those with and without foot pain (ankle dorsiflexion strength, hallux flexor strength, stride length, step length and walking speed). However, under this criterion, several additional variables emerged as being associated with disabling foot pain. Compared to the remaining cohort, individuals with disabling foot pain, using Definition B, had...
significantly reduced flexor strength of the lesser toes, increased foot reaction time, increased postural sway on both the floor and foam surfaces and an increased time spent in double support combined with decreased time spent in the single support phase of the gait cycle (see Table 1).

**Table 2:** Mean difference (95% CI for difference) between foot pain and no-pain groups for each component of the SF-36 Health Survey. Definition A: At least one item scored at ‘on some days’ or ‘on most/every day(s)’; Definition B: At least one item scored at ‘on most/every day(s)’.

<table>
<thead>
<tr>
<th>SF-36 component</th>
<th>Foot pain Definition A</th>
<th>p - value</th>
<th>Foot pain Definition B</th>
<th>p - value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical function</td>
<td>12.4 (7.6 – 17.2)</td>
<td>&lt;0.001</td>
<td>22.1 (16.9 – 27.2)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Role - physical</td>
<td>17.9 (9.2 – 26.7)</td>
<td>&lt;0.001</td>
<td>26.3 (16.4 – 36.2)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Body pain</td>
<td>18.2 (13.2 – 23.2)</td>
<td>&lt;0.001</td>
<td>22.4 (16.8 – 28.0)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>General health</td>
<td>12.2 (8.1 – 16.3)</td>
<td>&lt;0.001</td>
<td>17.5 (12.9 – 22.1)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Vitality</td>
<td>11.9 (8.2 – 15.6)</td>
<td>&lt;0.001</td>
<td>14.9 (10.7 – 19.0)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Social function</td>
<td>8.8 (4.1 – 13.6)</td>
<td>&lt;0.001</td>
<td>12.9 (7.5 – 18.2)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Role - emotional</td>
<td>11.3 (4.0 – 18.6)</td>
<td>0.003</td>
<td>19.3 (11.0 – 27.6)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Mental health</td>
<td>3.8 (0.4 – 7.2)</td>
<td>0.029</td>
<td>5.5 (1.7 – 9.4)</td>
<td>0.005</td>
</tr>
<tr>
<td>Dimension 1 (physical)</td>
<td>14.5 (10.7 – 18.4)</td>
<td>&lt;0.001</td>
<td>20.1 (16.5 – 24.9)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dimension 2 (mental)</td>
<td>9.8 (6.5 – 13.2)</td>
<td>&lt;0.001</td>
<td>14.3 (10.6 – 18.0)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Total</td>
<td>12.2 (8.6 – 15.7)</td>
<td>&lt;0.001</td>
<td>17.8 (14.0 – 21.7)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Table 3 shows the breakdown of responses by the participants with foot pain for the individual items of the MFPDI. Of the 10 items characterising functional problems, the presence of foot pain resulted in a high proportion (> 40%) of participants avoiding standing, avoiding hard/rough surfaces, walking slowly, avoiding walking distances and using the car/bus more. A higher proportion of participants under Definition B were affected by foot pain for all items of the MFPDI. Within the individual constructs, Definition B had a significantly higher number of responses under each item of the functional problems construct except for avoiding walking outside and irritability when feet hurt. The proportion of participants reporting that foot pain affected personal
appearance did not differ between the two foot pain definitions and two of the five items under the pain intensity construct were significantly higher using Definition B (see Table 3).

**Table 3:** Prevalence of disability among people with foot pain for each item of the Manchester Foot Pain and Disability Index. Definition A: At least one item scored at ‘on some days’ or ‘on most/every day(s)’; Definition B: At least one item scored at ‘on most/every day(s)’.

<table>
<thead>
<tr>
<th>Functional problems</th>
<th>Definition A</th>
<th>Definition B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoid walking outside</td>
<td>14.3</td>
<td>22.5</td>
</tr>
<tr>
<td>Avoid walking distances</td>
<td>44.2</td>
<td>67.6*</td>
</tr>
<tr>
<td>Don’t walk normally</td>
<td>30.3</td>
<td>46.8*</td>
</tr>
<tr>
<td>Walk slowly</td>
<td>46.8</td>
<td>64.2*</td>
</tr>
<tr>
<td>Have to rest</td>
<td>31.6</td>
<td>54.3*</td>
</tr>
<tr>
<td>Avoid hard/rough surfaces</td>
<td>49.0</td>
<td>70.9*</td>
</tr>
<tr>
<td>Avoid standing</td>
<td>50.7</td>
<td>71.6*</td>
</tr>
<tr>
<td>Use car/bus more</td>
<td>41.8</td>
<td>63.8*</td>
</tr>
<tr>
<td>Need help with</td>
<td>18.3</td>
<td>30.4*</td>
</tr>
<tr>
<td>Irritable when feet hurt</td>
<td>35.7</td>
<td>44.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pain intensity</th>
<th>Definition A</th>
<th>Definition B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carry on but in more pain</td>
<td>56.2</td>
<td>76.3*</td>
</tr>
<tr>
<td>Constant pain in feet</td>
<td>37.4</td>
<td>58.0*</td>
</tr>
<tr>
<td>Pain worse in morning</td>
<td>29.8</td>
<td>38.0</td>
</tr>
<tr>
<td>Pain worse in evening</td>
<td>48.4</td>
<td>55.5</td>
</tr>
<tr>
<td>Shooting pain in feet</td>
<td>29.7</td>
<td>40.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Personal appearance</th>
<th>Definition A</th>
<th>Definition B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-conscious about feet</td>
<td>25.2</td>
<td>34.6</td>
</tr>
<tr>
<td>Self-conscious about shoes</td>
<td>20.1</td>
<td>28.8</td>
</tr>
</tbody>
</table>

* indicates significant difference between Definition A and B foot pain groups (p < 0.05).

**DISCUSSION**

Few studies have reported the prevalence of foot pain in large, randomly-selected samples of older people. Foot pain classified using the traditional MFPDI definition (score ≥ 1; Definition A) was prevalent in 49.7% of the participants. This prevalence rate is very similar to the 54% reported by Munro and Steele, who surveyed older residents within the same regional area to the current study, 12 years prior. A recent review paper reported the prevalence of foot pain among older people to vary from 10
to 70%. These between-study differences can be attributed to variations in the
definitions of foot pain used in each of the studies. As such, using a more conservative
cut-off point for the MFPDI (Definition B) yielded a lower prevalence of disabling foot
pain of 26%, the same prevalence rate of foot pain as reported in the North West
Adelaide Health Study\textsuperscript{11} of community-dwelling older people of a similar age to the
present participants. The difference in prevalence rates justifies the use of Definition B,
as a high proportion of participants with foot pain classified under Definition A
probably included people with relatively mild foot pain symptoms. In agreement with
several other studies investigating factors associated with foot pain, women and those
with a higher BMI were found to have a higher prevalence of foot pain.\textsuperscript{9-11}

The extent to which disabling foot pain impacts on an individual’s ability to
carry out activities of daily living is evident in Table 3. Almost half of the participants
with foot pain indicated that foot pain resulted in them avoiding hard or rough surfaces,
standing and caused them to walk more slowly. A higher proportion of participants
with disabling foot pain classified using Definition B were functionally impaired
because of their foot pain on all components of the MFPDI. In particular, the more
conservative cut-off was a better discriminator of the functional construct of the
MFPDI, whereby the frequency of responses was significantly higher under Definition
B for all but two items in this construct. Of concern, over two-thirds of the participants
with foot pain avoided hard or rough surfaces, walking distances and standing because
of their foot pain. Participants with foot pain also scored significantly lower on the total
SF-36 and all sub-components. Using Definition B further highlighted the difference
between those with disabling pain and those without for all components of the SF-36, in
particular physical functioning. These findings suggest that foot pain not only impedes
functional capacity, but is also associated with an overall decreased quality of life, whereby social function, vitality and mental health status are reduced.

Using the traditional MFPDI criteria for foot pain, no difference in the balance tests performed on either the floor or foam surfaces was observed. Interestingly, when the more conservative cut-off for foot pain was applied, individuals with disabling foot pain displayed significantly greater postural sway on both tests. This suggests that poorer balance may contribute to an increased fall risk in those with more disabling foot pain. Menz and Lord\textsuperscript{16} found no difference in the same balance tests between older people with \((n = 27)\) and without \((n = 108)\) foot pain, although foot pain was assessed as a simple yes/no response. They did, however, find that those with foot pain performed more poorly on a coordinated stability task and other functional tests (stair ascent/descent, alternate step-up, timed 6 m walk), which was consistent with our present findings of impaired functional ability with foot pain.

Reducing walking speed is a well-established compensatory mechanism in individuals with foot pain.\textsuperscript{6, 16, 35} Although reduced walking speed and step/stride length are also known to distinguish fallers from non-fallers,\textsuperscript{36, 37} these gait variables cannot be the direct mechanism causing older people to fall. The reduced step/stride length and walking speed evident in these older people with foot pain may be partly attributed to the reduced foot and ankle muscle strength also evident in this group. Toe flexor weakness will reduce an individual’s ability to control shifts of body weight and propel the body forward during walking, whereas ankle dorsiflexor weakness may reduce the ability to lift the foot and toes off the ground during the swing phase of gait to avoid tripping. In fact, reduced toe clearance and maximal ankle dorsiflexion throughout the swing phase have been found to be characteristic of older people with a history of falling.\textsuperscript{36, 38} Decreased ankle dorsiflexion strength has been also been found to be a risk
factor for falls in older people with peripheral neuropathy and diabetes. Furthermore, our prospective falls study on the same cohort of older people as in the current study, identified muscle weakness of the hallux and lesser toes as fall risk factors. Therefore, these findings suggest that foot and ankle muscle weakness in older people with foot pain may be contributing to an increased risk of falling.

The causal link between muscle weakness and foot pain cannot be determined from this study. Although it is possible that reductions in mobility in those with foot pain may lead to muscle atrophy through disuse, it is also possible that pain inhibited the ability of the individuals to optimally perform the strength assessment tasks. This needs to be taken into consideration when providing interventions to individuals with disabling foot pain. Although it is important to address muscle weakness in those with foot pain, strength gains may be limited if pain inhibits the ability to perform prescribed exercises and is likely to compromise compliance. Therefore, it is vital that interventions directed towards this population combines treatment/management of foot pain with strengthening of the foot and ankle musculature in order to improve functional capacity and to reduce the risk of falling.

It must be acknowledged that this study focussed solely on foot pain and did not take into consideration musculoskeletal pain at other joints. However, individuals with foot pain, regardless of definition, scored significantly worse on the body pain component of the SF-36, indicating they experienced body pain more than those without foot pain. Studies have suggested that older adults with disabling foot pain are more likely to report pain in other parts of the body (back, hips, knees, and hands or wrists). Furthermore, multi-joint pathologies have been found to increase the risk of functional impairment to a greater extent than single joint problems.
Fifty-six to seventy-six percent of the participants with foot pain (Definition A and B, respectively) reported carrying on with daily activities, but in more pain (see Table 3). Older adults with foot pain should therefore be encouraged to seek professional treatment for their feet. Despite two-thirds of the participants with foot pain having visited medical personnel about their feet, it appears that the remaining individuals may be ignoring their symptoms. Using Definition B, at least one item scored at ‘most/every day(s),’ was a better discriminator of those with more disabling foot pain and functional limitation, and may therefore be the most appropriate definition to identify older people who may require treatment for their foot pain.

**CONCLUSIONS**

In addition to reduced quality of life and functional impairment, older people with disabling foot pain display altered foot characteristics, in particular reduced foot and ankle muscle strength. It is possible that these alterations to foot function, in addition to poorer balance in those with more severe foot pain, may contribute to an increased risk of falling. Providing interventions to older people that treat foot pain and improve foot function may play a role in reducing fall risk and improving quality of life.
REFERENCES


Chapter 8
Summary, strengths and limitations, conclusions and recommendations for future research

SUMMARY

Identifying modifiable risk factors for falls in older people is a vital step towards providing falls prevention interventions to older people in order to reduce the consequences of falls in the community. This thesis aimed to identify foot pathologies associated with an increased risk of falling among community-dwelling older people. This was achieved by conducting a comprehensive assessment of foot structure and function in a randomly-selected cohort of 312 community-dwelling men and women aged over 60 years. Participants were then followed prospectively for 12 months to determine their falls incidence. Section A (Chapters 2 and 3) of this thesis used the prospective falls data to identify foot pathologies that increased the risk of falling in community-dwelling older people. After it was confirmed that toe deformities and foot pain were risk factors, Section B (Chapters 4-7) explored these foot pathologies in further depth to identify structural and functional characteristics of the individuals with these pathologies to better understand the mechanisms that may be contributing to their increased risk of falls.

In Chapter 2, the associations between hallux valgus, lesser toe deformities and falls were investigated. Hallux valgus and lesser toe deformities are common foot problems in older people and one factor contributing to the development of these toe deformities is reduced toe flexor strength. As adequate toe flexor strength is also crucial in maintaining balance, it was hypothesised that poor toe flexor strength and toe
deformities would increase the risk of falls in community-dwelling older people. During the 12-month prospective follow-up, 107 (35%) participants experienced a fall. It was found that these fallers displayed significantly less strength of the hallux and lesser toes and were more likely to have hallux valgus and lesser toe deformities compared to non-fallers.

Despite its associations with impaired balance and walking ability, few studies have investigated the relationship between foot pain and fall risk. Surprisingly, no previous research has systematically investigated whether high plantar pressures are associated with foot pain in older community-dwelling adults or, more importantly, whether foot pain and/or dynamic plantar pressures are fall risk factors in this population. Therefore, the purpose of Chapter 3 was to determine whether foot pain and/or plantar pressures generated during ambulation were associated with falls in community-dwelling older adults. As hypothesised, fallers displayed a significantly higher prevalence (58%) of foot pain than non-fallers (49%). Fallers also generated a significantly higher peak pressure and pressure-time integral under the foot compared to non-fallers. It was concluded that high plantar pressures generated during gait may contribute to increased foot pain and discomfort, thereby contributing to an increased risk of falls.

Section A (Chapters 2 and 3) identified that older people with toe deformities and foot pain were at a significantly higher risk of sustaining a fall than people without these pathologies. One suggested intervention for these individuals is to provide comfortable footwear that cushion the foot under areas of high pressures. Although foot problems are often attributed to ill-fitting footwear, many foot deformities affect foot anthropometrics and, in turn, lead to further shoe fit problems. In order to design comfortable, well-fitting shoes for older people, we must first have a better
understanding of the shape of the older foot, as well as factors that can influence older foot morphology. Therefore, the purpose of Chapter 4 was to characterise the dimensions and shape of the feet of older people and to determine whether foot anthropometrics were influenced by the presence of foot problems. Results of this study indicated that older people who had moderate-to-severe hallux valgus, lesser toe deformities, swollen or flat feet exhibited different foot anthropometrics to those without foot problems. As comfortable footwear is vital to protect the older foot and to allow older individuals to ambulate without pain, footwear for older people should be designed to cater for their altered foot morphology, particularly those older individuals with foot problems.

Despite many anecdotal reports suggesting atrophy of the soft tissue structures under the metatarsal heads in those with toe deformities, there are few quantitative in vivo studies to support this notion. Therefore, the purpose of Chapter 5 was to determine whether thickness of the plantar soft tissues in individuals with toe deformities differs from otherwise healthy older adults. As hypothesised, individuals with hallux valgus had significantly reduced total soft tissue thickness under the 1st metatarsal head and individuals with lesser toe deformities displayed significantly reduced total soft tissue thickness under the 5th metatarsal head compared to controls. Results of this study revealed that fat pad thickness did not differ between cases and controls. Based on this finding, it was speculated that the musculotendinous complex of the forefoot was compromised, and may result in reduced toe function in those with toe deformities. This conclusion supported the findings of Chapter 2, whereby individuals with toe deformities had reduced strength of the toe flexor muscles and were at a greater risk of falling.
To further explore the mechanisms that contribute to a greater fall risk in older people with toe deformities, Chapter 6 compared the gait, balance and plantar pressure characteristics of individuals with toe deformities to gender-, age- and BMI-matched controls without toe deformities. The results indicated that although there were no effects of toe deformities on spatiotemporal gait characteristics or postural sway, older people with hallux valgus and lesser toe deformities were found to display altered forefoot plantar pressure patterns. These findings suggest that toe deformities alter weight distribution under the foot when walking, although the relationship between toe deformities and falls may be mediated by factors other than changes in spatiotemporal gait parameters or impaired postural sway.

Finally, Chapter 7 examined foot function, gait and balance characteristics in those with foot pain in order to improve our understanding of movement control in this group at risk of falls. It was found that, in addition to reduced quality of life and functional impairment, older people with disabling foot pain displayed altered foot function, in particular reduced foot and ankle muscle strength. It is possible that these alterations to foot function, in addition to poorer balance in those with more severe foot pain, may contribute to an increased risk of falling. Therefore, providing interventions to older people that treat foot pain and improve foot function may play a role in reducing fall risk and improving quality of life.

STRENGTHS AND LIMITATIONS

This thesis was one of the first known studies to comprehensively assess foot structure and function in a large, randomly selected cohort of independently living older people. The use of prospectively measured fall occurrence via monthly diaries minimised recall bias associated with retrospective studies. Several strategies were employed, including,
reminder follow-up calls and personal engagement (sending Christmas and birthday cards) to ensure a high retention rate (97%) over the 12-month follow-up period to strengthen the study design. In regards to identifying fall risk factors, many influences, particularly environmental variables, which were not assessed in this study, may have been important in determining the likelihood of suffering a fall.

When identifying individuals with toe deformities it is acknowledged that, while the dichotomous classification of lesser toe deformity used in our study may oversimplify the pathology, this method allowed us to assess the prevalence of toe deformities in a large cohort of older people, as measuring the severity of the deformity via x-ray or MRI was not appropriate. It is also acknowledged that in order to compare the foot function of those participants in the present study with toe deformities to those without, only the right foot was used to satisfy the statistical assumption of data independence. Therefore, individuals who had unilateral left foot toe deformities were not included in the prevalence rate. However, a strength of this study design was the matching of toe deformity groups to controls based upon age, gender and BMI. This eliminated these factors as potential confounders on the biomechanical variables. Other strengths and limitations of the research have been discussed in each chapter.

**CONCLUSIONS**

The presence of hallux valgus, lesser toe deformities and foot pain are foot pathologies that increase the risk of falling in community-dwelling older people. Older people with these toe deformities display altered foot structure, whereby the foot anthropometrics differ and soft tissue thickness under the metatarsal heads is reduced compared to those without toe deformities. Although static balance and spatiotemporal gait characteristics do not seem to be affected by these toe deformities, load distribution under the forefoot
in the form of plantar pressures is altered during ambulation in older individuals with hallux valgus, lesser toe deformities and foot pain. Foot function is further impaired in older people with toe deformities whereby toe flexor strength is reduced, which is a possible contributor to their increased risk of falling. Similarly, individuals with disabling foot pain display altered foot function, in particular foot and ankle muscle weakness, again, a possible mechanism associated with an increased risk of falling. In addition, individuals with foot pain generated higher plantar pressures, which may be contributing to their foot pain, and experienced functional impairment and reduced health-related quality of life. Therefore, providing interventions to older people that treat foot problems, foot pain and improve foot function may play a role in reducing fall risk and improving quality of life.

RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the results from the thesis the following recommendations are made for future research with respect to foot structure and function in older individuals with foot pathologies and falls prevention interventions:

- The presence of hallux valgus, lesser toe deformity and reduced flexion strength of the hallux and lesser toes increase the risk of falling in older people. Furthermore, individuals with hallux valgus and lesser toe deformities had weaker flexor muscles of the associated toes. Therefore, a clinical trial that determines whether interventions designed to increase toe flexor strength can reduce the severity of toe deformities and risk of falling is recommended.

- Similarly, older people with foot pain are at a greater risk of falling. Further research is required to determine whether podiatric treatment, such as lesion debridement, appropriately designed foot orthoses and/or shoe modifications, are
effective in reducing the prevalence of foot pain and whether this can result in a reduction in the incidence of falls in older people.

- Altered foot loading in individuals with toe deformities did not affect their static balance or level, straight-line spatiotemporal gait characteristics. Whether toe deformities affect foot function and mechanical stability during more challenging locomotor tasks, such as recovering from a perturbation, changing direction or stair ascent and descent, warrants further investigation.

- Individuals with foot pain displayed reduced foot and ankle muscle strength. However, the causal link between muscle weakness and foot pain could not be determined from this thesis. Further research should investigate whether reductions in mobility in those with foot pain leads to muscle atrophy through disuse or whether pain inhibits the ability of an individual to perform maximal strength assessment tasks.

- The use of the Manchester Foot Pain and Disability Index with a conservative cut-off was able to identify individuals with more disabling foot pain and functional limitation. Further research should explore whether this tool can be used in clinical settings, such as hospitals and General Practitioner clinics, to identify older people who require treatment for their foot pain.