The Probability of Slipping During Level Walking

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Abstract

Worldwide falls-related accidents are the second leading cause of fatalities and of all falls, 67% are caused by slips and trips in the elderly and 32% in young populations. Foot slippage is reported as the most common unforeseen factor triggering falls while walking on the same level. The main human factors affecting slipping risk are gait characteristics and the health of the individual's sensory systems. The primary environmental factors are the frictional characteristics of the walking surface and footwear. The walker's slipping risk can be estimated by comparing the surface Coefficient of Friction (COF) to their friction requirement; the Required Coefficient of Friction (RCOF) calculated as the ratio of the vertical and horizontal ground reaction forces (GRF). In the biomechanical modelling undertaken in this project walking was regarded as safe, with respect to slipping, when the COF exceeded the RCOF.

This study investigated ageing effects on RCOF by measuring the foot-ground reaction forces of young and older healthy female and male participants. Mathematical modelling of the RCOF distribution was used to estimate slipping probability using a technique developed by Best and Begg (1999) to assess tripping risk using minimum foot-ground clearance (MFC) distributions. This modelling allowed for the non-normal (skewed and kurtotic) high variability also seen in RCOF data distributions. In previous experimental studies slipping has often been determined using laboratory gait biomechanics data collected over a relatively small number of walking trials. In the present project RCOF data were computed from GRF data collected over multiple trials, up to 100, during continuous walking at both normal and fast speeds to allow modelling of the complex non-normal RCOF frequency distribution seen in previous reports.

RCOF computations were initially employed (i) excluding the F_X, medial-lateral force, as in many previous investigations and (ii) including the F_X component. RCOF significantly increased using the Fx-included method, with the increment greater for older adults. As per these results, all further RCOF calculations were calculated including F_X. The comparisons of RCOF between the groups showed an age effect with young adults (YA) having a higher mean RCOF (0.206 $\pm$ 0.025) at normal speed than older adults (OA) (0.196 $\pm$ 0.025). However, the in the 99th percentile data OA had higher RCOF values (0.298 $\pm$ 0.122) than YA (0.241 $\pm$ 0.031). No gender effect was noted at normal speed. When walking faster RCOF increased significantly for all participants from Normal speed (Young Females 0.207, Older Females 0.194, Young Males 0.203, Older Males 0.197) to Fast (Young Females 0.223, Older Females 0.198, Young Males 0.208, Older Males 0.208). Indeed, when analysing the speed effect, interaction was noted for both age and gender. At fast speed, a significant age effect was noted for mean RCOF (OA 0.230, YA 0.224). The investigation of probability of slipping (PS) showed a larger group range for older adults with individual patterns noted in all groups. The investigation of total slipperiness in the very slippery and hazardous surfaces (friction 0- 0.2) indicated that the older females have the safest walking pattern at both normal and fast speed. Indeed, a significant age effect was noted at normal ($p \leq 0.001$) and at fast speed ($p = 0.023$) for right foot with the OA. Similarly, on the slippery and hazardous surfaces (COF 0.2-0.4) OA had significantly greater area values at both normal and fast speeds. Case analysis of PS clarified the importance of individual analysis instead of comparisons of group means. All groups had individual patterns with a higher variability skewness and kurtosis noted especially for the older adults.

By modelling individual participants' slipping probability using their RCOF distribution, considerable within-group variation was found, reflecting high individual variability in friction demand, especially in older people. While ageing-related gait adaptations would tend to reduce older participant's slipping risk on lower friction surfaces, their wider RCOF distribution would serve to increase their slipping risk on unknown surfaces. When estimating slipping probability considerable inter-individual variability must be allowed and individual case studies are recommended.

Doctor of Philosophy Student Declaration

"**I**, Tuire Karaharju-Huisman, declare that the PhD thesis entitled "The Probability of Slipping During Level Walking" is no more than 100,000 words in length including quotes and exclusive of Tables, Figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

[redacted] _23.12.2016___________

Signature Date

Table of Contents

List of Figures

List of Tables

List of Equations

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1 Introduction

Falls are a leading cause of human death and disability and one third of people over 65 years fall at least once per year (Gomes et al., 2013; Meschial et al, 2014). With an ageing population, falls can be considered a significant medical, economic and societal global challenge (Debi et al., 2009). In Australia, it is estimated that the number of people aged 65 years and over will have increased from 13% (2010) to 24% by 2050, or approximately 9 million people (Australian Bureau of Statistics, 2008). One million Australians aged 65 years and over fall every year with consequences including serious injury, lack of confidence, decreased activity levels and social isolation among others (Sherrington and Tiedemann, 2015). A recent report on falls-related injuries in community-dwelling older people in Victoria also commented that previous estimates of the burden of hospitalisation may have been underestimated (Vu, Day, and Finch, 2014). With these rapidly increasing numbers it is important to investigate the reasons of falls with respect to walking mechanics that may be associated with increased falls risk in older people In Australia the most common causes of injuries requiring hospitalisation are falls on the same level due to tripping, slipping or stumbling. Previous gait biomechanics research has investigated and modelled tripping risk in older adults (Best and Begg, 2008; Best, Begg and James, 1999). The research presented here investigated the less well-documented biomechanical characteristics of walking that may increase *slipping* risk as we get older.

Many factors influence an individual's risk of falling (World Health Organization, 2007) and as the biological, behavioural, environmental or socioeconomic risk factors increase, the risk of falling increases. Of the biological risk factors, gait and balance impairments as well as lower extremity muscle weakness are highly associated with falls (Tinetti, Speechley, and Ginter, 1988). In a considerable research literature describing ageing effects on gait and balance, the walking gait has been quantified using biomechanical methods to assess limb movement and speed (kinematics) and forces (kinetics). Using these variables walking mechanics have been mapped for healthy populations of all ages, allowing comparative analysis within and between various sub-population groups. Elderly gait is characterised by slower walking, increased step width, decreased step length, decreased cadence and increased time in double support when both limbs have ground contact (Dobbs et al., 1993; Elble, Higgins, Thomas, and Colliver, 1991; Gavin and Vardaxis, 2002; Grabiner, Biswas, and Grabiner, 2001; Imms and Edholm, 1981; Prince, Corriveau, Hebert, and Winter, 1997; Winter, 1991; Woo, Ho, Lau, Chan, and Yuen, 1995). These age-related changes are evident at both normal and fast walking speeds, most important is that some of these age-related changes in walking mechanics may increase the probability of slipping (Lockhart, Woldstad and Smith, 2003).

Slipping has been defined as “a sudden loss of grip, often in the presence of liquid or solid contaminants and resulting in sliding of the foot on a surface due to a lower coefficient of friction that is required for the momentary activity” (Grönqvist, 1999). During level walking, slipping is most likely either during initial contact when only the rear part of the shoe is in contact with the ground, or just prior to toe off when the fore sole has ground contact (Perkins, 1978; Strandberg and Lanshammar, 1981). Friction loss at initial contact (heel strike) causes an anterior slip while a slip at toe off causes a posterior slip. Of these, the initial contact phase of the walking cycle is suggested to impose a larger risk of slipping because loss of stability causes the foot to slide anteriorly (Redfern, Cham, Gielo-Perczak, Grönqvist, et al., 2001) while recovery is more likely in a posterior slip because the lead foot will support most of the body weight (Grönqvist, 1999).

Either type of slip, anterior or posterior, can be explained by the frictional properties of the walking surface and the traction demands imposed by the walker. By comparing surface friction to the friction requirement, it is possible to determine slipping risk. The available surface friction, Coefficient of Friction (COF), can be quantified by mechanical measurements in both laboratory and field conditions (Chang, Grönqvist, et al., 2001; Strandberg, 1983). The frictional demand of walking can be quantified using the Ground Reaction Forces (GRF) to calculate a Required Coefficient of Friction (RCOF), also referred to as the utilized friction. RCOF is often defined as the ratio of the anterior-posterior (F_Y) and vertical (F_Z) force components (Figure 1.1) (Perkins, 1978; Strandberg and Lanshammar, 1981).

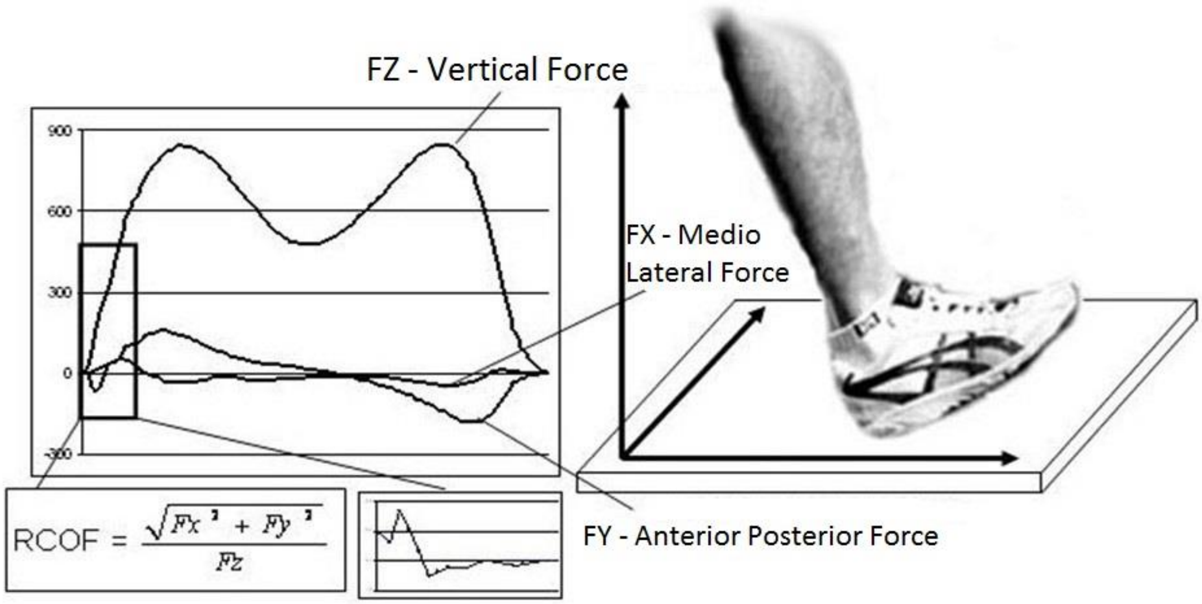


Figure 1.1 The Calculation of the Required Coefficient of Friction (RCOF)

Chang, Chang, and Matz (2011) questioned the RCOF computation using only F_Y by showing that RCOF increased when the F_X component was included, as in the equation in Figure 1.1. Higher RCOF increases the surface friction demanded to avoid slipping and walking is, therefore, regarded as safe when the surface friction (COF) is greater than utilised friction (RCOF). In other words, a slip will not occur if the friction of the surface exceeds the friction criterion defined by the RCOF (Grönqvist, 1999; Barnett, 2002). Several authors have used these principles to estimate the likelihood of slipping using RCOF computed from force plate data (Barnett, 2002; Burnfield and Powers, 2006; Chang, 2004; Hanson, Redfern, and Mazumdar, 1999).

Previous research has shown that older adults have increased gait parameter variability compared to young adults (Kobsar, Olson, Paranjape, Hadjistavropoulos, and Barden, 2014; Oberg and Karsznia, 1993, 1994; Owings and Grabiner, 2004). Gait variability has also been linked to an increased risk of falls in the elderly (Hausdorff, Rios, and Edelberg, 2001; Lord, Howe, Greenland, Simpson, and Rochester, 2011; Lord, Lloyd, and Li, 1996). Ageing effects of gait variability in the swing limb have been investigated using minimum foot clearance (MFC), the closest point of the foot to the ground and, therefore, the point of maximum risk of tripping on an unseen obstacle. Best and Begg (1999) developed a mathematical modelling technique to assess tripping risk by estimating the probability distribution of MFC height taking into account the non-normal features of the MFC distribution (Best and Begg, 2008a; Best, Begg and James, 1999). This model has been trialled during continuous treadmill walking and MFC distributions have been found to be non-normal (skewed and kurtotic) with high variability. Indeed, Begg, Best, Dell'Oro, and Taylor (2007) stated that none of the participants in their study had normally distributed MFC data sets. As walking is cyclic in which the foot alternates between the swing phase (foot off the ground) and stance phase (foot on the ground), this demonstrated non-normal distribution may be hypothesized to be present in ground reaction forces and, therefore, RCOF.

In the present experiment, the Best and Begg (2008a) tripping probability model was used to estimate slipping risk by determining the distribution characteristics of RCOF, as shown in Figure 1.2. As far as is known the experiment presented here represents the first comprehensive study of slipping probability based on statistical modelling of the RCOF distribution. As with the earlier tripping work the aim was to investigate biomechanical factors contributing to high falls risk in older adults by modelling critical gait features. In the tripping work the MFC during the swing phase was modelled, while in this project we modelled RCOF at initial ground contact to estimate slipping probability. This method has been reported previously by Karaharju-Huisman, Begg and Best (2004, 2006) but it was concluded that precise quantitative estimation of slipping probability would require considerably longer walking trials to provide sufficient gait cycles to model RCOF variability. Most previous studies took repeated RCOF measurements on a short walkway but the variability required to statistically model the RCOF distribution requires considerably more extended data sets. In the present study samples of up to 100 cycles were collected over a longer duration to quantify slipping based on RCOF data in a way that better reflects the characteristics of everyday steady-state walking.

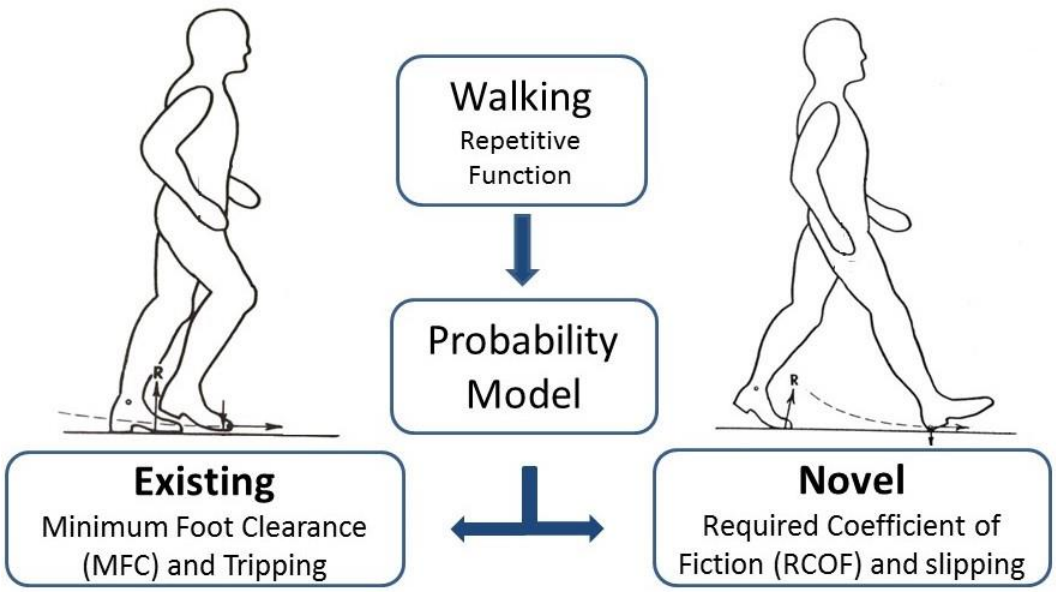


Figure 1.2 Suggested application of probability modelling to estimate the probability of slipping. (Images from Winter, 1991)

While falls are clearly identified as a major burden to society, ageing-related changes to gait function that increase the risk of falling need further investigation. Previous studies of slipping have identified some features of ageing that increase slipping risk but the biomechanics of long term walking in the highest risk group for falls, those aged 65 years and over, has not yet been mapped. The aim of this study was to investigate the intrinsic frictional properties of foot-ground kinetics in younger and older adults of both genders during uninterrupted long-term walking on a level surface at both self-selected normal and fast speeds. The scope of this study was therefore restricted to; 1) populations without walking impairments 2) testing in a laboratory setting. 3) All participants were wearing their own, comfortable shoes that fitted the requested footwear profile.

The specific research aims were as follows:

1) To investigate age, gender and limb effects on the RCOF distribution in long term data from overground walking at self-selected normal and fast walking speeds.

2) To implement a new mathematical model for estimating the probability of slipping allowing for gait variability and non-normal RCOF distribution.

2 Literature review

This section reviews the literature on: (i) the epidemiology of ageing and falls including slipping falls, (ii) principles of gait biomechanics and, (iii) research methods employed in the current study.

2.1 Epidemiology of Ageing and Falls

Globally the number of people over 60 years or older is growing faster than any other age group with an estimated 688 million worldwide in of this age bracket in 2006 but predicted to increase to nearly 2 billion by 2050 (United Nations, 2004). In Australia, the same trend is seen, with the growth in older age groups stronger that any younger cohorts (Figure 2.1).

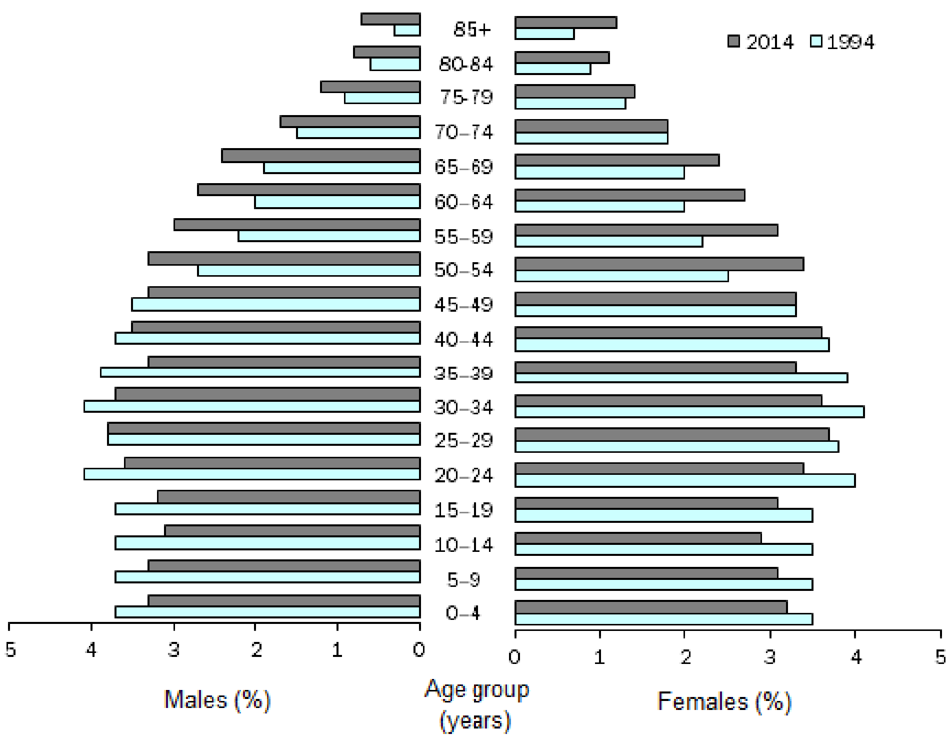


Figure 2.1 Population Structure, Age and Gender in Australia- 1994 and 2014. (Australian Bureau of Statistics, 2014)

Between 1973 and 2013 the population in Australia over 65 years tripled from 1.1 to 3.3 million with a sixfold increase in those over 85 years. Over the same time the number of Australians under 25 years increased by only 22%. In 2013 14% of the population was aged over 65 which is a significant increase to 9% in 1973 (Australian Institute of Health and Welfare, 2014). During the decade 1994 – 2014 the Australian population aged 65 years and over increased from 11.8% to 14.7% with those over 85 years nearly doubling from 1% to 1.9%.

It can also be noted that the size of all age groups over 50 years increased while those under 50 years decreased (Australian Bureau of Statistics, 2014). The population of Australians is projected to increase; however, the growth is not consistent over the age groups with a continuous increase of those aged 65 years and more (Figure 2.2) (Australian Institute of Health and Welfare, 2014).

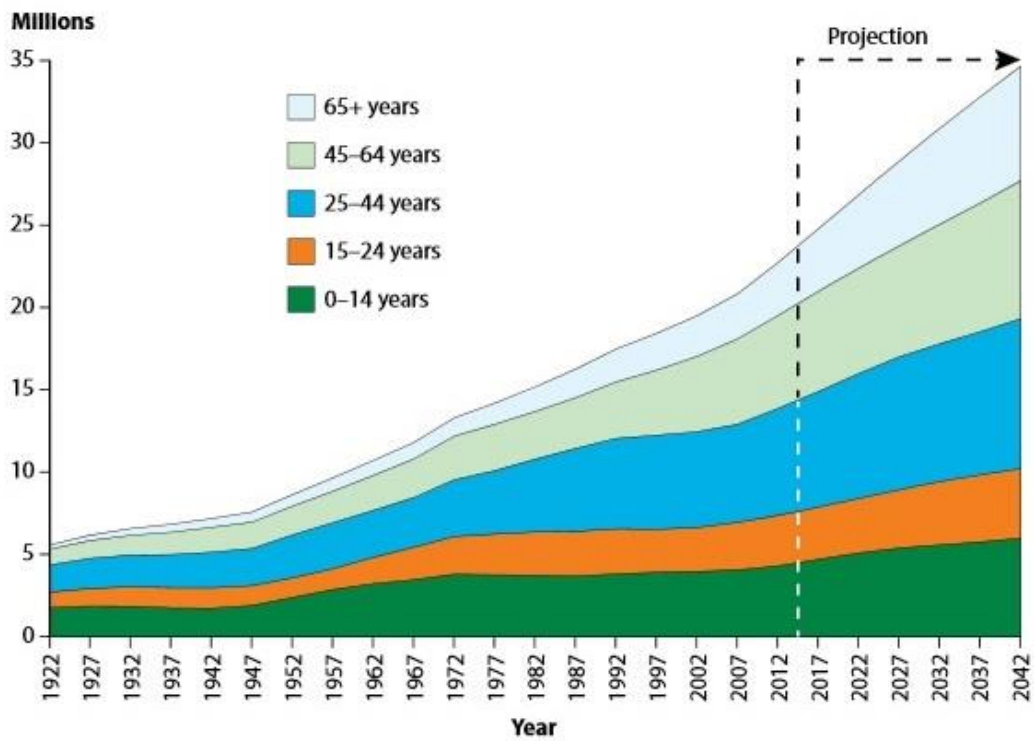


Figure 2.2 Australian population – past, present and future (Australian Institute of Health and Welfare, 2014)

Worldwide, falls are the second leading cause of fatalities (Courtney et al., 2001) and the leading cause of accidental death in people over 75 years (Lilley, Arie, and Chilvers, 1995). Approximately one third of community dwelling people over 65 years will fall at least once a year with the number of falls increasing with age and frailty and approximately 50% of those aged 80 years or more fall at least once a year (Blake et al., 1988; Cripps and Carman, 2001; Dolinis, Harrison, and Andrews, 1997; Gabell, Simons, and Nayak, 1985; Kreisfeld, Newson, and Harrison, 2004; Lord, Ward, Williams, and Anstey, 1993; National Ageing Research Institute, 2004; Prudham and Evans, 1981; World Health Organization, 2007).

The current estimates are that the proportion of people aged 65 years and above in Australia will increase from 13% (13 million people) in 2010 to around 24% (9 million) by the year 2050 (Australian Bureau of Statistics, 2008). By 2050 it is estimated that around 2.7 million older Australians will fall annually with the national annual health cost from fall-related injuries increasing to an estimated $1.4 billion (Moller, 2003). A recent publication looking at the falls-related injuries in these community-dwelling older people in Victoria also commented that the previous estimates of the burden of hospitalization were underestimated (Vu et al., 2014). With the rapidly increasing number of fallers and consequential costs, it is of importance to investigate the circumstances and mechanics of falls, with the aim of finding ways to prevent them.

With the increase in the proportion of elderly people, coupled with the high rate of falls, it is important to investigate all the factors leading to better understanding of those at risk. By exploring risk factors that contribute to falls and then identifying and predicting individuals at risk, strategies of falls prevention can be implemented. The following section describes the risk factors for falling and specifically falls due to slipping.

2.1.1 Risk Factors for Falls

Many factors influence an individual’s risk of falling (National Injury Prevention Advisory Council, 1999; World Health Organization, 2007) and falls often have multiple factors rather than a specific pathology (Tinetti, McAvay, and Claus, 1996). The World Health Organisation classifies falls risk factors as biological, behavioural, environmental and socioeconomic (Figure 2.3). Biological factors include the physiological changes due to ageing, including sensory impairments (visual, proprioceptive and vestibular) and reduced physical and cognitive capacities. Biological factors, sometimes referred to as "intrinsic", are important because they influence the risk of falling due to decreased capacity to maintain balance associated with reduced, real or perceived limits of stability or ability to sway without taking a step and declining muscular strength and joint mobility. (Blake et al., 1988; Campbell et al., 1989; Kerrigan, Todd, and Della Croce, 1998; Lord et al., 2007; Maki, 1997; National Injury Prevention Advisory Council, 1999; O'Loughlin, Robitaille, Boivin, and Suissa, 1993; Owings, Pavol, Foley, Grabiner, and Grabiner, 1999; Prudham and Evans, 1981; Snow, 1999; Tinetti et al., 1988a; Whittle, 2007). Intrinsic facors predict recurrent falls (Blake et al., 1988; Graafmans et al., 1996; Wolf and Gregor, 1999).

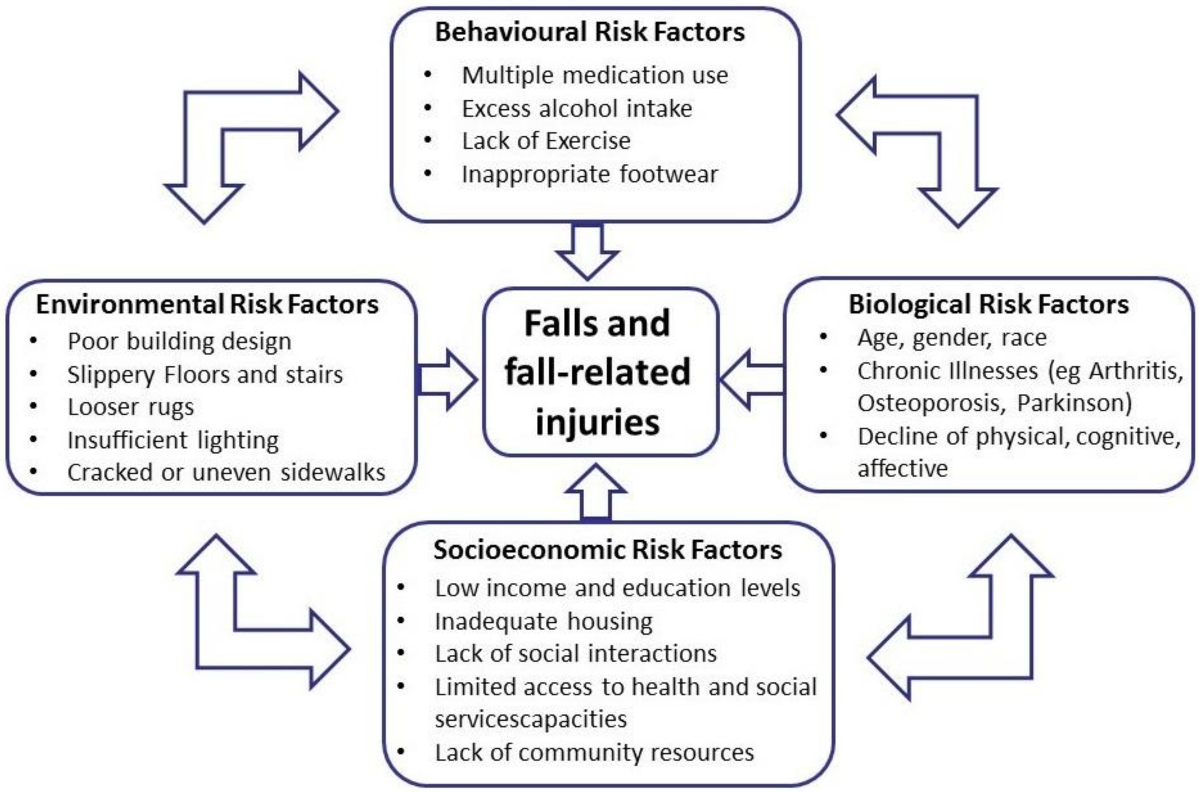


Figure 2.3 Risk factors for falls in older adults. Adapted from (World Health Organization, 2007)

Behavioural risk factors are related to daily life choices such as food and alcohol intake, medications and exercise (or inactivity). Socioeconomic risk factors are the social and economic conditions of communities, such as financial conditions and access to health and welfare services. Environmental influences are due to the interaction between the person and their environment, at home and outdoors; for example, hazards to walking posed by poor lighting, surface friction (slipperiness), surface irregularities (cracked footpaths, roadside kerbs), footwear, and in-house tripping hazards such as loose carpets and everyday objects on the floor (Hill, Schwarz, Flicker, and Carroll, 1999; Lord et al., 2007). Of importance here is that environmental factors include slippery floors, unsecured mats and rugs, furniture and lightning. Intrinsic and extrinsic factors interact, with the extrinsic factors often creating the opportunity for a fall. Australian injury and health records have shown that 54% of falls were caused by external factors (Cripps and Carman, 2001). Of these falls 39.1% we due to trips, slips and stumbles. In slipping, the interaction between these two factors is central, as the probability of a slip is reflected in the precise relationship between shoe and ground frictional properties and features of gait biomechanics that influence the pattern of forces imposed by the feet on the walking surface.

Whilst injury rates increase as co-morbidities increase, falls rates are not limited to the frail elderly (American Geriatrics Society, 2001) as falls also occur and result in significant injury, in apparently healthy older people (Prince et al., 1997). Whilst older adults with one or more risk factors are more prone to falls it is important to prevent all falls, as even the first fall can have serious consequences in a previously healthy older person (Hill et al., 1999) and older people who have experienced a fall are at greater risk of a further fall. One study of community-dwelling fallers and found that 57% would have another fall within a year and 31% two or more falls (Nevitt, Cummings, Kidd, and Black, 1989). The number of repeat falls is affected by the activity or frailty level with frail people more than twice as likely to fall as vigorous individuals (Northridge, Nevitt, Kelsey, and Link, 1995). When comparing frail and vigorous older people for a 12-month period, 52% of the frail people fell whilst only 17% of the people in the active group experienced a fall (Speechley and Tinetti, 1991). The rate of falls is also affected by a number of medical conditions with reports of increased number of falls in people with vestibular disorders, Parkinson’s disease and stroke (Ashburn, Stack, Pickering, and Ward, 2001; Forster and Young, 1995; Herdman, Blatt, Schubert, and Tusa, 2000; Jørgensen, Engstad, and Jacobsen, 2002; Koller, Glatt, Vetere-Overfield, and

Hassanein, 1989; Schrag, Ben-Shlomo, and Quinn, 2002; Wood, Bilclough, Bowron, and Walker, 2002).

Many physiological systems, such as muscle strength, balance ability and vestibular function contribute to stability and locomotion. Normal physiological ageing includes the significant decline in sensorimotor function even when no diagnosed diseases are present. Up to 55 years limited changes in sensorimotor function are observed but above this age a progressive loss is seen, with a greater rate of decline as ageing progresses. Indeed, there is a rapid decline to less than 50% of function by 65 years (Lord et al., 2007). Ageing-related changes in sensory and neuromuscular functions can be considered risk factors for falls, such as visual acuity, visual edge-contrast sensitivity, muscle strength and reaction time (Adelsberg, Pitman, and Alexander, 1989; Campbell, Borrie, and Spears, 1989; Ivers, Cumming, Mitchell, and Attebo, 1998; Klein, Klein, Lee, and Cruickshanks, 1999; Lord, 2006; Lord, Clark, and Webster, 1991; Lord, Ward, Williams, and Anstey, 1994; Nevitt et al., 1989; Tinetti, Speechley, and Ginter, 1988a)

Bradley (2013a) analysed falls statistics in Australia from 2000 to 2011 and reported that the age-standardised rates of fall injury cases had increased 2% annually over that 12 years (Bradley, 2013a). Nearly 25,000 cases of people aged 65 years and older were added to the rate of falls during 1999-2000. The report noted, however, a decrease in hip fractures due to falls but reported rapidly increasing (7% per year) falls-related head injuries, more commonly in men. A significant increase in falls-related hospitalisations was also reported (Bradley, 2013a) with patient days due to fall-related injuries doubling between 1999 and 2011 to a total of 1.4 million (Bradley, 2013b). In all age groups women presented with a higher number of falls than men, raising the question of whether the gait biomechanics of females may play a role in predisposing them to falls.

In Australia, the most common causes of injuries requiring hospitalisation are falls on the same level due to tripping, slipping or stumbling (Bradley, 2013b). On average 70% of falls occurred either at home or in an aged care facility. Half of the recorded falls occurred in the outdoor areas, bathroom and bedroom. Other authors have stated that close to half of the falls occur in the home and its immediate surroundings with most occurring in the highly-used areas such as the bedroom, living room and kitchen (Campbell et al., 1990; Luukinen, Koski, Laippala, and Kivelä, 1995).

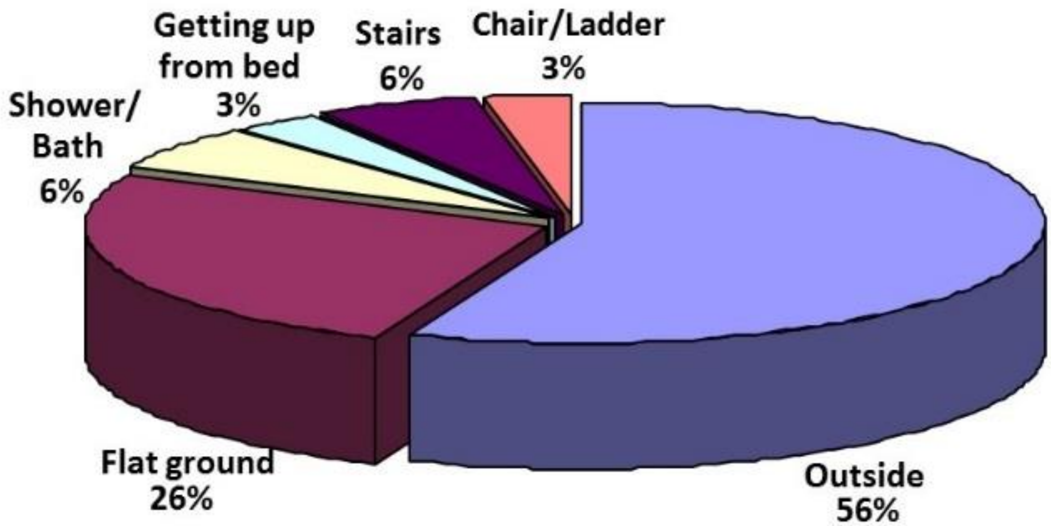


Figure 2.4 Locations of falls in older people. Adapted from (Lord, Sherrington, Menz, and Close, 2007)

Figure 2.4 summarises the locations of falls in older people and reports that 56% of the falls occur outside. These incidents are likely to relate to other factors affecting normal gait function, such as uneven surfaces, sudden obstacles (i.e. cracked pavers) or sudden changes in surface frictional properties (i.e. wet pavers). The location of falls may relate to frailty, but again, may also be affected by gender and age. Falls outside the home decrease with age with a consequently increased number of falls inside on a level surface (Lord, Ward, Williams, and Anstey, 1993). Campbell et al. (1990) reported that women fell more than men inside the home (65% and 44% respectively) whilst more men fell outside (25% compared to 11% of falls in women). A further study elaborated by reporting that women were more prone to fall due to trips, whilst men were more likely to slip. Women more commonly fall inside and men outdoors (Berg, Alessio, Mills, and Tong, 1997).

It is also important to discuss the reasons of falls (Figure 2.5). Most reasons relate to ambulation with tripping, slipping and poor balance noted as the main reasons. Apart from these factors relating to ambulation, insecurity is also reported as a relatively common reason behind falls.

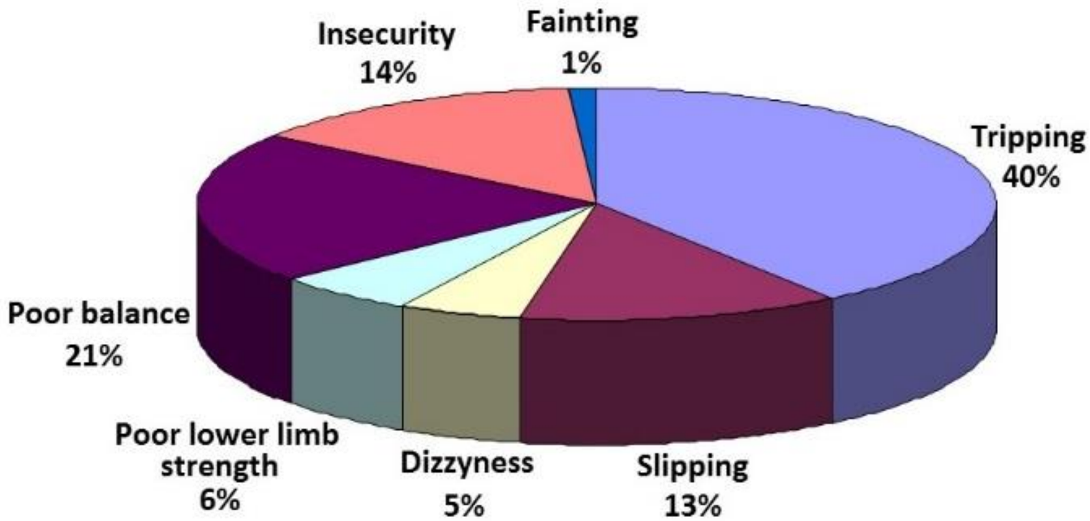


Figure 2.5 Reasons for falls in older people. Adapted from (Lord et al., 2007)

2.1.2 Slipping Falls

Slipping is an important consideration when analysing causality and prevention in falls research. It has been reported that 67% of falls in the elderly and 32% in young people are caused by slips and trips (Lloyd and Stevenson, 1992). In older people slipping is the second most common explanation for a fall (Gabell et al., 1985; Lord et al., 1993) and across all age groups foot slipping is the event most often causing a fall either at the same or lower levels (Andersson and Lagerlof, 1983; Courtney, Sorock, Manning, Collins, and Holbein-Jenny, 2001; Grönqvist, Chang, et al., 2001). Slips account for 25% of all fall-related injuries (Berg et al., 1997). When considering all environments, domestic and occupational, falls due to slips are common in all age groups with slipping being a contributing factor in 12% of occupational accidents (Strandberg and Lanshammar, 1981) and the slip related falls causing lengthy absences from work (Chiou, Bhattacharya, Lai, and Succop, 2002; Leclercq, 1999).

Slipping has been defined as a "...condition underfoot which may interfere with human beings, causing a foot slide that may result in injury or harmful loading of body tissues due to a sudden release of energy" (Grönqvist, Chang, et al., 2001, p 1102). Another definition of slipping is "...a sudden loss of grip, often in the presence of liquid or solid contaminants and resulting in sliding of the foot on a surface due to a lower coefficient of friction than that required for the momentary activity" (Grönqvist, 1999, p 352). The definition "underfoot accident" was used by Manning in situations where a fall or injury was initially caused by interaction between the person's foot and ground (Grönqvist, 1999).

A slip incident is very fast. In less than a second after losing the grip to the ground a body part, often pelvis or an outstretched arm will have ground contact (Figure 2.6).

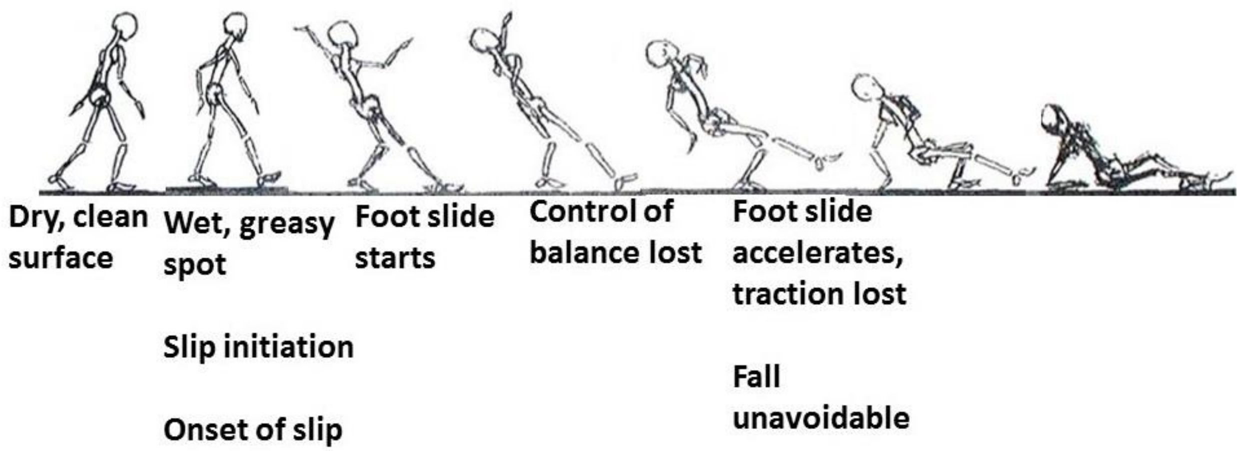


Figure 2.6 Events leading to a slip (Grönqvist, Chang, et al., 2001)

If the contact surface does not fulfil the friction requirement, e.g. due to a contaminant, a slip is initiated. At this point, balance can be still maintained if the body centre of mass (COM) remains within the base of support (BOS). During the foot slide balance is challenged as COM reaches the boundaries of BOS, and will be lost once COM is outside BOS. A fall is unavoidable as the foot slide accelerates and traction is lost (Grönqvist, Chang, et al., 2001).

Slipping is most likely either at initial ground contact when only the rear part of the shoe (such as the heel) is involved, or close to toe-off when only the sole has contact (Perkins, 1978; Strandberg and Lanshammar, 1981). Heel contact causes a slip anteriorly of the lead foot while a slip at toe off will lead to a posterior slip under the sole as the stance foot pushes off. Of these two slipping events, recovery is easier in the latter as the lead foot will carry most of the body weight (Grönqvist, 1999). Conversely, heel contact imposes the greater risk because body weight remains on the lead foot due to forward momentum, causing the foot to slide and seriously challenging stability recovery (Redfern, Cham, Gielo-Perczak, Grönqvist, et al., 2001).

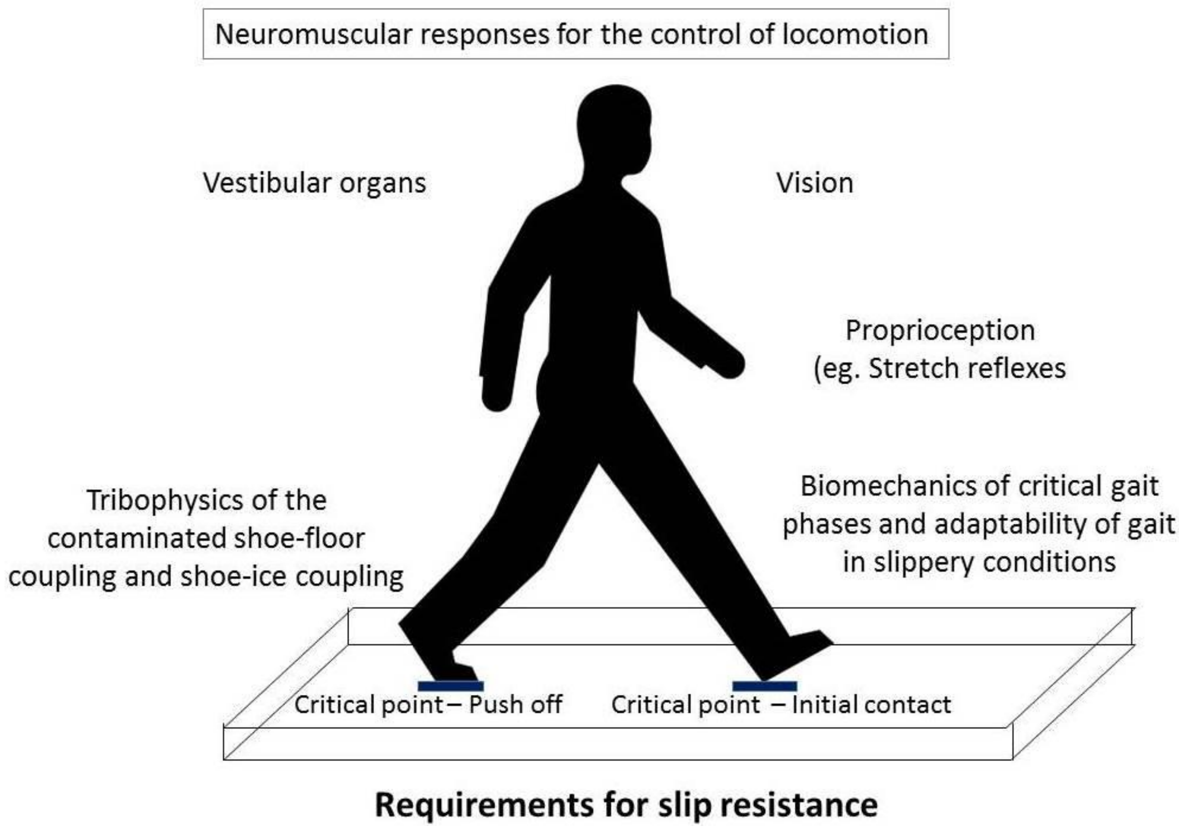


Figure 2.7 Requirements for Slip Resistance (Grönqvist, 1999).

For safe ambulation, interaction must exist between the sensory system (vision, vestibular organs and proprioception), the control of gait, balance and posture, and the frictional properties of the ground-footwear interface. With an appropriate function and reaction of these systems, a fall can be avoided if a sudden change of surface slipperiness is noted (Chang, Kim, Manning, and Bunterngchit, 2001; Grönqvist, Chang, et al., 2001; Redfern, Cham, Gielo-Perczak, Grönqvist, et al., 2001) (Figure 2.7).

Slipping injuries are related to the forces created during gait as well as the frictional properties of the ground and footwear; the presence of contaminants will also impact these properties (Grönqvist, Chang, et al., 2001) (Figure 2.8).

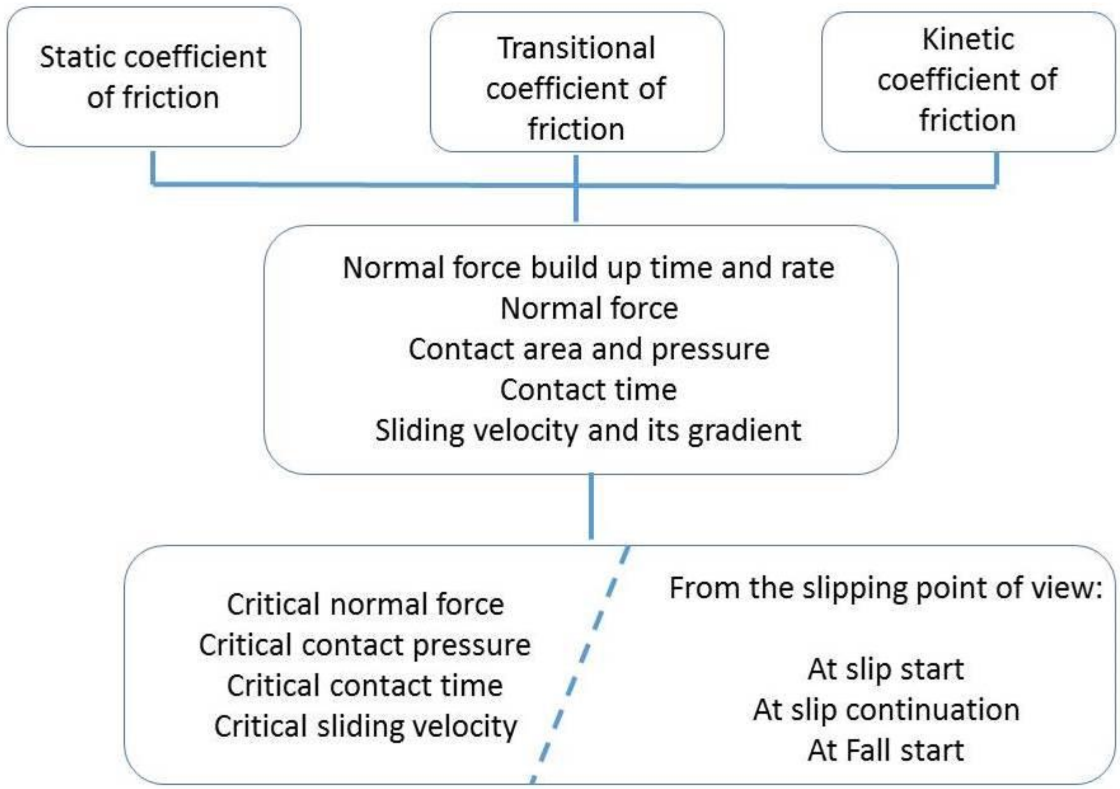


Figure 2.8 Biomechanical parameter model for determining slip resistance. (Grönqvist, 1999)

During the initial contact with the surface, adequate control of the lower limb is required (Winter, 1991). The controlled, gentle heel contact reduces the contact forces between the shoe and the ground during weight acceptance. This is important in order to reduce the hydrodynamic load support and thus increase friction and slip resistance (Cappozzo, 1991; Grönqvist, 1999). Even in non-slippery conditions, however, a non-threatening micro-slip is seen at initial heel contact (Perkins, 1978; Strandberg and Lanshammar, 1981). During normal walking on non-slippery surfaces the heel can slide forward 1-3 cm without a corrective postural response (Redfern, Cham, Gielo-Perczak, Grönqvist, et al., 2001). The micro-slip was initially defined as less than 1 cm (Leamon and Son, 1989) but was later defined to be up to 3 cm (Leamon and Li, 1990). Often this slight slide at the beginning of initial contact, even on non-slip surfaces, is not perceived (Strandberg and Lanshammar, 1981).

On a slippery surface the forward slide distance of the foot is increased and occurs with faster heel velocity, requiring a rapid and well-coordinated biomechanical response to avoid a fall. A slip in itself does not, therefore, necessarily lead to fall, rather falling is a consequential action that depends on the mechanics of the slip and the individual's response. As walking speed increases, a fall is more likely (Bhatt, Wening, and Pai, 2005) due to factors including increased forward heel displacement (Brady, Pavol, Owings, and Grabiner, 2000; Strandberg, 1985; Strandberg and Lanshammar, 1981), a larger foot-to-ground angle due to a long step (Brady et al., 2000) or the centre of mass being located behind the base of support (You, Chou, Lin, and Su, 2001).

2.1.3 Risk Factors for Slipping

Section 2.1.2 discussed the general risk factors in slipping and they can be assigned to two categories (Figure 2.9); (1) within an individual, the intrinsic or human factors (i.e. gait, vision, sensory system, neuromuscular system, ageing), or (2) factors affecting the walking environment, extrinsic or environmental factors (i.e. walking surface, shoe/surface interface). These factors can also be combined and identified as system factors (Grönqvist, Abeysekera, et al., 2001). The primary factor for slipping has been identified as poor friction between the foot and the underlying surface (Grönqvist, Abeysekera, et al., 2001). The secondary risk factors are related to several intrinsic and extrinsic factors such as uneven surfaces, poor postural control, ageing, dizziness, alcohol or drug use, inadequate lighting, or poor surface and stairway design (Grönqvist, Abeysekera, et al., 2001). These secondary factors often make people more susceptible to a slip and fall in case of a sudden change in surface slipperiness.

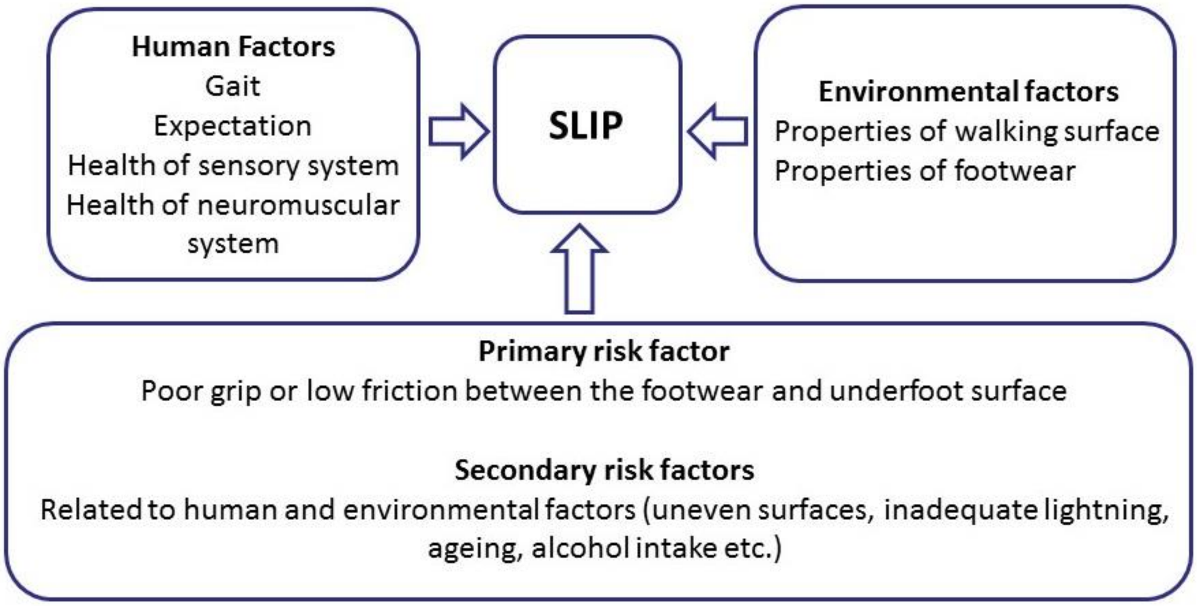


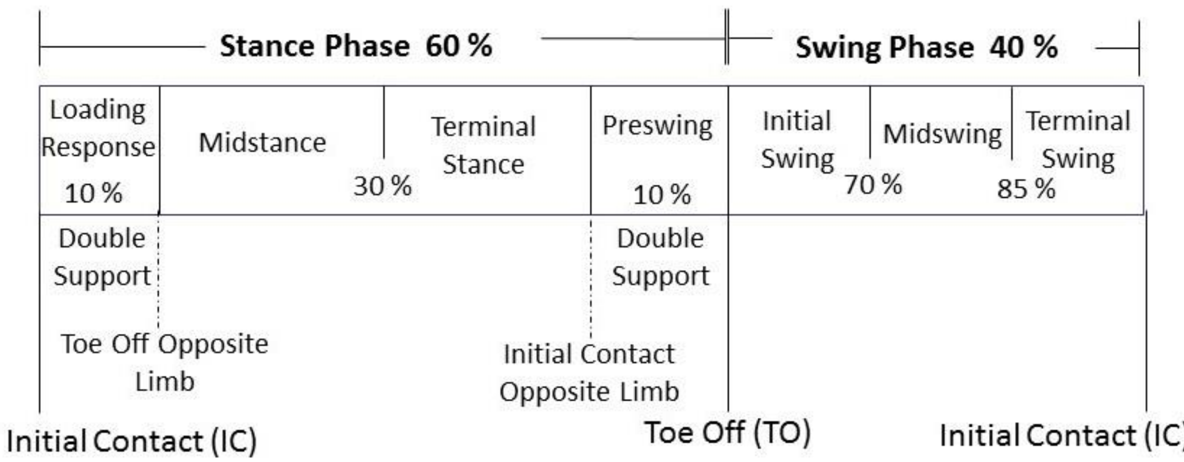
Figure 2.9 Risk factors of slipping (Grönqvist, Chang, et al., 2001).

The magnitude of slipping and falling risk depends on health status, anthropometry, perception, cognition of a possible hazard and ability to control and recover balance upon a slip (Grönqvist, Abeysekera, et al., 2001; Redfern, Cham, Gielo-Perczak, Grönqvist, et al., 2001; Strandberg, 1985; Tisserand, 1985). The likelihood of slipping also depends on the activity at the time of the slip, the properties of the surfaces (floor materials and incline/decline, footwear) and also any external conditions that may alter the frictional properties of the foot-ground interface (obstacles, contaminants) (Grönqvist, Chang, et al., 2001).

Studies on slipping have varied from automated tests of frictional properties of shoes and surfaces, to the analysis of human factors. The risk of slipping has been estimated by modelling slipping data using the details of surface friction, the coefficient of friction (COF) or the required coefficient of friction (RCOF) (Hanson et al., 1999; Barnett, 2002). These studies estimate the risk of slipping based on human and environmental factors and explore the relationship between measured friction, frictional requirements and slips and falls.

2.2 Principles of gait biomechanics

Walking is a cyclical pattern of movements and each cycle has characteristic events and phases, as shown in Figure 2.10. The stride defines a gait cycle, the interval between two successive foot contacts with the ground. Within the gait cycle there are clearly identified events that allow us to analyse an individual's gait. The key events are: (1) Initial contact; (2) Opposite toe off; (3) Opposite initial contact; (4) Toe off; (5) Foot clearance; (6) Tibia vertical; (7) Initial contact (Kirtley, 2006; Rose and Gamble, 2006; Whittle, 2007; Winter, 1991). These events divide the gait cycle into seven phases – four during the stance phase with the foot on the ground (loading response, mid stance, terminal stance, preswing) and three during the swing phase with the foot moving forward (initial swing, mid swing, terminal swing).



Stance Phase – the time when the foot is in contact wit ground. Normally 60% of the gait cycle.
Swing Phase – The time when the foot is not in contact with ground. Normally 40% of the gait cycle.
Double Support – The time when both feet have ground contact.
Single Support – the time when only one limb has ground contact

Figure 2.10 Gait Events (Rose and Gamble, 2006; Whittle, 2007)

These gait events have specific functions during the gait cycle (Table 2.1) and are used to describe gait control and any compensation due to ageing or other impairments. Gait function can also be presented using time-distance or temporal-spatial parameters such as cycle time, cadence (number of steps per minute), step and stride length, step width and speed (Figure 2.11).

Table 2.1 Gait functions at different events (Rose and Gamble, 2006)

Gait Period	% Cycle	Function	Opposite Limb
Initial Double Support	0-12	Loading, weight transfer	Unloading and preparing for swing
Single limb support	12-50	Support of entire body weight, centre of mass moving forward	Swing
Second double limb support	50-62	Unloading and preparing for swing	Loading, weight transfer
Initial Swing	62-75	Foot Clearance	Single limb support
Mid swing	75-85	Limb advances in front of body	Single limb support
Terminal Swing	85-100	deceleration, preparation for weight transfer	Single limb support

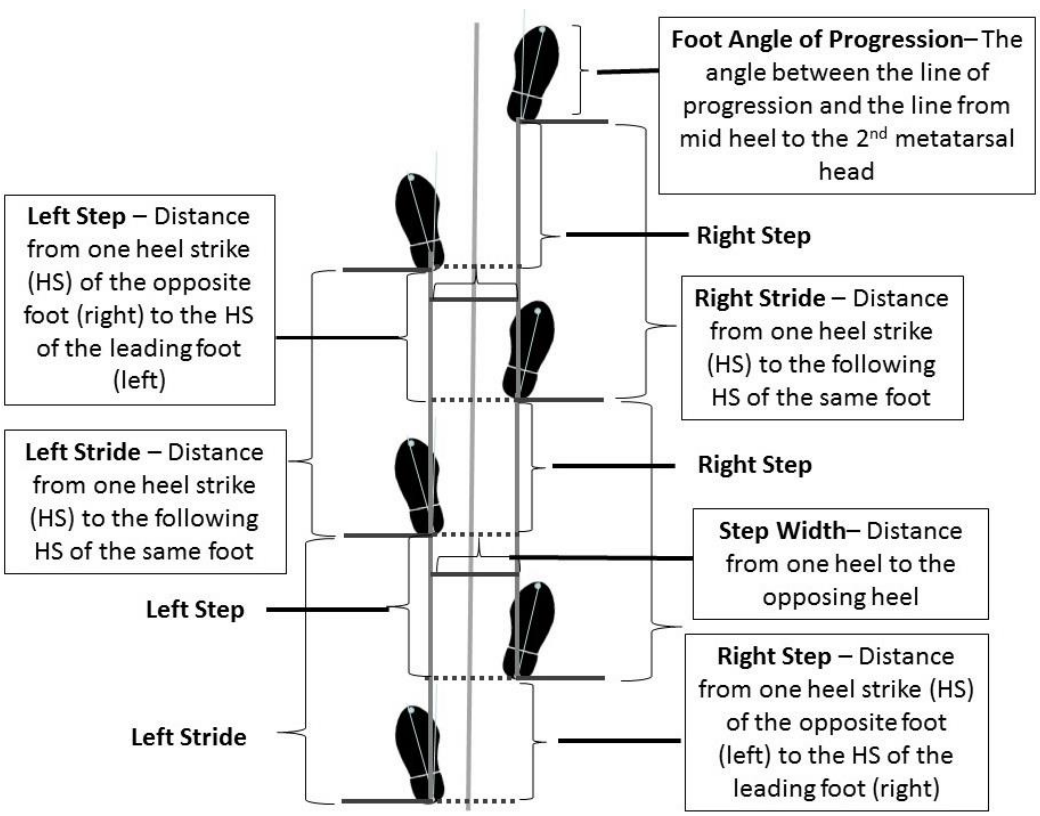


Figure 2.11 Distance Events

Speed is a commonly presented descriptor of gait. Whittle (2007) (table 2.2) reported the normal walking speed ranges to be for young males (18-49 years) to be 0.94-1.66 m/s, or older males (65-80 years) 0.80-1.52 m/s, young females (18-49 years) 1.10-1.82 m/s and for older females (65-80 years) 0.81-1.61 m/s. A number of authors have reported on the normal and fast self-selected speeds with the mean values varying between 1.30-1.39 m/s and 1.63-1.97 m/s reported for young people walking at slow and fast speeds respectively and 1.36-1.42m/s and 1.63-1.80 m/s for older people and normal and fast speeds respectively. (Alexandre et al., 2012; Chang et al., 2011; Chang et al., 2012a; Fino and Lockhart, 2014; Wojcik et al., 2001).

Table 2.2 Average range (95%) values for gait parameters at self-selected walking speed (Whittle, 2007)

Age (years)	Cadence (steps/min)	Cycle Time (s)	Stride Length (m)	Speed (m/s)
		Female		
13-14	103-150	0.80-1.17	0.99-1.55	0.90-1.62
15-17	100-144	0.83-1.20	1.03-1.57	0.92-1.64
18-49	98-138	0.87-1.22	1.06-1.58	0.94-1.66
50-64	97-137	0.88-1.24	1.04-1.56	0.91-1.63
65-80	96-136	0.88-1.25	0.94-1.46	0.80-1.52
		Male		
13-14	100-149	0.81-1.20	1.06-1.64	0.95-1.67
15-17	96-142	0.85-1.25	1.15-1.75	1.03-1.75
18-49	91-135	0.89-1.32	1.25-1.85	1.10-1.82
50-64	82-126	0.95-1.46	1.22-1.82	0.96-1.68
65-80	81-125	0.96-1.48	1.11-1.71	0.81-1.61

Kinetic parameters describe movement by investigating the forces that cause the motion. The forces exerted by the body towards the ground can be measured with force transducers that quantify the applied force by generating a proportional electrical signal. The applied force causes strain on the transducer that then correlates to a change in electrical voltage (Kirtley, 2006; Winter, 2009). A common way to measure Ground Reaction Forces (GRF) is by using a force platform, a metal plate with a rigid contact surface and multiple transducers in three axes allowing accurate measurement of forces in the three principal axes (Figure 2.12). Whilst only the foot has contact with the plate, the forces applied are a summary of forces from the mass and inertia of the whole body. In order to define the details at a segment level, a combination of kinematic and kinetic measurements is used (Kirtley, 2006; Whittle, 2007; Winter, 1991, 2009).

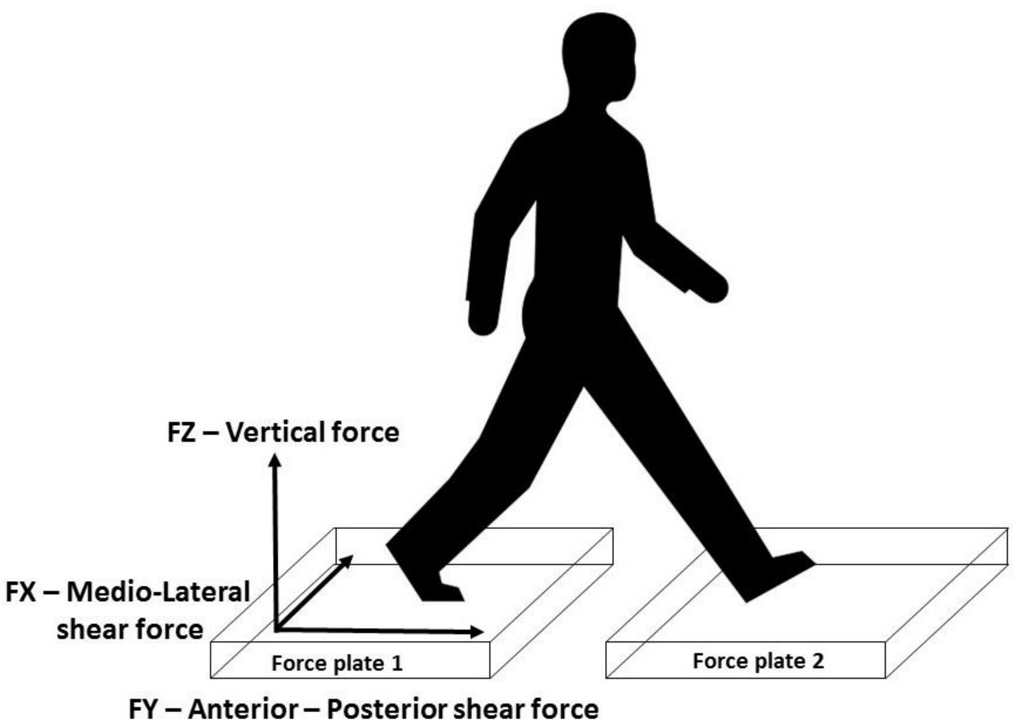


Figure 2.12 Force plates measuring the three-dimensional Ground Reaction Forces during walking.

Normal foot-ground reaction forces (GRF) have well established magnitudes and timing (Chao et al. 1983). When standing, gravity pulls the person toward the ground with a force equal to body weight and an equal and opposite reaction force is produced. During quiet standing GRF is primarily vertical but during movement two other GRF components act on the body, the anterior-posterior (F_Y) and medio-lateral (F_X) forces (Figure 2.12). An essential feature of F_Y and F_X is that they depend upon friction between the foot and the ground (Kirtley, 2006; Rose and Gamble, 2006).

The vertical reaction force (F_Z) is always positive as the force applied during gait is toward the ground and it has five key events (Figure 2.13). During initial support (1), force rapidly increases as body weight is transferred from double support to the supporting limb. The force soon rises above body weight (2). At this stage, the mean normalised force is 117 $\pm$ 9% bodyweight (BW) (Giakas and Baltzopoulos, 1997). During midstance force drops below body weight (3) with the mean force reported to be 75 $\pm$ 6% BW. After midstance the force reaches its second peak (4) again above body weight, mean value 109 $\pm$ 5% BW. After the second peak the force quickly reduces as weight is transferred to the opposite limb (Kirtley, 2006).

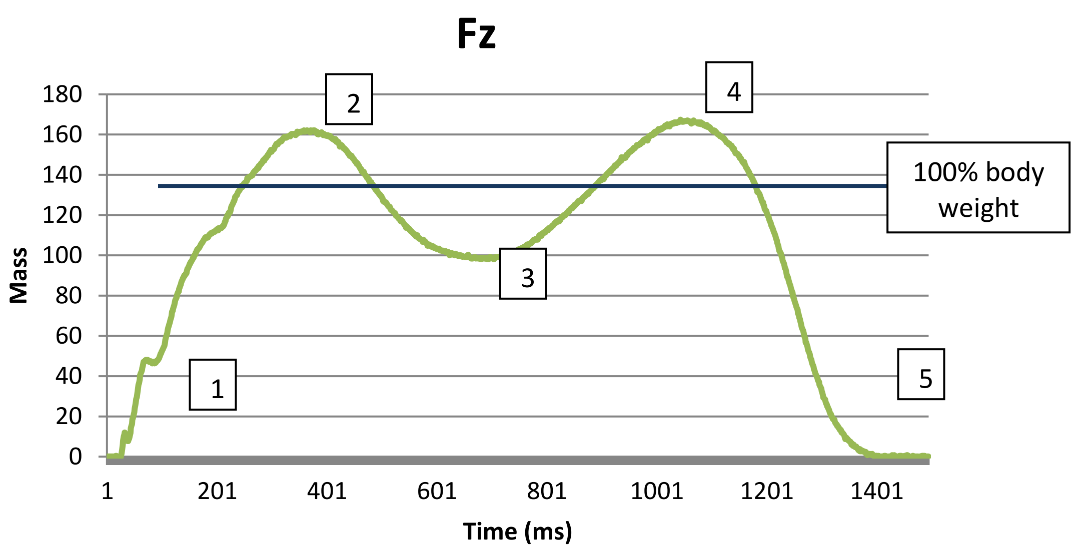


Figure 2.13 Vertical ground reaction force (F_Z) during normal gait.

Anterior-posterior forces (F_Y) cause braking and propulsion (Figure 2.14). The first peak (1) is the posterior peak resisting anterior movement of the heel upon landing. The second peak (2) is the propulsive, anterior force, providing the toe with the friction required for push off.

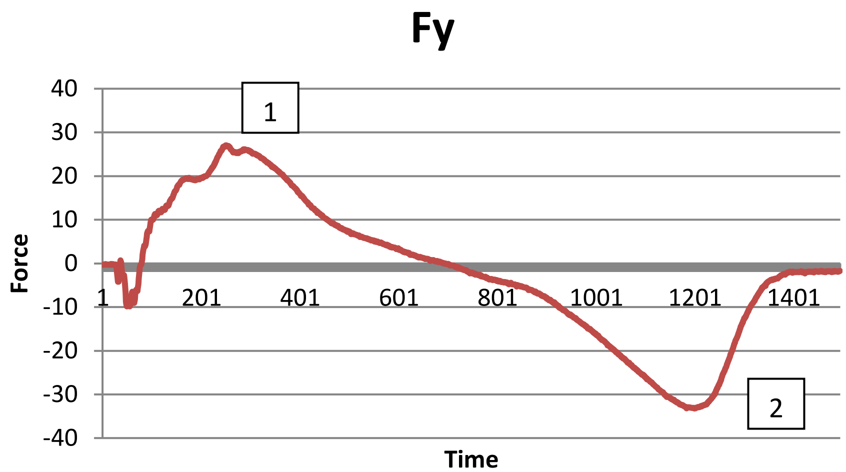


Figure 2.14 Anterior-Posterior ground reaction force (F_Y) during normal gait.

The third component, the medial-lateral force (F_X) (Figure 2.15) is created as the GRF acts medially and laterally during mid stance. During initial contact (1) a lateral force peak is seen as the body weight is on both feet during double support. During stance body weight is held on a single foot with the force applied laterally through the outer side of the foot and thus a medial force is created (peaks 2 and 3). F_X is proportional to stride width (Kirtley, 2006; Whittle, 2007; Winter, 2009). Whilst the F_X is a relatively small force, its impact on gait especially in older people has been identified (Vardaxis, Cooper, and Koceja, 2001).

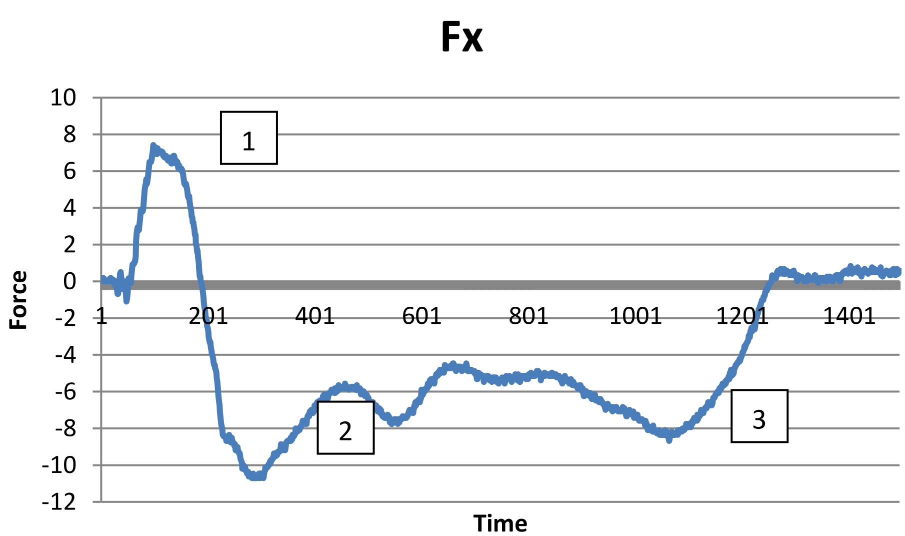


Figure 2.15 Medio-lateral ground reaction force (F_X) during normal gait.

2.2.1 Ageing Effects on Gait Biomechanics

During walking, more than 100 muscles create movement at 100 joints made of over 200 bones (Clark, 1995). A constant dynamic regulation of upright stance puts the body in a place of instability while moving the body weight between the two limbs. During single limb support, lasting for 40% of every stride for each limb, the body weight is supported the medial side of the foot only (Winter, 1991). Ageing is associated with lower walking speed, increased step width, decreased step length, decreased cadence and increased double support time (Baloh et al., 1994; Lord et al., 2007; Prince et al., 1997; Wolfson, Whipple, Derby, Amerman, and Nashner, 1994; Dobbs et al., 1993; Elble et al., 1991; Gavin and Vardaxis, 2002; Grabiner et al., 2001; Imms and Edholm, 1981; Prince et al., 1997; Winter, 1991; Woo et al., 1995). For young females aged 20-40 years the walking speed is 0.84–1.59 m/s, for young men aged 10–38.5 years 1.23-1.36 m/s. For older women aged 60-74 years, normal speed is 0.7-1.32 m/s and for older men aged 60–67.1 years 1.27–1.38 m/s (Buzzi, Stergiou, Kurz, Hageman, and Heidel, 2003; Finley, Cody, and Finizie, 1969; Hageman, Leibowitz, and Blanke, 1995; Oberg and Karsznia, 1994). Many authors have suggested that the slower walking speed is a consequence of a shorter step length, increased double limb support time or reduced cadence (Elble et al., 1991; Finley et al., 1969; Lord et al., 1996; Oberg and Karsznia, 1993; Winter, Patla, Frank, and Walt, 1990).

One explanation for slower gait in ageing is the need for increased safety as slower gait allows more stable walking (Menz, Lord, and Fitzpatrick, 2003; Prakash and Stern, 1973; Sudarsky, 1990; Woollacott and Tang, 1997). Another function is to allow more stable gait by increasing the base of support due to step width. Whilst some researchers found no differences in step width between young and older adults (Gabell and Nayak, 1984) others have concluded that in normal ageing step width increases in males (Murray, Kory, and Clarkson, 1969). Some researchers have found wider steps in those more prone to falls (Clark, Lord, and Webster, 1993; Gehlsen and Whaley, 1990) and step width variability is significantly larger in older people when compared to younger participants (Grabiner et al., 2001).

Lord et al. (2007) summarised the changes in level walking known to be associated with falls (Figure 2.16). When comparing older fallers to non-fallers, fallers walk with reduce speed and step length (Guimaraes and Isaacs, 1980; Imms and Edholm, 1981; Maki, 1997), increased cadence variability (Clark et al., 1993; Lord et al., 1996; Maki, 1997) and increased step length variability (Hausdorff, Edelberg, Mitchell, Goldberger, and Wei, 1997; Hausdorff et al., 2001; Lord et al., 1996; Maki, 1997).

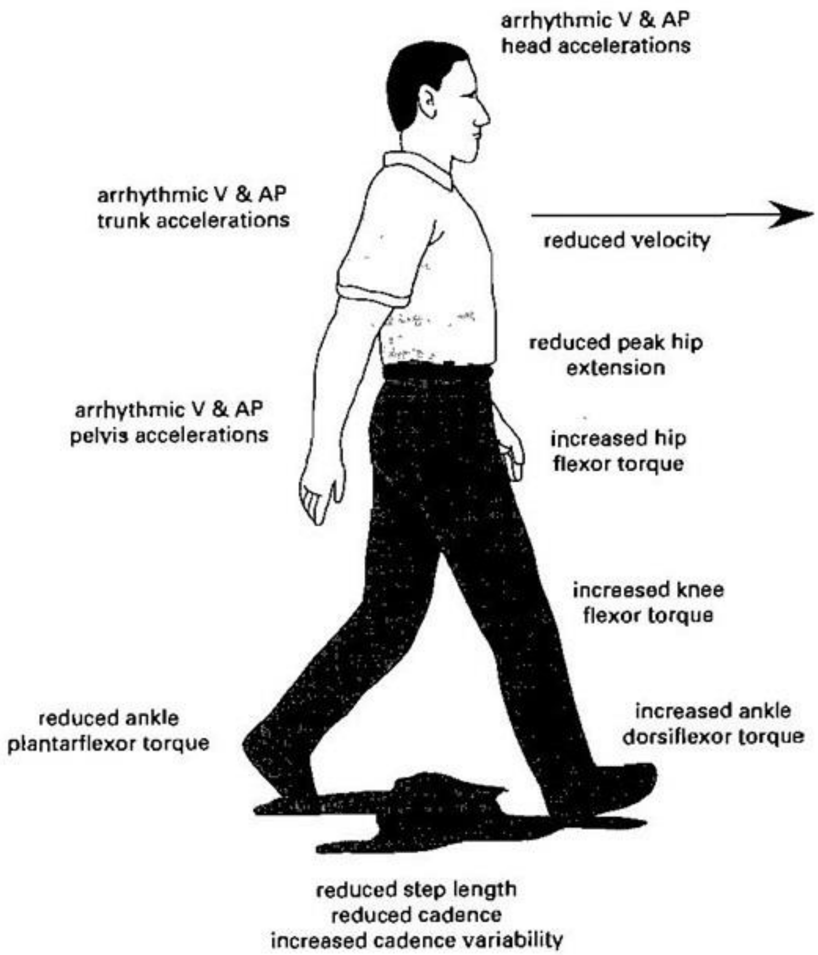


Figure 2.16 Changes in walking patterns during level walking with association to an increased falls risk (V = vertical, AP = anterior-posterior)(Lord et al., 2007).

Increased falls risk has also been linked to hip joint dynamics (Kerrigan, Lee, Collins, Riley, and Lipsitz, 2001). The changes in the time-distance parameters (e.g. reduced speed, reduced step length, reduced cadence and increased cadence variability) are significantly associated with the physiological factors that are also associated with an increased risk of falls, e.g. slowed reaction time, increased postural sway, reduced lower limb strength and reduced peripheral sensation. These physiological factors can be further emphasized by cognitive associations such as fear of falling and anxiety.

Menz et al. (2007) studied the relationship between the reduced sensorimotor function seen in older people, fear of falling and a number of gait patterns commonly seen in older people. The results of the study showed that the impaired sensorimotor function and fear of falling are related to a shorter step length which may lead to altered acceleration patterns of the head and pelvis. This study suggested that fear of falling may lead older people to adopting a safer walking pattern which consequently alters the dynamic movement and actually reduces stability during walking.

Gait variability has been linked to an increased risk of falls in the elderly (Hausdorff et al., 2001; Lord et al., 2011; Lord et al., 1996). It has been suggested that increased variability reflects the neural control of gait with sensitivities to ageing and pathological processes (Hausdorff, 2007). Increased variability is not only related to frailty as even healthy older adults show an increased variability when compared to healthy young adults (Kobsar et al., 2014; Oberg and Karsznia, 1993, 1994; Owings and Grabiner, 2004). Kang and Dingwell (2008) showed that increased variability in gait in the elderly was due to other factors rather than speed. The variability of different parameters can help in identifying different functions, e.g. step width and double support variability reflect postural control, whilst stride time variability reflects the ability to walk in a rhythmical gait cycle (Gabell and Nayak, 1984).

2.2.2 Gender Effects on Gait Biomechanics

Gender effects on gait have been studied in young and older, healthy and impaired people. Kerrigan, Todd and Della (1998) investigated gender differences in gait kinetics and kinematics in young adults (20-40 years) and found that females had greater hip flexion but less knee extension prior to initial contact, as well as greater knee flexion moment and greater knee peak power absorption pre-swing.

Samson et al. (2001) studied preferred walking speeds in females and males aged 19-90 and found that the absolute walking speed was lower for women in all age groups. Inoue et al. (2016) investigated factors affecting gait speed in community dwelling older adults and found that gait speed in older males was determined by age, body mass index and quadriceps strength while the determinants for older females were BMI and the strength of hip flexion hip abduction and quadriceps muscles. They also stated that in older females hip abduction strength relates to gait cycle variability.

While many authors report no gender effects on gait symmetry (Auvinet et al., 2002; Patterson, Nadkarni, Black, and McIlroy, 2012; Senden, Grimm, Heyligers, Savelberg, and Meijer, 2009), Kobayashi, Kakihana, and Kimura (2014) found a significant gender effect on gait symmetry with female participants showing greater symmetry than males. The authors also stated that the gender differences were higher in older participants compared to younger with older participants showing lower symmetry and regularity suggesting a combined effect of age and gender on gait asymmetry.

McKean et al. (2007) investigated individuals affected with osteoarthritis (OA) and reported the interaction of OA and gender in knee flexion angle and knee moments. While females with OA had altered biomechanics, males had similar biomechanics to healthy individuals. Similarly, Phinyomark, Osis, Hettinga, Kobsar and Ferber (2016) reported that females with knee OA exhibited greater hip adduction and knee abduction angles compared to males. Ro et al. (2016) also studied older adults without OA with similar findings; females presented with higher peak knee adduction moment, step width and pelvic width/height ratio. Castro, Pataky, Sole and Vilas-Boas (2015) investigated gender effects in ground reaction force production and found that females produced higher anterior-posterior and vertical forces in early stance.

2.2.3 Walking Speed Effects on Gait Biomechanics

Both vertical and anterior-posterior forces are affected by walking speed, step length and width. As speed increases, force peaks increase with the mid stance valley in the vertical force curve decreasing (Figure 2.17) (Andriacchi, Ogle, and Galante, 1977; Keller et al., 1996; Kirtley, 2006; Schwartz, Rozumalski, and Trost, 2008; Stansfield et al., 2001). Similarly, the anterior-posterior peaks increase with a flat phase between the posterior and anterior peaks become more prominent. As can be observed in Figure 2.17, at very low speeds vertical force resembles a square without the typical "two hump" pattern, rather a line representing 100% of body weight.

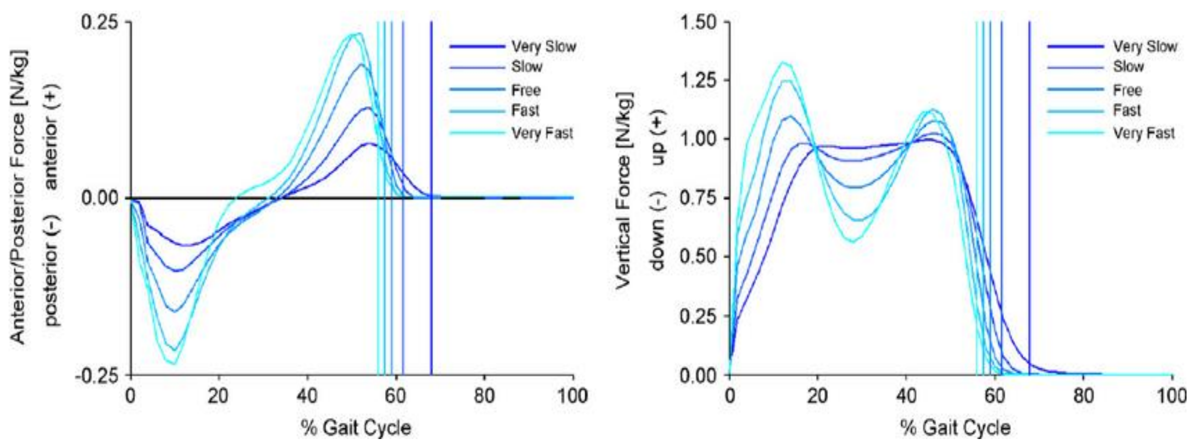


Figure 2.17 The effect of walking speed to force production in vertical and anterior-posterior directions. (Schwartz et al., 2008)

Simpson and Jiang (1999) investigated the kinetic data for individuals with toe-in, toe-out and neutral positions and found that the medio-lateral axis appeared to be sensitive to various positions of the feet upon landing. In some cases, the medio-lateral loading of the foot increased as the degree of toe-out increased. Individuals who walked with greater degrees of toe out created greater medial forces and impulses during the propulsive gait phase

Several authors have used ground reaction forces to quantify abnormal limb loading especially in patients with hip joint malfunction (James, Nicol, and Hamblen, 1994; McCrory, White, and Lifeso, 2001; Stauffer, Smidt, and Wadsworth, 1974). Other authors have used the frequency domain analysis and wavelet transformation of force-time-data to quantify the changes between populations. When comparing young and older female participants it has been noted that an ageing effect exists in the anterior-posterior direction, suggested because of a lower walking speed in the group of older people (Stergiou, Giakas, Byrne, and Pomeroy, 2002). In a similar manner, Winter (1991) observed very similar force data for young and older adults, with the only notable difference seen during the F_Y push off stage with less force produced by the older people (Winter, 1991). By combining the kinetic and kinematic data, moments and powers at the major joints can be analysed providing more detailed information on gait data.

Testing in the current study was done at two self-selected walking speeds. The self-selected preferred speed was used to reflect normal walking without a forced cadence. Self-selected walking speed has previously been used in a number of studies of walking function in older people (Alexandre, Meira, Rico, and Mizuta, 2012; Choi, Kang, Shin, and Tack, 2014; Kim and Kim, 2014; Kressig et al., 2004; Wewerka, Wewerka, and Iglseder, 2015; Wojcik, Thelen, Schultz, Ashton-Miller, and Alexander, 2001). Furthermore, Anderson et al. (2014) found that age differences in RCOF data disappeared when gait was controlled for walking speed and step length. The authors suggested that it is, therefore, important to allow for personal gait characteristics when investigating age-related differences in frictional biomechanics.

2.2.4 Measuring Slipping

A number of human-centred approaches have been used to evaluate slipping (Figure 2.18) such as using biomechanical methods associated with ground reaction forces (GRF) to estimate the walker's friction demand and centre of pressure (COP) trajectories, the movements and speeds of body segments, joint angles and moments, muscle activity, slip distances and speeds and time distance parameters of gait (Anderson, Franck, and Madigan, 2014; Brady et al., 2000; Chang et al., 2011; Chang, Matz, and Chang, 2012a; Kim, Lockhart, and Yoon, 2005; Redfern and Bloswick, 1997; Strandberg and Lanshammar, 1981; You et al., 2001). Human factors can also be assessed using subjective ratings such as rating scales, rankings and comparisons of footwear or floors and observations of protective responses to slipping. These two approaches can also be combined (system factors).

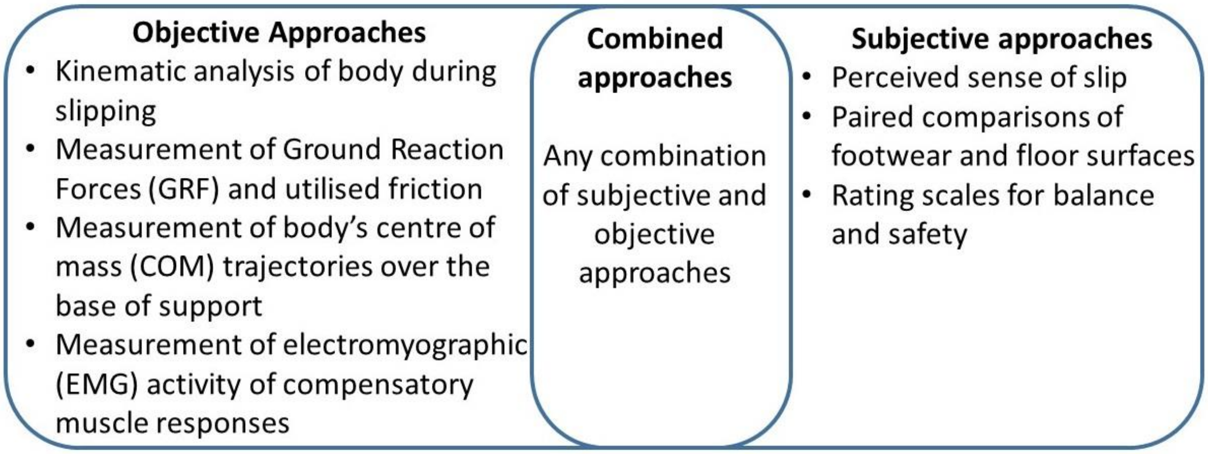


Figure 2.18 Human centred approaches to the measurement of slipperiness. Adapted from (Grönqvist, Abeysekera, et al., 2001)

The approach taken in the current study was to explore the intrinsic slipping risk factor associated with the individual's friction requirement based on foot-ground reaction force data. The Required Coefficient of Friction (RCOF), also referred to as the utilized friction, has been defined as the ratio of the horizontal shear and vertical force components of the GRF (Figure 2.19) (Perkins, 1978; Strandberg and Lanshammar, 1981).

Figure 2.19 presents the forces that create the friction requirement, the Horizontal force (F_H), the Vertical Force (F_V) and their ratio F_H/F_V. In this study vertical force is identified as F_Z, and the two shear forces are anterior-posterior force (F_Y) and medio-lateral force (F_X). During a gait cycle six RCOF peaks can be identified (Figure 2.19). Peak 1 represents the anterior force as the heel hits the force plate, peak 2 is the results of the posterior force exerted on the heel during early landing, peaks 3 and 4 are caused by anterior force. Peaks 5 and 6 are recorded during the toe off with toes applying posterior force recorded as an anterior ground reaction force.

Walking is regarded safe when the COF (μ) is greater than the ratio of the horizontal and vertical forces (RCOF), $\mu > F_H/ F_V$, that is, no slip will occur if μ between the shoe and the surface exceeds a critical friction criterion μC, i.e. if $\mu > \mu C$ no slip will occur (Grönqvist, 1999: Barnett, 2002) (Figure 2.20). This critical friction has been reported to be between 0.15 and 0.30 (Grönqvist, 1999).

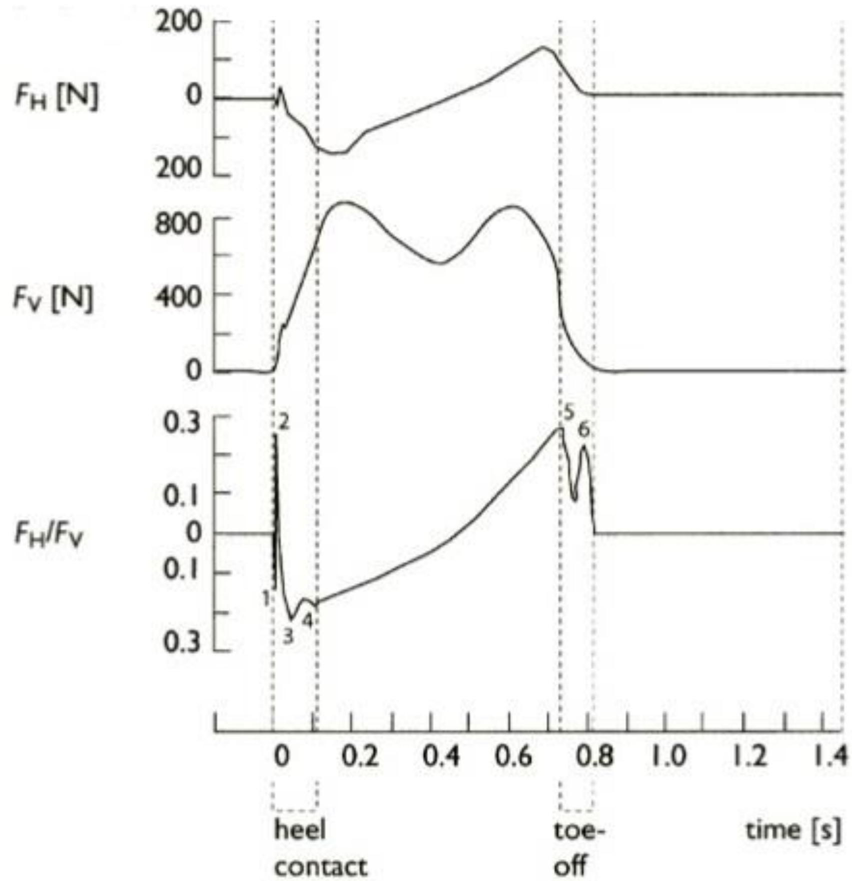


Figure 2.19 The Horizontal force (F_H), vertical force (F_V) and their ratio F_H/F_V, the required coefficient of friction. Six specific peaks can be identified in RCOF graph. (Grönqvist, 1999).

Calculating the required friction created by the GRFs as per an individual's walking style is a well-established method. The calculation has been used to quantify slipperiness on non-slippery flat surfaces (Fong, Hong, and Li, 2009; Kim et al., 2005; Redfern, Cham, Gielo-Perczak, Grönqvist, et al., 2001), inclined surfaces (Cham and Redfern, 2002b) and on contaminated surfaces (Cham and Redfern, 2002a; Fong et al., 2009; Liu, Li, Lee, Chen, and Chen, 2010; Manning and Jones, 2001), during a variety of walking tasks (Nagano, Sparrow, and Begg, 2013) and for a variety of age and ability groups (Burnfield and Powers, 2002; Lockhart and Kim, 2006; Lockhart, Woldstad, and Smith, 2002; Lockhart, Woldstad, and Smith, 2003; Moyer, Chambers, Redfern, and Cham, 2006).

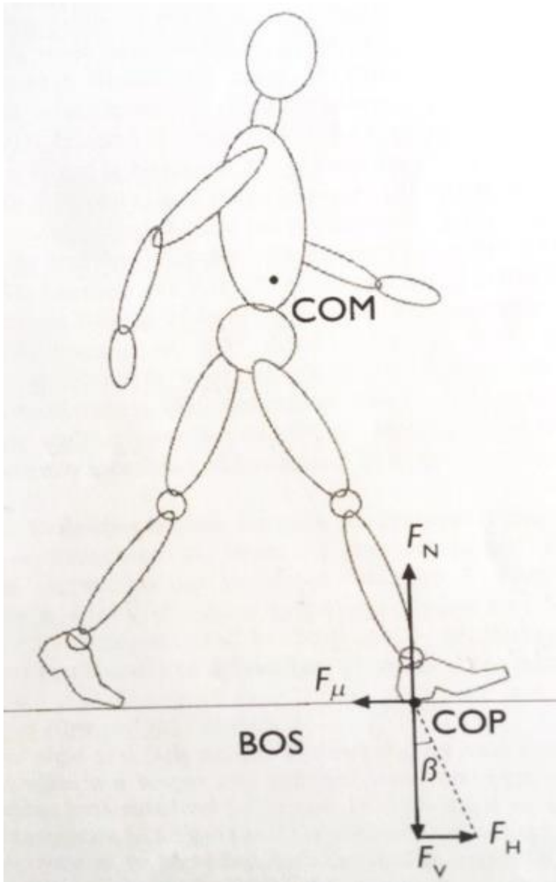


Figure 2.20 Minimum Friction Requirement for Slip Avoidance (Grönqvist, Chang, et al., 2001)

Zamora et al. (2011) suggested that people had different strategies to perceive and adjust when walking on surfaces with different frictional properties. 1) On surfaces with low COF (<0.25) the gait pattern is adjusted so that RCOF < COF in order to avoid slipping. In the optimum friction range (COF = 0.25-0.55) a balance exists between a soft landing and powerful push-off. In this optimum range a higher variability that in the other ranges. On high friction surfaces (COF > 0.55) gait has to be modified to maintain smooth landing. Beschorner et al. (2007) did a study using experimental tribometry and showed that friction measurements are affected by speed, shoe angle and normal force.

2.2.5 Ageing Effects on RCOF

Many ageing-related changes to gait biomechanics affect RCOF (Figure 2.21). Kim et al. (2005) reported that older adults walked at slower speed with decreased heel contact velocity and thus created a lower RCOF than young adults. It was, however, noted that the differences in the heel contact velocity were due to effects of walking speed and it was suggested that for older adults heel contact velocity was a good predictor of RCOF whilst for young adults walking speed, step length and the transitional acceleration of whole body Centre of Mass (COM) were better predictors. Others have also suggested that the slower transfer speed of COM from one limb to the other, is a risk factor for slip-induced falls (Lockhart and Kim, 2006; Lockhart et al., 2003; You et al., 2001).

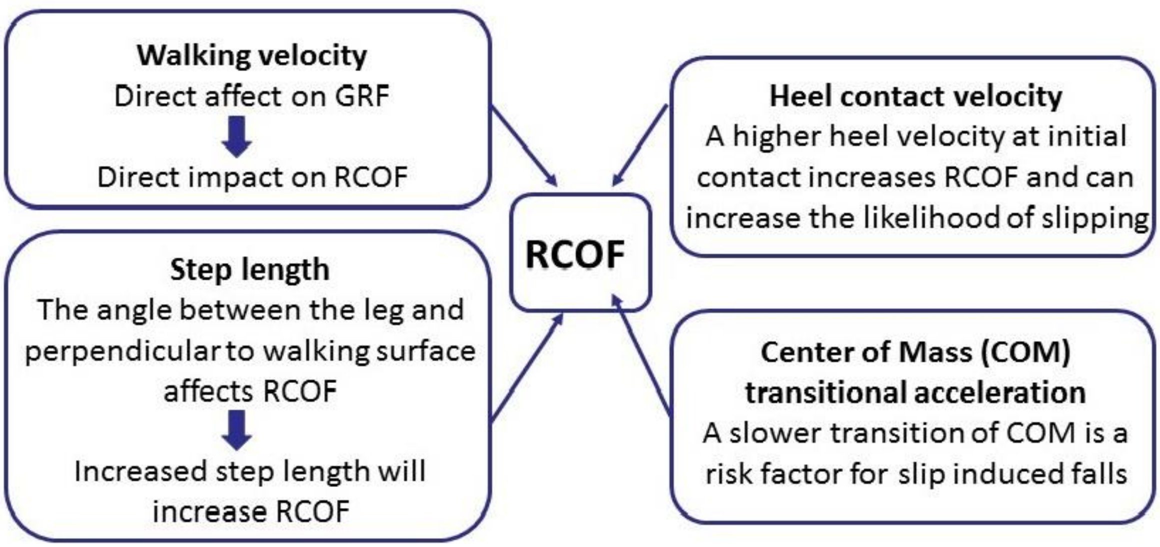


Figure 2.21 Slipping risks related to gait affected by ageing

An increase in RCOF has also been associated with the relative angle of the foot at ground contact thus implicating an increased RCOF with an increased step length (Grönqvist, Roine, Järvinen, and Korhonen, 1989; Moyer et al., 2006; Perkins, 1978). Vardaxis et al. (2001) stated that older participants had increased amplitude and variability in the peak medio-lateral (F_X) ground reaction forces (Vardaxis et al., 2001). Because F_X increases RCOF, it can be assumed that those with higher F_X, would also have higher RCOF. Other gait variables linked to increased slipping risk include decreased cadence and a faster foot-floor angular velocity at initial contact. Older adults showed a safer walking style (Moyer et al., 2006).

Some authors have indicated no significant difference in mean RCOF when comparing young and middle aged adults (Lockhart et al., 2002). Burnfield and Powers (2002), however, did find that a middle-aged group (40-59 years) had increased RCOF when compared to both young and old participants at all speeds (Table 2.3). It appears, therefore, that reliable changes in RCOF begin to appear with more advanced age and Kim et al., (2005) identified older adults as having significantly lower RCOF due to slower walking and heel contact velocity. In contrast, Lockhart et al. (2002) reported that RCOF in the elderly was not significantly different to that of young and middle aged adults. In another study Lockhart et al (2003) used both dry and randomly slippery surfaces and found that the older participants' heel contact velocity was significantly higher, step length was shorter and the transitional acceleration of full body COM was lower. No difference was found between the RCOF values of young and older adults.

Table 2.3 The data presented by Burnfield and Powers (2002) on RFOC values in age and gender groups

	Walking speed	Slow	Medium	Fast
Young (20-39 yo)	Females	.24 (.05)	.24 (.02)	.25 (.04)
	Males	.21 (.04)	.19 (.02)	.27 (.03)
Middle (40-59 yo)	Females	.24 (.04)	.27 (.02)	.26 (.05)
	Males	.22 (.05)	.26 (.06)	.32 (.09)
Senior (60-79 yo)	Females	.23 (.04)	.22 (.03)	.22 (.06)
	Males	.19 (.02)	.22 (.04)	.24 (.06)

Lockhart (2008) discussed the identification and prevention of slip induced falls in older people. The full understand of the factors involved in a slip requires not only a comprehensive analysis of intrinsic (ageing effects) and extrinsic (aspects of the environment) factors, but also by the choice of an approach and the various aspects and a chain of events and the hazards, events and outcome, as presented in Figure 2.22.

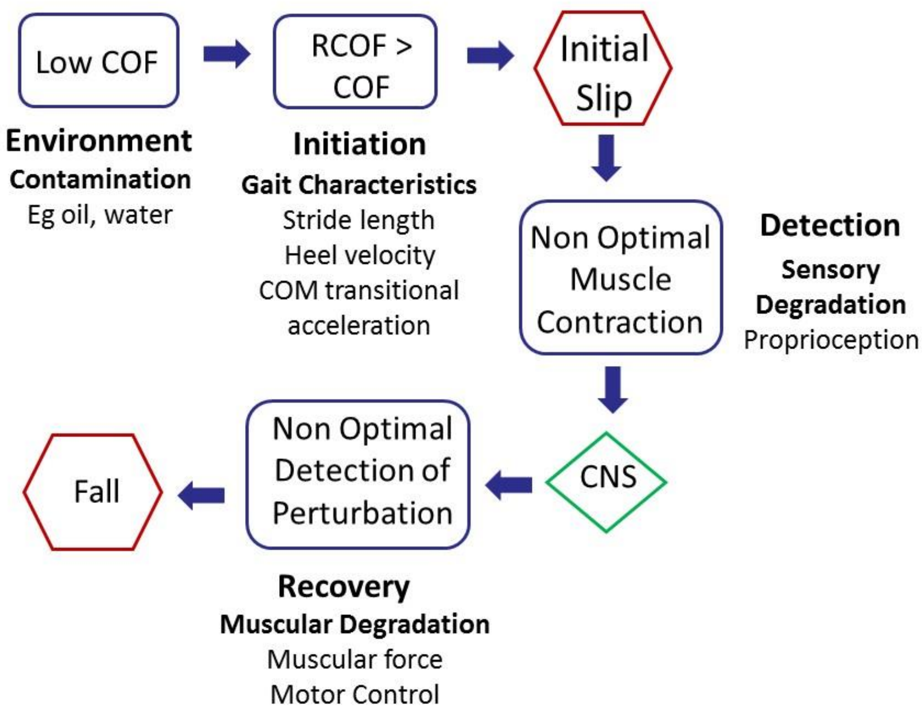


Figure 2.22 The process of unexpected slips and falls with potential causes and ageing related effects (Lockhart, 2008)

2.2.6 Gender Effects on RCOF

Research suggests that older women are more prone to falls than older men (Gabell et al., 1985; Prudham and Evans, 1981; Sattin et al., 1990; Talbot, Musiol, Witham, and Metter, 2005) with some studies reporting that the rate of recurrent falls in females is nearly twice that of males (Thaler-Kall et al., 2015). Gomes (Gomes et al., 2013) reported that the individuals at most risk of falls were single females with a lower muscular strength and physical performance of balance and gait as well as low independence of daily living motor tasks. Whilst many studies have suggested a higher incidence of falls in women, research findings on balance performance measurements are not consistent. Some authors have reported no gender differences while others have concluded that females seem to have more difficulties with the more demanding tasks of postural control (Baloh et al., 1994; Hageman et al., 1995; Wolfson et al., 1994). During stair descent, females are also reported to have greater COM displacement and peak instantaneous COM velocity (Hsue and Su, 2014). Berg et al. (1997) reported that the falls rate was similar for both genders but differentiated the circumstances of falls, suggesting that women most often fell due to trips and men due to slips. Furthermore, Berg et al. (1997) reported that females most commonly fell indoors at home (30% of falls) or outdoors at home (28%) whilst males fell outdoors at home with much higher frequency (46%) and only rarely fell indoors at home (5%). Whilst many studies have reported on the increased falls in older females, the research suggests that falls and their circumstances must be determined in both genders. One interpretation of the Berg et al. (1997) report is that males fell due to slips in the winter months associated with outdoor activities, such as snow clearing. It is, therefore, to be determined whether the rate and underlying cause of falls (slips and trips) in the genders are due to extrinsic factors (slippery surfaces in the winter months, tripping hazards in home indoor and outdoor spaces), rather than intrinsic factors associated with gender specific gait function.

Gender effects on force production during gait have been investigated and Li et al. (2001) and Chao et al. (1983) found that females create larger medio-lateral and anterior-posterior forces than men. Furthermore, at slower speeds, females use a longer stride than males (normalised to body height) while at faster speeds, males have a longer normalised stride than females (Kerrigan et al., 2001). Step length and heel contact angle affect RCOF and these gait changes are likely to be reflected in gender differences. Indeed, Burnfield and Powers (2002) analysed the gait data of three age groups (young, middle age and senior) and three walking speeds (slow, medium and fast) and found that women had higher RCOF values at slow speed whilst men had higher RCOF values at a fast walking speed. At medium speed the middle-aged participants had higher RCOF values than both young and older adults.

Rozin Kleiner, Galli, Araujo do Carmo and Barros (2015) investigated the effect of flooring on barefoot gait according to age and gender and reported that females had larger RCOF values during heel contact. They concluded that friction during walking was affected by age, gender and flooring. In a similar manner both age and gender were noted as factors by Björnstig et al. (1997) who stated that elderly women and young men are more prone to slips when walking on ice and snow.

2.3 Literature Review of Research Methods

2.3.1 Ground Reaction Force Sampling Frequency

Perkins (1978) discussed measurement of the grip between the shoe and ground and described a method using ground reaction forces to calculate the static coefficient of friction from which slipping might be predicted. Earlier studies conducted in the 1950s and 1960s had used the ratio of Horizontal force (F_H) vertical force (F_Y) to define slipping probability. Perkins (1978) then explored these GRF-based predictions by combining kinetic and kinematic data using force plate and time-exposure photography to closely observe the foot's motion (Perkins, 1978). Perkins used 400 Hz which allowed the "...maximum natural frequency to be obtained" and was high for the technology of the time. As technology has advanced, data can be sampled at much higher frequencies. In the slipping literature, sampling frequencies from 60 Hz to 2400 Hz are reported with some authors not reporting their sampling frequency (57).

2.3.2 RCOF Calculations and Slipping Probability

Perkins (1978) used the ratio of horizontal force (F_H) to vertical force (F_Y) to calculate RCOF, the friction demand. While suggesting that the medio-lateral force (F_X) could be included in the RCOF denominator Perkins used only the anterior-posterior force (F_Y) component, concluding that "...the error caused by ignoring F_X was less than that which would have been obtained by electronically calculating the resultant...". He suggested, furthermore, that F_X makes a relatively small contribution to the horizontal force when walking (Perkins 1978, p. 73) and historically many studies, consistent with Perkins have not included F_X.

More recently, some investigators reported including the medio-lateral (F_X) force component in their RCOF calculation while others did not specify whether F_X was considered (Table 2.4).

Table 2.4 Sampling frequencies, filtering methods and RCOF calculations used in previous studies

Sampling Frequency	Filter	RCOF calculation	Author
200 Hz	-	F_Y/F_Z	(Cooper et al., 2008)
1000 Hz	4th order zero-lag Butterworth Low pass, cut off 36Hz	F_Y/F_Z and $F_X + F_Y/F_Z$	(Chang et al., 2011)
1200 Hz	-	$F_X + F_Y/F_Z$	(Nagano et al., 2013)
60 Hz	-	F_H/F_Z, F_H not defined	(Lockhart et al., 2003)
1200 Hz		Mention F_H, but state F_X/F_Z as per Perkins (1978)	Kim et al., 2005)
600 Hz	-	Mention Horizontal force, state F_H/F_Y as per Perkins (1978)	(Lockhart, Smith, and Woldstad, 2005)
2400 Hz	Low pass wavelet, cut off 50 Hz	Divide shear force by the normal force. Also mentioned anterior	(Osis, Worobets, and Stefanyshyn, 2012)
1200 Hz	4th order zero lag Butterworth cut off 250 Hz	F_Y/F_Z	(McGorry, DiDomenico, and Chang, 2010)
1000 Hz	4th order zero-lag Butterworth Low pass, cut off 36Hz	$F_X + F_Y/F_Z$	(Chang et al., 2012a)
1000 Hz	4th order zero-lag Butterworth Low pass, cut off 36Hz	$F_X + F_Y/F_Z$	(Chang, Matz, and Chang, 2013)
240 Hz	-	F_H/F_Z, F_H not defined	(Hanson et al., 1999)
-	-	F_Y/F_Z	(Zamora et al., 2011)
1000 Hz	4th order zero-lag Butterworth Low pass, cut off 36Hz	$F_X + F_Y/F_Z$	(Chang et al., 2012a)
400 Hz	-	F_Y/F_Z	(Perkins, 1978)
500 Hz	-	$F_X + F_Y/F_Z$	(Grönqvist, Matz, and Hirvonen, 2003)
350 Hz			(Cham and Redfern, 2002b)

Chang et al. (2011) studied the effect of F_X on the calculation using three age groups at self-selected normal and fast walking. Their results showed a significantly higher RCOF for every participant in all speed conditions, with the medio-lateral force component increasing RCOF by more than 10% in 7.2% of step cycles. The authors also found that by including F_X, RCOF existed earlier (in ms) than when using vertical force only.

In the present project RCOF was calculated following Chang et al. (2011) using all three dimensions of ground reaction force:

$$\text{RCOF} = \frac{\sqrt{F_y^{\ 2} + F_x^{\ 2}}}{F_z}$$

Equation 2.1 RCOF, F_x included

where F_Y is Anterior-Posterior force, F_X medio-lateral force and F_Z Vertical force.

To confirm the effect of the medial-lateral force in the calculation RCOF was also calculated excluding F_X as originally presented by Perkins:

$$\text{RCOF } (F_X \text{ excluded}) = \frac{F_y}{F_z}$$

Equation 2.2 RCOF F_X Excluded

where F_Y is the Anterior-Posterior force and F_Z is the vertical force.

A number of authors have estimated the risk of slipping and an early study by Harper et al. (1961) estimated the likelihood of slipping using RCOF excluding F_X and presented the data as a mean values only. The study reported the mean RCOF as 0.17 (SD 0.04) for men and 0.16 (SD 0.03) for women. Harper et al. (1961) used Pearson curves and the limited β- function to estimate the chance of RCOF and concluded that an able-bodied person had a one in a million chance of slipping if the friction between surface and footwear was 0.36 when walking on a level surface. Their data were later analysed by Pye (1994) who presented a calculation that showed a 1 in 20 chance of slipping when COF was 0.24. The participants in this study had a much higher chance of slipping at that COF level. The percentage estimates of the value RCOF 0.2 to appear were 56% and 41% for older females and males respectively and 41% and 16% for young females and males respectively. These higher probabilities are, however, likely due to the much greater RCOF reported in this study.

Statistical methods have usually been employed to estimate slipping risk, for example Hanson et al. (1999) used a model where fall incidents were compared with values of available friction. Their study used the mean RCOF and COF with a logistic regression model to predict the probability of slips and falls in ramp walking and showed a relationship between measured friction, slips and falls. This study was based on data from five young adults and a small number of trials and there was no examination of variability either within or between participants.

Barnett (2002) used mathematical modelling to quantify the probability of slipping in different walking conditions. In Barnett's model surface/floor friction coefficients of the same floor material were measured repeatedly to plot a COF distribution and the scatter and asymmetry of COF described. This model provided a straightforward simulation of the relationship between various surfaces with different frictional properties and the probability of slipping. While Barnett (2002) focused on modelling the environment using surface friction data and not measuring for human force-production variability, the important effects of high and low human variability could be simulated. Barnett and Poczynok (2003) discussed the floor reliability with respect to slip and fall theories. Their calculation on an imaginary surface with COF 0.366 showed that walks of 10 steps caused 10% of the walkers to slip and a in a walk of 1000 steps this increased to 97%.

Chang (2004) created a model that assumed a stochastic distribution of RCOF given previous reports of the variability of human gait and concerns about using only the mean to represent RCOF (Barnett, 2002; Marpet, 2002). Chang et al. (2004) found significant differences between his model and previous models and discussed the limitations of ignoring the stochastic nature of both available and required friction coefficient data. More recently Chang, Matz, and Chang (2014) developed their model further for different surfaces. Besser, Marpet, and Medoff, (2009) used a logistic regresson model to discuss pedestrian safety. In their model probability was presented as a graph illustrating that a steper curve implies higher precision. A similar statement can be made from our data.

Many slipping probability calculations have assumed a normal distribution in the RCOF data. As discussed earlier, gait variability increases as we age and is considered to be associated with an increased risk of falls (Hausdorff et al., 2001; Lord et al., 2011; Lord et al., 1996). Begg et al. (2007) found that Minimum Foot Clearance (MFC) distributions were non-normal (skewed) and variability was high (Begg et al., 2007). Best and colleagues (Best and Begg, 2008a; Best et al., 1999) then developed a mathematical model to calculate the probability of tripping on an obstacle of a specified height assuming no pre-planned correction to the foot's swing phase trajectory. The prediction was achieved by estimating MFC probability accounting for skewed and kurtotic data.

Similarly, the RCOF distribution can be used to estimate the probability of a chosen RCOF value. The model presented by Best and Begg (Best and Begg, 2008a, 2008b), initially developed to estimate the likelihood of tripping, was applied here to estimate slipping probability. A previous report (Karaharju-Huisman et al., 2004) indicated that this method could be suitable for estimating slipping probability by calculating RCOF and then comparing the probability data to known surface friction values to estimate slipping probability.

Past research has advanced the estimation of slipping risk but a larger number of trials is needed in order to quantify slipping risk while allowing for human variability. This study was designed to fill the knowledge gaps of previous studies on slipping risk estimation. The Best et al. (1999; 2000) model, adopted later by Karaharju-Huisman et al., (2004) was used to estimate slipping probability (PS) during level walking.

2.4 Aims and Hypotheses

Falls in older people are global challenges with investigations on the reasons leading to falls considered a high priority in the healthcare sector. There is ample evidence that slipping contributes greatly to the incidence of falls in older adults. Previous research on slipping risk has focused on both intrinsic and extrinsic factors, with the aim of estimating slipping risk via examinations of the interface of foot and the underlying surface. The common method of analysing the intrinsic slipping properties has been through investigations of the required coefficient of friction. This data has frequently been presented as a mean value, despite the problem of information being lost when averaging the data. Variability is often presented via standard deviation, however, the individual inconsistency presents in various forms, such as kurtosis and skewness in the data distribution. Therefore, alternative methods must be created to treat the data in a way that allows for individual estimations on slipping risk.

The investigations of gait function are commonly done over series of repeated trials on a walkway. These trials often conducted in a situation where a verbal command is given to the participant for start and stop. It has been reported that the choice of the protocol affects the data, including several time-distance parameters as well as variability. In slipping studies it is a customary practice to use the repeated trials. In many cases, slippery surfaces are introduced and thus only one trial is included in data analysis. When estimating the steady-state gait, as used in daily activities, a longer data sample must be included and gait must be investigated during ongoing walking.

A knowledge gap exists when discussing slipping risk in older people. As variability is known to increase in the gait of older people, data from ongoing walking needs to be investigated. Also, the gait data from older people is likely to have a non-normal distribution and needs to be correctly modelled to estimate the true slipping risk. The aim of this study is to incorporate these features in the analysis of slipping risk to provide more comprehensive information that may lead to improved strategies for the prevention of slipping, and therefore a reduction on the incidence of falls in older adults.

This study was designed to investigate the intrinsic frictional properties of two age groups, healthy younger adults and healthy older adults, during continous long-term overground walking on a level surface at both self-selected normal and fast speeds. The individual and group characteristics of RCOF were determined explored and effects of walking speed, age and gender tested. Furthermore, the probability of slipping during level walking was estimated using a novel mathematical probability model.

The aims of this study were as follows:

(1) To Investigate methodological issues: (i) to determine the effect of mediolateral forces in the RCOF calculation and (ii) to determine appropriate presentation of central tendency. Null Hypothesis: No significant effect in the outcome in the calculation of the Required Coefficient of Friction (RCOF) when the medio-lateral force is included in the calculation of the required coefficient of friction (RCOF).

(2) To determine the intrinsic frictional preoperties by the determination of the effect of age, gender and walking speed on major descriptive statistics of RCOF distribution during long term walking. Null Hypothesis: (i) No significant effect of walking speed upon the major descriptive statistics of RCOF; (ii) No significant effect of age upon the major descriptive statistics of RCOF; (iii) No significant effect of gender upon the major descriptive statistics of RCOF.

(3) To investigate the probability of slipping for both genders in the younger and older poplulations at normal and fast walking speeds by applying a novel mathematical model. Null Hypothesis: (i) No significant age affect in the probability of slipping; (ii) No significant gender effect in the probability of slipping; (iii) No significant speed effect in the probability of slipping.

3 Research Methods

3.1 Participants

A total of 104 healthy young and older participants (53 male and 51 female) were recruited and divided into four groups as follows: (1) 25 healthy older females aged 65–86 years (mean age 71.4, SD 5.4 years), (2) 26 young females aged 22-36 years (mean age 27.9, SD 4.6 years), (3) 25 healthy older males aged 65-85 years (mean age 72.3, SD 5.0 years) and (4) 28 young males aged 19 to 38 years (mean age 29.5, SD 4.7 years). Body mass, height and other anthropometric data are in Appendix F. The young participants (18–35 years) were recruited from the VU academic community and from the author's friends and associates. The older adults were recruited via advertisements in local newspapers, newsletters to walking groups and cultural groups and some had been participants in previous studies at Victoria University.

All participants were physically active with the ability to walk at comfortable self-selected normal speed for a minimum of 30 minutes and at fast speed for 15 minutes. They were screened for slipping history and medical history and the 50 older people (equal number of males and females) underwent a further examination to assess falls history, cognitive state and mobility function as described in sections 3.1.1. All screened candidates who satisfied the requirements for the study were eligible to take part.

3.1.1 Screening for Older Adults

All older participants underwent three screening processes. First was a verbal assessment via telephone when the prospective participants initially contacted the researcher. The key questions were: (1) Do you consider yourself fit and active? (2) Are you free from any musculoskeletal or neurological diseases? (3) Have you had any falls within the last 24 months? (4) Are you aged between 65 and 85 years of age?

If participants were considered suitable after the initial telephone interview an information pack (appendix A) including the screening procedures, inclusion and exclusion criteria and the biomechanical testing procedures were mailed to them. The information pack also included a health check form to be filled by the participants' general practitioner (Appendix B) to confirm good health with no medical conditions (neurological, musculoskeletal or cardiopulmonary) that would preclude participation. Approval from the general practitioner made the prospective participant eligible to undertake in the screening tests, the inclusion and exclusion criteria are presented in Table 3.1.

Table 3.1 Inclusion and exclusion criteria for the healthy older participants

Inclusion	Exclusion
○ Aged 65 years or over ○ Living independently ○ Relatively fit and healthy ○ Regular walking without any walking aids	○ History of falls in the previous 12 months ○ Recent lower limb fracture or serious orthopaedic conditions (e.g. joint replacement, chronic low back pain, severe osteoarthritis limiting joint movement) ○ Any neurological conditions affecting ambulation (e.g. stroke, brain injury, dizziness, unsteadiness) ○ Any cardiopulmonary disease affecting long term walking ○ Any visual impairments not correctable with glasses

Prior to the commencement of the trial in the laboratory a number of clinically verified screening tests (Table 3.2) were completed to assess the eligibility of the participants. The screening tests consisted of commonly used tests: questionnaires of slipping and medication history, modified mini-mental state test and modified falls efficacy test. Tests of vision included the Melbourne Edge Test (vision edge contrast sensitivity) and the Bailey-Lovie Log Mart chart (Visual aquity). The Timed Up and Go was the selected mobility test.

Table 3.2 Clinical tests and the exclusion cut off values

Area tested	Test used	Exclusion criteria
Fear of falling	Modified Falls Efficacy	Score <7.7
Cognition	Modified Mini-mental state	Score <23
Vision edge contrast sensitivity	Melbourne edge test	Score <16 dB
Visual acuity	Bailey-Lovie Log MART chart	logMAR 0.4
Mobility	Timed Up and Go	Time > 8.5 sec to complete

3.1.1.1 Fear of falling

The modified falls efficacy scale (MFES) is a questionnaire relating to the level of fear experienced during daily activities (Hill, Schwarz, Kalogeropoulos, and Gibson, 1996) in which the participants rate their confidence when performing 14 everyday tasks. Confidence is marked on a visual analogue scale (0-10) with zero indicating no confidence and 10 very confident. This questionnaire has been found to be reliable for evaluation of fear of falling in community dwelling older adults. Hill et al. (1996) (Appendix D) found that the mean test score for a group of normal active elderly adults with no history of falls was 9.76 (SD 0.32) and the mean score of the clients of the falls clinic was 7.69.

3.1.1.2 Cognitive function

The Modified mini-mental state examination (MMSE) (Folstein, 1975) (Appendix E) is a test of cognition comprising questions about orientation, registration, attention, calculation, recall, language and spatial orientation. The maximum test score is 30. Previous research has found that the cut off for poor cognitive state and thus risk of falls is 23 (Lord and Clark, 1996; Murden, McRae, Kaner, and Bucknam, 1991), the value also set as exclusion in the present study.

3.1.1.3 Vision – contrast sensitivity

The Melbourne Edge Test (MET) (Verbaken and Johnston, 1986) measures contrast sensitivity using 20 circular patches with a series of edges, gradually declined in contrast and orientation. The participant's task is to identify the correct orientation of the circular patch, with the last correct orientation indicating the edge contrast sensitivity score, measured in decibels (1 bB = -10 log). The lower the MET score is, the worse the contrast sensitivity, and higher the risk of falls. Lord et al. (Lord, Clark, and Webster, 1991) stated that scores of less than 16 dB are considered as poor edge contrast sensitivity.

3.1.1.4 Vision – visual acuity

Visual acuity, distance vision, was measured using the Bailey-Lovie logMAR chart (Bailey and Lovie, 1976). The test consists of 14 rows of five letters, with letters progressively decreasing in size with every row. The participant views the letters from the distance of 3 meters. If glasses are normally worn, they are to be used during the test. The participant attempts to read the letter from the largest to the smallest, from the top row, from left to right. The test is finished when the participant is unable to read the letters or identifies a letter incorrectly. The score of the last row correctly read is the score of vision acuity. Lord et al (1991) rated a logMAR 0.4 as poor and this value was used as the exclusion criteria.

3.1.1.5 Mobility

The Timed Up and Go test (TUG) is one of the most used clinical tests to examine functional mobility in community dwelling older adults (Beauchet et al., 2011; Donoghue, Savva, Cronin, Kenny, and Horgan, 2014; Kojima et al., 2015; Savva et al., 2013). In the test, the participant is seated on a standard chair (seat height 45 cm) with their back against the back of the chair and arms resting in the chair arms. When the tester says "go" the participant is to stand up from the chair, walk three meters to a mark at their comfortable walking speed, turn around, walk back to the chair, turn and sit back down. Timing starts at the command "go" and stops when the participant returns and is seated with their back against the back rest. The time taken is the test score. In their study Shumway-Cook et al. (Shumway-Cook, Brauer, and Woollacott, 2000) found that the mean score for the test in the group of non-fallers was 8.4 (range 6.4 - 12.6).

3.2 Biomechanical Testing Procedures

To allow for normal walking mechanics, participants wore their own comfortable walking shoes with high friction rubber soles and rounded heels. Participants were first familiarised with the walkway to ensure comfort and safety. This procedure also allowed the researcher to observe the participant's preferred footfall pattern and adjust the marker cones to maximise the frequency of complete force plate contacts, without any pre-planned adjustments to target the force plates. The walkway was a rectangular 30m path on the laboratory floor (Figure 3.1). Timing gates were placed along the straight part of the walkway five meters apart to measure self-selected walking speed, allowing for possible deceleration and acceleration before and after the measured distance. The walking speed (m/s) was calculated as 5m/(time taken in s) and was measured every time the participant walked through the timing gates.

The task was to walk for either 30 minutes or for the time needed to complete 100 strides at normal self-selected walking speed. Following a 5 to 10 minutes rest break the test was repeated at a self-selected fast walking speed for 15 minutes or at least 50 strides suitable for analysis, where clean right and left heel contacts were recorded by the force plates. Ten older females, 9 older males and 1 young male requested stopping testing at normal walking speed before the target number of trials. Eight older females, 9 older males, and 1 young female stopped the fast walking trials earlier than the criterion. All participants attempted both normal and fast walking trials.

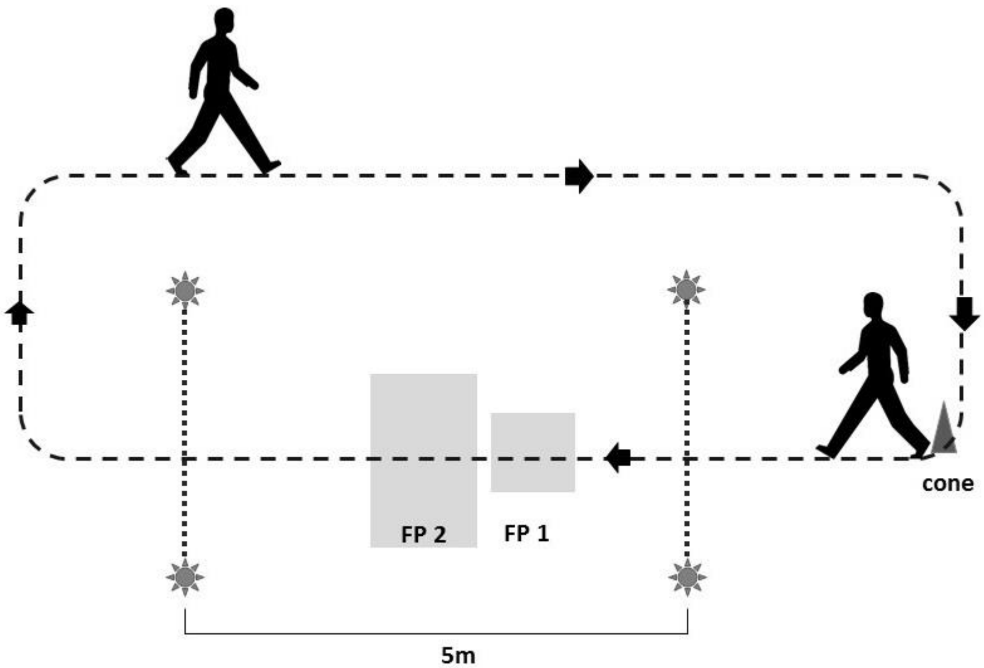


Figure 3.1 The setup of the walkway with 2 force plates, light gates for the measurement of time taken and a cone to be used as an adjustment for heel positioning thus allowing for gait adjustment outside the measurement area.

The participants walked clockwise to step on two AMTI force plates (FP) (Figure 3.1, force plate 1 (FP1) and force plate 2 (FP2) embedded in the middle of the walkway. The walkway was covered with a high friction mat and the participants were unaware of the location of the force plates to avoid pre-planned adjustments to target them. The participants were advised that testing would take about 30 minutes. It was also reinforced that they could stop at any time if the if they experienced any discomfort or fatigue. Testing was concluded after 100 successful strides had been sampled.

After the normal walking speed trials, there was approximately 15 minutes resting before undertaking the fast speed trial. Participants were instructed that this condition would take around 20 minutes since approximately 50 successful strides were sampled.

3.3 Data Processing

Each participant had, on average, 100 trials (normal speed) and 50 trials (fast speed) with the number of processed files exceeding 16,000. Data processing was carried out in Matlab. Sampling frequency was 4000 Hz and the raw force-time data were smoothed using a Butterworth 4th order filter with a cut off frequency of 36 Hz (Chang et al. 2011). The required coefficient of friction (RCOF) for every step was then calculated from the filtered GRF data and from the F_X, F_Y and F_Z data the coefficients of friction calculated (Figure 3.2).

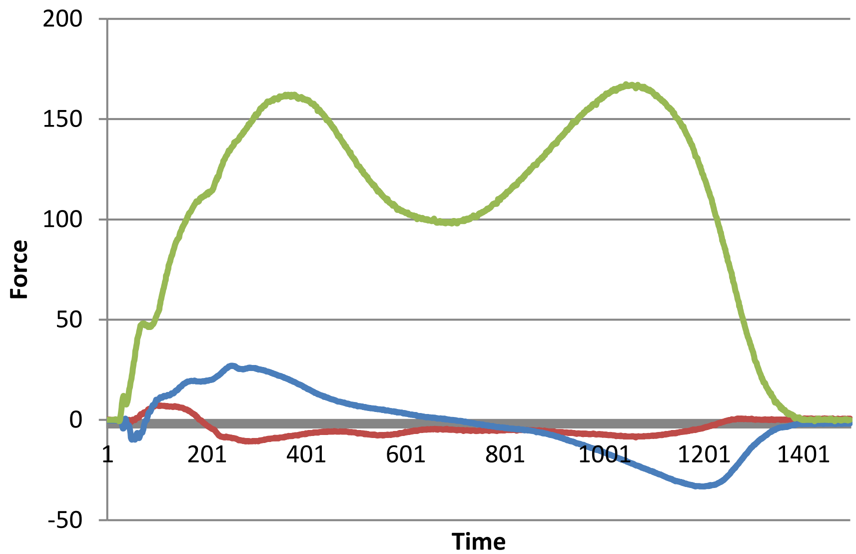


Figure 3.2 Ground Reaction Forces

To confirm any RCOF asymmetry, footedness was detected from the force-time data using the mediolateral force (F_X) trajectory. F_X typically shows an initial lateral force followed by a medial force. If F_X initially has a positive (lateral) peak, a right foot contact is identified while an initial negative (medial) peak indicates left foot contact. (Figure 3.3).

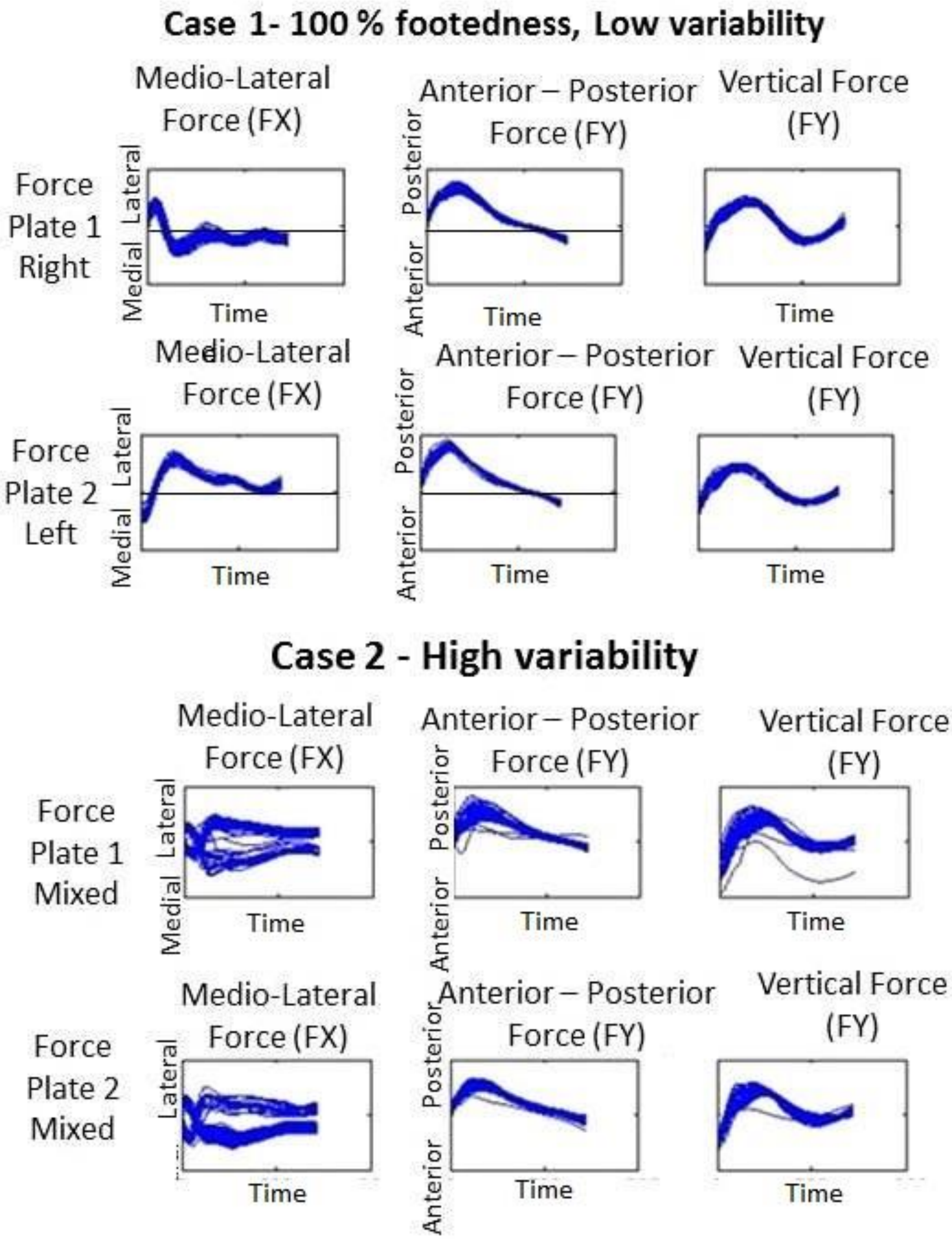


Figure 3.3 Using Ground Reaction Force to define footedness

Figure 3.3 presents the bilateral GRF data from two participants. In case one the participant has the optimal walking pattern with all data samples on one force plate with the same foot. Right foot is stepping on FP 1 as identified by the F_X graph.

Similarly, all hits of FP 2 are by the left foot. In case 2 more variability can be seen and it can also be noted that the force plates are contacted by both feet. With the definition of footedness using the F_X data, all data samples can de clearly identified as either right or left foot.

Raw GRF data was also used to detect unusual variability, often due to poor force plate contact. Case 1 (Figure 3.4) presents data with greater variability, with a few alternate foot contacts. Whilst some data sets must be deleted, most files are included in analysis.

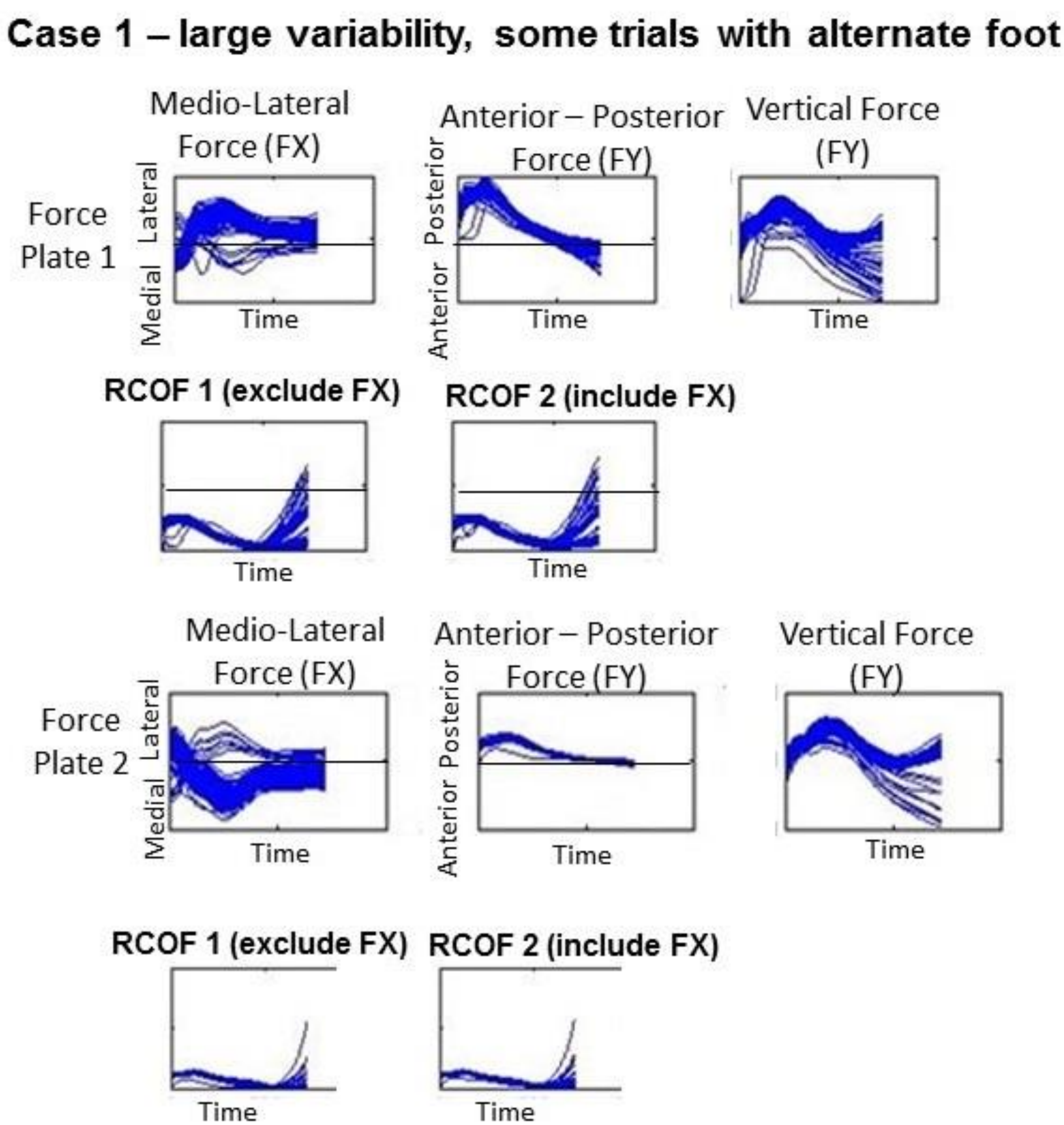


Figure 3.4 Excessive data variability, case 1

Figure 3.5 however presents data from a participant whose data inclusion has to be carefully analysed. It can be noted that foot contacts alter, but also by using the vertical force (F_Z) data a normal force pattern is not detected and therefore a clear contact cannot be verified. By using the data selection principles, the data files not filling the criteria are excluded.

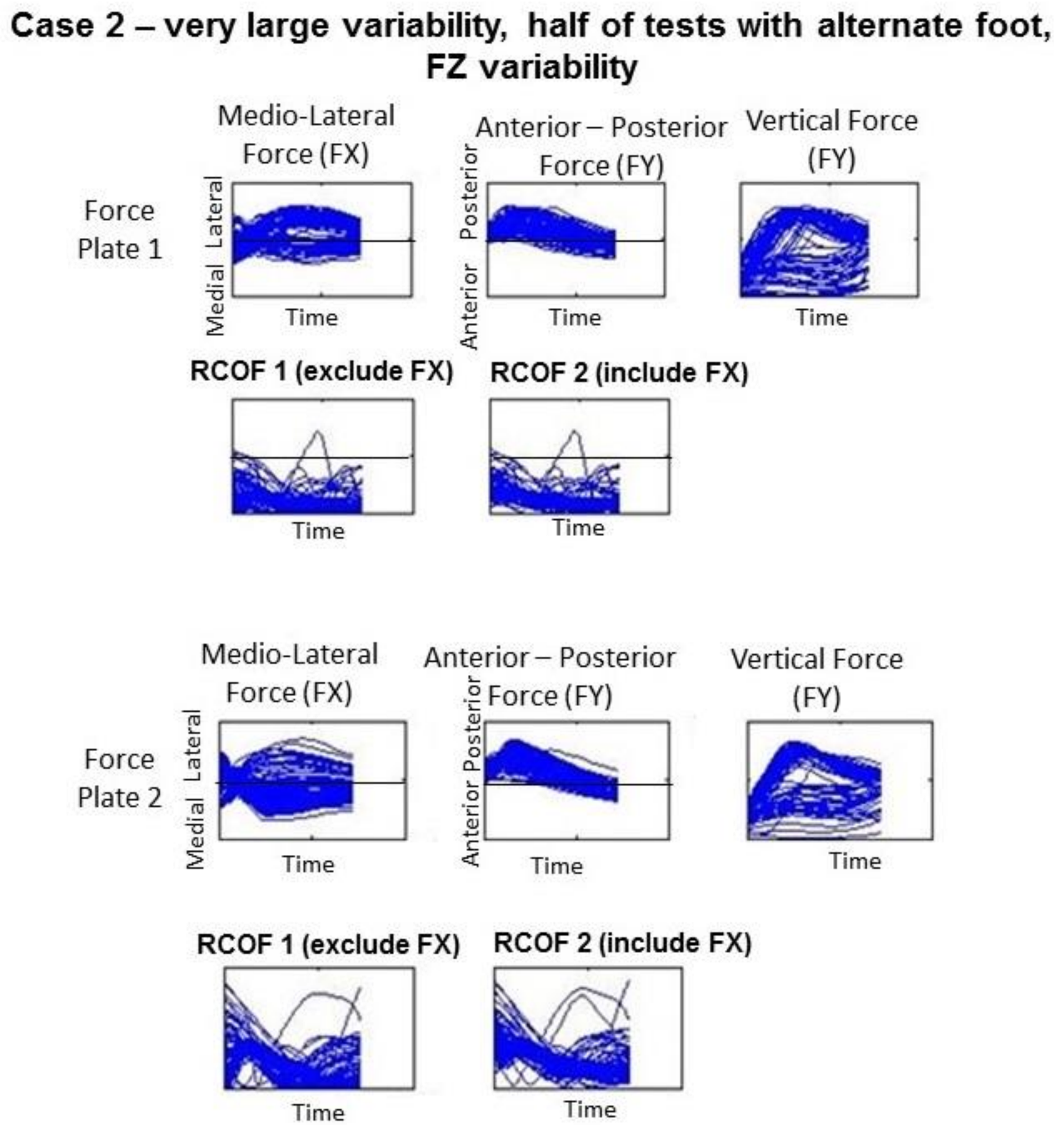


Figure 3.5 Excessive data variability, case 2

In the Matlab program heel contact was identified when the vertical force (F_z) was greater or equal to 10 N (Chang et al., 2011). To confirm this event the following 3 data points were required to increase, i.e.: (1) F_z $Data_x$ had to exceed 10 Newtons and (2) F_z $Data_x$ < F_z $Data_{x+1}$ and (3) F_z $Data_{x+1}$ < F_z $Data_{x+2}$ etc. From the 10 N criterion, the following 200ms of data were included in the RCOF calculations. The data were processed following the principles of the pseudo code: the constants were defined and the file names and vectors required for the program execution were included. Upon starting the program all individual files were converted to analysis vectors and filtered. The start and end points of the analysis, as well as the footedness, were defined and the RCOF values calculated. If the data fulfilled the criteria, the data were stored. If violations were found, the data were discarded. The complete program can be seen in Appendix H

3.3.1 Estimating RCOF Probability

As illustrated in Figure 3.6, a data set with the same mean value may present a variety of distributions, two types often seen in gait data are kurtosis and skewness.

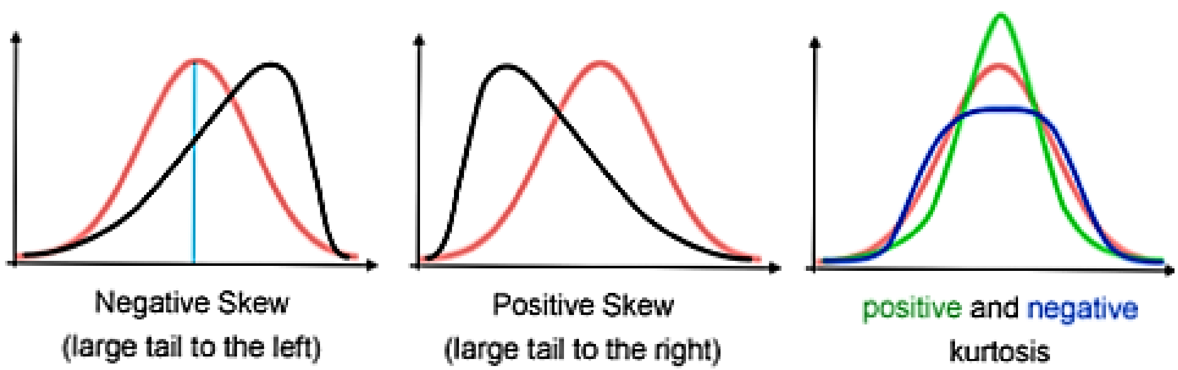


Figure 3.6 Non-normal data distribution – examples of negative and positive skewness and kurtosis. (Scrathapixel, 2016)

Kurtosis is a measure of the shape of a data distribution centred around the midpoint and can be referred to as a description of the peakiness or flatness compared to a normal distribution. Positive kurtosis describes a steep peak with a higher maximum than in the normal distribution and negative kurtosis gives a flatter shape. Skewness of a data sample is a measure of the asymmetry of the probability distribution around its statistical mean. A skewed data set is described by the shift of the data to the left (negative skew) or with a tail to the right (positive skew). Negative skew indicates a larger concentration of data points to the left of the mean with a tail to the left, whereas positive skew is reflected in a greater concentration of data to the right of the mean and a tail to the right. These two skew patterns have been seen in RCOF data as shown in Figure 3.6

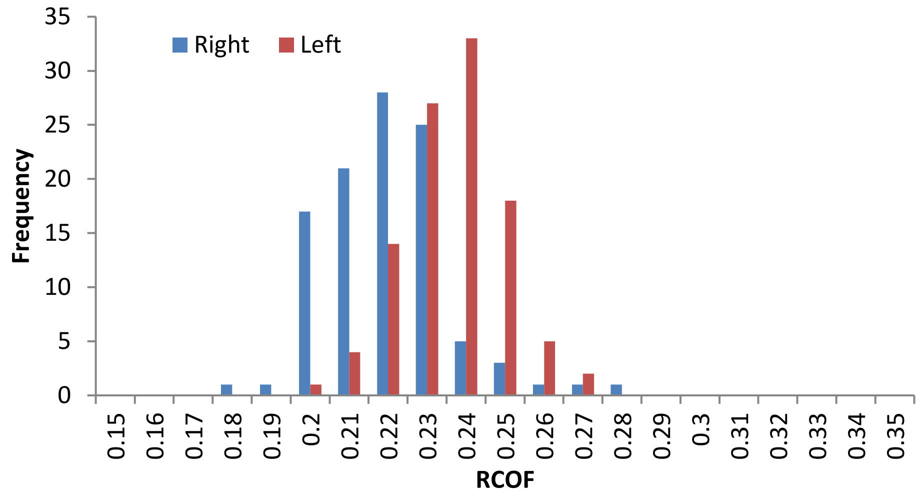


Figure 3.7 RCOF distribution for right and left limbs over 105 steps walked by male.

The mean RCOF value for the right is 0.22 and for the left 0.24. Note the different data distribution with the right-side data having a strong positive kurtosis and slight skewness and the left foot less kurtosis and minimal negative skew, as summarised in Table 3.3. Observation of the RCOF data shows that, in the case of slipping, those with positive kurtosis would be expected to have safer walking mechanics with the greater frequency of lower RCOF values implying less friction demand on the walking surface. Similarly, positively kurtotic data represent more data points around the mean and the mean can be considered a good representation on the RCOF distribution.

Table 3.3 Descriptive RCOF data (mean, kurtosis and skew) over 105 consecutive steps by a male

	Right	Left
Steps (n)	105	105
Mean RCOF	0.22	0.24
Kurtosis	1.95	0.18
Skew	0.79	-0.02

Box et al. (1969) first modelled general non-normality of data distributions and later Best (1996) and Best et al. (1999) used their approach to model MFC (toe clearance) distributions characterised by skewness and kurtosis allowing accurate probability estimation, as described below.

The Best et al. (1999) probability model first accounts for skewness (S) in a complete population:

$$S = \frac{m_3}{\sigma^3}$$

where m_3 is the third moment or the sum of the cube of the difference between sample X_i and the average of all samples summed over all samples and divided by the number of samples:

$$m_3 = \frac{\sum_{i=1}^{n}(X_i - X_{mean})^3}{n}$$

and σ is the standard deviation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(X_i - X_{mean})^2}{n}}$$

The skewness of a data series, where only a sample is used, requires a correction to the population skewness calculation to accommodate variations due to the small sample size 'n'.

$$S = \frac{n}{(n-1)(n-2)} \frac{\sum_{i=1}^{n}(X_i - X_{mean})^3}{{\sigma_a}^3}$$

where

$$\sigma_a = \sqrt{\frac{\sum_{i=1}^{n}(X_i - X_{mean})^2}{n-1}}$$

By transforming the data using a power function, modelling of the skewness can be achieved and the power is varied until the skewness S = 0, shown by the equation below:

$$x = y^w$$

where y is the initial data and x is the transformed data. Using Davis, Swann and Campeys (DSC) optimisation algorithm (Box et. al, 1969) the optimal power could be found to satisfy skewness S = 0.

The model then accounts for, kurtosis, defined for a population as:

$$K = \frac{m_4}{(\sigma^2)^2}$$

where

$$m_4 = \frac{\sum_{i=1}^{n}(X_i - X_{mean})^4}{n}$$

and

$$\sigma^2 = \frac{\sum_{i=1}^{n}(X_i - X_{mean})^2}{n}$$

For normally distributed data the value for kurtosis is 3, so the deviation from this normally distributed view is often described as “excess kurtosis" which is defined:

$$K = \frac{m_4}{(\sigma^2)^2} - 3$$

As for skewness, when the data are a sample the equation is adjusted to allow for the sample set size. Excess sample kurtosis then becomes:

$$K = \frac{n(n+1)}{(n-1)(n-2)(n-3)} \frac{\sum_{i=1}^{n}(X_i - X_{mean})^4}{{\sigma_a}^4} - \frac{3(n-1)^2}{(n-2(n-3)}$$

considering the general exponential power distribution function (Box and Tiao, 1973)

$$p(x|x_{mean}, \sigma_x, \beta) = \frac{\omega(\beta)}{\sigma_x} exp\left[-c(\beta)\left|\frac{(x - x_{mean})}{\sigma_x}\right|^{2/(1+\beta)}\right]$$

where

$$c(\beta) = \left\{\frac{\Gamma[(3/2)(1+\beta)]}{\Gamma[(1/2)(1+\beta)]}\right\}^{1/(1+\beta)}$$

and

$$\omega(\beta) = \frac{\{\Gamma[(3/2)(1+\beta]\}^{1/2}}{(1+\beta)\{\Gamma[(1/2)(1+\beta)]\}^{3/2}}$$

where c(β) and $\omega(\beta)$ are defined as constants to assist in defining deviation from the normal distribution.

The value β is related K by the following relationship:

$$K = \frac{\Gamma[(5/2)(1+\beta)]\Gamma[(1/2)(1+\beta)]}{\{\Gamma[(3/2)(1+\beta)]\}^2} - 3$$

Using the DSC optimisation algorithm β is varied until it equals the excess sample kurtosis value.

After modelling for kurtosis and skewness slipping probability is defined by numerically integrating the power distribution equation:

$$PS = \int_{-\infty}^{x} \frac{\omega(\beta)}{\sigma_x} exp\left[-c(\beta)\left|\frac{(x - x_{mean})}{\sigma_x}\right|^{2/(1+\beta)}\right] dx$$

Between x_{mean} and -∞ the integral equals 0.5 or 50% probability, therefore when $x < x_{mean}$ the equation becomes:

$$PS = 0.5 - \int_{x}^{x_{mean}} \frac{\omega(\beta)}{\sigma_x} exp\left[-c(\beta)\left|\frac{(x - x_{mean})}{\sigma_x}\right|^{2/(1+\beta)}\right] dx$$

therefore alleviating the need to integrate to -∞. When $x > x_{mean}$ the equation becomes:

$$S = 0.5 + \int_{x}^{x_{mean}} \frac{\omega(\beta)}{\sigma_x} exp\left[-c(\beta)\left|\frac{(x - x_{mean})}{\sigma_x}\right|^{2/(1+\beta)}\right] dx$$

The trapezoidal rule was used for numerical integration with the step size nominally set to:

$$\frac{|x_{mean} - x|}{10000}$$

Using the Best et al. (1999) model, in this study, *slipping* probability was calculated from RCOF as shown in Figure 3.8. RCOF probability (PRCOF), the probability of a RCOF value to appear, is on the vertical Y axis, varying from 0 (0%) to 1 (100%) and corresponding RCOF on the horizontal X axis. At lower RCOF the PRCOF values approximate zero but as RCOF increases, the PRCOF values also increment, representing a higher likelihood of the value to appear during walking. Eventually, 100% probability is reached, representing a "safe zone" for surfaces with a greater COF value because, all experimental RCOF values for a given subject are of this value or less.

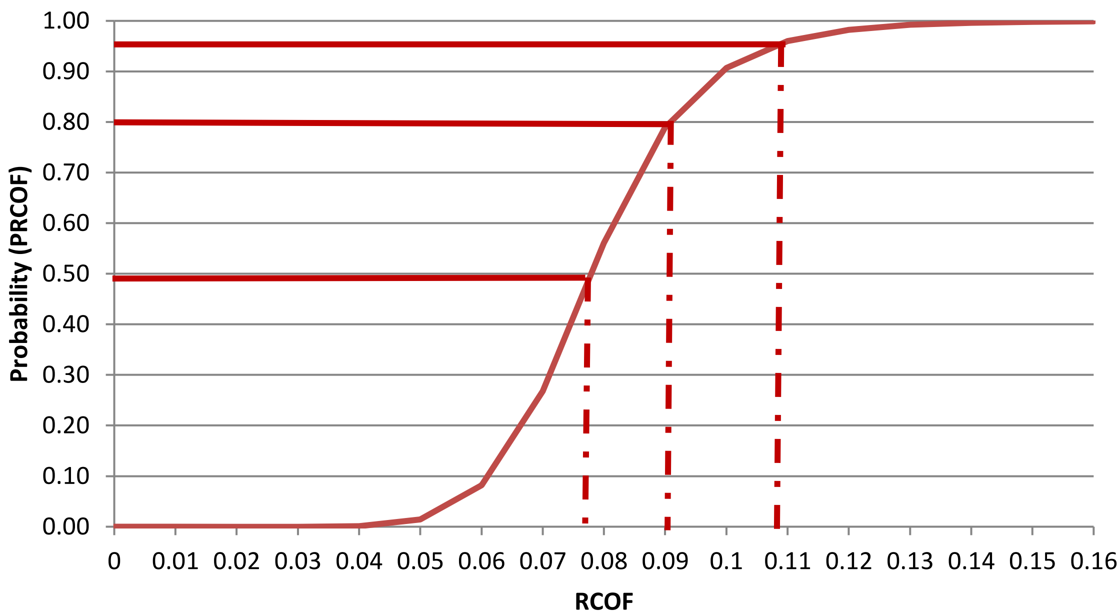


Figure 3.8 RCOF Probability (PRCOF) Function

The shape of the RCOF probability function (Figure 3.8) describes an individual's RCOF variability, the steeper the graph, the smaller the individual's RCOF range and vice versa. A typical pattern seen in healthy adults with low variability is a tightly distributed half-a-bell shaped pattern, as in Figure 3.8. In this example, it can be observed that during normal walking an RCOF of 0.078 has a 50% probability, RCOF = 0.09 80%, and RCOF = 0.11 95%. The 100% criterion is reached at RCOF = 0.14. As walking is considered safe when the surface friction is greater than RCOF, it can be predicted that this individual is safe when walking on surfaces with friction (i.e. COF) of 0.14 or higher.

3.3.2 Surface friction

The slipperiness of a surface can be measured with tribometric systems. Several publications have listed known surface friction (COF) values for different materials, often clean and contaminated (e.g. Samson et al., 2001). Every surface has a specific surface friction that though varies by the show type (e.g. leather vs. rubber) and possible contaminants that can reduce the friction. Surfaces with a high coefficient of friction (COF) are considered safe. This statement aligns with the previously defined theory: “Walking is regarded safe when the COF is greater than the ratio of the horizontal and vertical forces (RCOF)”, no slip will occur if COF between the shoe and the surface exceed RCOF (Barnett, 2002; Grönqvist, 1999). As per this theory it can be stated that a surface with high friction COF caters for walking styles with high ground reaction forces with a high friction demand and slipping in avoidable for all.

Table 3.4 Coefficient of Friction (COF) values for some flowing materials (Samson et al., 2001)

	Leather Sole				Rubber sole			
	Dry		**Wet**		**Dry**		**Wet**	
Floor material	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic
Concrete	0.54	0.45	0.37		0.74	0.71		
Vinyl tile	0.46	0.39	0.30	0.11	0.58	0.54	0.63	0.47
Rubber	0.45	0.63	0.43	0.27	0.44	0.63	0.87	0.50
Sheet Vinyl	0.43	0.39	0.78	0.29	0.48	0.67	0.82	0.63
Cork tiles	0.42	0.34	0.78	0.55	0.53	0.50	1.00	0.98
Linoleum	0.27	0.25			0.42	0.36		
Varnished	0.31	0.25			0.50	0.40		
White Oak waxed	0.24		0.17					
Ice	0.1		0.08					
Asphalt	0.55	0.45	045					

The literature states that surface friction COF values above 0.4 are considered safe (Samson et al., 2001). Many surfaces though have a COF value lower than that with all surface having an even lower surface friction if contaminants are applied (e.g. water, oil). Table 3.4 presents several COF values for a number of surfaces (Samson et al., 2001). Most of these values are higher than the safe value, COF > 0.4 but many values also fall under. Attention needs to be paid to the footwear type with the leather sole presenting lower values, thus a higher risk for those with RCOF values.

These values can be added to the previously presented probability of a RCOF value to appear (PRCOF) model (Figure 3.10). In the Figure the three ”risk zones” are identified; the safe zone of COF values of 0.4 and above, the slippery and hazardous zone of COF values 0.2-0.4 and the very slippery and very hazardous COF under 0.2 (Samson et al., 2001).

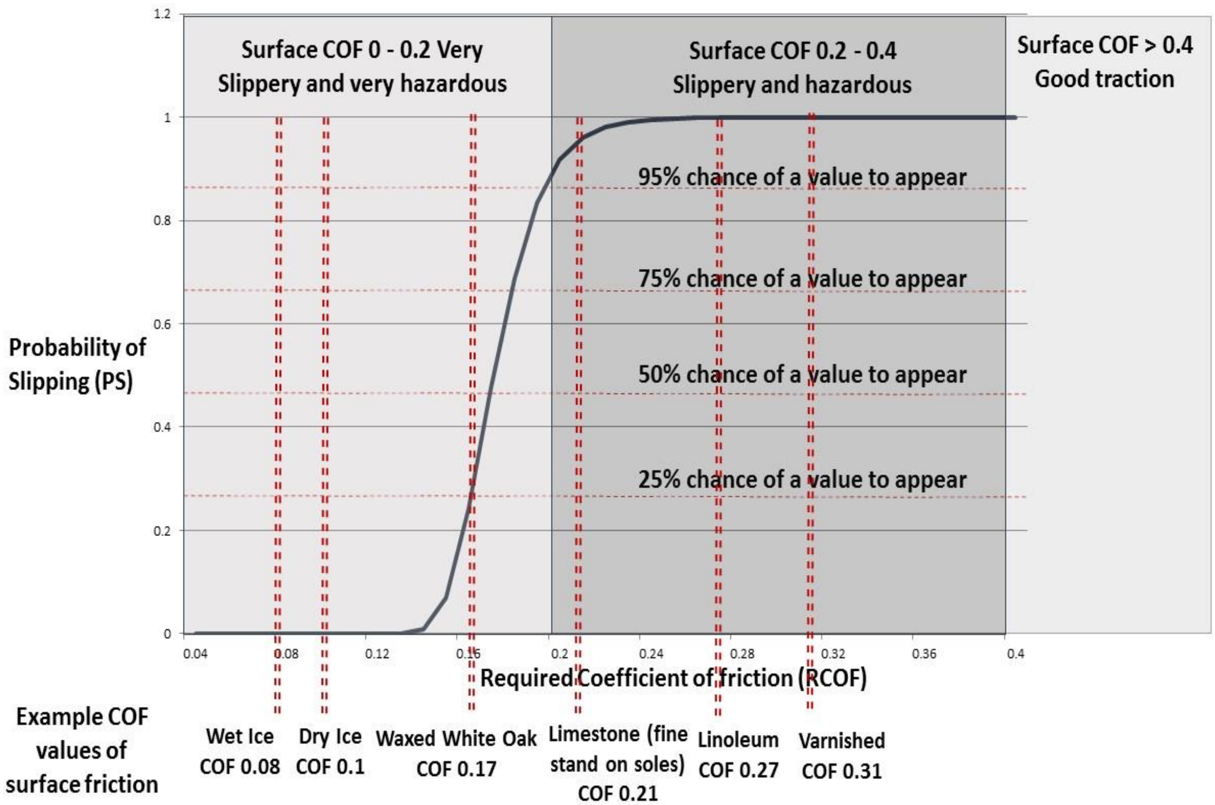


Figure 3.9 The Probability of slipping as presented with the three slipperiness categories and selected surface friction examples.

The single graph line presents an individual data and the chance of a RCOF value to appear during walking. The shaded areas are the slipping risk ”zones”, the horizontal lines the selected % values (25 %, 50 %, 75 % and 95 %) and the vertical dashed lines selected floor surface COF values in the slipping risk zones (COF = 0.0 – 0.2).

The PRCOF graph identifies the chances of RCOF values to appear. This value can then be compared to the known COF value of the surface. As per the previous statement, *”If RCOF > COF, a slip will happen”*. Eg in the example data (Figure 3.9) the probability of the RCOF value 0.17 to appear is 25 %. As this value is the requirement the gait pattern makes towards the surface and its friction, it can be said that RCOF must be bigger than COF to avoid slipping. Thus, this person has a 25 % chance of slipping if stepping on a floor made of waxed white oak (COF 0.17) without prior knowledge. The data also allows for the verification of a person’s safe limits, describing how often a particuar RCOF value will appear, eg. What are the values that have 25 %, 50 %, 75 % etc chance of appearing.

3.3.3 Estimating Slipping Probability on a Known Coefficient of Friction (COF)

The above described probability presentation, PRCOF, presents a probability graph based on the RCOF distribution, allowing for the estimation of a known RCOF value. This calculation can be further developed to describe the probability of slipping (PS) on a surface with a known friction, COF, by calculating 1- PRCOF. The relationship of the two probability graphs, PRCOF and PS, is presented in Figure 3.10. As PRCOF increases, PS decreases such that when PRCOF = 0, PS = 1 and the individual will have a 100% slipping probability on a surface of the corresponding surface friction. Similarly, when PRCOF = 1, the individual has a 0% probability of slipping on the same surface. When considering the case presented in Figure 3.10; if COF is 0.04 or less the individual has 100% chance of slipping. The PS then decreases until zero PS is reached at COF = 0.14 and the individual is risk-free when walking on surfaces of that frictional coefficient or more.

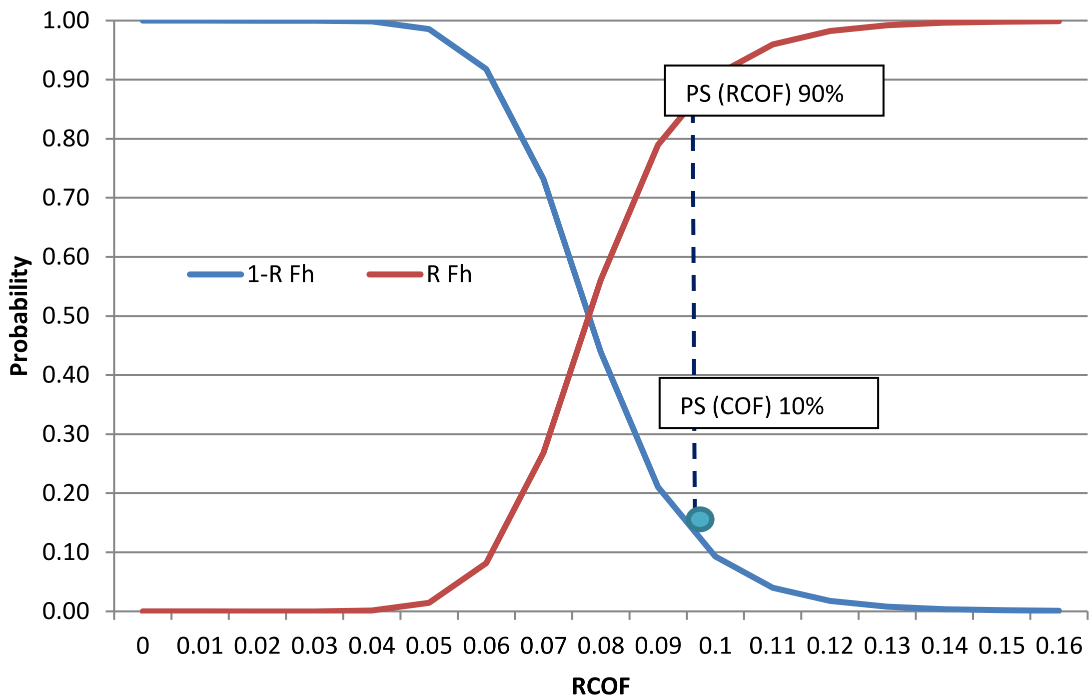


Figure 3.10 The probability of slipping on a surface of known COF. This individual has a 90% chance of RCOF = 0.1 and a 10% chance of slipping on a surface with COF = 0.1.

3.3.4 Total Slipping Area Estimation (Trapezoidal Area)

PRCOF and the estimated probability of slipping (PS) can be represented graphically to reveal total slipping probability at any point of interest. While the probability graph represents an individual's slipping function, the critical areas and the variability, it does not estimate total slipping propensity. This property can, however, be calculated by applying integral mathematics. To evaluate the area under the curve between given boundaries the solution to the following definite integral is required;

$$Area = \int_{x0}^{xn} f(x)dx$$

Equation 3.1 Area of Function f(x) dx

As the function for the equation of the line is unknown linear approximation can be used to estimate total area using the trapezoidal rule. The following equation is used when there is a uniform interval 'x'.

$$Area = \int_{x0}^{xn} f(x)dx = \frac{\Delta x}{2}(f(x0) + 2f(x1) + 2f(x2) + \cdots. +2f(xn-1) + f(xn))$$

Equation 3.2 Area expresses as the sum of a series of terms

This can be simplified for each individual interval as

$$\frac{(a+b)}{2} \times d$$

Equation 3.3 Area of Interval

Figure 3.10 presents the slipping probability on a known surface, presented with a RCOF graph. As per the trapezoidal rule, the total slipping probability of an individual can be estimated at a known RCOF point. Every PRCOF value can be converted to a PS value. When PRCOF is close to 0, PS is close to 100%, thus the lower the PRCOF, the higher is the risk of slipping on surfaces with a low friction. This calculation can also be used when estimating the total slipping area, such that the greater area represents safer gait.

Total slipping area is presented in Figure 3.11 and the trapezoidal area calculation reads ((a+b)/2) × d, where ‘a’ and ‘b’ are two consecutive probabilities for specified RCOFs, for example, 0.16 and 0.17 and ‘d’ is the distance between them (0.01). The area under the probability graph between any two boundaries defines total slipping probability. The maximum area between any two RCOF data points is 0.01 as the distance between any two points is constant (0.01) and at 100% probability the graph reaches the maximum value of 1. The closer, therefore, to the maximum value of 0.01, the safer the gait. The sum of these areas over a chosen range defines total PS with the total maximum area being the distance between measurement points x the number of sections.

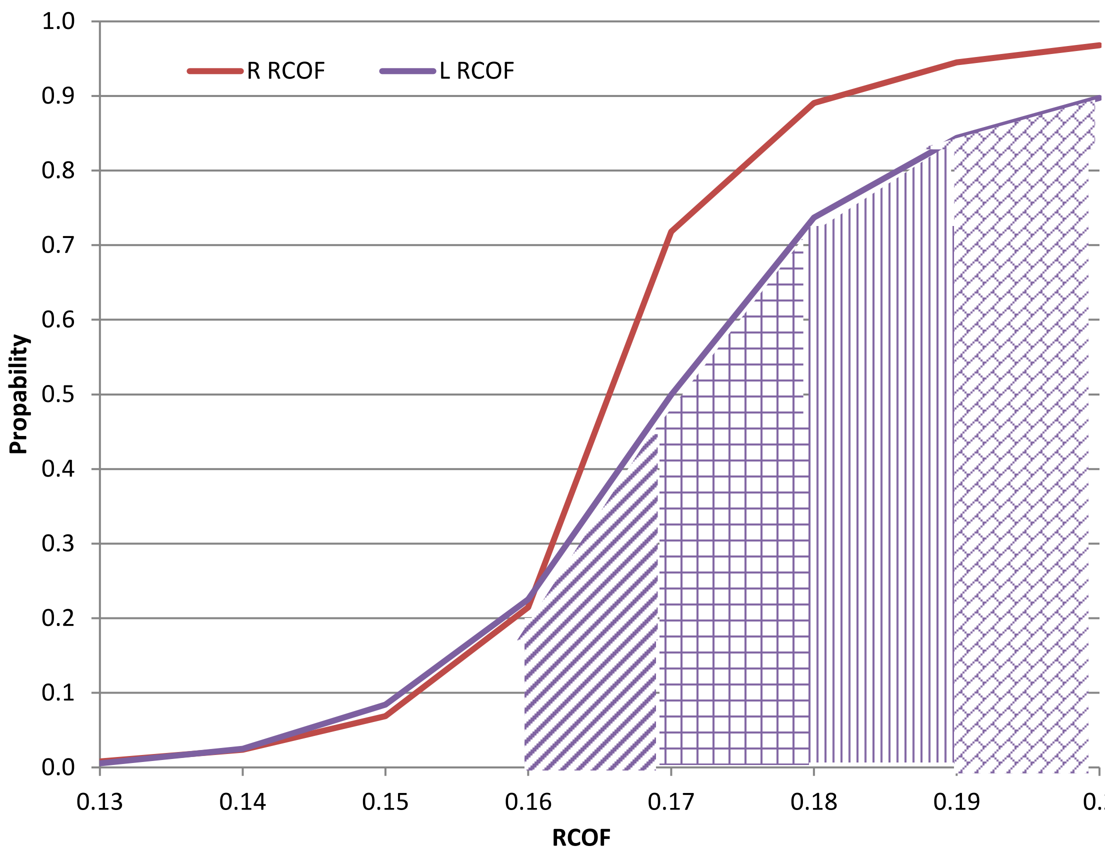


Figure 3.11 The trapezoidal area calculation in estimating the total probability at a specified RCOF

Surfaces with COF 0-0.2 are identified as very slippery and hazardous and with COF 0.2-0.4 as slippery and hazardous with walking surfaces with COF above 0.4 considered safe with a COF (Samson et al., 2001) (Figure 3.12). By using the trapezoidal calculation, an individual's total slipperiness in a selected friction zone, such as the very slippery and hazardous area, can be calculated. Also, these risk areas can be further divided into smaller zones to estimate total risk at points of interest: 1 (0.1 – 0.15), 2 (0.15 – 0.2), 3 (0.2 – 0.25), 4 (0.25-0.3), 5 (0.3-0.35) and 7 (0.35 – 0.4) to investigate the differences between the population groups and individuals.

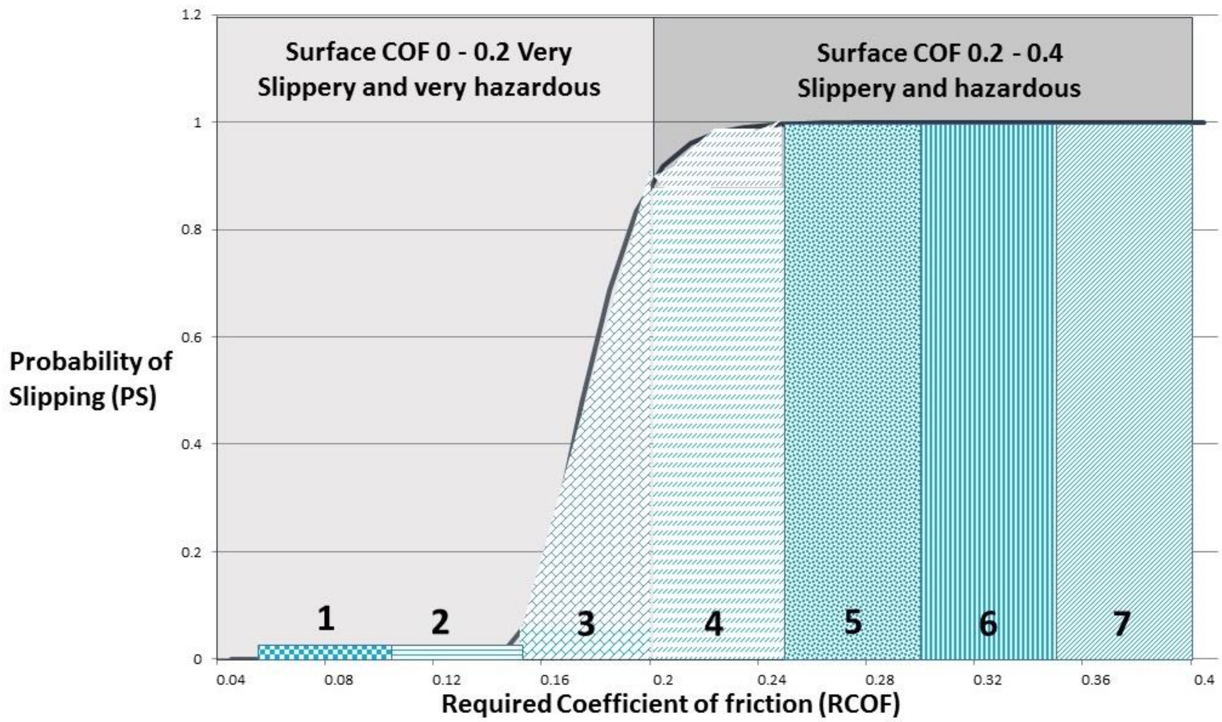


Figure 3.12 Slipping zones calculated as trapezoidal zone

3.4 Verification of Walkway Surface Friction

As the aim of this study was to investigate intrinsic factors only; the walkway was a safe, high friction surface (Flotex floor tiles, Bonar Floors Ltd, Derbyshire, UK). The frictional properties of the walking surface were quantified by Intertile Research Pty Ltd. (Figure 3.13) using a portable skid-resistance tester (Munro-Stanley, London, UK). The testing apparatus consists of a rigid body and an adjustable swinging leg with an attached exchangeable rubber sole.

Figure 3.13 The Pendulum Friction Tester

The pendulum test was then performed by releasing the pendulum from the base (Figure 3.15) and as it swings across the flooring sample friction slows the pendulum and a gauge measures the highest swing angle. The swing angle is, therefore, proportional to the slowing friction from which the surface coefficient of friction (COF) can be quantified.


Figure 3.14 Calibrating the Pendulum Friction Tester

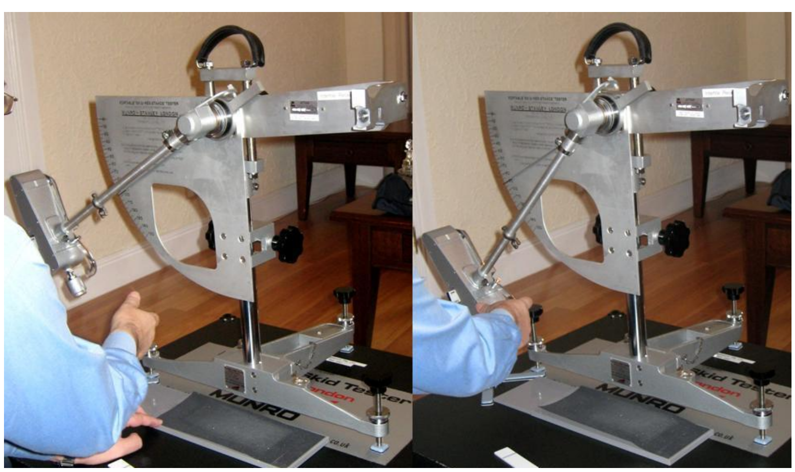


Figure 3.15 The Pendulum Leg

In addition to an unused floor tile, four tiles from a highly-used area of the walkway area were selected to quantify the effect of wear; tiles 1-1, 1-3, 2-3, 2-4, as identified in Figure 3.16. Two rubber soles were used to reflect footwear effects. A softer rubber sole (TRL) was selected to represent the typical running and walking shoes worn in the study, while a harder sole (4S rubber) was chosen to reflect more formal everyday footwear, such as a men's business shoe. The testing procedure was repeated five times for every tile with the last three trials used for quantification of COF. Test results showed that for the soft and hard soles the floor tiles had COF ranging from 0.84 and 1.8 with the highest friction where the heel contact is assumed (1-3, 2-3). These friction values matched the unused floor tiles showing that the data collection area had consistent friction despite wear.

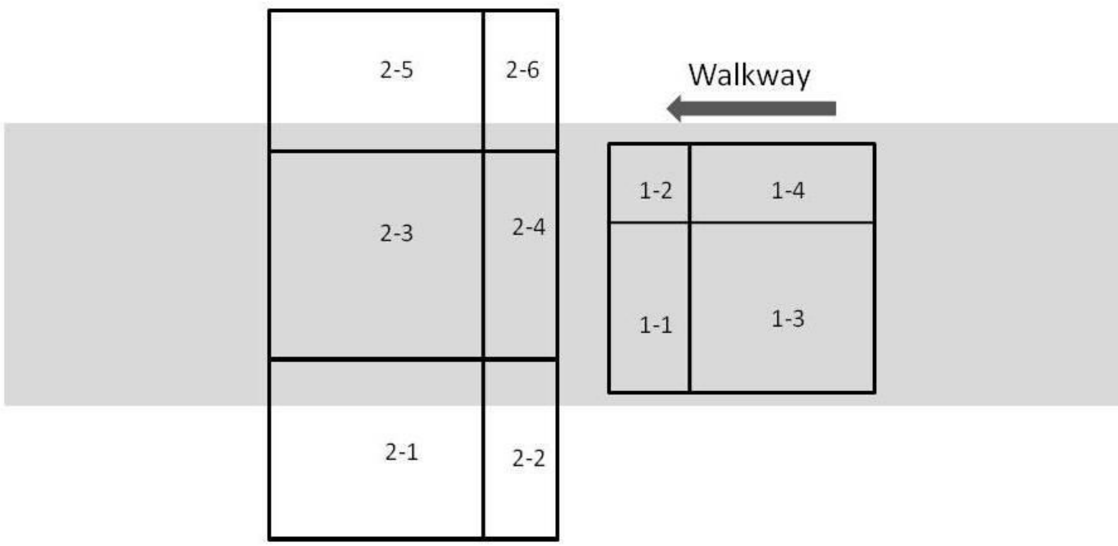


Figure 3.16 The floor tiles of the walkway

3.5 Design and Analysis

Experimental Condition (preferred normal and preferred fast) effects on walking speed were determined using an Age (2) X Gender (2) Split Plot Analysis of Variance (SPANOVA). Similarly, the same SPANOVA design was used to reveal the Fx effect on the RCOF Calculation by comparing RCOF1 (F_X excluded) and RCOF2 (F_X included) across the gender and age groups. In both SPANOVA designs Age (2) and Gender (2) were the between-subjects factors and Condition and Calculation method within-subject factors. Similarly, separate SPANOVAs, one for each walking speed condition (Normal and Fast), were undertaken to investigate Age, Gender and Limb effects (right vs left) on (i) the mean F_X-included RCOF and (ii) 99th percentile data only. In these designs limb was the within-subject factor.

Between-group differences in slipping risk for specified RCOF were confirmed using a group (older female, older male, young female, young male) 4X4 RCOF values (0.1, 0.15, 0.2, 0.25) SPANOVA. Assumption for rightness was tested with the Leven's test for homogeneity of variances. If the assumption failed, values for "variance not assumed" were used.

The effect of age on RCOF was tested with an independent groups T-test with age the independent variable and the dependent variables mean and 99th percentile RCOF. Testing was conducted at both walking speeds. Gender effect was excluded by repeating the test for the two gender groups.

Total slipperiness (TS) was calculated using the Trapezoidal rule by integrating the area between specific RCOF values (friction range) and also for two predetermined slipperiness zones: (i) COF 0.0-0.2 the very slippery and very hazardous zone and (ii) COF 0.2 – 0.4. SPANOVA was initially used to estimate the age and gender effects on total slipperiness. Assumption tests were Box's test of equality and covariance (homogeneity), Mauchly's test (sphericity) and Leven's test (homogeneity of variance). If any of these tests were violated, independent groups T-tests were used to estimate age and gender effects on TS. The four analyses corresponded to (i) the right and (ii) left foot at normal speed and (iii) the right and (iv) left foot at fast speed.

The assumptions underlying SPANOVA are the same for more conventional ANOVA procedures, such as independent measures ANOVA. When SPANOVA results were presented in this thesis, these assumptions were not violated. Also, additional assumption tests, Leven's and Box's tests were also used. As indicated in the design and analysis section when Leve's test was violated "variance not assumed" values were used to determine the significance of effects.

Furthermore, when applicable (when testing the difference between 2 variables) T-tests were used to verify differences between groups thus increasing relevant sample size and minimising the issue of spherity and variability.

3.6 Summary of Hypotheses and Methods

This study used several methods to investigate the intrinsic frictional properties of gait and then determine the probability of slipping. The study hypotheses and associated methods are summarised in Figure 3.17.

NULL HYPOTHESIS	METHODS
1. No significant effect in the outcome in the calculation of the Required coefficient of friction (RCOF) when the medio-lateral force is included in the calculation of the RCOF	• Collection of Ground Reaction forces using a force plate • Calculation of the RCOF using 2 algorithms: RCOF 1 $= \frac{F_y}{F_z}$ RCOF 2 $= \frac{\sqrt{F_y^2 + F_x^2}}{F_z}$ • Comparison of the data
2. No significant effect of age, gender or walking speed upon the major descriptive statistics of RCOF	• Calculation of the RCOF values • Definition of RCOF descriptive statistics • Verification of the effect of age, gender and walking speed using statistical methods
3. No significant age, gender or walking speed affect in the probability of slipping	• Calculation of the Probability of RCOF to appear (PRCOF) and the probability of slipping (PS) and further definition with following methods: Graphical, numerical, trapezoidal area • Comparisons on age, gender, walking speed

Figure 3.17 Summary of methods to respond to the null hypotheses

4 Results

The participants' anthropometric characteristics and preferred walking speeds are summarised first, followed by the F_X effect on RCOF. Age, gender and walking speed effects on RCOF are then presented. The final section addresses age, gender and walking speed effects on the probability of slipping.

4.1 Participant Characteristics and Self-selected Walking Speeds

Participant characteristics and walking speeds are presented in Table 4.1. Both groups of older adults were aged over 70 years and both groups of young adults were aged under 30 years. Young females were 5.6cm taller than older females and young males were 6.1 cm taller than the older males. Older females were 2.3 kgs heavier than the young females and young males were 4.5 kgs heavier than the older males.

Table 4.1 Participant characteristics and walking speeds

		Age (years)	Height (cm)	Mass (kg)	Normal speed (m/s)	Fast speed (m/s)
Older adults	Female (n = 25)	71.4 ± 5.4	160.0 ± 7.9	67.3 ± 9.5	1.19 ± 0.18	1.67 ± 0.17
	Male (n = 25)	72.3 ± 5.0	173.1 ± 7.7	78.2 ± 12.6	1.25 ± 0.17	1.69 ± 0.18
Young adults	Female (n = 26)	27.9 ± 4.6	165.6 ± 5.9	65.0 ± 10.1	1.36 ± 0.16	1.43 ± 0.16
	Male (n = 25)	29.5 ± 4.7	179.2 ± 7.7	82.7 ± 13.8	1.31 ± 0.15	1.55 ± 0.23

As presented in Figure 4.1, the highest normal walking speed was for young females (1.36m/s) and the lowest for the older females (1.19m/s). At fast speed the fastest group was young males (1.69m/s) and the slowest were the older females

(1.43m/s). When comparing normal and fast speeds, young males had the largest increase (30.05%) and older females had the smallest increase (19.66%). Both young females and older males increased their speed by 23%.

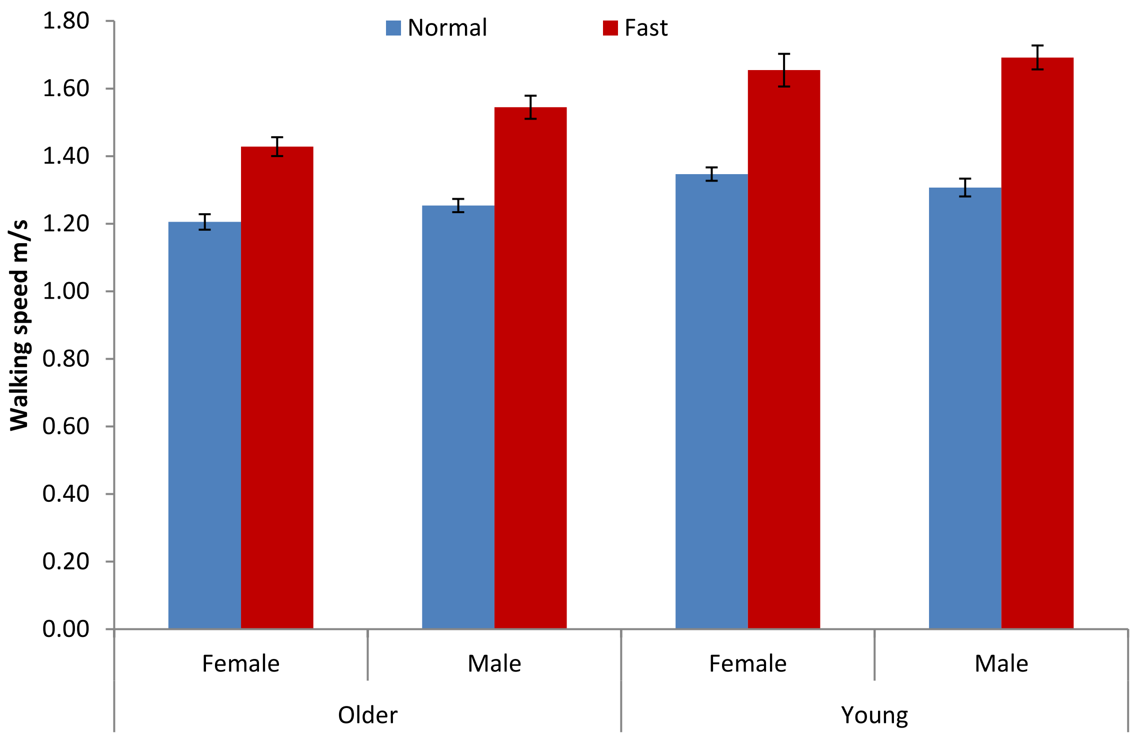


Figure 4.1 Walking speed by Age and Gender

SPANOVA results confirmed a significant condition effect on walking speed $F(1,95) = 572.2$, p<.001 but also a condition X age $F(1,97) = 12.7$, p<.001 and condition X gender interactions $F(1,97) = 8.1$, p<.005. The interactions indicated that while speed increased significantly from the normal to fast condition the increase was also affected by both age and gender. A post hoc Tukey's HSD revealed that in both speed conditions (normal p = .016, fast p < .001) young females walked faster (normal = 1.35m/s, fast = 1.65m/s) than older females (normal = 1.21 m/s, fast = 1.43 m/s). In contrast at normal walking speed the young (1.31m/s) and older (1.25m/s) males were not significantly different, however, the young males (1.69m/s) had higher walking speed in the fast condition (p < .028) than their older counterparts (1.54m/s). Figure 4.2 presents these interactions clearly showing that the older females have the slowest speeds at both normal and fast walking. The differences in the male groups are also clear; while at normal speed the difference between the groups is small, at fast speed the young males are the fastest group while the older males have a smaller increase between the conditions.

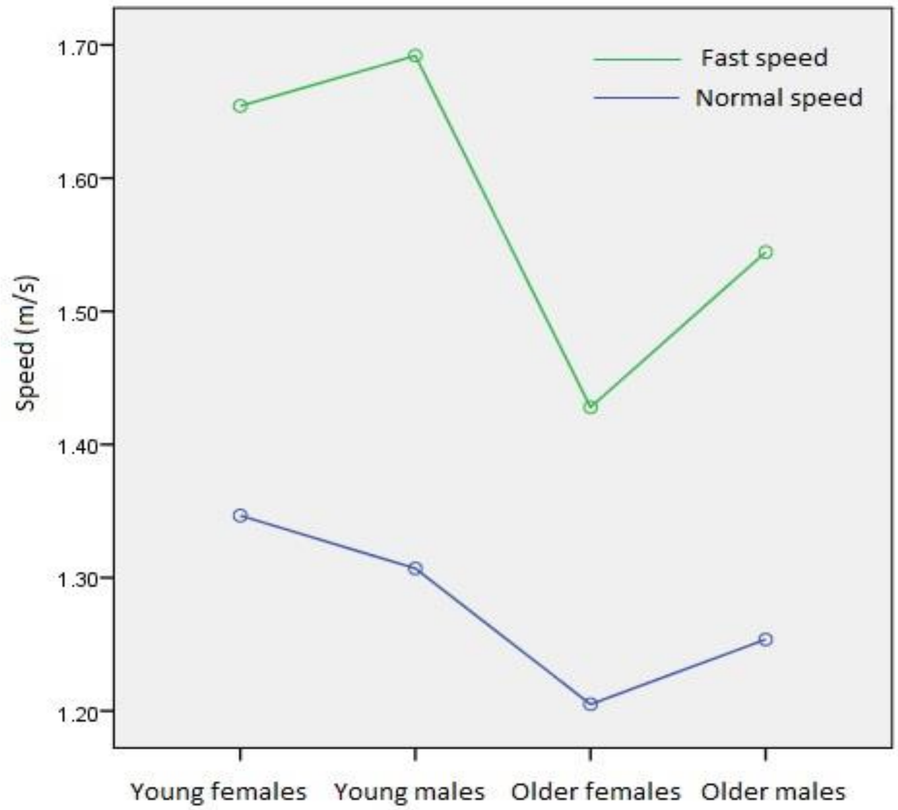
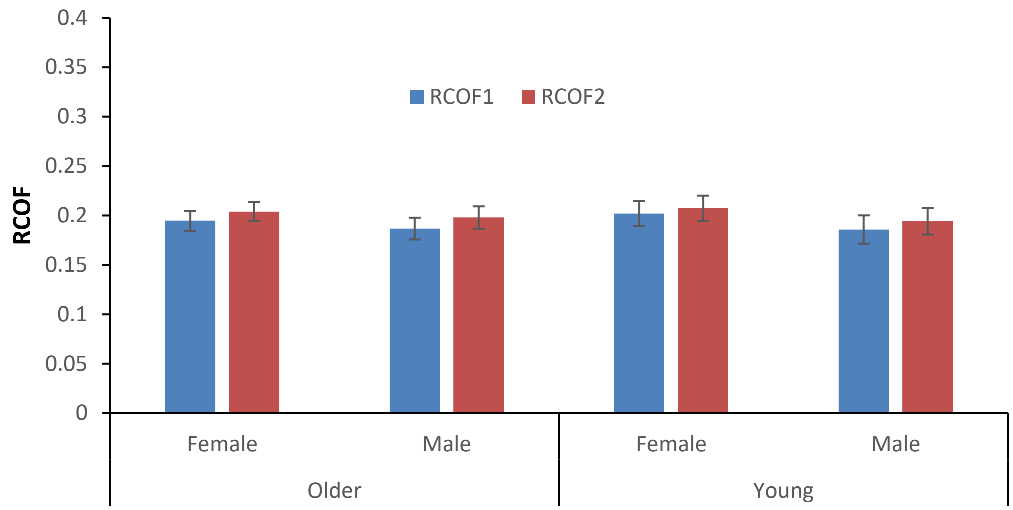


Figure 4.2 Walking speed interactions, age and gender

4.1.1 The Effect of Medio-lateral Force (F_X) on the Required Coefficient of Friction (RCOF) Calculation

As expected the inclusion of F_X caused mean RCOF to increase in both walking speed conditions and, as seen in Figure 4.3, the increase was consistent across participant groups. SPANOVA age (2) X gender (2) X calculation (2) results for the normal speed analysis confirmed significantly increased RCOF with F_X included (i.e. a calculation main effect) for both limbs (right $F(1,100) = 126.3$, p<.001 and left $F(1,100) = 129.3$, p<.001). The same result was found at fast speed: right $F(1,100) = 110.5$, p=.<.001) and left $F(1,100) = 166.9$, p= <.001).

A)



B)

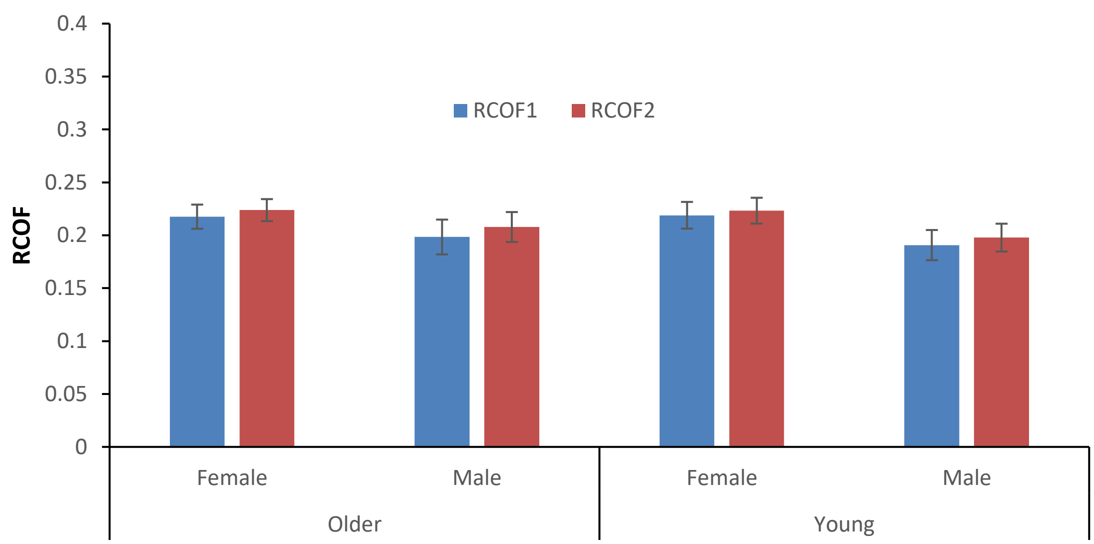


Figure 4.3 The effect of F_X in the RCOF mean at A) Normal speed B) Fast speed

At normal speed, however, calculation X gender interactions for both the right foot *F*(1,100) = 4.61, p=.034) and left foot *F*(1,100) = 4.77, p=.031) revealed that the Fx inclusion effect was associated with significantly higher RCOF for males only. The increased RCOF associated with including the medial-lateral component was, therefore, only due to increased RCOF in male participants with Fx inclusion having no significant effect on the female data as presented in the top two panels of Figure 4.4. During fast walking a calculation X age effect was confirmed for only the right limb, $F(1,100) = 5.4$, $p = .023$ such that F_X inclusion only increased RCOF significantly in older adults, this interaction can be observed in the bottom two panels of Figure 4.4.

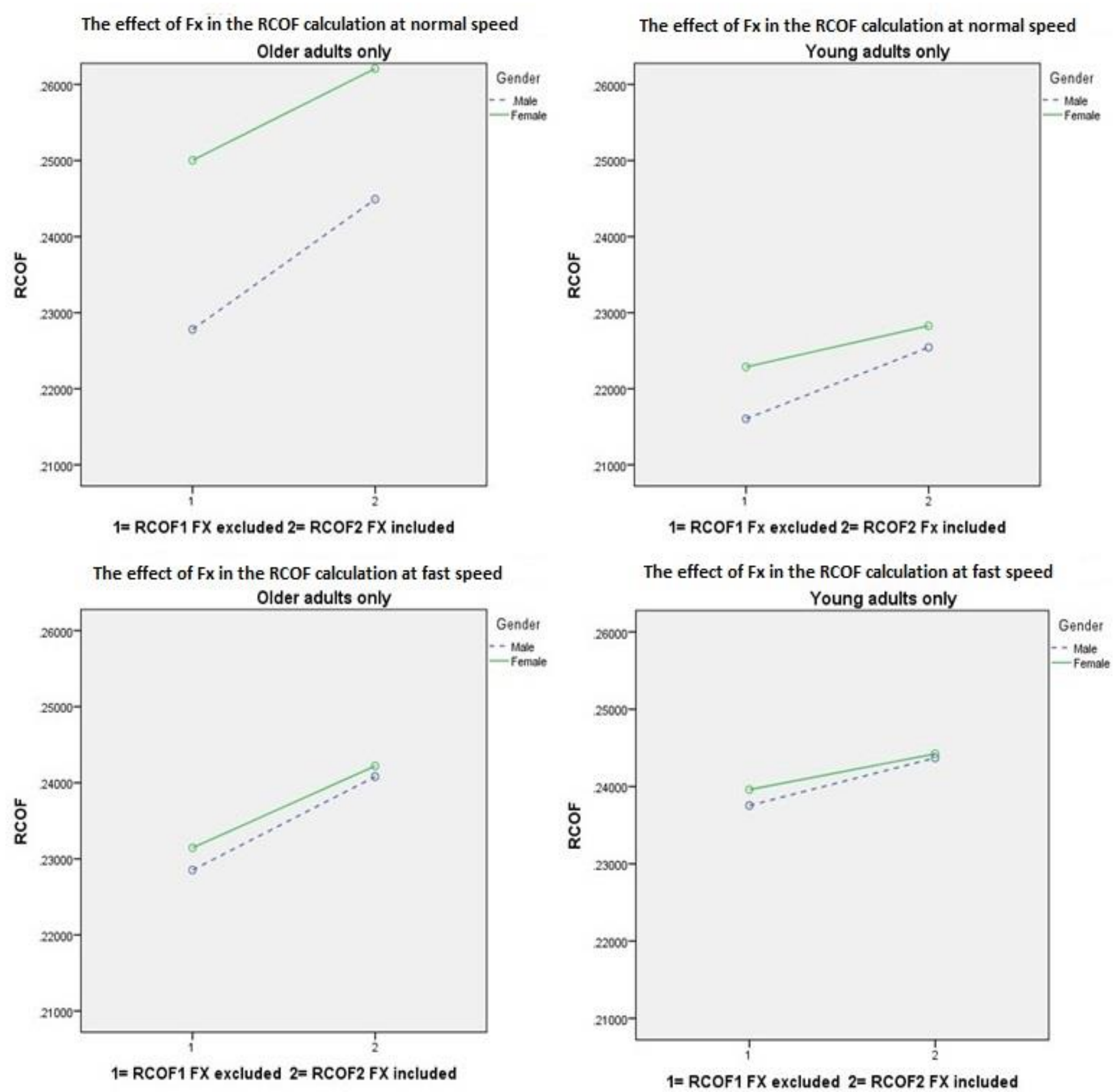


Figure 4.4 Age and gender interactions in F_X inclusion in RCOF

The effect of F_X inclusion was also investigated graphically using the raw RCOF data (Figure 4.5). RCOF is defined as the maximum data point, excluding the first 10ms following initial contact, (a). When F_X was included in the RCOF calculation (second data column) a second peak, (b), was sometimes observed prior to maximum RCOF. This can be noted when walking at both normal and fast speeds for both right and left foot. If the first 10 ms were not excluded from the analysis, a wrong data point could be used to represent RCOF. This additional peak was only noted for some participants, implementing a brief increase in F_X at initial contact.

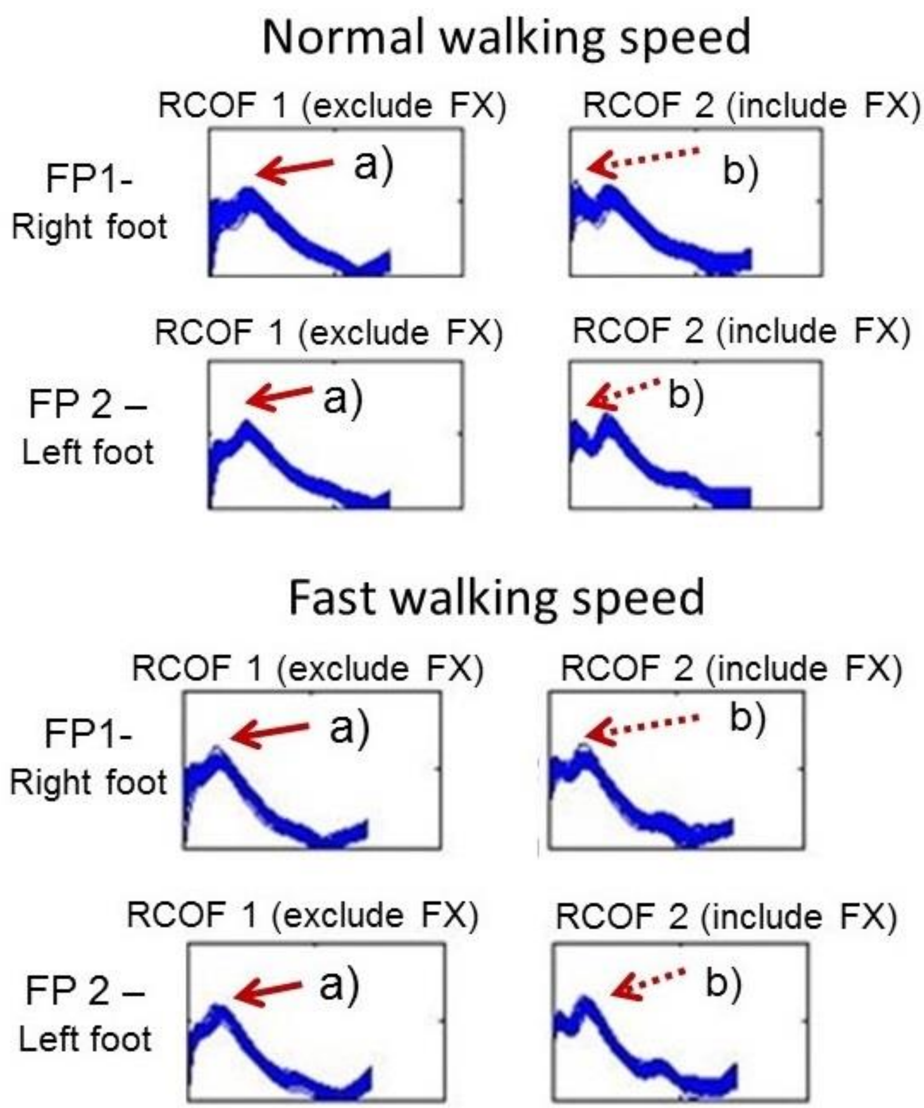


Figure 4.5. RCOF1 and RCOF2 data at normal and fast speeds.

4.1.2 Measures of Central Tendency and Dispersion (Variability)

A large data set allows examination of variability effects by comparing RCOF at the mean, median, 95th, 97th and 99th percentiles. RCOF would be expected to increase when a larger proportion of the distribution is accounted for. The sample groups were, however, different in this respect across the distribution. As shown in Figure 4.6, the two young adult groups had similar RCOF for all descriptive statistics at both walking speeds; while in the older samples there were gender differences with older females having higher 95th and 97th percentile RCOF at normal speed. Mean RCOF for both older groups was lower than for the young and in both groups of older people as well as the young males; the median was lower than the mean. By using the percentile data, allowing variability to be accounted for, older adults showed a larger increase of RCOF in both walking conditions. Similarly, in fast walking the increase was higher for older adults but for both age groups the increase smaller when walking faster, with the 99th percentile RCOF values similar in both age groups.

Table 4.2 compares the mean and 99th percentile only and the impact of including more data is noticeable. At normal walking speed, for example, RCOF increased by 17.4% and 17.7% for young females and young males respectively and by 52.6% and 52.3% for older females and older males.

Table 4.2 Comparison of the RCOF mean and 95th percentile values

		Normal speed			Fast speed		
		Mean	99%	Difference	Mean	99%	Difference
Young adults	Female	.207	.243	17.4%	.223	.254	13.9%
	Male	.203	.239	17.7%	.224	.256	14.3%
Older adults	Female	.194	.296	52.6%	.198	.261	31.8%
	Male	.197	.300	52.3%	.208	.253	21.6%

These changes can also be noted in Figure 4.6. The young adults presented with resembling results for both genders, similar values for mean and median values, as well as only a slight increase in RCOF using the percentile values. The older adults in contrast, at both walking speeds, showed gender differences, presented with median values lower than means and greatly increased RCOF when using the percentile values, especially at normal speed.

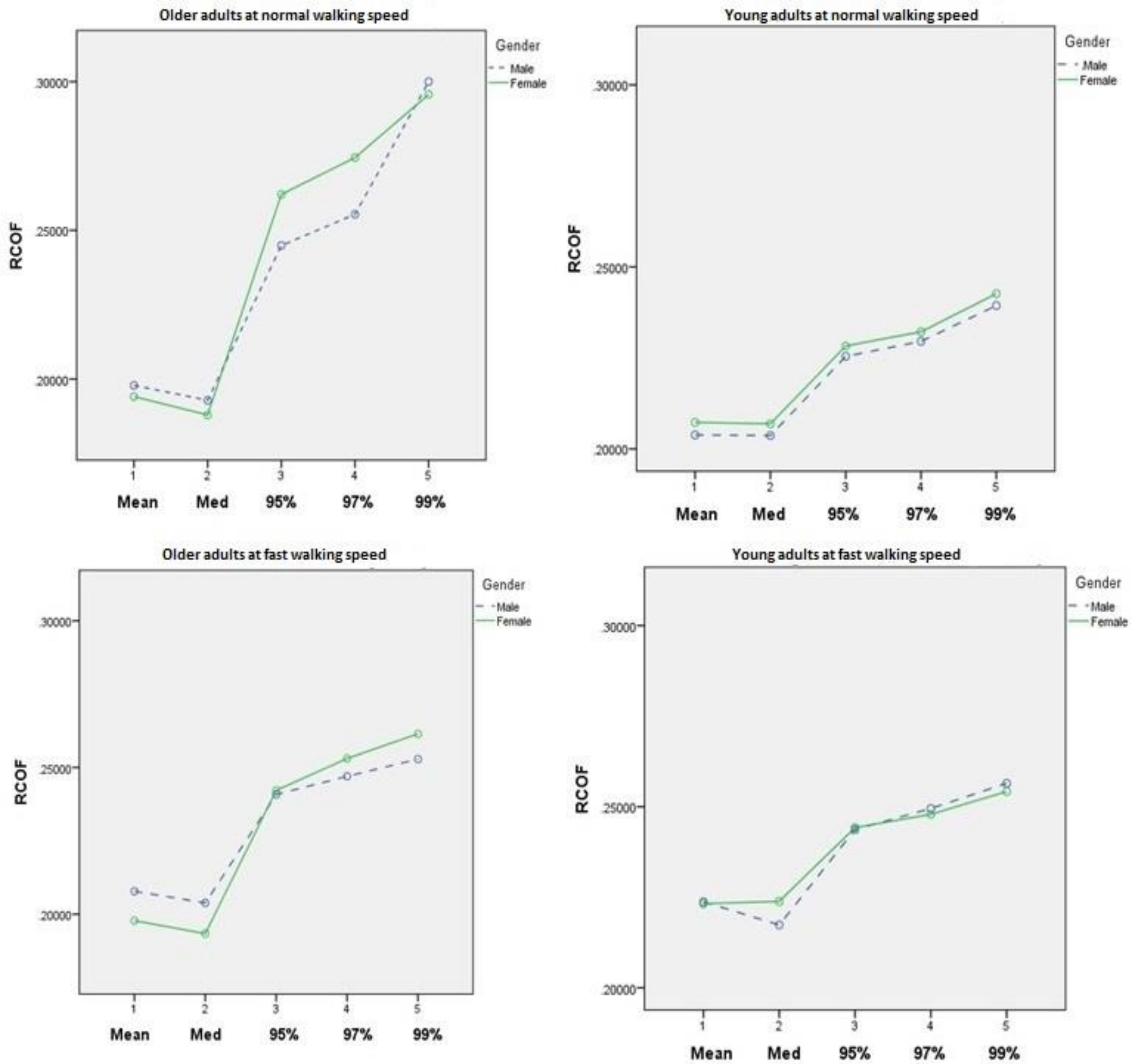


Figure 4.6 RCOF values when using mean, median, 95th, 97th and 99th precentile for all populations walking at normal and fast speed

In summary, these results indicated that using mean or median RCOF may underestimate the friction requirement, especially in the older adults. In contrast, while in most cases the median was lower than the mean, the 95th, 97th and 99th percentile RCOF increased. These results reflect the variability in ageing gait and suggest that when analysing slipping risk, 95th-99th percentile values should be considered. Given these results, all further analysis in this study was reported using both the mean RCOF (RCOF mean) and 99th percentile data (RCOF 99).

4.2 RCOF Changes

4.2.1 Limb Effects on RCOF

At normal speed SPANOVA results confirmed no limb effect (no significant asymmetry) but there was an interaction of limb X gender, $F(1,100) = 4.8$, $p=.031$. The limb effect did, however, approach significance at normal speed $F(1,100) = 3.7$, $p=.058$. At fast speed, again, no limb effect was noted. While not showing a statistically significant difference in RCOF the RCOF data for the two limbs is presented separately in the following results.

4.2.2 Speed, Age and Gender Effects on RCOF

Figure 4.7 presents RCOF mean for all groups at both walking speeds. Most groups had a greater RCOF mean at fast speed; however, the older females' left limb RCOF reduced when speed increased. Furthermore, young adults had a greater RCOF mean at both speeds. SPANOVA results confirmed the speed effect, with RCOF increasing as speed increased; RCOF mean right limb, $F(1,100) = 29.7$, $p<.001$ and left limb, $F(1,100) = 39.2$, $p<.001$. Also, a speed X age interaction effect was shown for both limbs: right $F(1,100) = 6.0$, $p=.016$) and left $F(1,100) = 14.8$, $p<.001$). Also a speed X gender interaction was found for left $F(1,100) = 14.1$, p= $p<.001$) due to both young groups having a greater increase in RCOF mean at fast speed; RCOF increased by 0.020 and 0.016 for young males and females respectively, 0.010 and 0.004 for older males and females respectively for right foot data. For the left limb, the increase was greater for both groups of males, 0.024 for the young males and 0.016 for the older males.

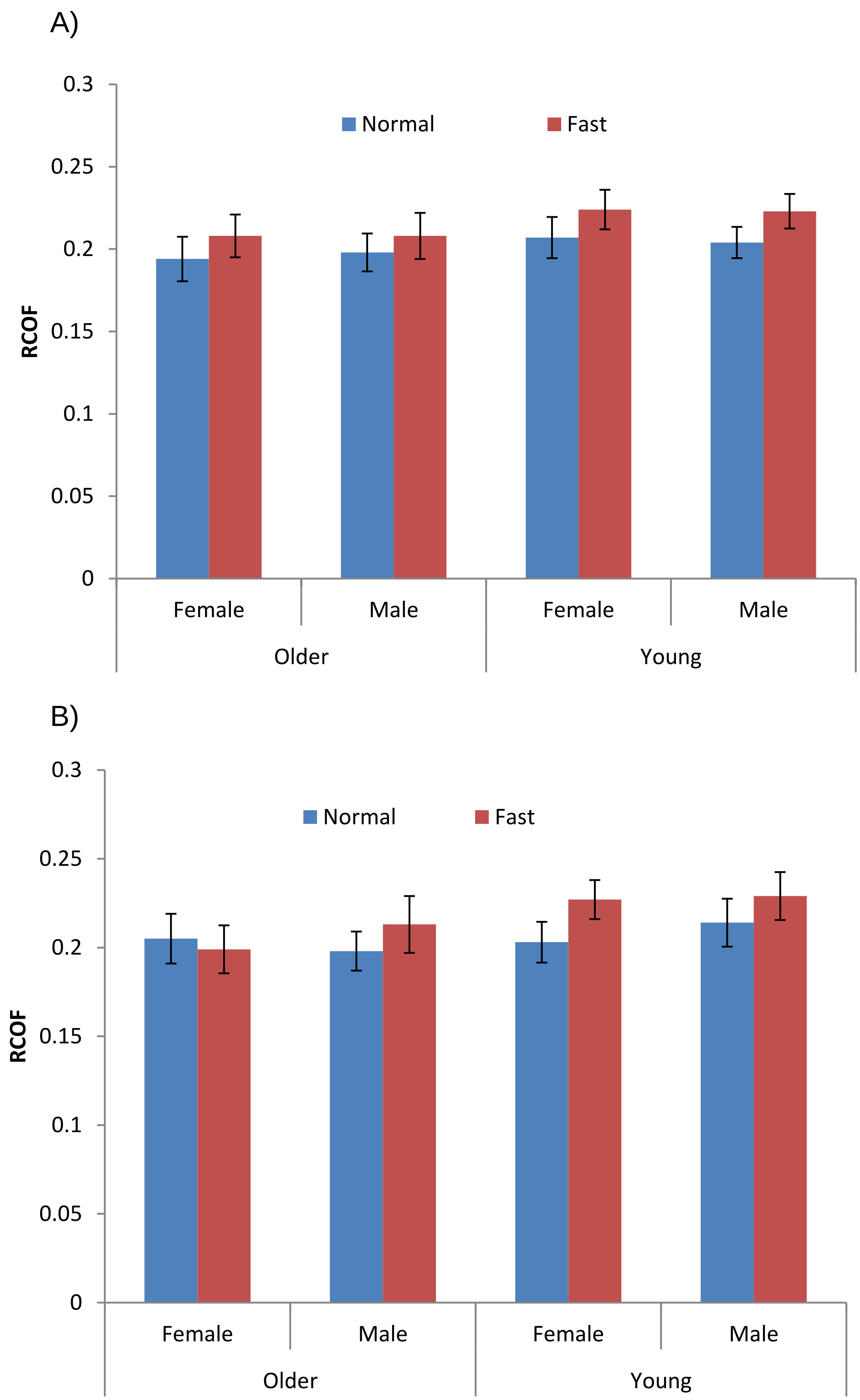


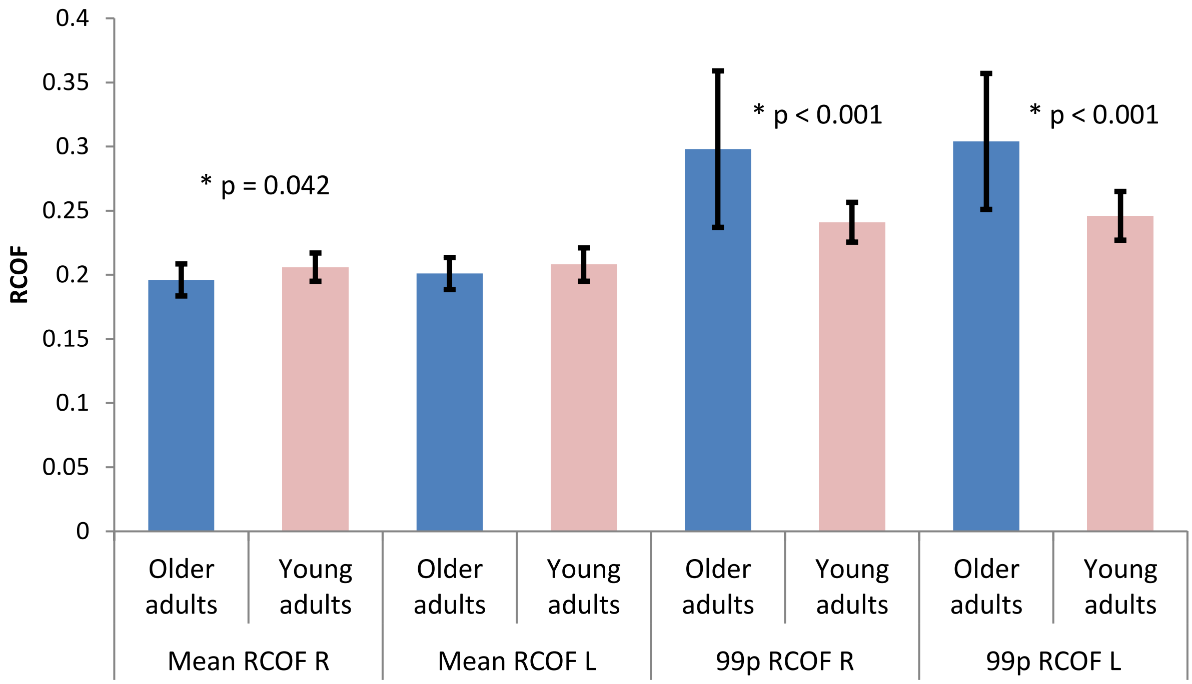
Figure 4.7 Mean RCOF for all groups at both walking speeds: A) Right Limb B) Left limb

As presented in section 4.1.2, the difference between RCOF mean and RCOF 99 was more than 50% for older adults, compared to ~17% for the young, therefore, both the mean and 99th percentile data were considered in the data analysis. While the young adults had higher RCOF mean at both speeds, older adults had greater RCOF 99, with an increased variability, as observed in the standard deviations. The gender comparisons at normal speed were similar, with a slightly greater RCOF mean and RCOF 99 for females. At fast speed males had a greater RCOF 99 with a greater variability in the left limb while females had greater RCOF in all other data.

When 101 was used to analyse the speed effect on the RCOF 99, the homogeneity assumption (Box's M) was violated bilaterally and corrected f-ratios were used. For the right limb an interaction of speed X age was noted, $F(1,100) = 7.3$, $p = .008$ due to young adults increasing RCOF 99 during fast walking while the older adults decreased their RCOF 99. In addition, larger RCOF variability was noted in the older people. In the left limb RCOF 99 data a interaction of age and gender was noted $F(1,100) = 7.3$, $p = .008$, indicating greater variability in the older males.

As the homogeneity assumption test was violated for RCOF mean, further tests of age and gender effects on RCOF were conducted using One-way ANOVA. An age effect (Figure 4.8) was confirmed on RCOF mean, with young adults having a greater RCOF, as follows: Normal speed right limb $F(1,102) = 4.2$, $p = .042$; Fast speed right limb $F(1,102) = 17.9$, $p<.001$ and left limb $F(1,100) = 17.1$, $p<.001$. For RCOF 99 the assumption of homogeneity of variances was again violated but the following effects were, however, found in the One-way ANOVA for normal speed with older adults having higher RCOF 99 than young in both the right limb $F(1,102) = 110$, $p<.001$ and the left limb $F(1,100) = 14.3$, $p<.001$.

A)



B)

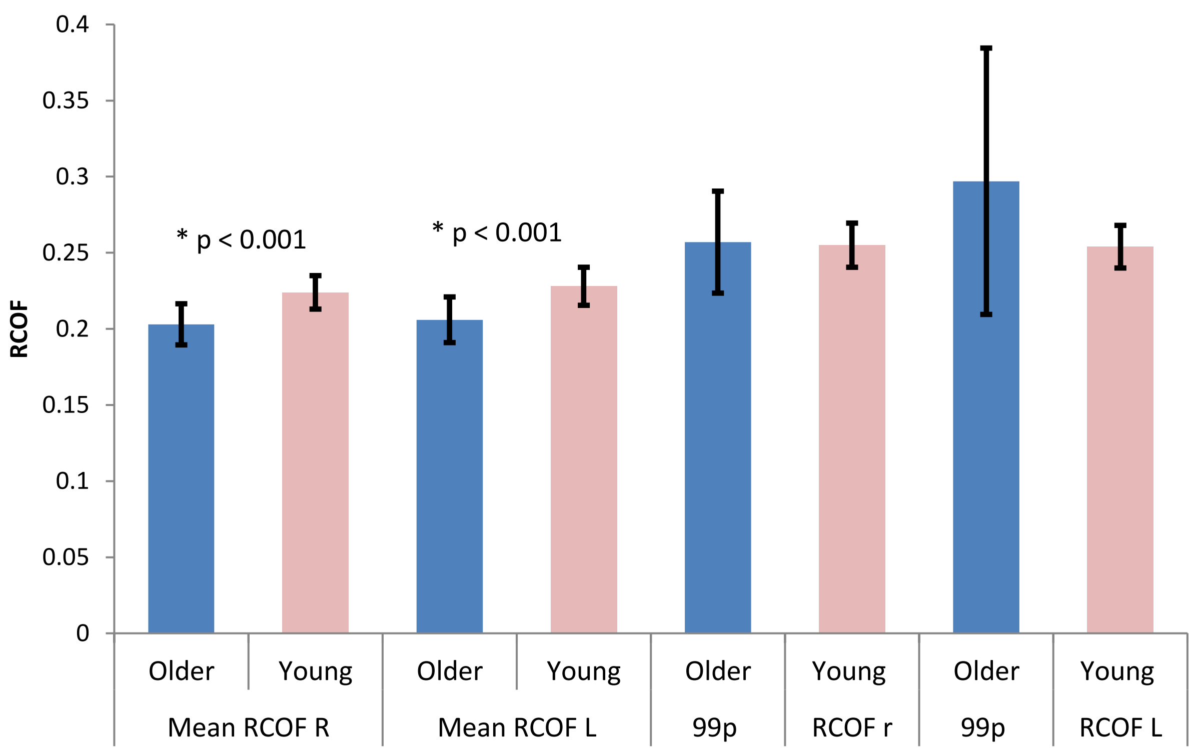
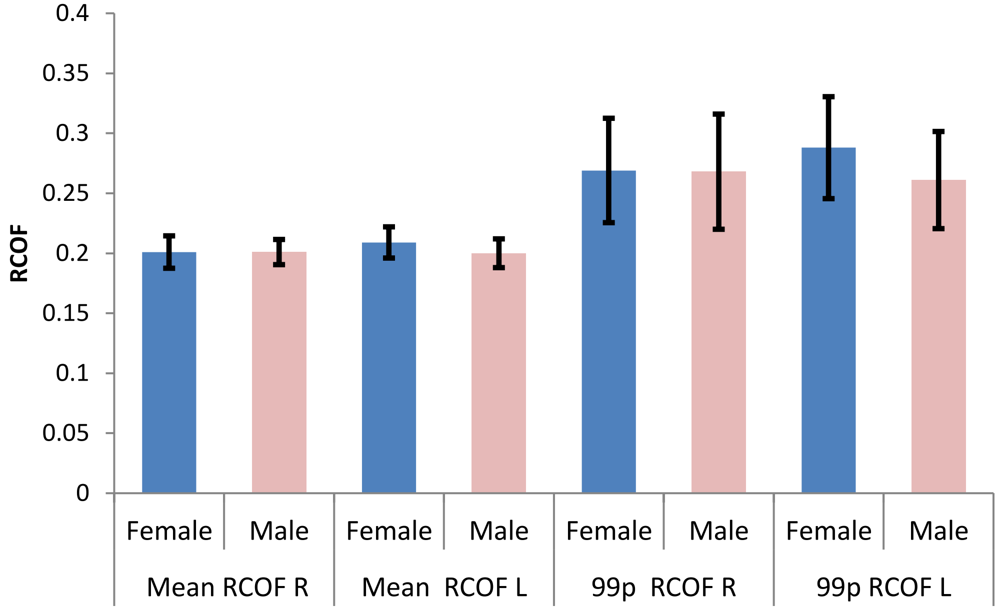


Figure 4.8 Age effect on RCOF A) Normal speed B) Fast speed

A)



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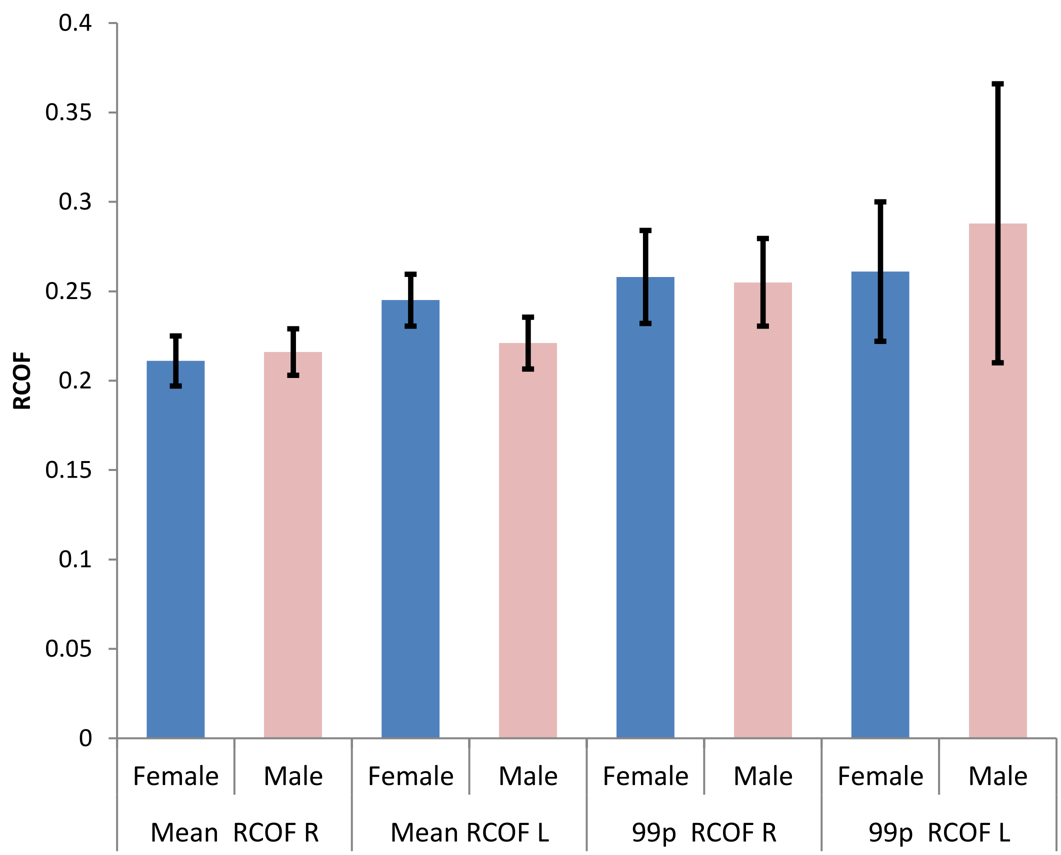


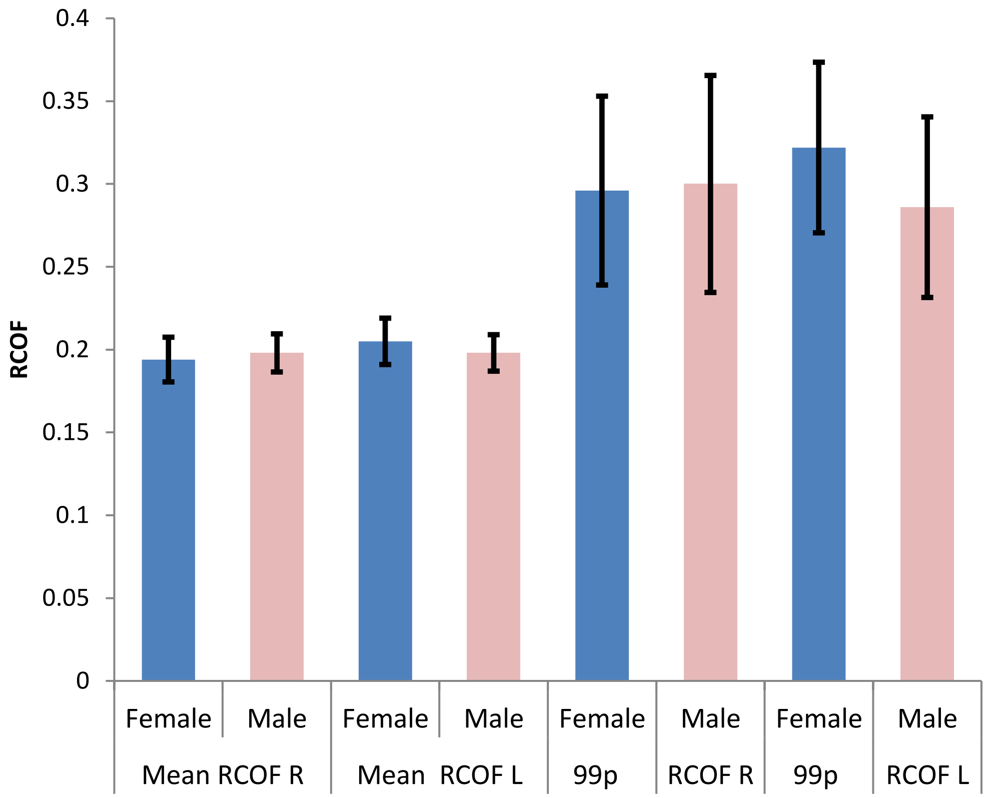
Figure 4.9 Gender effect on RCOF. A) Normal speed B) Fast speed

One way ANOVA did not reveal gender effects (Figure 4.9) on either RCOF mean or RCOF 99. The older adults' RCOF 99 data were generally characterised by greater variability than their RCOF mean. At both normal and fast speed the young adults had similar RCOF mean and RCOF 99 variability with both gender groups presenting equivalent data.

Figures 4.10 and 4.11 present RCOF mean and RCOF 99 for the four population groups at normal and fast speed giving a further insight to the age and gender effects. In general, young adults presented with lower variability at both speeds. RCOF 99 was only slight greater than RCOF mean with a slightly greater range for the females in the RCOF 99 data. In the data of the older adults a key factor was the increased variability seen as the difference between RCOF mean and RCOF 99 for both genders, especially at normal speed. Interestingly the variability was less at fast speed. A greater difference between limbs was also noted in the RCOF 99 data.

In a summary, RCOF data were significantly affected by speed and age, but not gender. In general, RCOF increased as speed increased, however, an interaction between age and speed reflecting the age effect in RCOF especially at fast speed with older adults presenting with lower RCOF values. Variability of RCOF was greater for older adults especially at normal speed indicating the need for further investigation and the use of other presentations than mean.

A)



B)

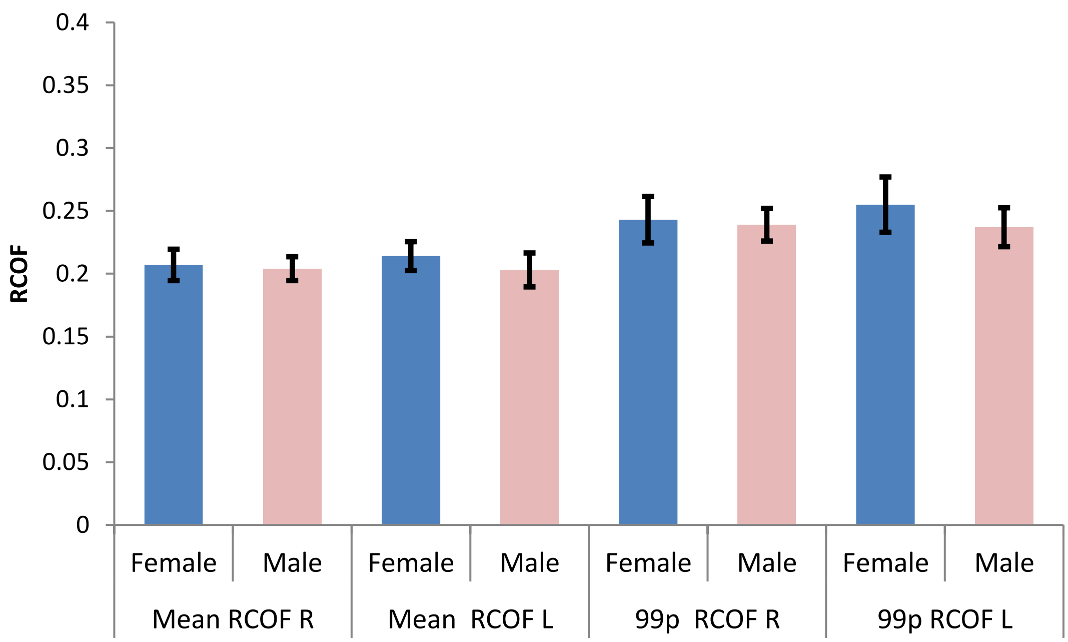
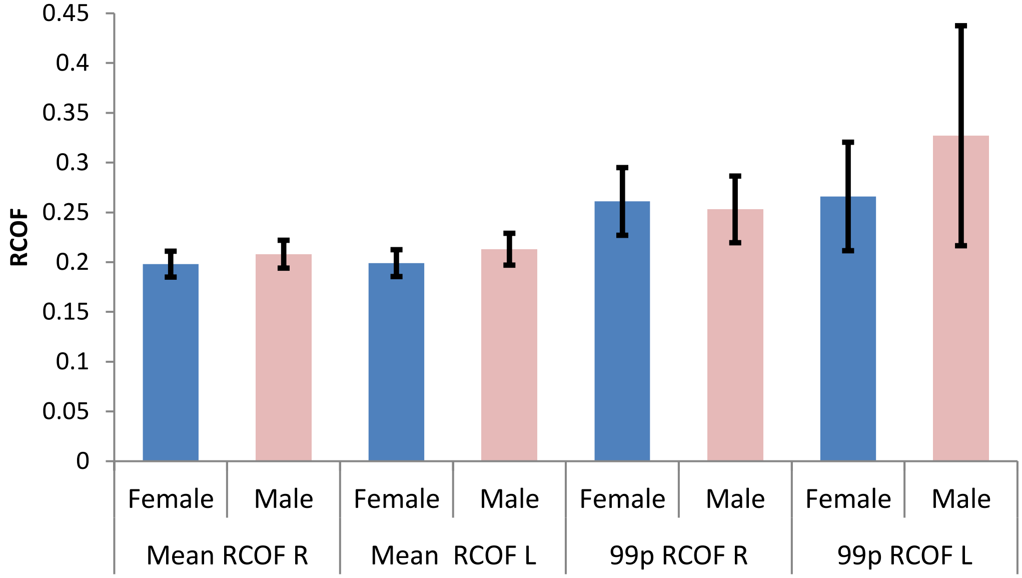


Figure 4.10 Gender effect on RCOF, age divided groups, normal speed. A) Older adults B) Young adults

A)



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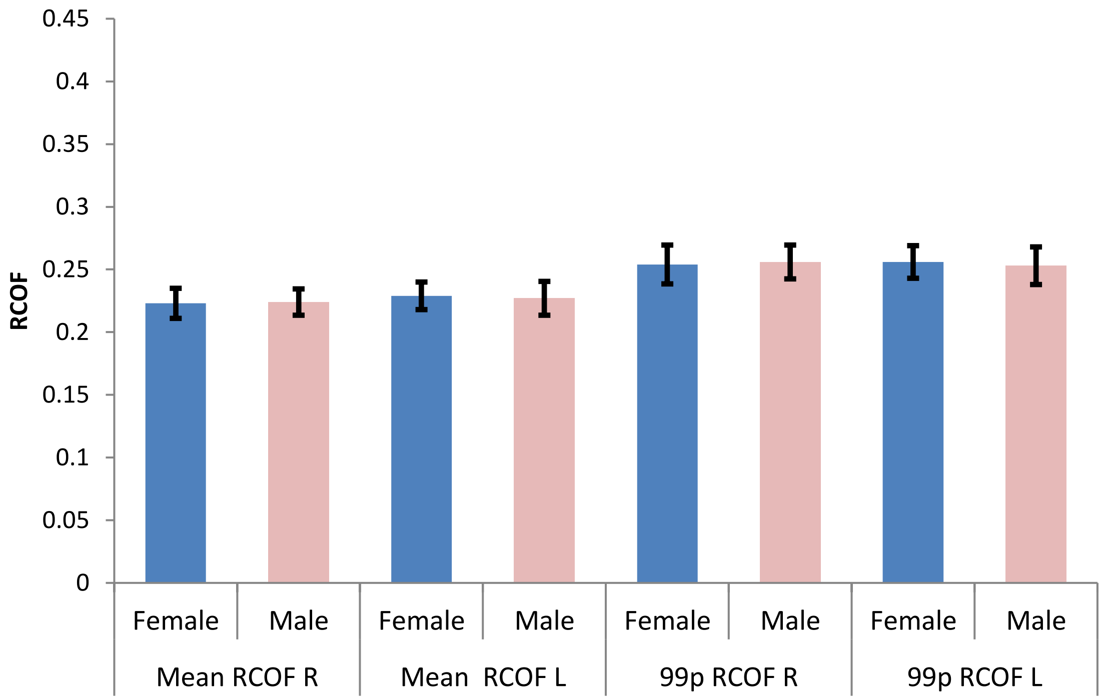


Figure 4.11 Figure 5.18 Gender effect on RCOF, age divided groups, fast speed. A) Older adults B) Young adults

4.3 Slipping Probability

The previous sections discussed speed, age and gender effects on RCOF. This section reports the slipping probability analysis based on RCOF distributions. Probability analysis was conducted for a total of 26 young females, 25 young males, 20 older females and 22 older males. Some participants' data were excluded due to their data not meeting requirements of the Best and Begg (1999) modelling algorithms. The data are presented as: (i) Slipping probability at known RCOF values, (ii) Slipping probability functions (graphical presentation), (iii) Total slipperiness (Trapezoidal calculation) and (iv) Case studies.

4.3.1 Slipping Probability at Known RCOF Values (PRCOF)

In the probability calculation, the participant's RCOF distribution can be used to calculate a range of slipping probability estimates ranging from 0% to 100%. Slipping probability can be estimated for any RCOF as the likelihood of that value during walking, i.e. PRCOF. This value can be further converted to a Probability of Slipping (PS) (1-PRCOF) on a surface with a known friction COF based on the principle that if COF is less than RCOF, it does not meet the friction requirement and a slip is predicted. To further investigate PRCOF, the following RCOF values at both walking speeds were selected for analysis: 0.05, 0.1, 0.15, 0.2, 0.25, 0.3 and 0.35.

As presented in Figure 4.12 older females had lowest PRCOF i.e., less than 0.2. Previously a COF range 0.0–0.2 has been categorised as very slippery and very hazardous and, therefore, the older females presented with *safer gait* that the young adults whose PRCOF was ~ 0% and thus PS 100%, suggesting that they were 100% likely to slip on those very low friction surfaces. Indeed, the largest differences between the groups were observed at RCOF 0.2 while at RCOF 0.25 the two groups of older adults had very similar data with the young males deviating most from this trend.

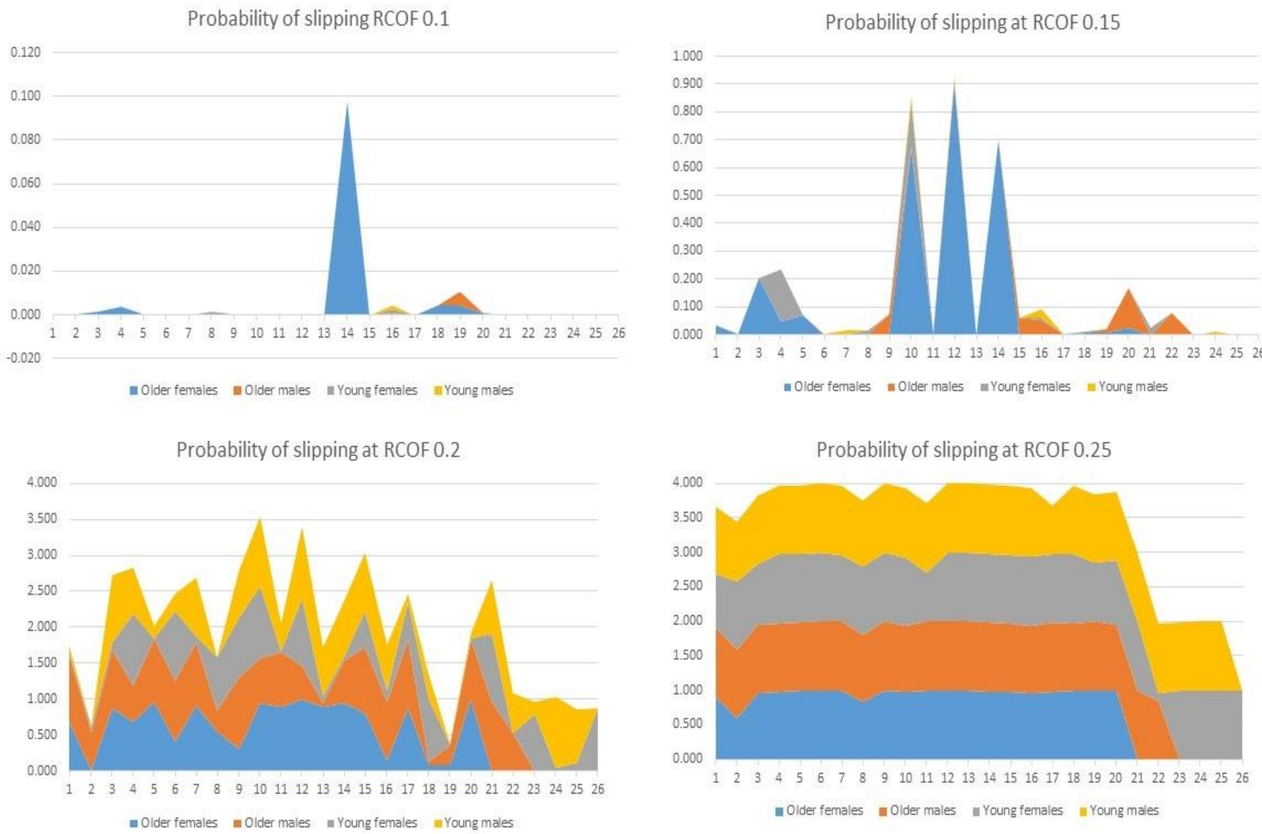
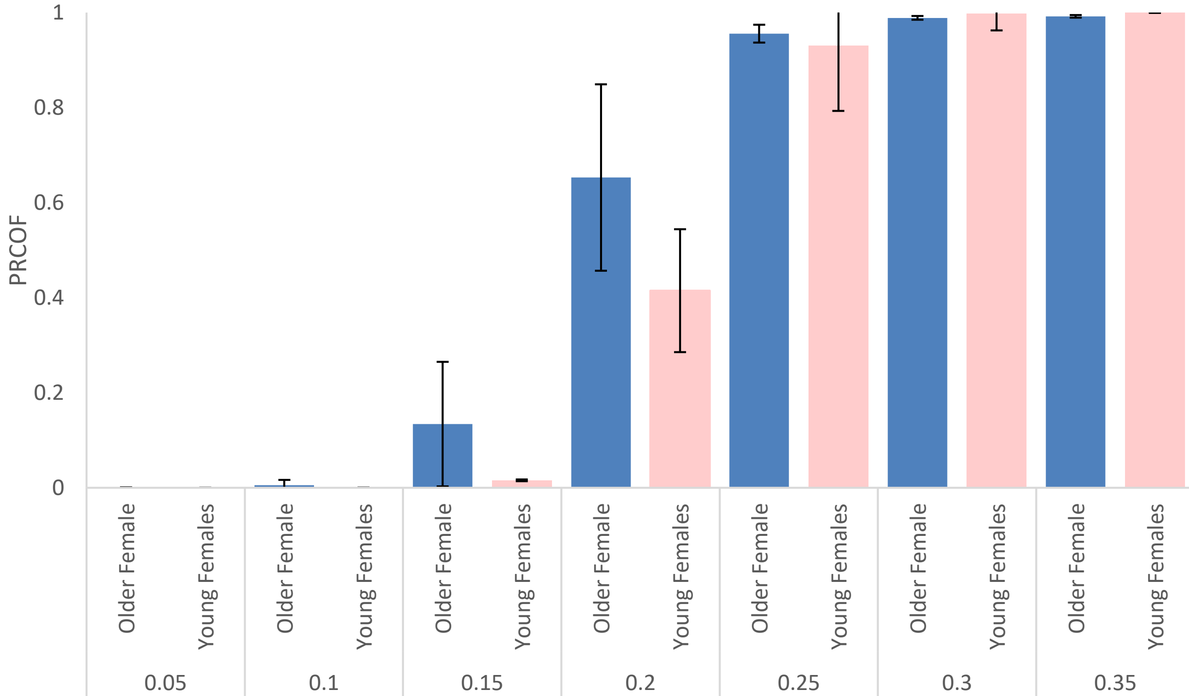


Figure 4.12 PRCOF for all subgroups for RCOF 0.1, 0.15, 0.2 and 0.25. Right limb, normal walking speed. PRCOF is presented in the Y axis. For RCOF 0.2 and .0.25 all groups 100% is presented.

Figure 4.12 demonstrates, furthermore, that at RCOF 0.1 only one older female had a PRCOF of 10% and thus a 90% chance of slipping (PS) at surface COF 0.1. All other groups had a 100% chance of slipping in that COF condition. At RCOF 0.15 three older females had high probabilities of the value appearing whilst most individuals did not have RCOF as low. At RCOF 0.2 most groups had high PRCOF whilst at RCOF 0.25 most participants had close to 100% chance of the target value appearing and close to 0% chance of slipping above COF 0.25. Figures 4.13–4.16 present PRCOF for both limbs at normal and fast walking speeds presented separately for the two genders.

A)



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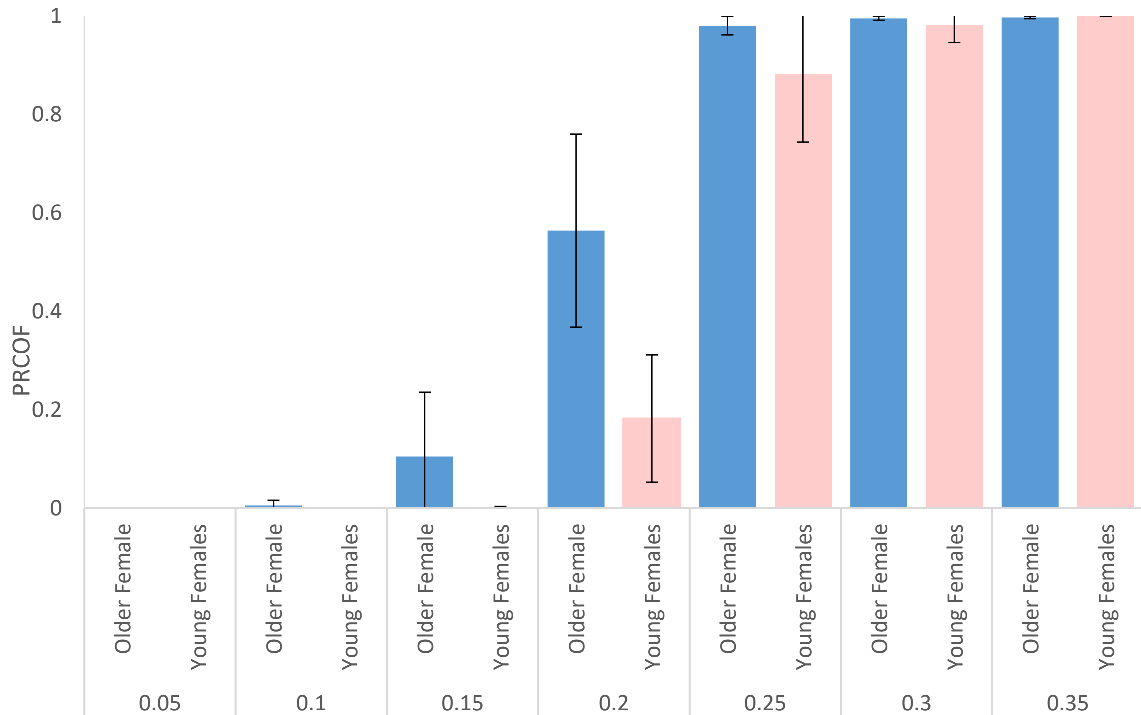
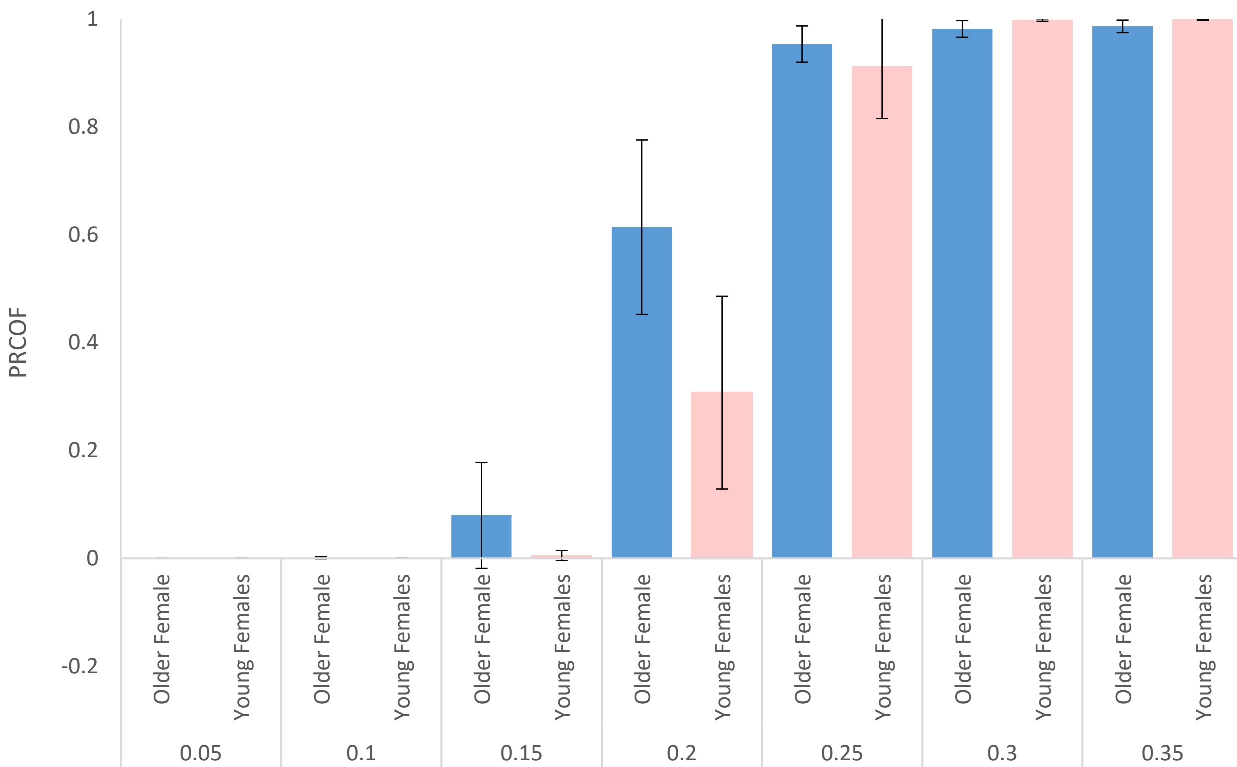


Figure 4.13 PRCOF females at RCOF 0.05, 0.1, 0.15, 0.2, 0.25, 0.3 and 0.35. Right limb; A) normal speed, B) fast speed.

At normal speed (right limb data, Figure 4.13), the older females presented at lower RCOF ranges (0.1–0.15) with a PRCOF of more than 60% and thus 40% PS at RCOF 0.2. In the same low ranges the young females had a PS 100% and a PS 60% at RCOF 0.2 at normal speed and a PS of more than 80% at fast speed. In the low RCOF values, the older females had a greater PRCOF at normal speed. At RCOF 0.25 the older adults were approximating 0% PS with the young adults close to 5% and 10% PS at normal and fast speeds respectively. The left limb data presents with similar trends as right limb data.

The two male groups presented a different pattern to the females as most of the older males were similar to the young, with RCOF appearing at 0.2. A difference between speeds can be noted with a greater PRCOF (above 60%) at 0.2 RCOF at normal speed compared to fast (PRCOF 40%). The young adults presented with lower RCOF at both speeds (~45% at normal and ~15% at fast). In PRCOF 0.25 at fast speed the older adults reached PRCOF 100% compared to 90% in the young. As seen in females, the left limb data were similar to the right limb data.

A)



B)

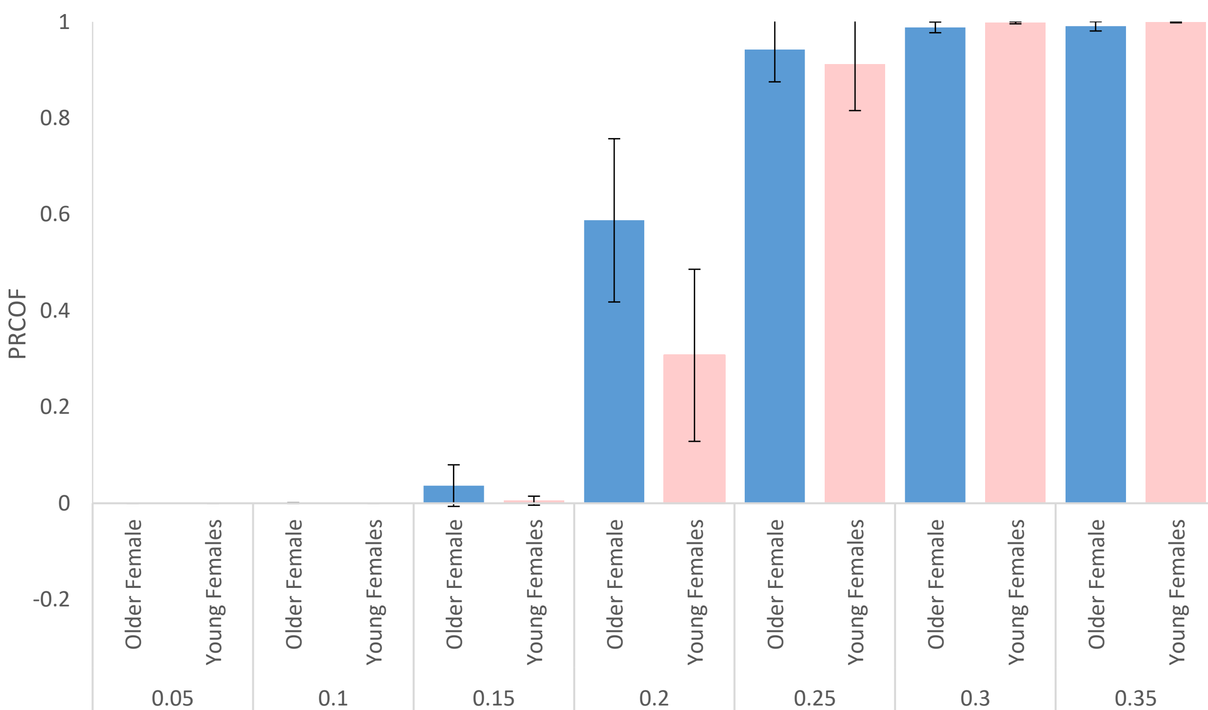


Figure 4.14 PRCOF females at RCOF 0.05, 0.1, 0.15, 0.2, 0.25, 0.3 and 0.35. Left limb; A) normal speed, B) fast speed.

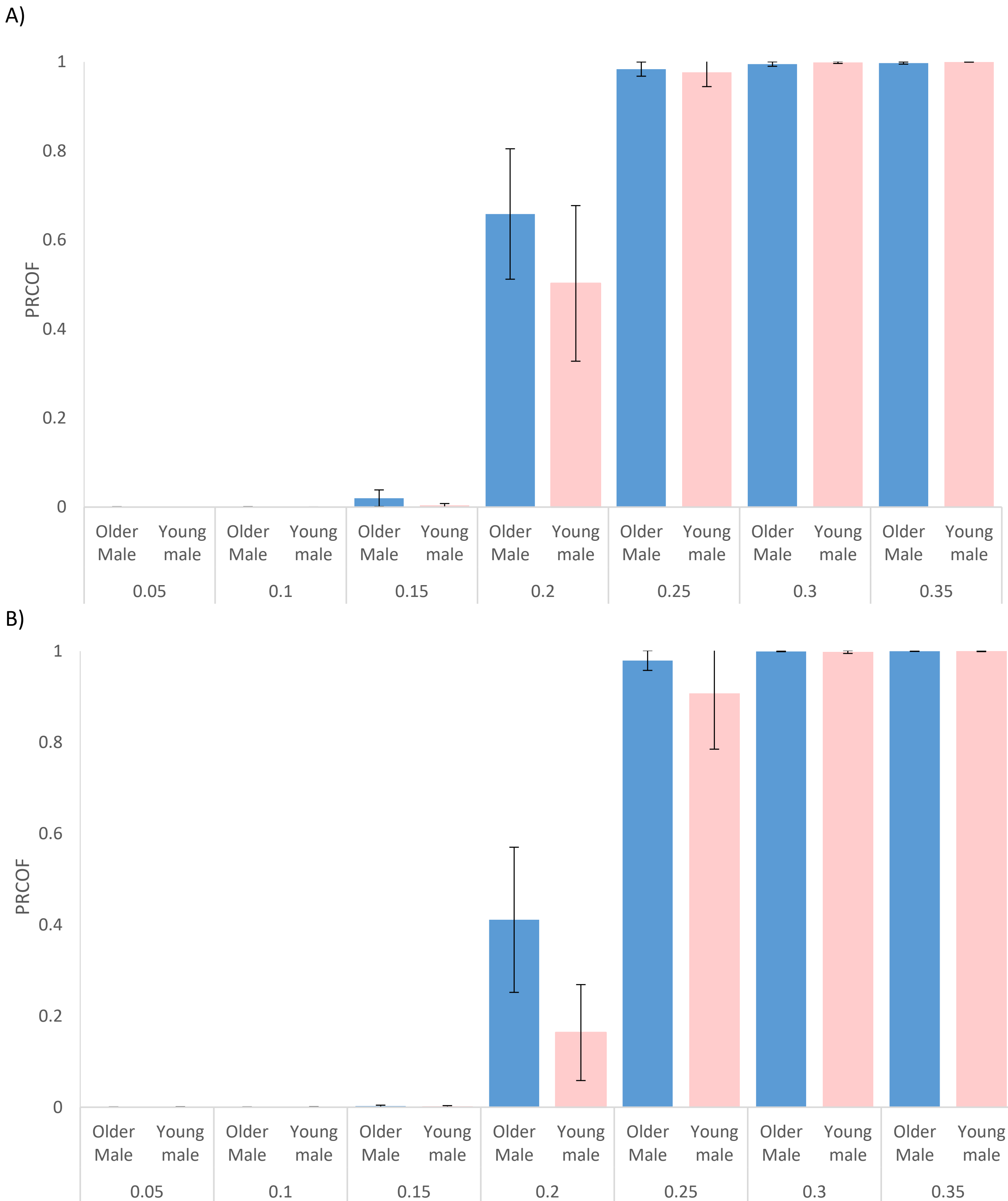


Figure 4.15 PRCOF for males at RCOF 0.05, 0.1, 0.15, 0.2, 0.25, 0.3 and 0.35. Right limb only; A) normal speed, B) fast speed

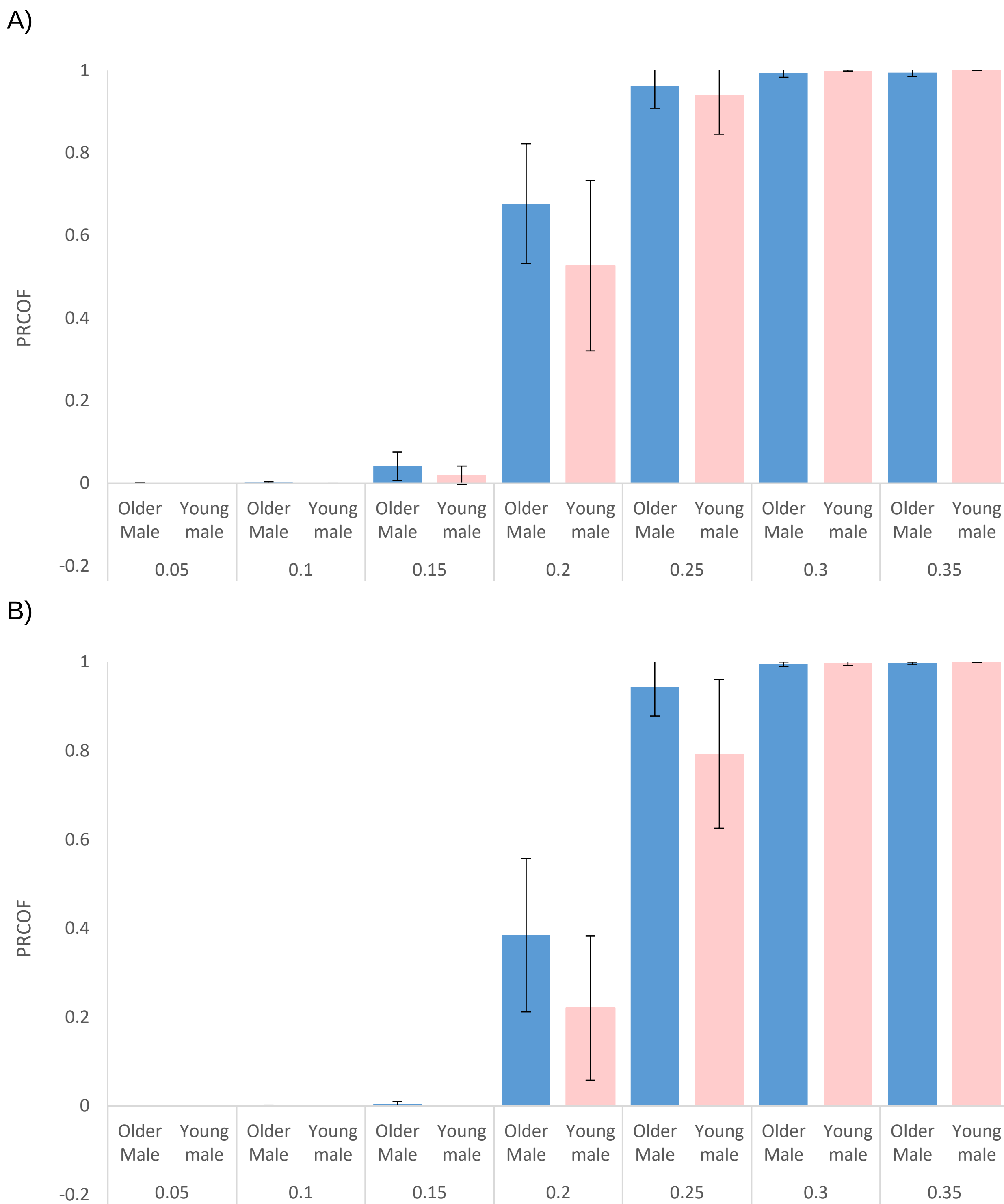


Figure 4.16 Figure 5 18 PRCOF for males at RCOF 0.05, 0.1, 0.15, 0.2, 0.25, 0.3 and 0.35. Left limb only; A) normal speed, B) fast speed

One-way ANOVA confirmed a significant group effect on PRCOF: right limb RCOF 1.5 $F(3,89) = 4.5$, $p = .005$ and for left limb .PRCOF 1.0 $F(3,89) = 3.4$, $p = .021$ and PRCOF 2.0 $F(3,89) = 5.1$, $p = .003$. At normal walking speed the critical area for probabilities was RCOF range 0.15–0.25 when most groups increased from 0% to 94-98% probability. At RCOF 0.15 most population groups had ~ 0% PRCOF but the mean probability for older females was 13% with a large SD showing group variability. When converting PRCOF to Probability of Slipping (PS) while all the other groups had 100% chance of slipping at COF 0.15, the older females only had 87% chance.

When converting all PRCOF to the PS values it is possible to examine the groups' slipping propensities on different surfaces. At RCOF 0.2, the limit for the very hazardous and slippery surface, the young females had 59% and 69% chance of slipping for right and left feet respectively, the young males 50% and 78% chance for right and left limbs respectively, older females 35% and 41% chance for right and left limbs respectively and the older males 34% and 62% chance for right and left limbs. It must also be noted that all population groups had a high PRCOF standard deviation at RCOF 0.2 confirming the within group variability.

At RCOF 0.25, the PS values decreased with the chance of slipping for right and left feet respectively for young females 7% and 9%, for young males 2% and 21%, for older females 4% and 6% and for older males 2% and 6%. It is important to note the higher risk associated with the left limb and the remarkably greater left foot slipping risk seen in young males.

In fast walking One-way ANOVA confirmed a significant group effect for PRCOF as follows: right limb RCOF 1.5 $F(3,89) = 3.7$, $p = .014$, RCOF 2.0 $F(3,89) = 9.4$, $p < .001$ and left limb RCOF 2.0 $F(3,89) = 4.6$, $p = .005$. At RCOF .0.1 all population groups had a 0% chance of RCOF appearing and, therefore, a 100% chance of slipping if surface COF is 0.1.

At RCOF 0.15 both male groups had PRCOF of 0% and both female groups had some data with PRCOF of 2% and 1% for young females for right and left limb respective and 10% and 4% for older females for right and left limb respectively.

At RCOF 0.2 all groups had increased PRCOF from 41% for young females to 66% for older males. When converting to the probability of slipping (PS) at COF 0.2, marking the boundary between very slippery and very hazardous and slippery and hazardous, young females had 59% PS, young males 50%, older females 35% and older males 34%. At COF 0.2 both older groups showed safer walking style than the young adults.

4.3.2 Slipping Probability Functions

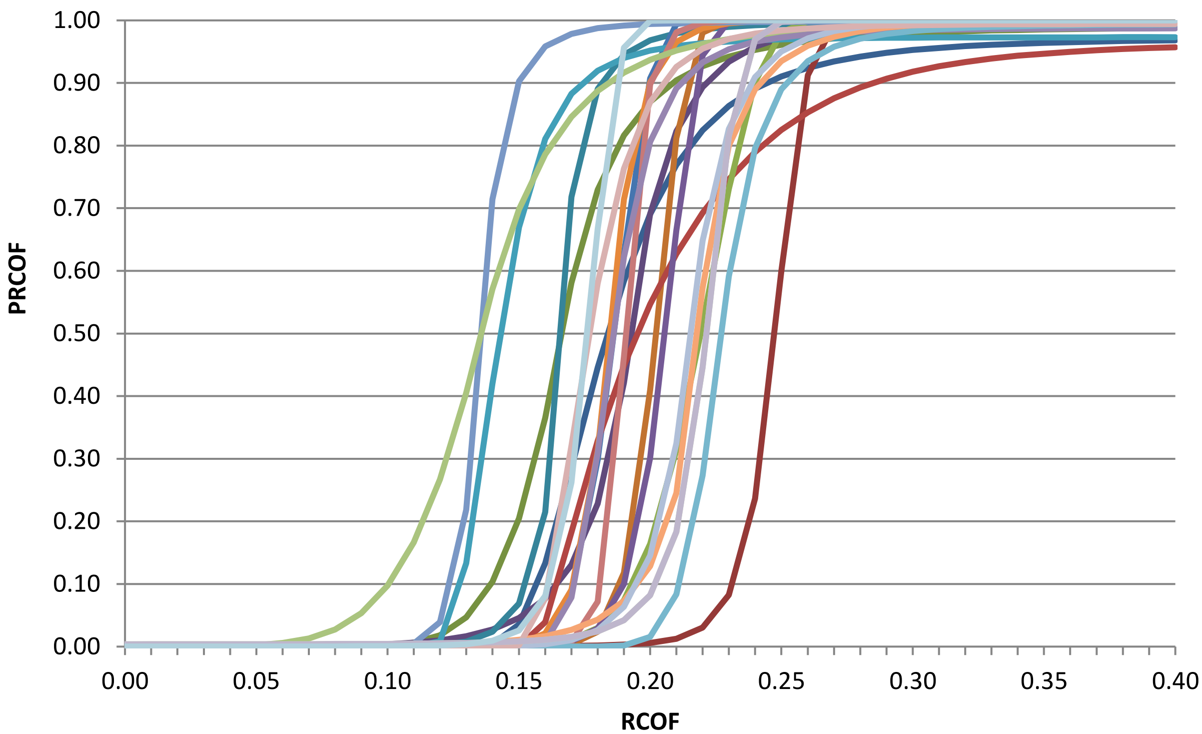
While the previous PRCOF analysis allowed slipping estimation at selected points on the probability function, this analysis does not provide a complete description of slipping probability. In a case of low variability, for example, it is possible for the individual to increase from 0% to 100% probability within a small RCOF range. To more completely estimate the probability of slipping one must examine the slipping probability function including all data. These slipping function data are presented in the figures below for both age and gender groups bilaterally at both walking speeds.

4.3.2.1 Older Females

Large variability between participants was noted in the PRCOF data of older females at both walking speeds (Figures 4.17 and 4.18) Some individuals had a small data range presented in a steep probability curve and a rapid increase from PRCOF 0% to 100% and others had a larger PRCOF range. For normal walking speed, for example, at 25% PRCOF, the RCOF range for older females right limb was 0.118-0.241 and left limb 0.131-0.230.

When PRCOF was converted to the PS (1 - PRCOF), older females had a 75% slipping probability on surfaces with the friction COF within the above ranges. At 50% probability the group range increased due to the data of a few individuals. Whilst most participants had a similar range and pattern varying between PRCOF of 0.16 and 0.21 at 50% others presented with steep probability curves, one at the low and one at the high end of the RCOF scale. A similar gradual increase was seen at the 75% probability.

A)



B)

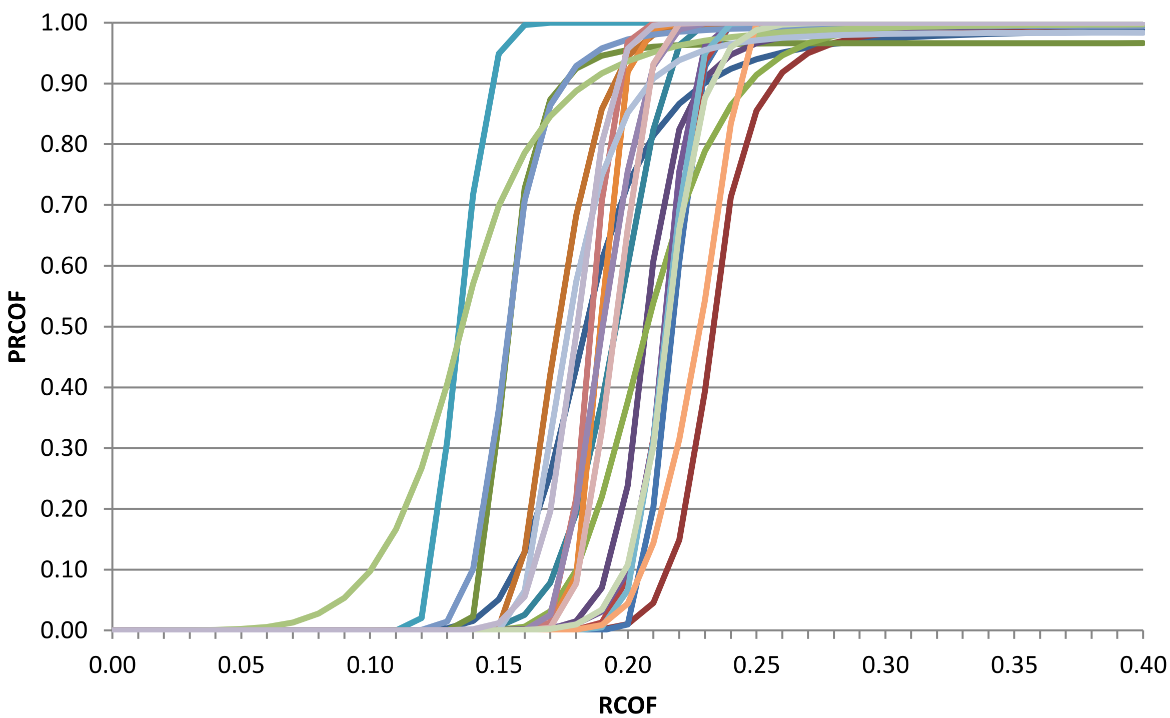


Figure 4.17 PRCOF – Older females at normal and fast speed, Right limb.

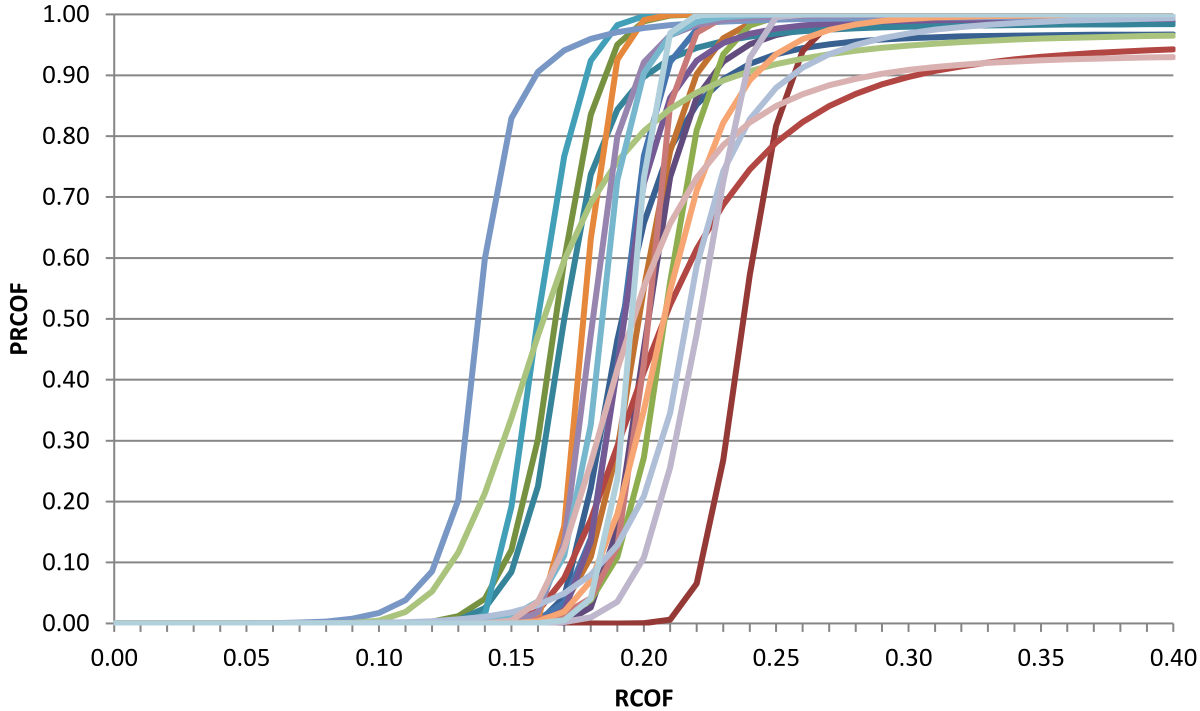
At 95% probability it was observed that at fast walking speed the max RCOF value was lower than at normal speed.

For the left limb data the maximum value at 95% was 0.456, above the assumed safe range (COF above 0.4). If PROC is 95%, PS is 5% and on a surface friction (COF) of 0.456 this indvidual has a 5% chance of slipping.

When walking at normal speed most older females had a slipping probability pattern showing a rapid increase in PRCOF representing a small probability range. Some individuals, however, had patterns with a slower increase and larger range with one participant representing extreme values. Furthermore, some individuals did not achieve the 100% probability. Given that slipping probability (PS) on a parcticular surface is calculated as 1- PRCOF, it must be noted that these individuals did not attain a 100% safe gait pattern, rather they remained at a 0-5% slipping risk.

It is important to observe that the fast speed data showed a characteristically different distribution. While there was still a large range between individuals, their patterns were more similar. Most individuals presented with a rapid increase from 0% to maximum and most reached the 100% PRCOF, thus 0% PS at COF 0.3 while some did not attain 100% safety.

A)



B)

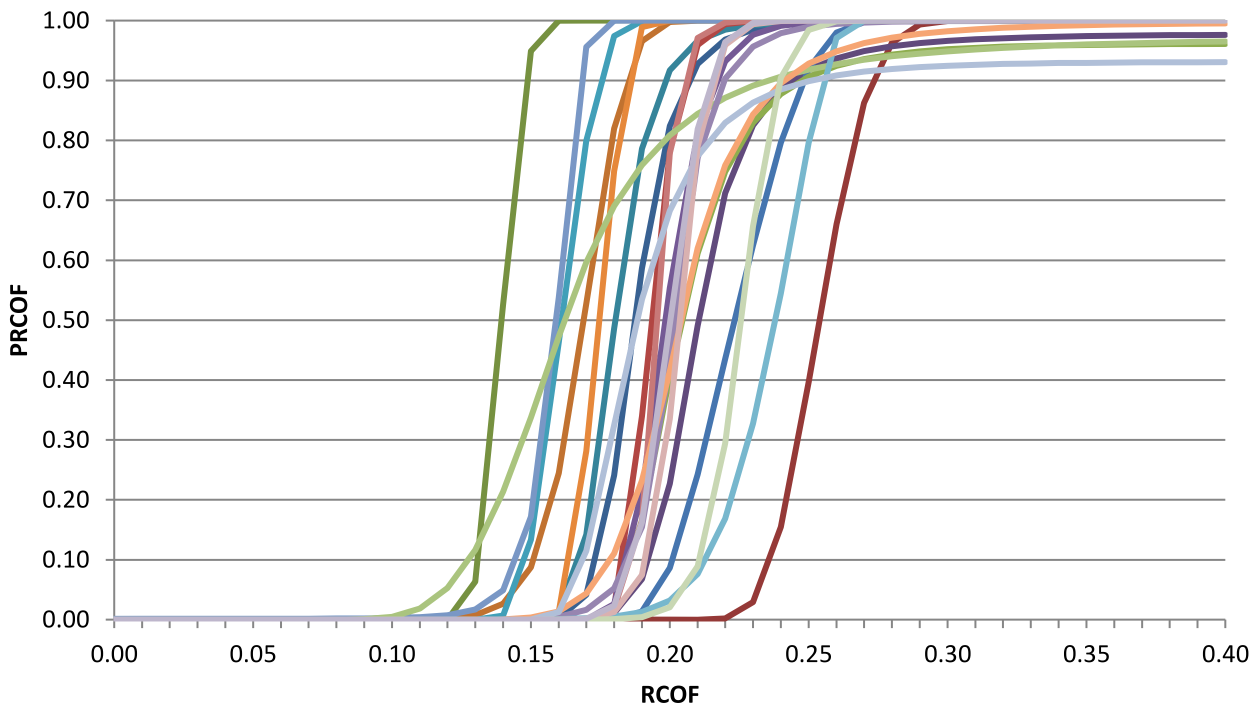


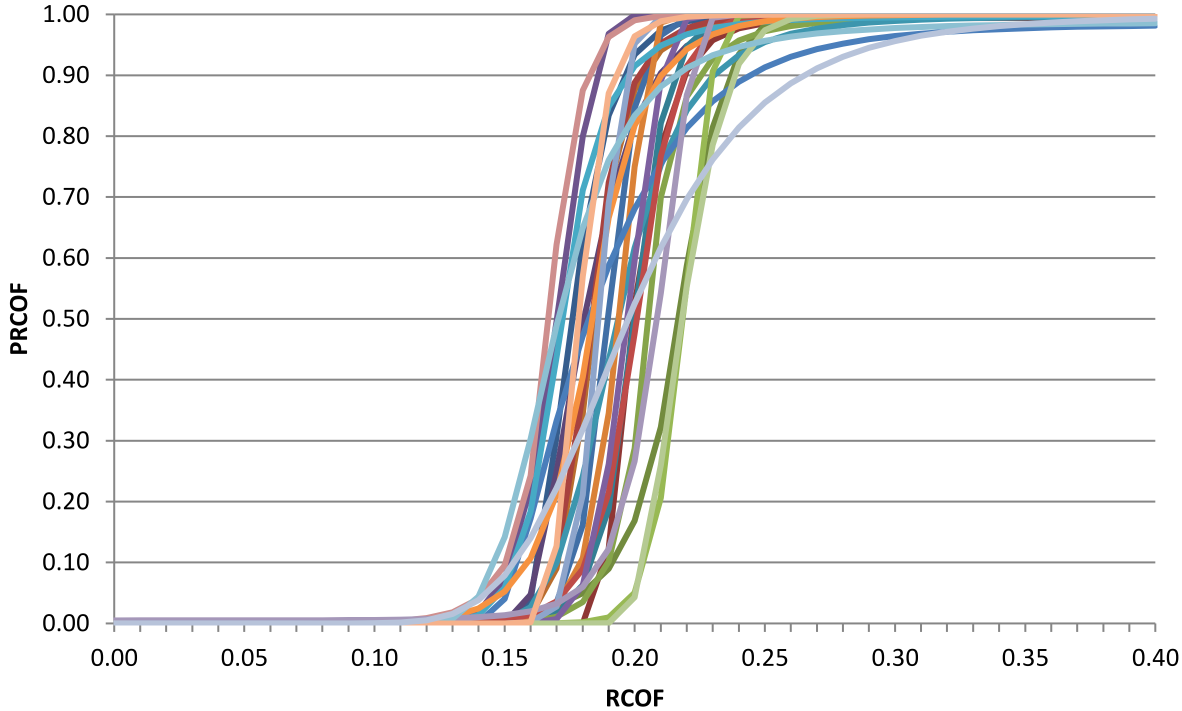
Figure 4.18 PRCOF – Older females at normal and fast speed, Left limb. A) normal speed B) fast speed

4.3.2.2 Older Males

For the older men walking at normal speed (Figure 4.19-4.20), similar to older females, most presented within a narrow PRCOF range. For the right limb, however, two individual's probability functions revealed an ”arch” pattern with a higher probability of lower RCOF. In these cases 100% was never reached, remaining at 91%. In the left limb more inter-subject variability was observed with different variations from the patterns of the right limb. Two individuals did not show the more familiar ”arch” pattern and many participants deviated from the typical pattern with a slowly increasing probability, with a greater range and higher maximum when compared to the right limb. Furthermore, as with the right limb, two individuals did not reach 100% PRCOF and had greater than 0% PS.

The PRCOF data of older men walking at fast speed were similar to the older women but with less intra-individual variability and a relatively rapid increase in probability. Whilst some individuals presented with higher RCOF, no atypical probability functions were observed for either limb. These observations on the probability ranges indicated a relatively safe walking pattern for the older males at fast walking speed. Unlike the older females, the males presented with lower PRCOF with the maximum PRCOF 0.309 noted at 95% risk at normal speed and all values fell below the safe COF of 0.4.

A)



B)

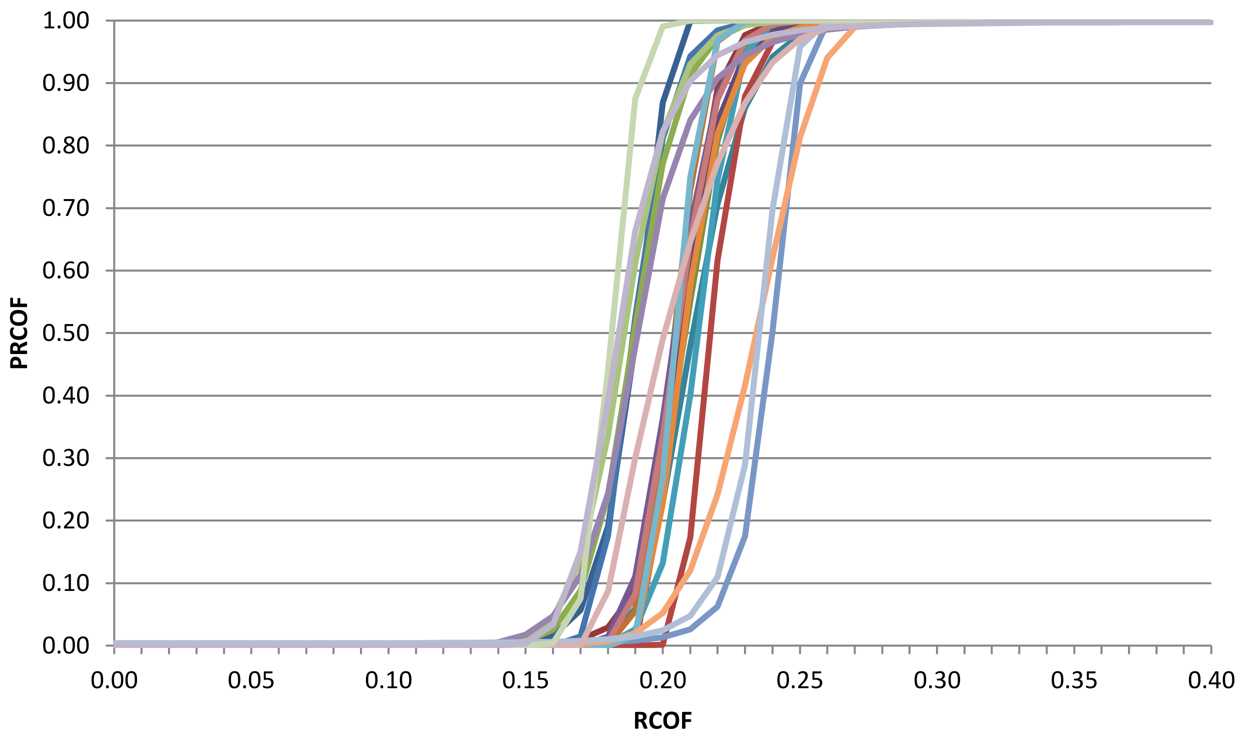
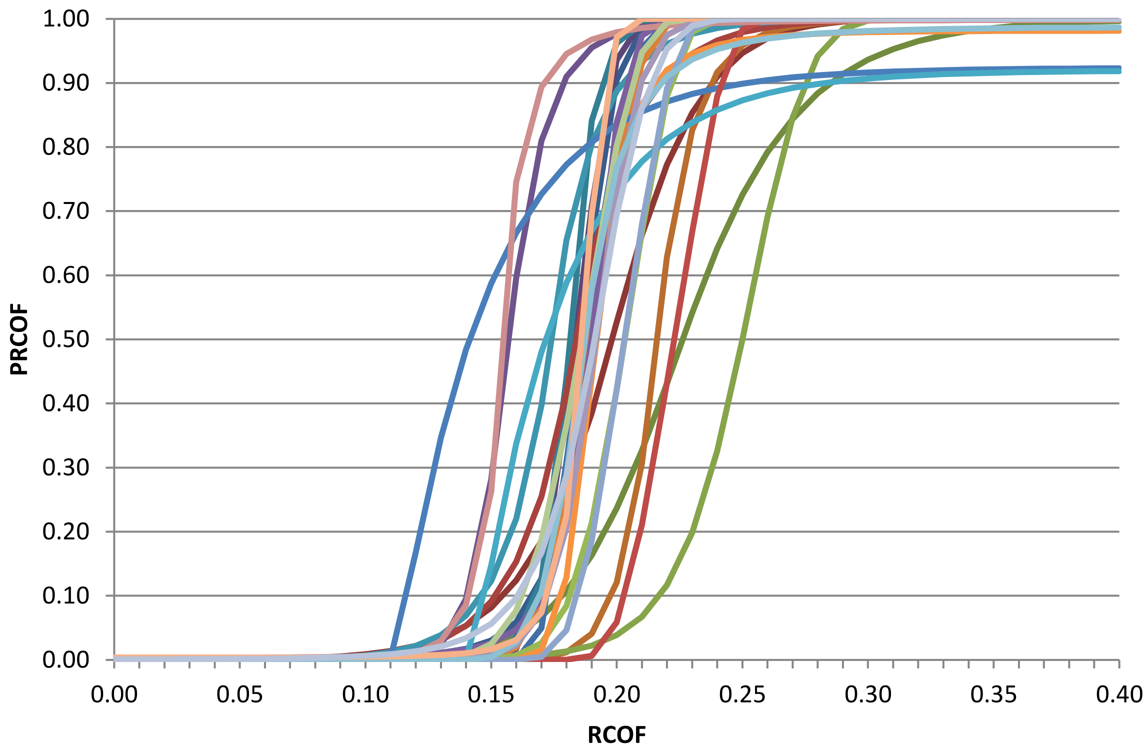


Figure 4.19 PRCOF – Older males at normal and fast speed, Right limb. A) normal speed B) fast speed

A)



B)

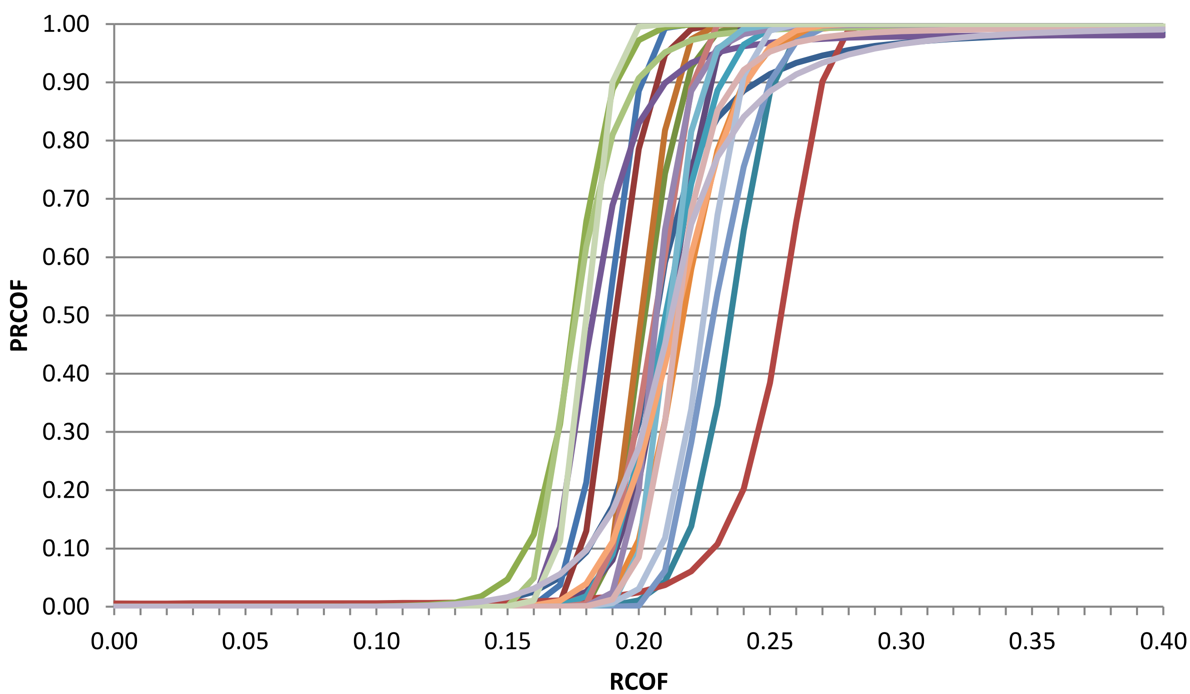
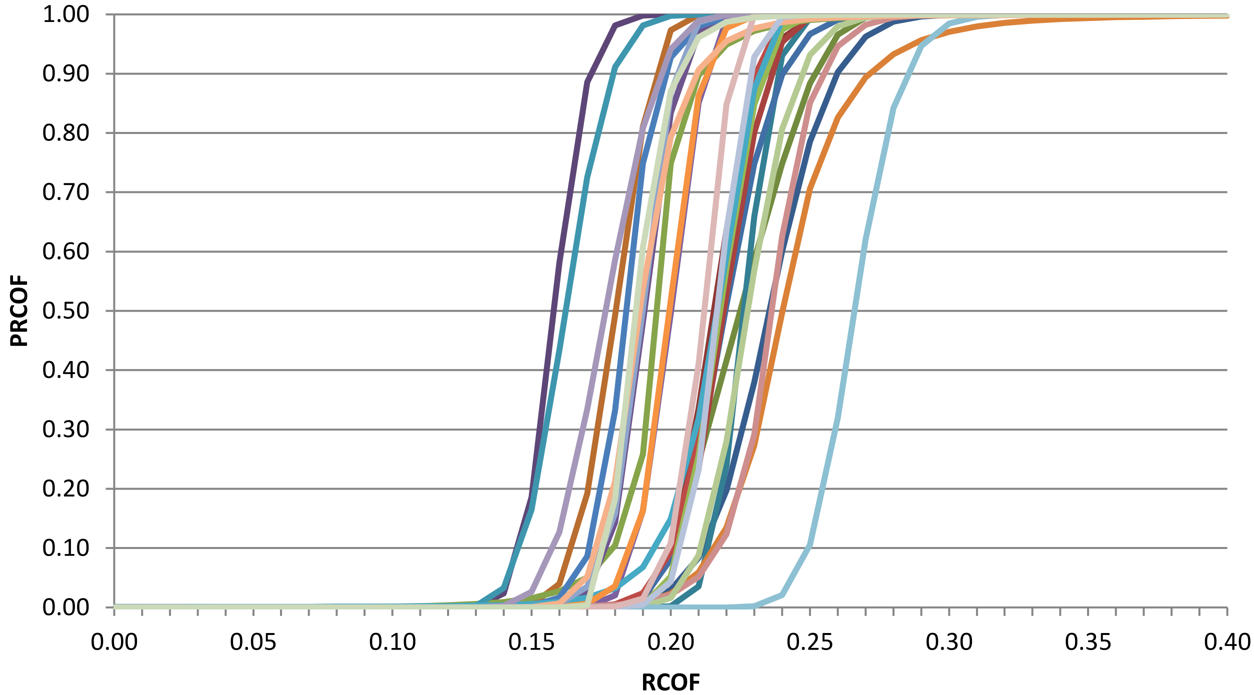


Figure 4.20 PRCOF – Older males at normal and fast speed, Left limb. A) normal speed B) fast speed

4.3.2.3 Young Females

Young females at normal walking speed (Figures 4.21 - 4.22) revealed generally homogenous PRCOF patterns and most had low variability, as seen by the rapidly increasing functions. Some had a very low RCOF (RCOF Range 0.13 – 0.19) setting a very low demand for the surface friction whilst others had a higher range (0.19 – 0.31). The patterns were similar for the right and left limbs, with a similar range. At fast walking speed some individual variation was observed, however, most distributions were within a narrow PRCOF range.

A)



B)

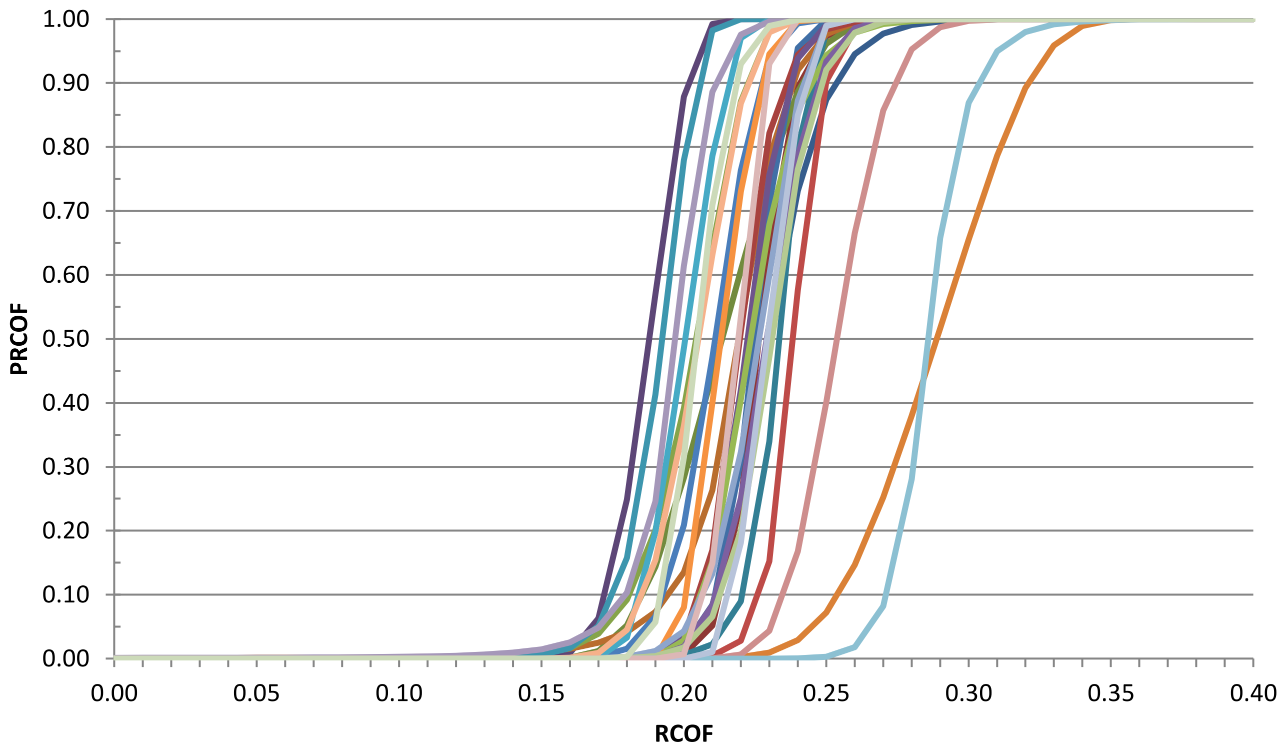
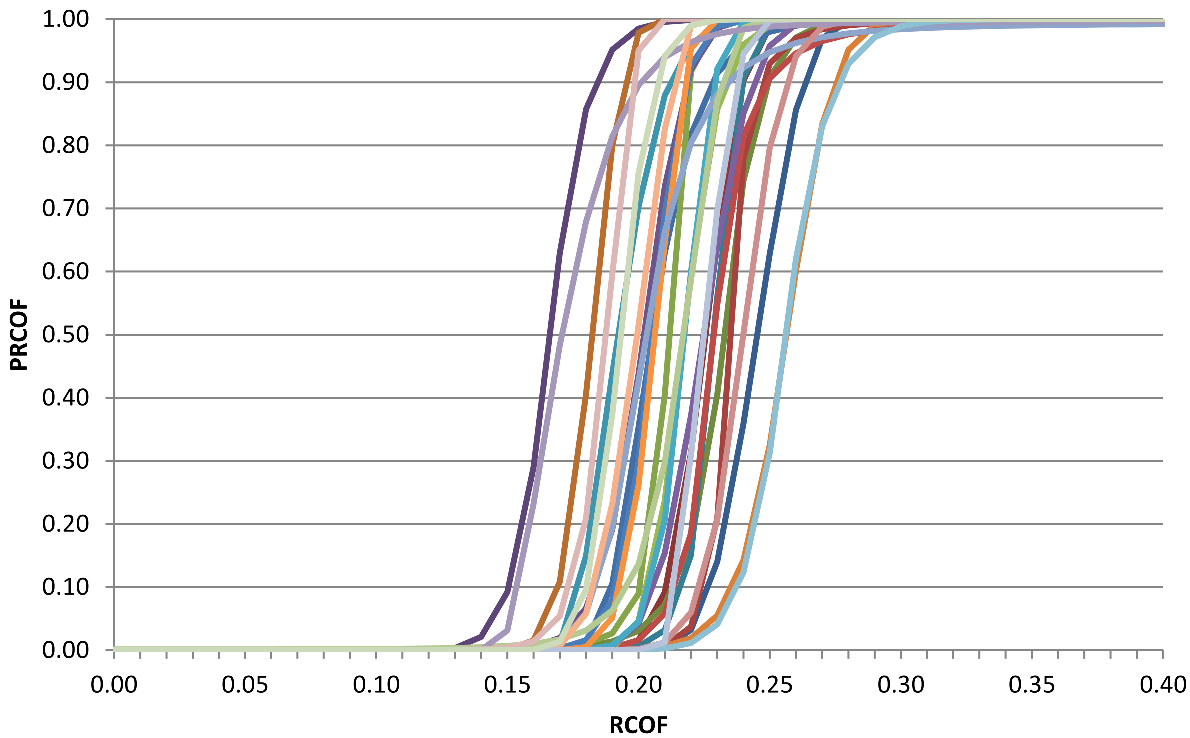


Figure 4.21 PRCOF – Young females at normal and fast speed, Right limb.
A) normal speed B) fast speed

A)



B)

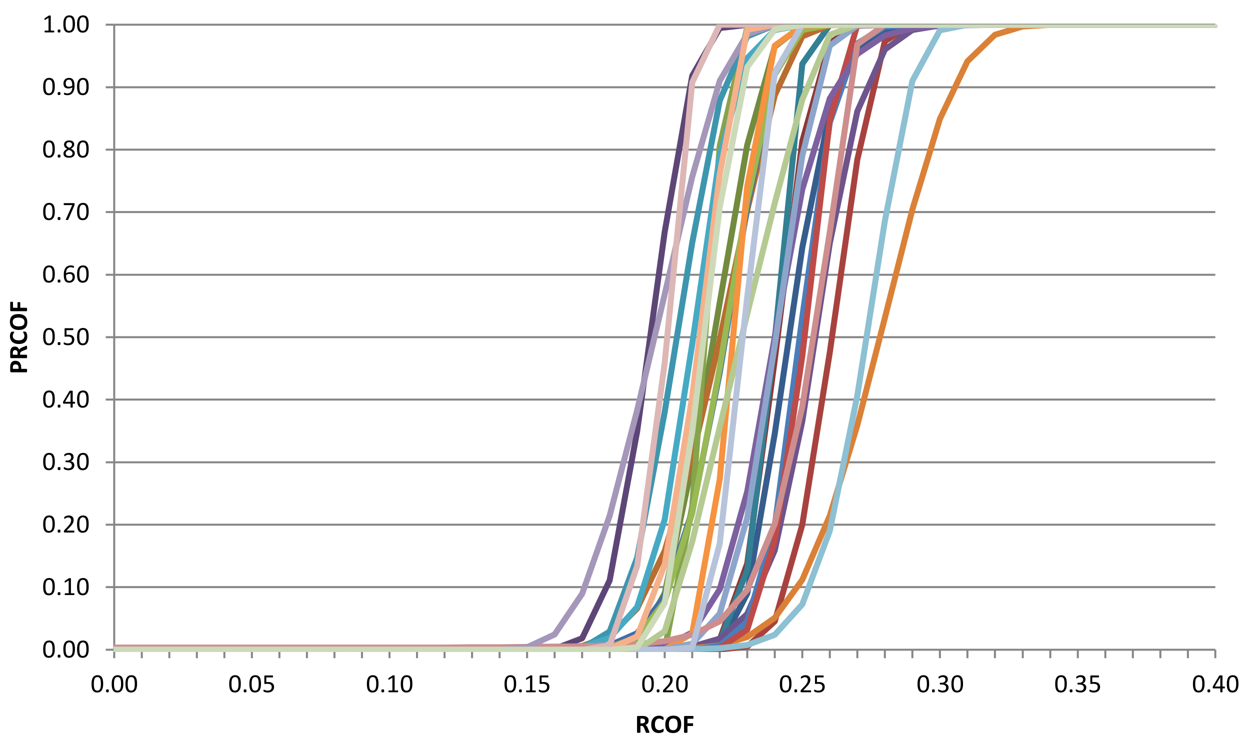


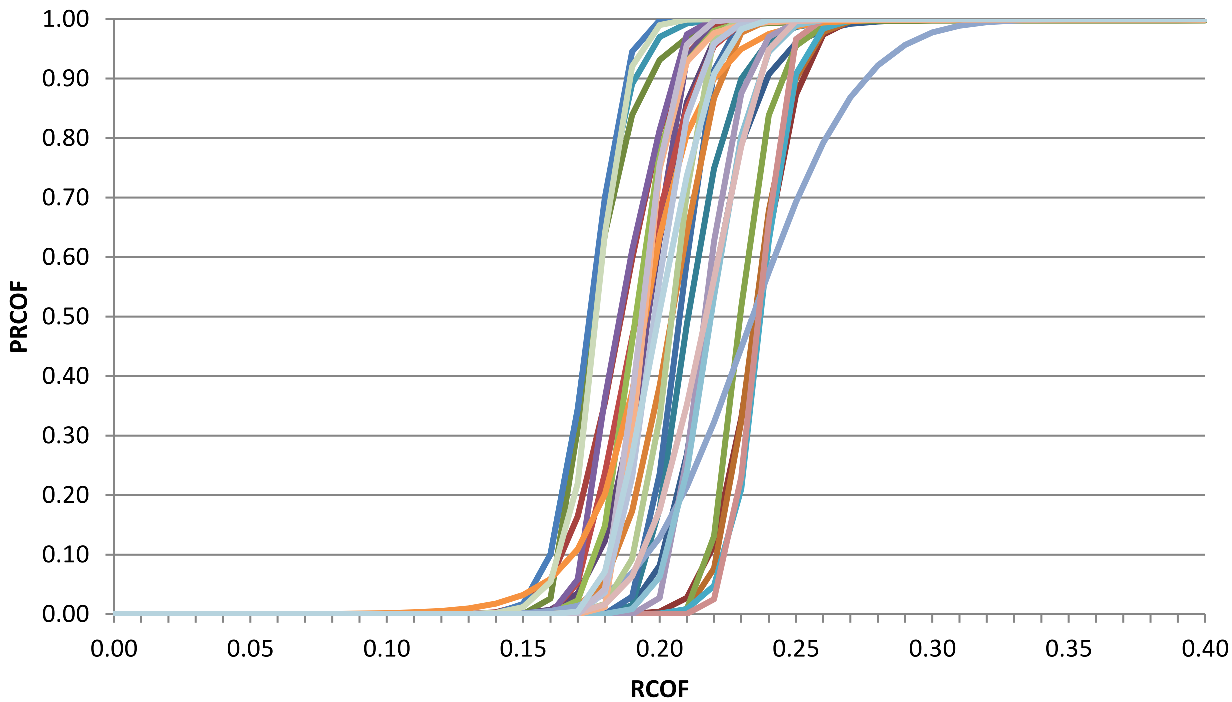
Figure 4.22 PRCOF – Young females at normal and fast speed, Left limb. A) normal speed B) fast speed

4.3.2.4 Young Males

Young men walking at normal speed (4.25 – 4.26) generally had similar PRCOF trends and a narrow range with the difference between 0% and 100% only 0.006. Most of the group reached the 100% PRCOF at RCOF 0.28 and had a 0% risk of slipping on surfaces with COF of 0.28 or more. The group range, as presented in Table 5.21 is inflated due to one participant with an outlying PRCOF graph (RCOF range at 50% at 0.160 – 0.271). If this participant was excluded, the maximum range would have been 0.235. The data were similar for both feet in all but one particpant.

At fast speed for the right limb more variability between individuals was observed. While most participants had patterns typical for a low variability in PRCOF, some produced a wide range and in some cases a higher RCOF at 100% PRCOF. Interestingly in the left limb data most individuals had a similar PRCOF patterns but different data ranges, representing individual differences.

A)



B)

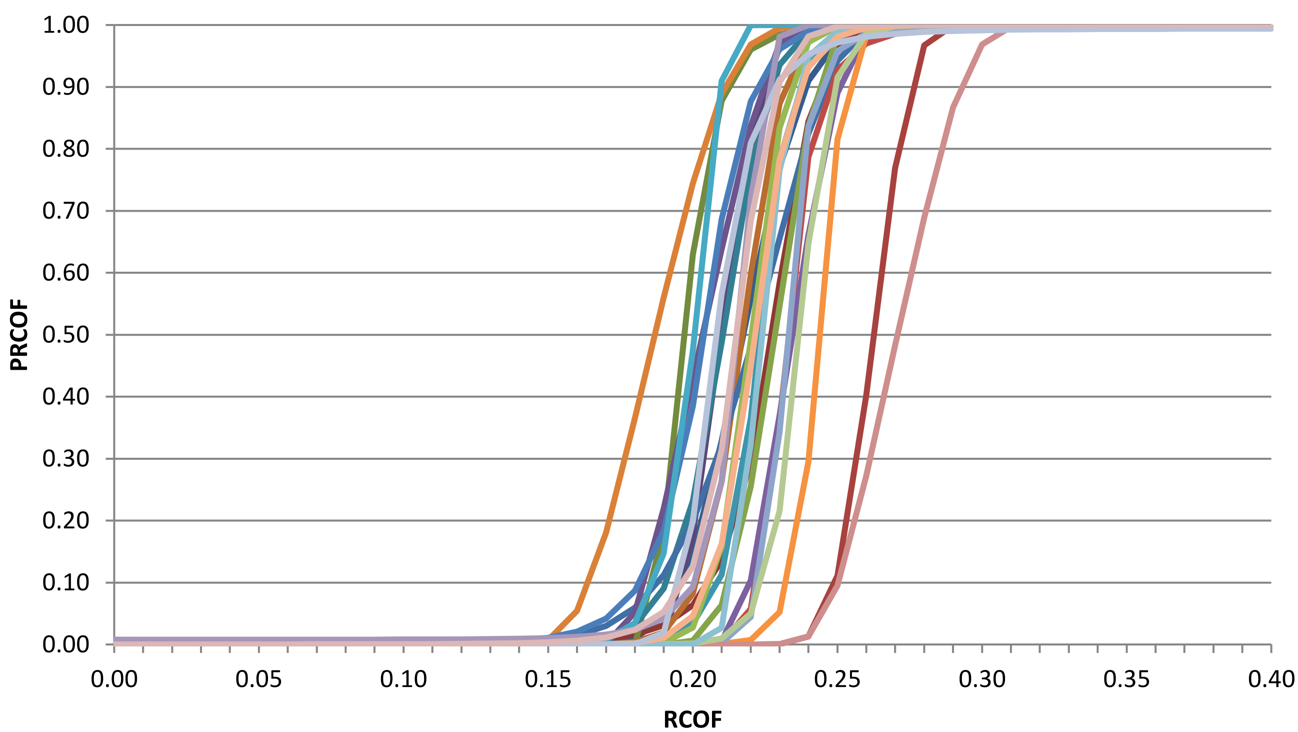
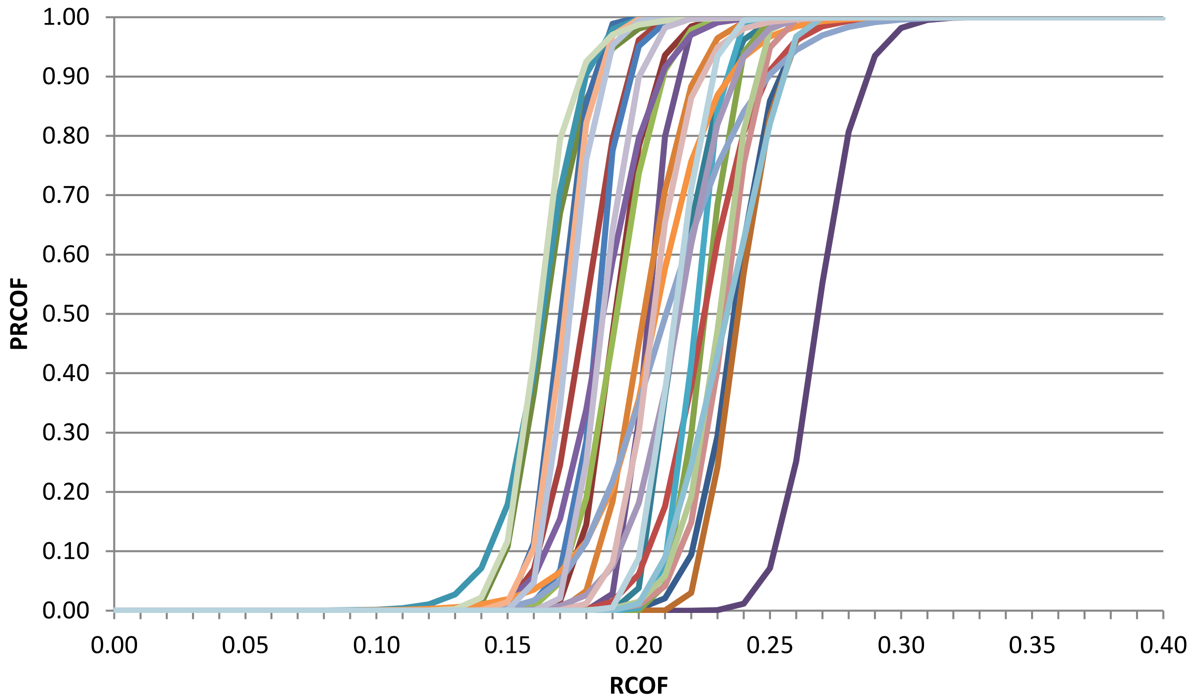


Figure 4.23 PRCOF – Young males at normal and fast speed, Right limb.
A) normal speed B) fast speed

A)



B)

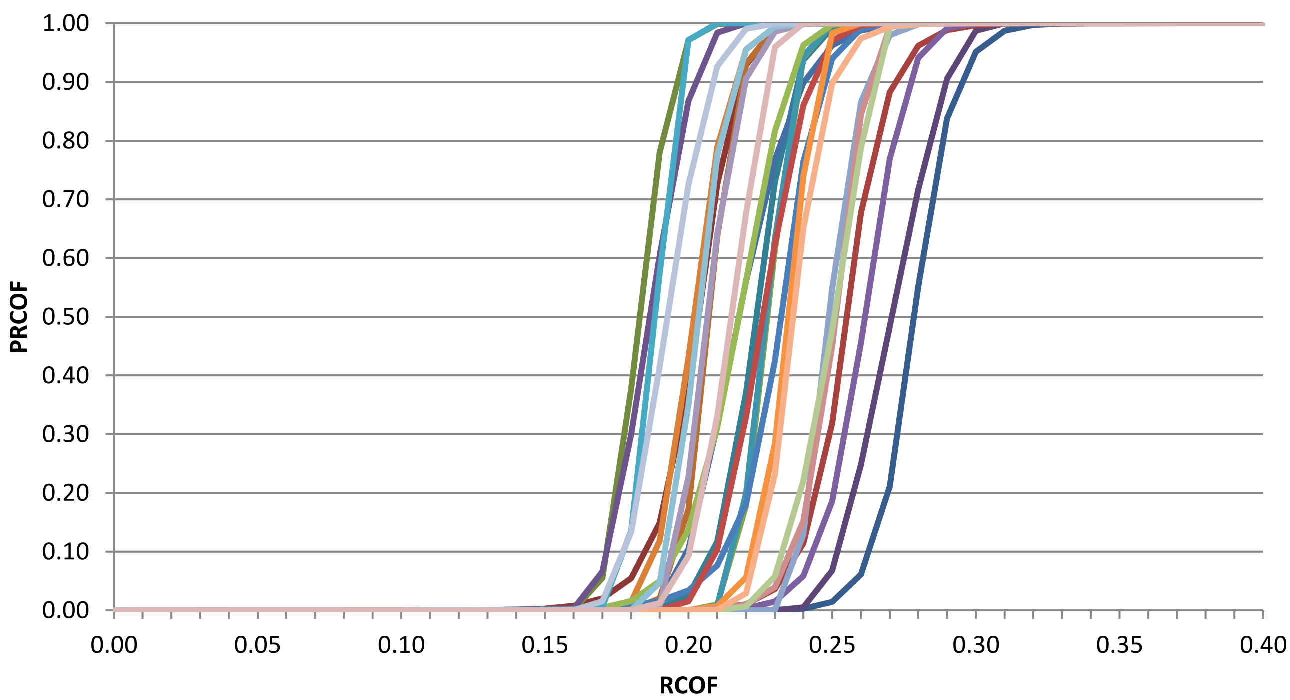


Figure 4.24 PRCOF – Young males at normal and fast speed, Left limb. A) normal speed B) fast speed

The previous sections presented probability functions for all participants as a PRCOF graph. Individual differences were noted, with variations in the data shape and range. The inspection of data range, rather than a single PRCOF value, allow for the analysis of not only individual, but also within-group variability. Tables 4.3 and 4.4 present the data ranges for all groups at 25%, 50%, 75% and 95% probability. The older females had the highest range with both the lowest and highest PRCOF at all probability percentages. The older people also had a greater RCOF differences between speeds while young females revealed the least speed effect on RCOF probability.

The large within-group ranges indicates the importance of using individual data rather than a group mean. It is important to further investigate the data with methods that allow for these individual features, yet allows for a group comparison.

Table 4.3 The Range of PRCOF for young males and young females at 25%, 50%, 75% and 95% probability. The total range is presented in brackets.

	Young males				**Young females**			
Speed	Normal		Fast		Normal		Fast	
Limb	Right	Left	Right	Left	Right	Left	Right	Left
25%	0.166 – 0.230 (0.064)	0.152 – 0.260 (0.108)	0.173 – 0.258 (0.085)	0.176 – 0.271 (0.095)	0.151 – 0.257 (0.106)	0.157 – 0.247 (0.090)	0.180 – 0.279 (0.099)	0.182 – 0.262 (0.080)
50%	0.174 – 0.237 (0.063)	0.161 – 0.268 (0.107)	0.187 – 0.271 (0.084)	0.183 – 0.279 (0.096)	0.158 – 0.266 (0.108)	0.166 – 0.257 (0.091)	0.187 – 0.289 (0.102)	0.194 – 0.278 (0.084)
75%	0.182 – 0.256 (0.074)	0.169 – 0.278 (0.109)	0.200 – 0.283 (0.083)	0.189 – 0.287 (0.098)	0.165 – 0.277 (0.112)	0.175 – 0.268 (0.093)	0.196 – 0.307 (0.111)	0.203 – 0.293 (0.090)
95%	0.191 – 0.288 (0.097)	0.185 – 0.293 (0.108)	0.214 – 0.299 (0.085)	0.198 – 0.300 (0.102)	0.177 – 0.291 (0.114)	0.190 – 0.285 (0.095)	0.206 – 0.329 (0.123)	0.213 – 0.312 (0.099)

Table 4.4 The Range of PRCOF for older males and females at 25%, 50%, 75% and 95% probability. The total range is presented in brackets.

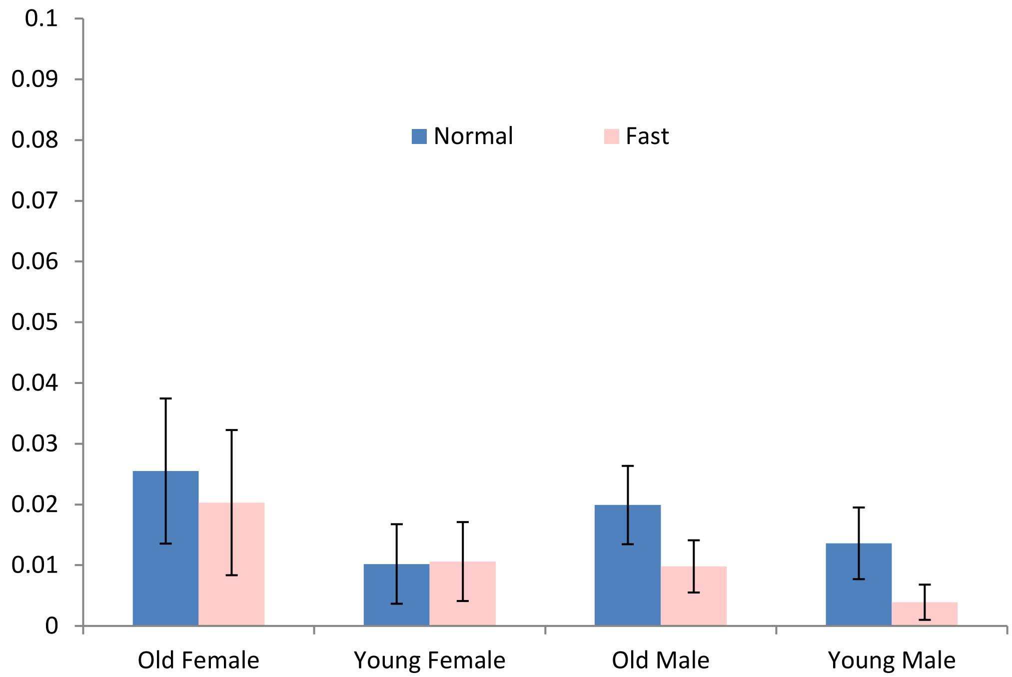
	Older males				**Older females**			
Speed	Normal		Fast		Normal		Fast	
Limb	Right	Left	Right	Left	Right	Left	Right	Left
25%	0.157 – 0.211 (0.054)	0.123 – 0.233 (0.110)	0.174 – 0.232 (0.058)	0.166 – 0.242 (0.076)	0.118 – 0.241 (0.123)	0.131 – 0.230 (0.099)	0.119 – 0.224 (0.105)	0.133 – 0.243 (0.110)
50%	0.167 – 0.218 (0.051)	0.141 – 0.250 (0.109)	0.181 – 0.240 (0.059)	0.175 – 0.254 (0.079)	0.136 – 0.247 (0.111)	0.138 – 0.239 (0.101)	0.134 – 0.233 (0.099)	0.139 – 0.253 (0.114)
75%	0.174 – 0.229 (0.055)	0.160 – 0.264 (0.104)	0.187 – 0.247 (0.060	0.183 – 0.264 (0.081)	0.141 – 0.255 (0.114)	0.147 – 0.248 (0.101)	0.141 – 0.242 (0.101)	0.146 – 0.264 (0.118)
95%	0.189 – 0.295 (0.106)	0.182 – 0.309 (0.127)	0.197 – 0.262 (0.065)	0.195 – 0.282 (0.087)	0.159 – 0.361 (0.202)	0.174 – 0.456 (0.282)	0.150 – 0.271 (0.121)	0.150 – 0.299 (0.149)

4.3.3 Total Slipping Probability, Trapezoidal Areas

The previous sections used graphical presentations of individual patterns and summary statistics to quantify mean differences between groups at chosen RCOF points, accounting for variability of the mean but not within-group variability. To capture individual variability while allowing quantitative analysis, the trapezoidal rule (described in section 3.3.4) was used.

The calculation was performed for two slipperiness hazard zones (section 3.3.4); very hazardous and very slippery (0.0-0.2) and slippery and hazardous (0.2 – 0.4). Initial analysis showed that no individuals had RCOF below 0.005 and the very slippery area was redefined as RCOF 0.005–0.2. Analysis was also performed on selected points to investigate the friction ranges for individual total slipperiness. The descriptive values for all groups in the two zones are presented in Figures 4.25-4.26.

A)



B)

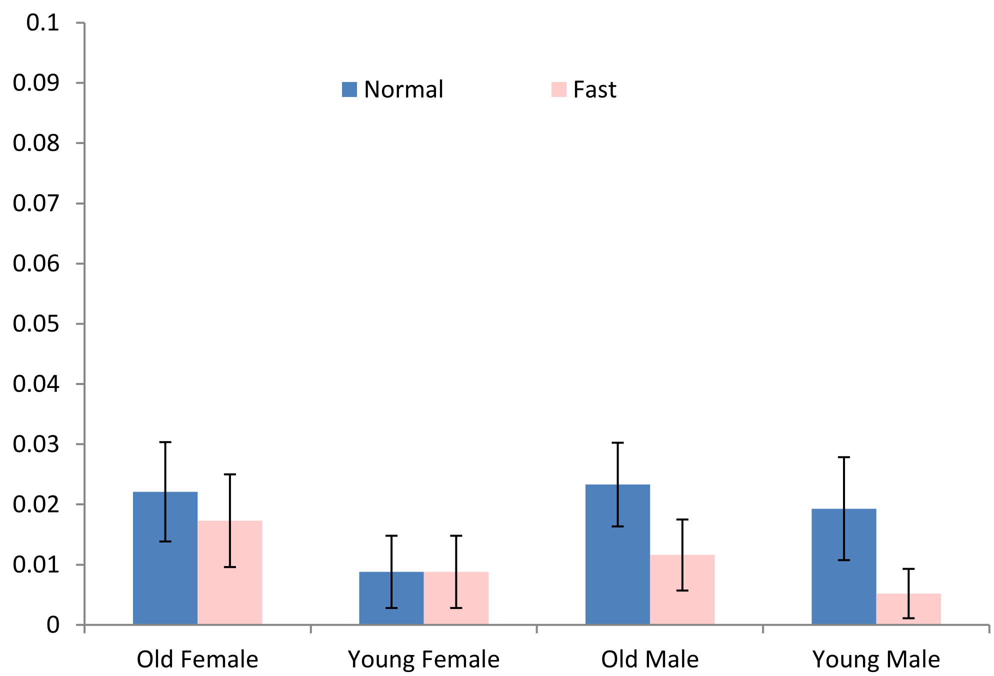
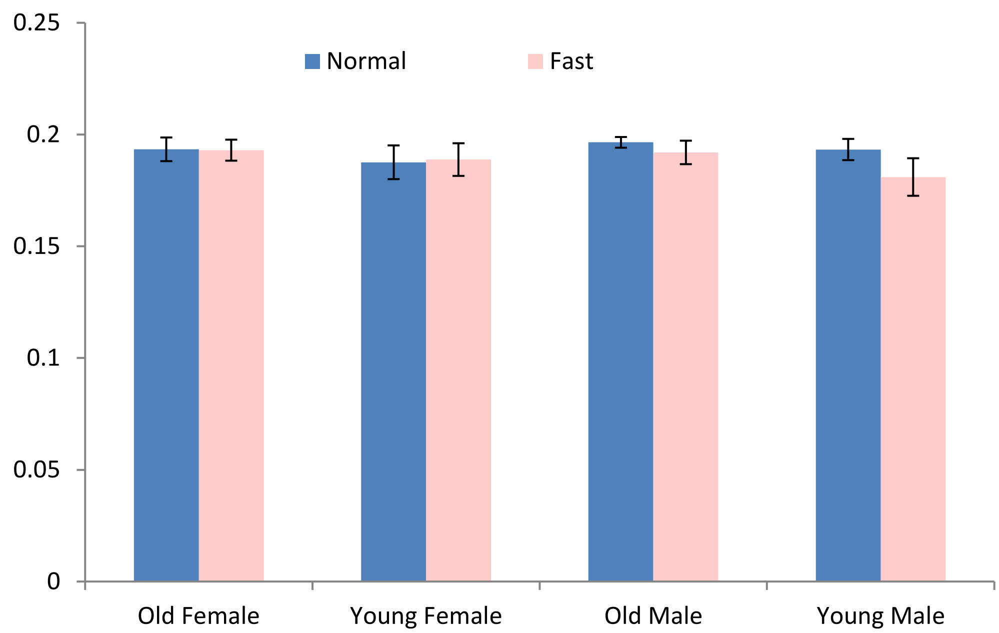


Figure 4.25 Trapezoidal area – Total slipperiness.
Very Slippery and hazardous zone COF 0 – 0.2 A) Right Limb B) Left Limb.

A)



B)

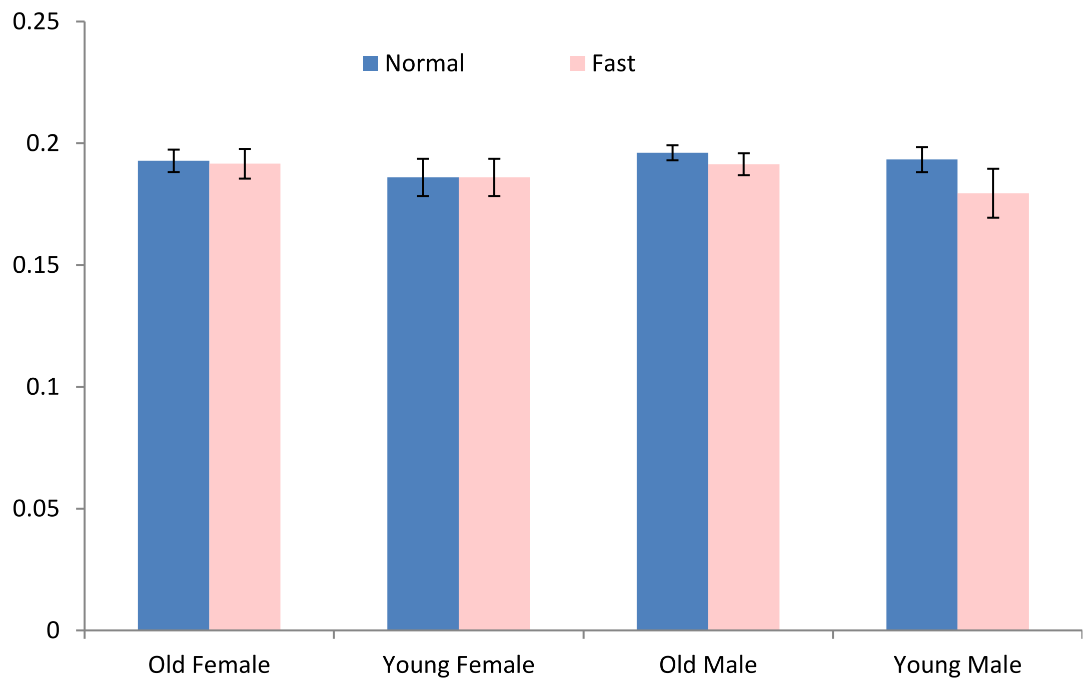


Figure 4.26 Trapezoidal area – Total slipperiness.
Slippery and Hazardous Zone COF 0.2-0.4 A) Right limb B) Left limb

When analysing slipping probability using the trapezoidal calculation, a greater area is seen as a lower slipping probability. Previously it has been stated that 0% PRCOF is 100% PS. As he trapezoidal area describes the area under the PRCOF graph, an increase in the area equals to a lower slipping probability and can be therefore be defined as the total slipperiness risk (TSR) at the selected COF range.

Figure 4.25 presents the total slipperiness in the very slippery and hazardous area, COF 0.0-0.2 at both speeds. Older adults have greater areas than young adults, bilaterally. The area is reduced at fast speed for all other groups than young females. In the slippery and hazardous zone, COF 0.2-0.4, speed effect can be noted for both male groups with a smaller area at fast speed. Both females groups have similar data.

The TSR data are discussed in detail under specific headings for age and gender.

4.3.3.1 Age and Gender Effects on Total Slipping Risk in the Very Slippery and Very Hazardous Zone

Age effects on total slipping risk in the very hazardous and slippery area (COF 0.0-0.2) are summarised in Figure 4.27. T-test results showed an age effect in all conditions: normal speed right ($p<0.001$) and left ($p=0.007$) as well as fast speed right ($p=0.023$) and left ($p=0.005$) with older adults having significantly higher trapezoidal area and, therefore, safer gait. Both young and older adults had lower TSR at fast walking speed suggesting increased slipping risk on lower friction surfaces. At normal walking speed, for both age groups, the left limb TSR were marginally higher but in fast walking the right limb area was larger.

No age effect was noted in the very slippery and very hazardous zone (Figure 4.28) in the right limb at normal walking speed. However, the left limb TSR at normal walking speed and right limb data at fast walking speed showed a significant difference between the gender groups ($p<0.033$ and $p<0.009$) respectively. It can also be noted that while all data points for the female group tended to show a linear trend with low variability, the male TSR were more variable between limbs and across walking speeds.

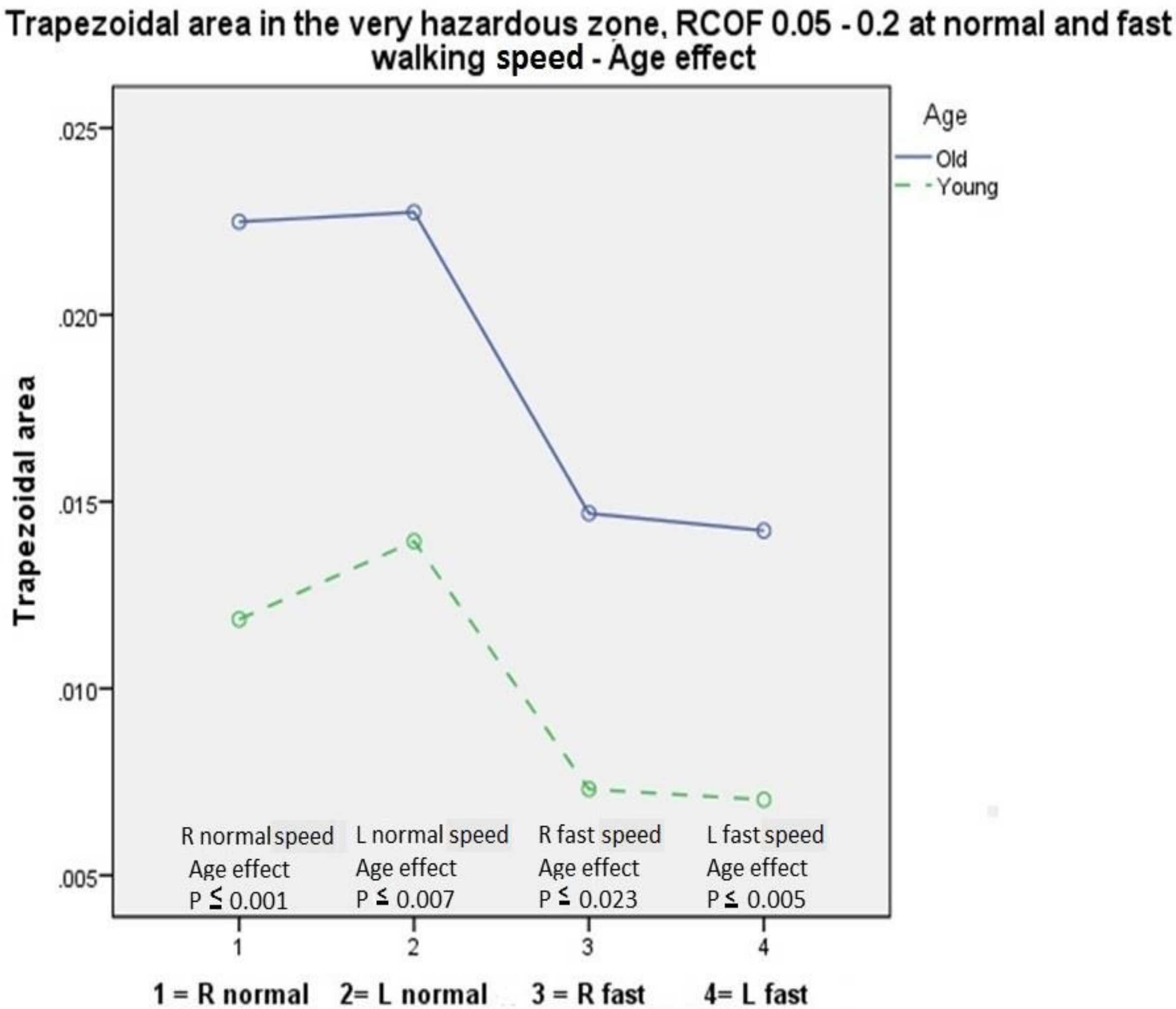


Figure 4.27 Age effect on total slipping risk in the very hazardous zone, RCOF 0.0 - 0.2 at normal and fast walking speeds

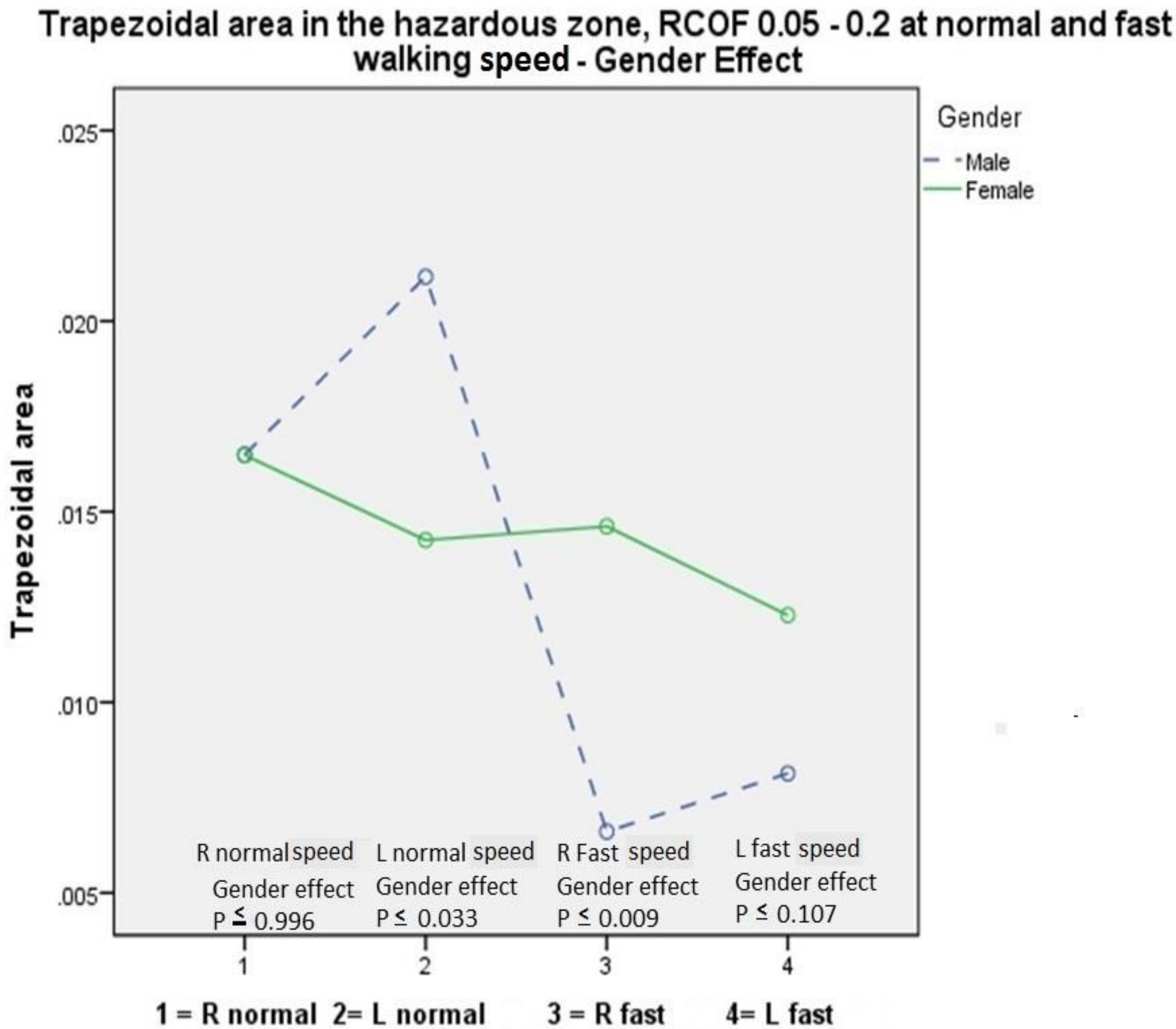


Figure 4.28 Gender effect on total slipping risk in the very hazardous zone, RCOF 0.0 - 0.2 at normal and fast walking speeds

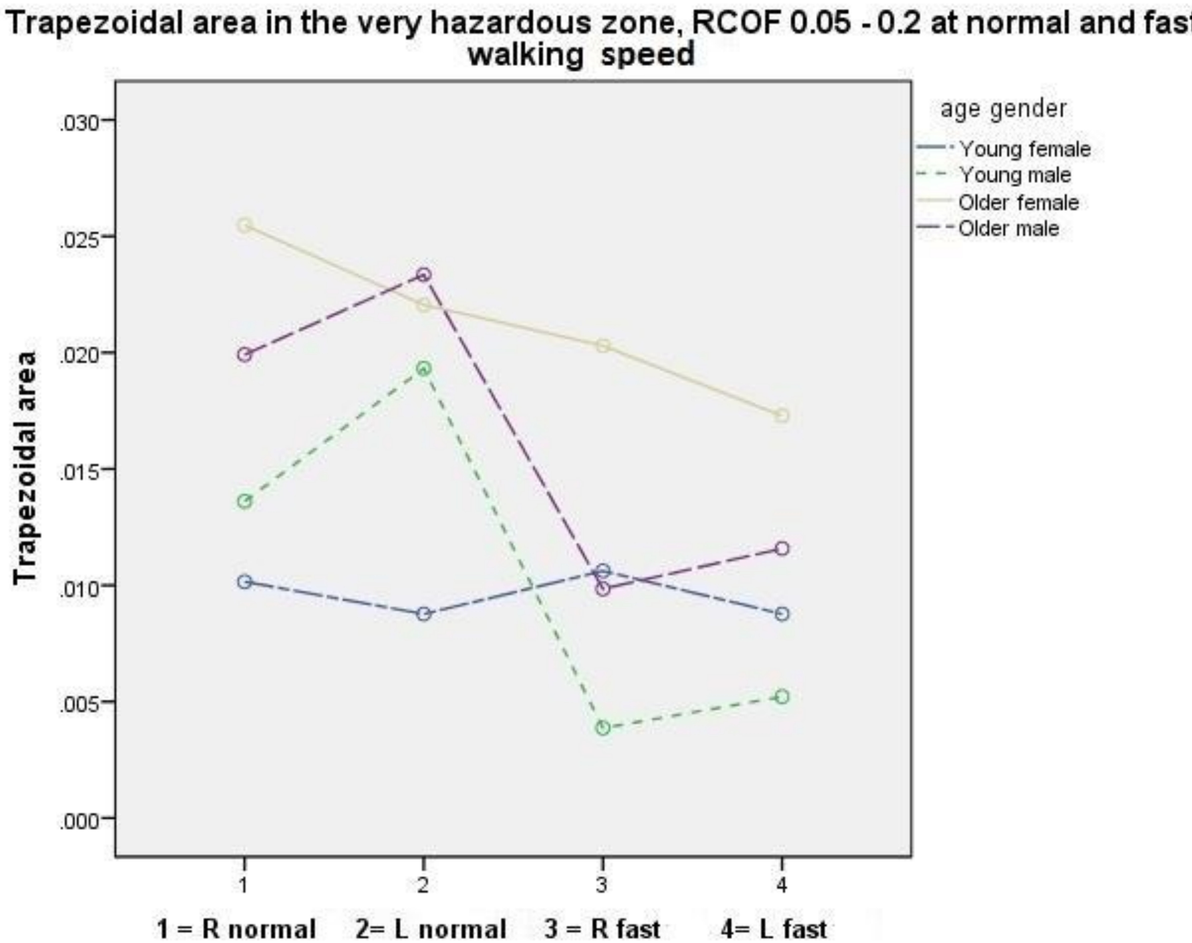


Figure 4.29 Age and gender divided groups - total slipping risk in the very hazardous zone, RCOF 0.05 - 0.2 at normal and fast walking speeds

Further observations on the groups are presented in Figure 4.29. In the right limb at normal walking speed older females had the highest values and young females the lowest. Young females were, therefore, at highest risk on a low friction surface but the only group with similar TSR for both limbs at both walking speeds, indicating high symmetry. Both male groups had higher TSR for the left limb at both speeds. When comparing the bilateral TSR between the two walking speeds, at fast walking speed both male groups showed lower TSR, with the left limb having higher values. In summary, in the very slippery and hazardous surface friction area with COF ranging from 0 to 0.2, older females were safest and both male groups' total slipping risk was more affected by walking speed.

4.3.3.2 Age and Gender Effects on Total Slipping Risk in the Slippery and Hazardous Zone

As shown in Figure 4.30, total slipping risk in the slippery and hazardous COF range (0.21-0.4) revealed a significant age effect at all TSR data points (right and left limb, normal and fast walking speeds) with older adults having a significantly greater TSR area at normal speed ($p<0.035$ and $p<0.027$ for right and left lower limbs respectively) and fast speed ($p<0.003$ and $p<0.02$ for right and left lower limb respectively) on surfaces with friction 0.21 – 0.4.

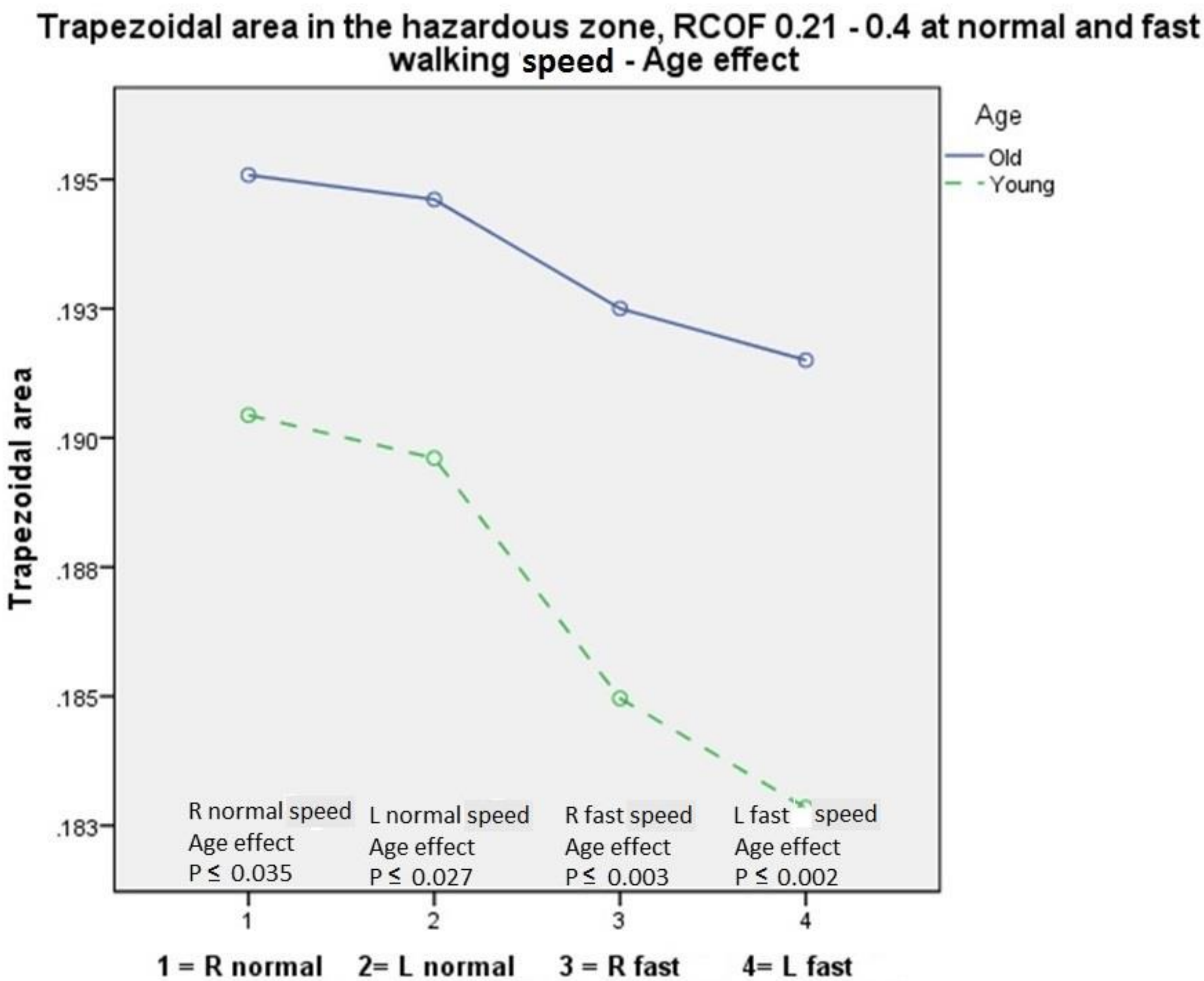


Figure 4.30 Age effect on total slipping risk in the hazardous zone, RCOF 0.21 - 0.4 at normal and fast walking speeds

Figure 4.31 presents the gender effect in the slippery and hazardous area. At normal walking speed the males had significantly higher TSR ($p<0.041$ and $p< 0.014$ for right and left limbs respectively). At fast speed, no gender effect was noted.

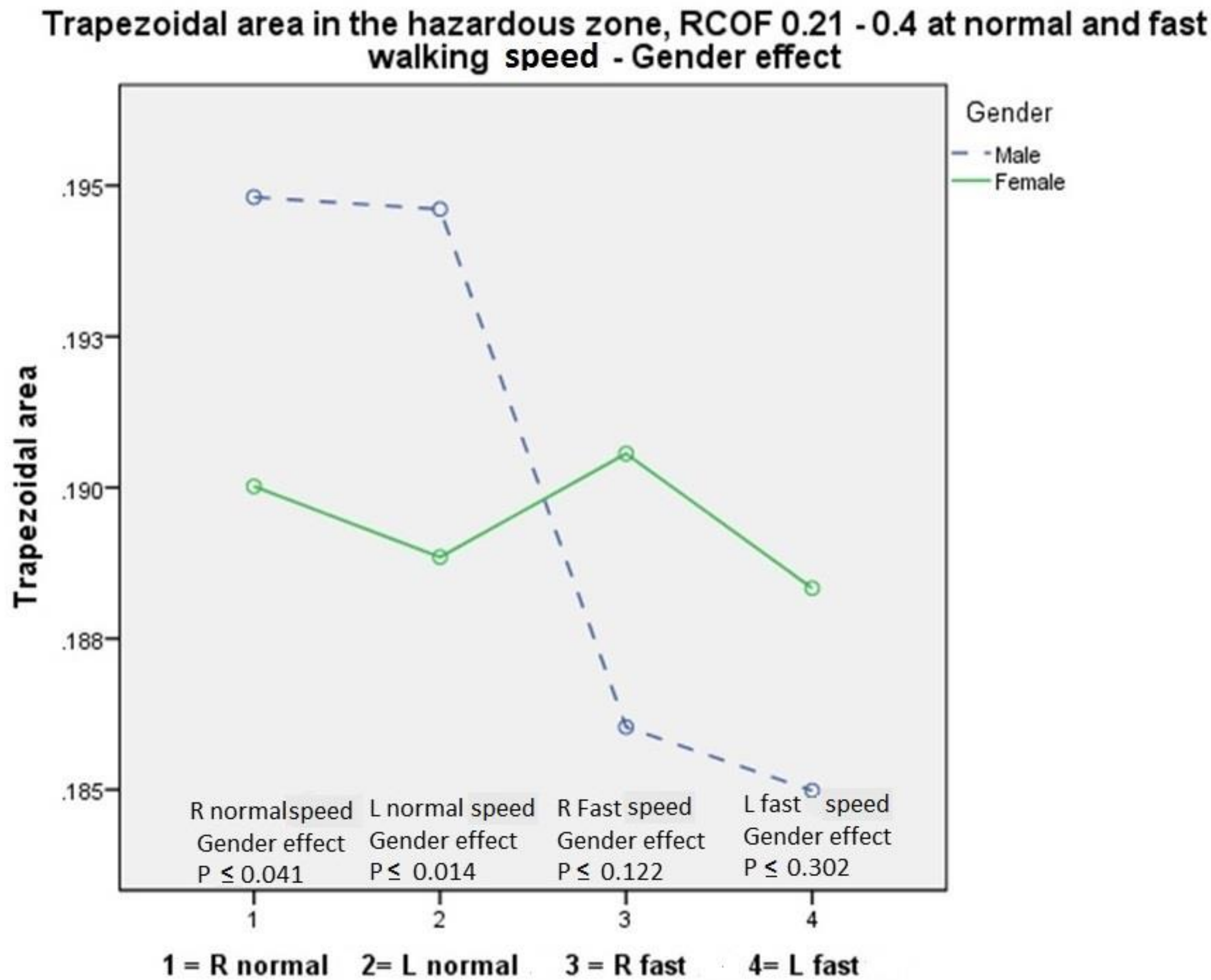


Figure 4.31 Gender effect on total slipping risk in the hazardous zone, RCOF 0.21 - 0.4 at normal and fast walking speeds

As illustrated in Figure 4.32, presenting the four age and gender groups, at normal walking speed the older females and young males were similar with lower TSR at fast speed. The older males had the highest TSR and young females the lowest TSR. At normal walking speed, most groups also showed similarity between limbs. The older females were similar for normal and fast speeds and had the highest TSR in fast walking. Young males had the largest differences in the TSR between speeds. Whilst a decrease in TSR could be noted in both male groups, the young males had the lowest TSR and, therefore, highest slipping risk.

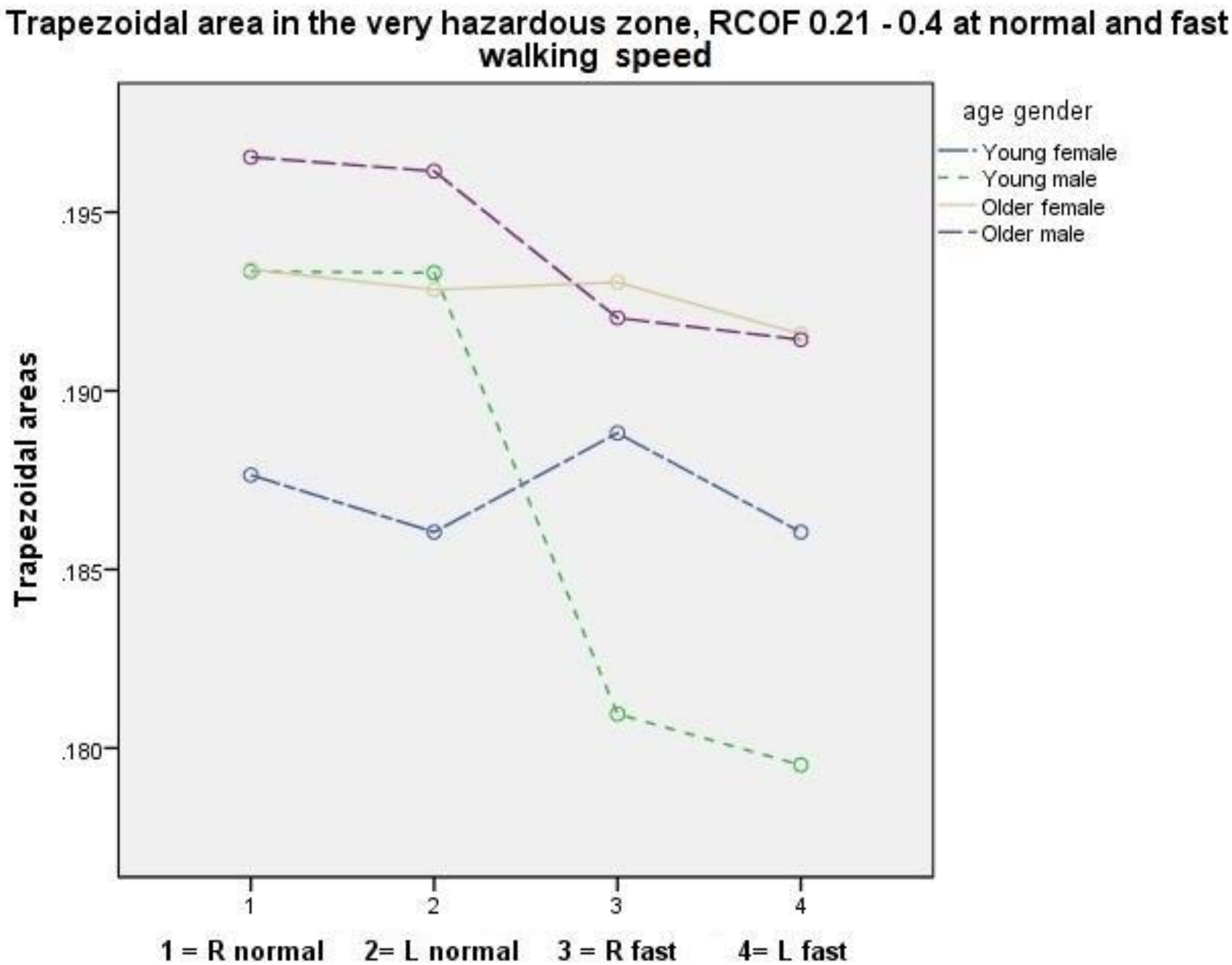


Figure 4.32 Age and gender divided groups - total slipping risk in the slippery and hazardous zone, RCOF 0.21 - 0.4 at normal and fast walking speeds

In summary, the trapezoidal area calculation makes a useful contribution to estimating age and gender influences on slipping propensity. The TSR analysis demonstrated that at both normal and fast speeds older adults had larger TSR areas and safer walking than young, being less prone to slipping in the slippery and hazardous COF zone. Gender comparisons confirmed that males had greater TSR areas at normal walking speed only.

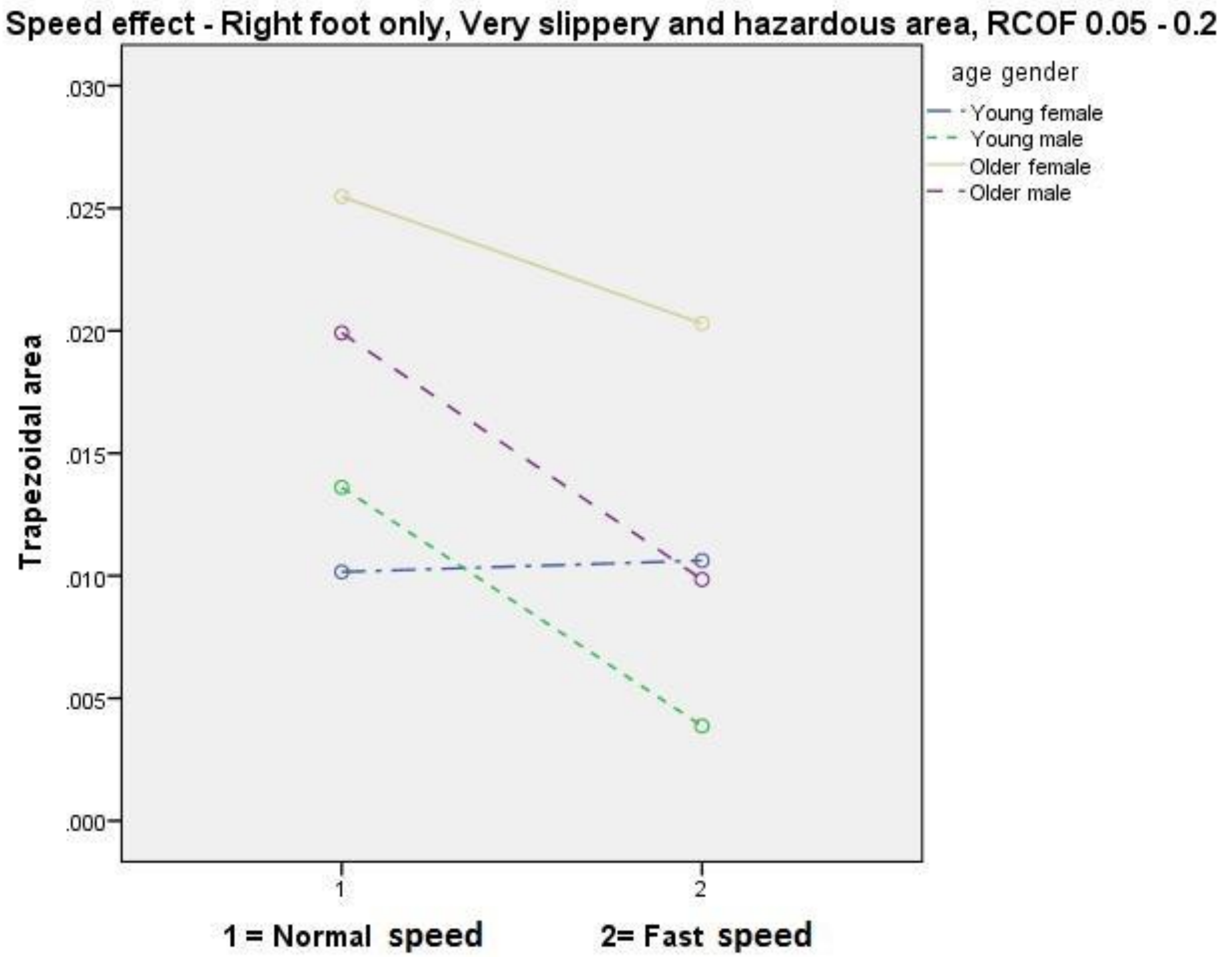


Figure 4.33 Right limb only -The effect of walking speed on the total slipping risk in the very slippery and hazardous area, COF 0.5 -0.20

Observation of the four groups at the two walking speeds for the right limb (Figures 4.33 and 4.34) illustrated group differences in slipping risk. In the very slippery and hazardous area (COF 0-0.2) all groups except young females reduced TSR at fast speed and therefore increased slipping risk. In the slippery and hazardous zone (COF 0.2-0.4) only males reduced TSR area while young females increased TSR area while older females showed little change in slipping risk as speed increased.

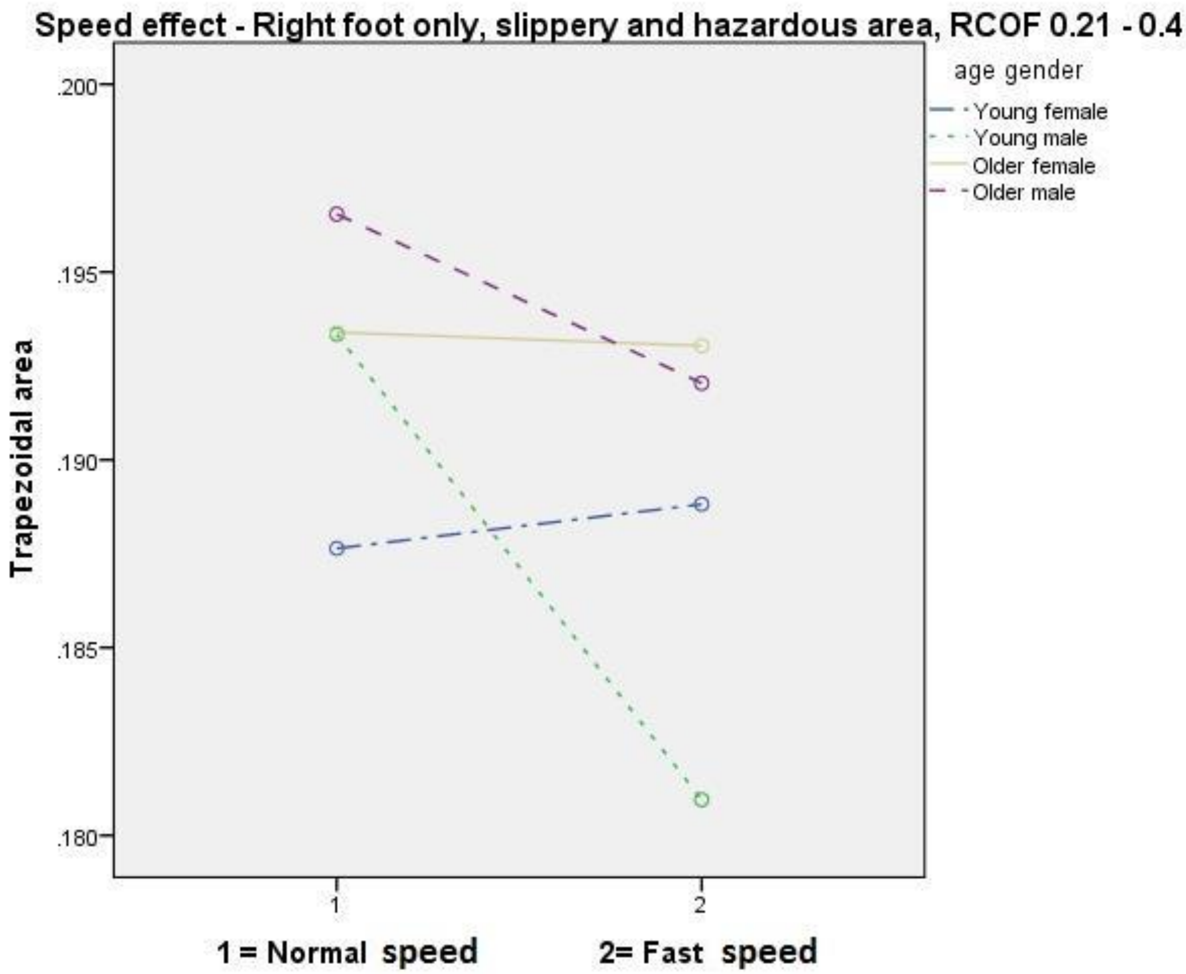


Figure 4.34 Right limb only -The effect of walking speed on the total slipping risk in the slippery and hazardous area, COF 0.21 -0.40

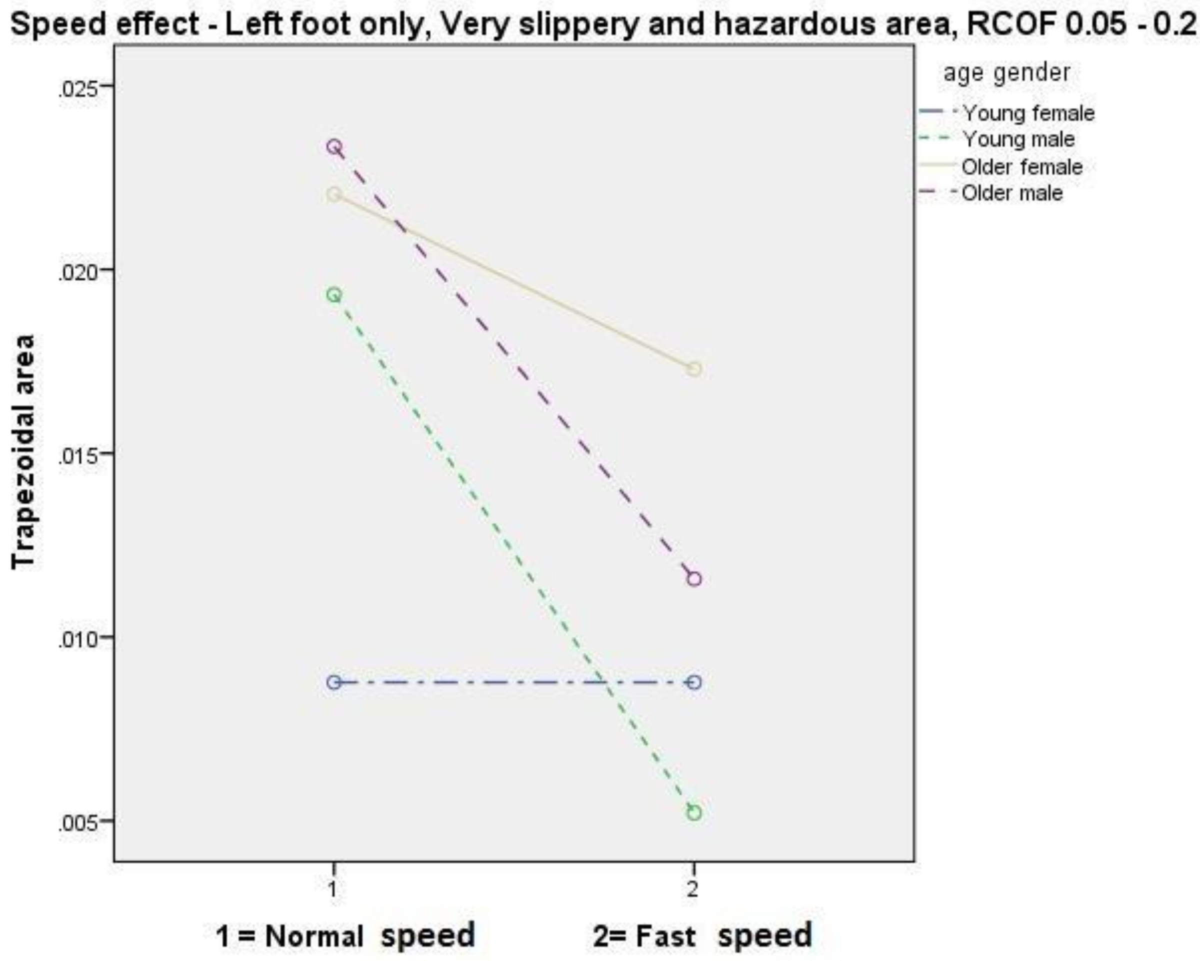


Figure 4.35 Left limb only -The effect of walking speed on total slipping risk the very slippery and hazardous area, COF 0.05 -0.20

In the left limb (Figure 4.35 and 4.36), similar trends could be seen in that, once again, in the very slippery and hazardous zone, all groups except young females had a lower TSR and higher slipping risk at fast speed. In the slippery and hazardous zone the young females had a similar area at both speeds while other groups reduced the area. The magnitude of decrease must be noted, however. because older females and young males had a similar area at normal speed but when speed increased older females had the highest and the young males the lowest area. It was interesting, therefore, that older females had the safest gait at the *faster* speed and the young males presented the highest slipping risk when walking faster than normal.

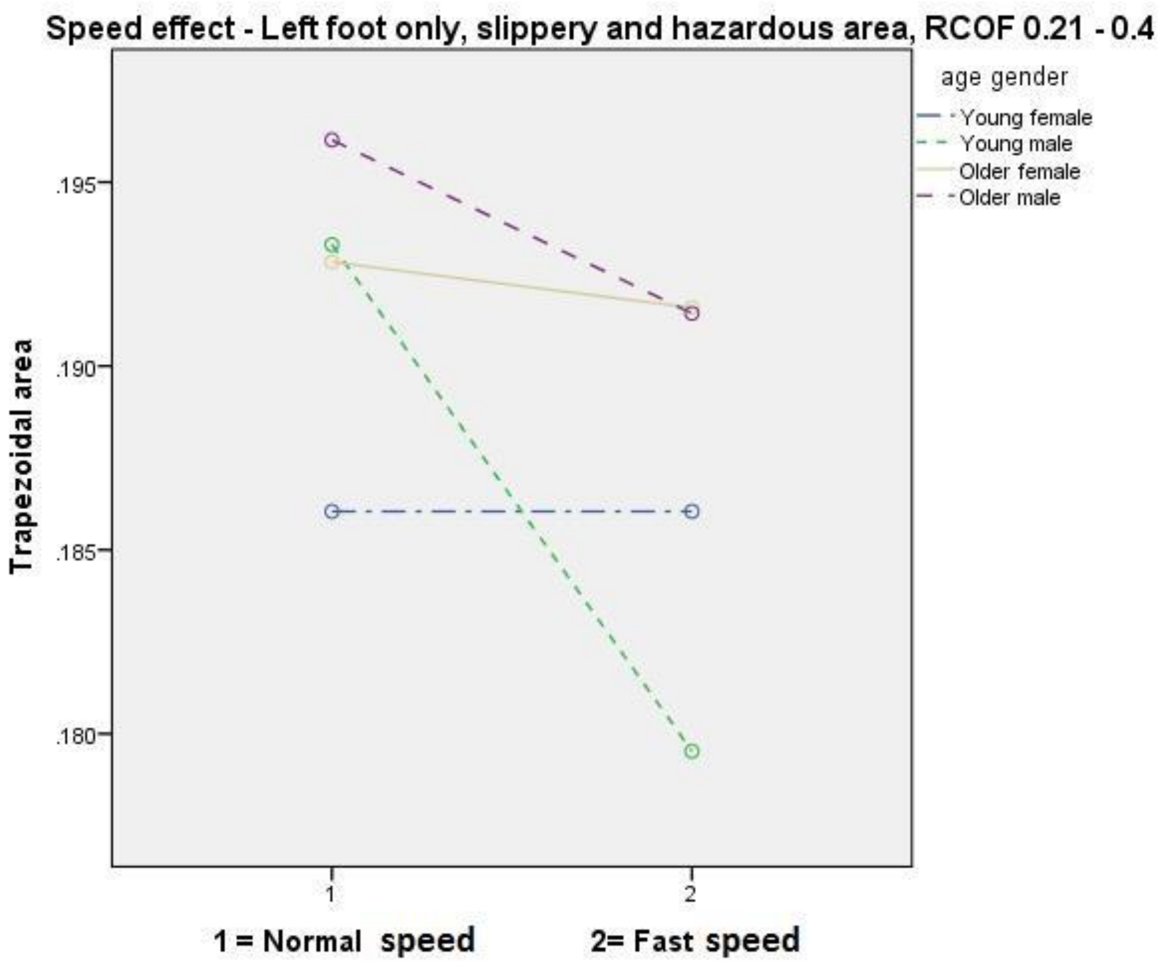


Figure 4.36 Left limb only -The effect of walking speed on total slipping risk in the slippery and hazardous area, COF 0.21 -0.40

4.3.3.3 Total Slipping Risk at Specific COF Values

Previous sections identified age and gender differences in total slipping risk in the two floor slipperiness zones, however, it was also instructive to identify specific slipperiness zones. For this analysis, COF range 0.0–0.4, was divided in to 7 zones; RCOF 0.0–0.1, 0.11–0.15, 0.16-0.2, 0.21–0.25, 0.26–0.3, 0.31–0.35, 0.36–0.4. Figures 4.37 (right limb) and 4.38 (left limb) present the descriptive data in the nominated slipperiness zones. For each segment the maximum is the distance (0.01) x 1 thus the maximum for each segment is 0.01 and the therefore the total maximum area is 0.05. At this point 100% probability has been reached.

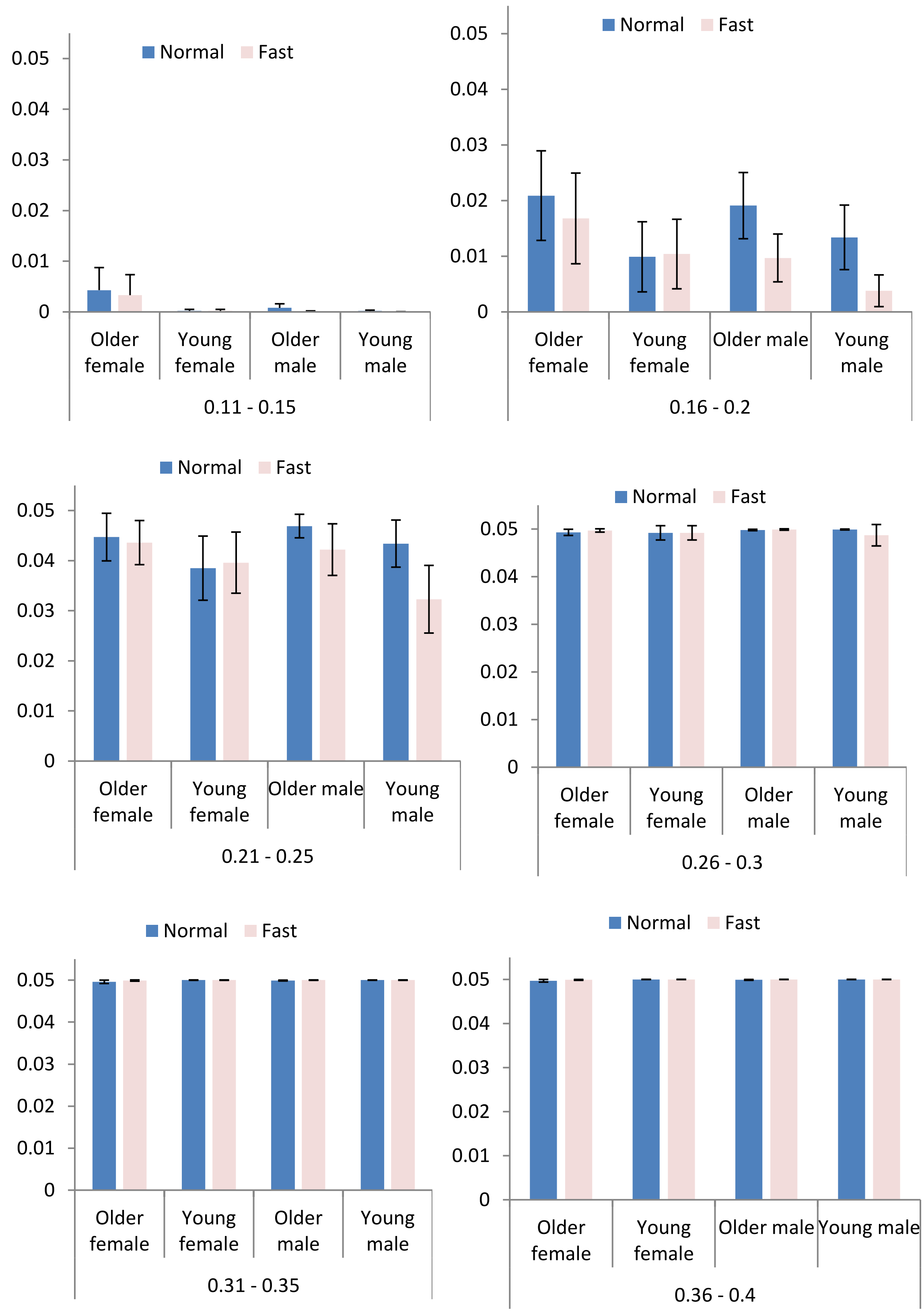


Figure 4.37 Trapezoidal areas in specific COF zones. Right Limb

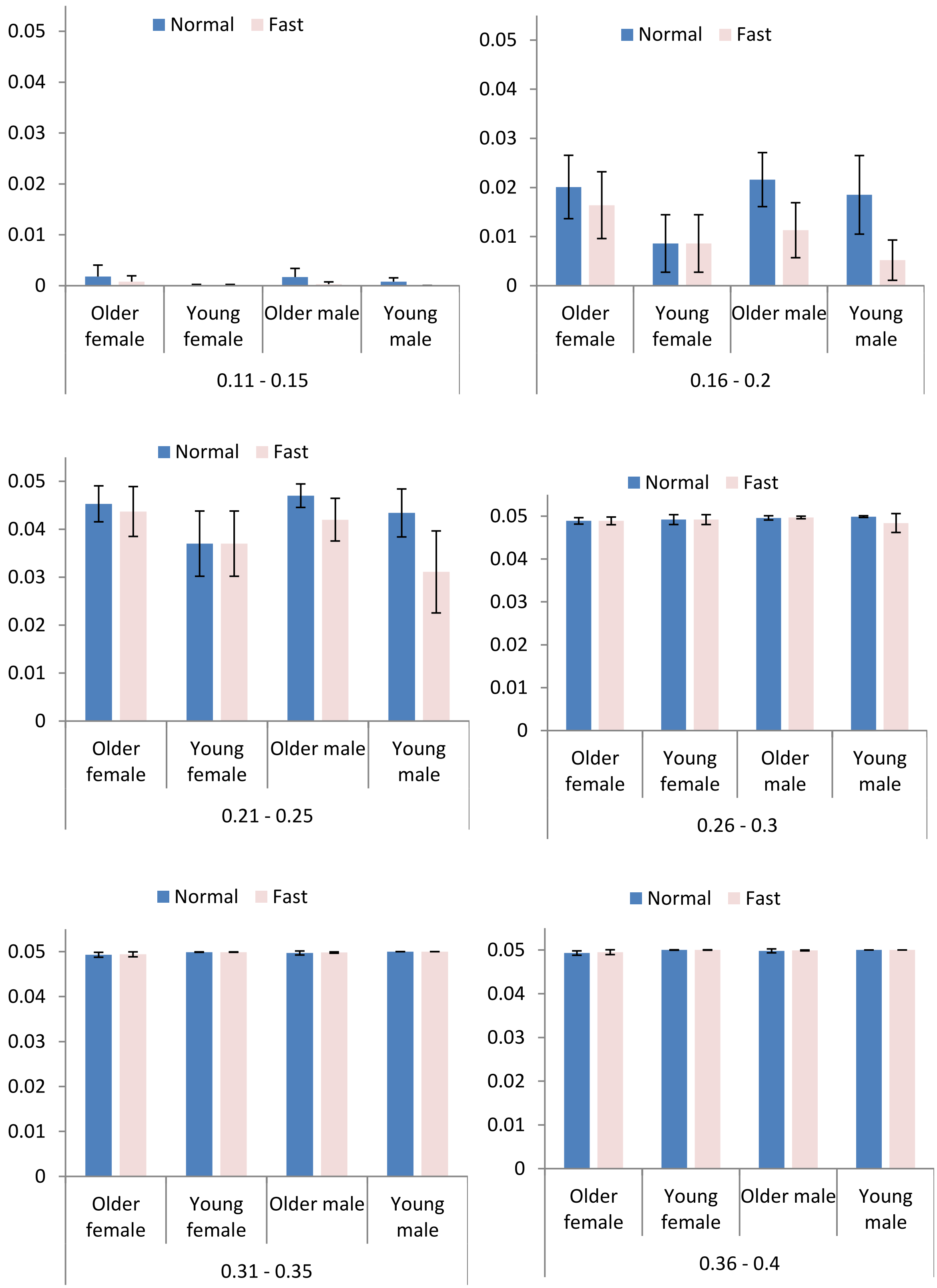


Figure 4.38 Trapezoidal areas in specific COF zones. Left Limb

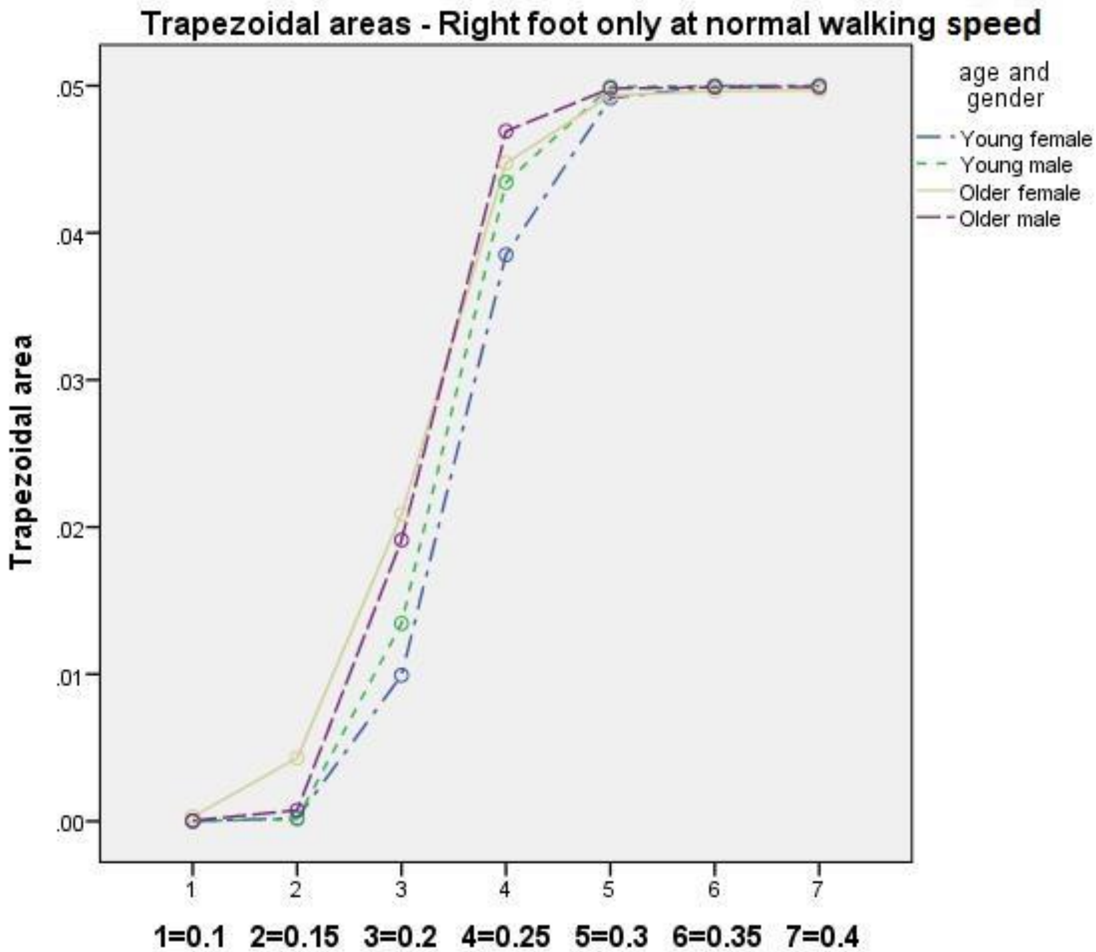


Figure 4.39 Total slipping risk at normal walking speed (Right limb only) in 7 defined COF zones within the slippery COF range: 1) 0-0.1, 2) 0.11 – 0.15, 3) 0.16-0.2, 4) 0.21 – 0.25, 5) 0.26 – 0.3, 6) 0.31 – 0.3, 7) 0.36 – 0.4.

Figure 4.39 presents the right limb data at normal speed and again older females produced low frictional forces relative to their normal forces, making them safer in the very slippery, low COF conditions. Young females had, throughout the zones, the lowest areas and at highest slipping risk. All samples reached the maximum area (0.05) at COF 0.3 showing that they were all safe when surface friction exceeded COF 0.3. In the left limb at normal walking speed (Figure 4.40) older females were within the range of the other populations throughout. Most groups had already created RCOF at COF 0.15 with a rapid increase in total probability until COF 0.3. As for the right limb, the young females had the lowest area and thus the highest slipping propensity in slippery areas.

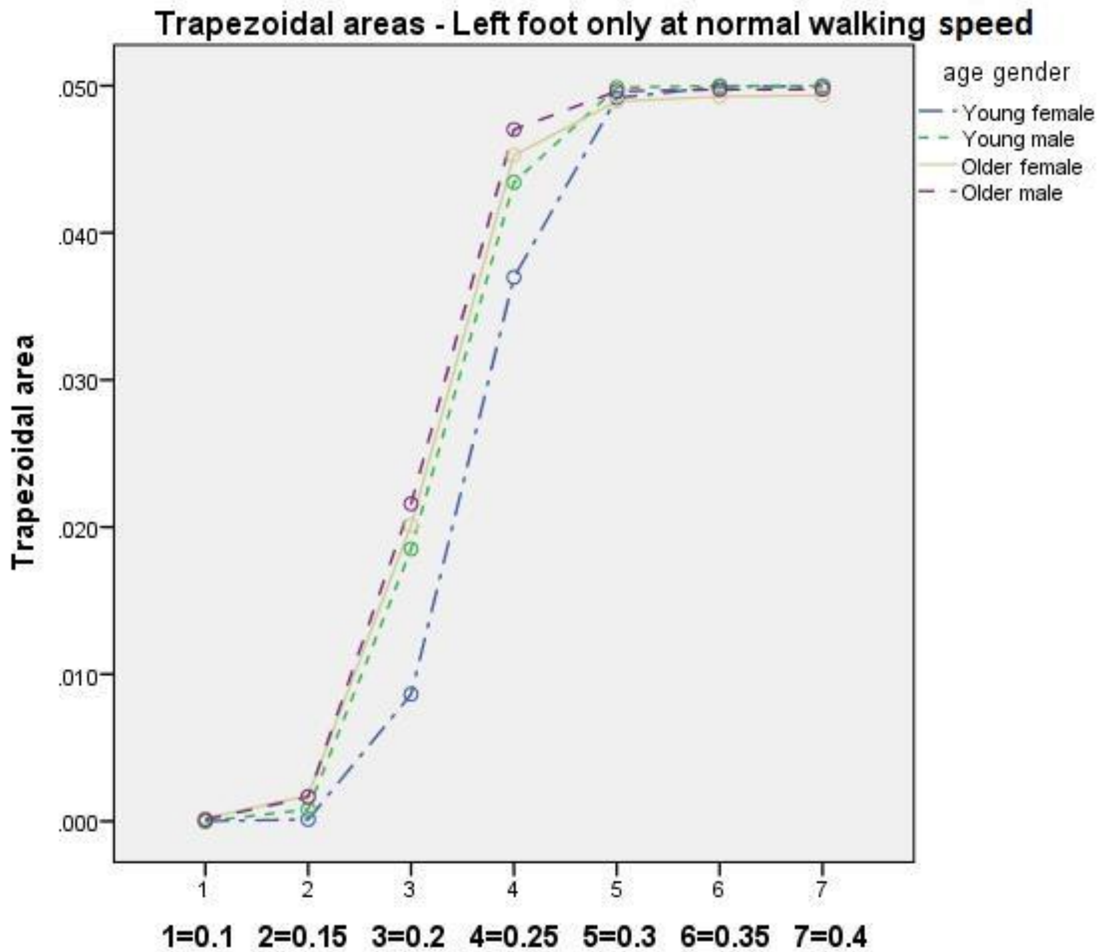


Figure 4.40 Total slipping risk at normal walking speed (Left limb only) in 7 defined COF zones within the slippery COF rang: 1) 0.0-0.1, 2) 0.11–0.15, 3) 0.16-0.2, 4) 0.21–0.25, 5) 0.26–0.3, 6) 0.31–0.3, 7) 0.36–0.4.

From the right limb data at fast speed (Figure 4.41) it was found that older females remained safest in the very slippery range COF 0.15-0.2, and young males had the lowest TSR and thus the highest risk. At faster speed the young populations had not attained the maximum area and this safe range was only noted at COF 0.35. In the left limb at fast walking speed (Figure 4.42) young males had the smallest areas throughout, i.e. the highest slipping risk. In contrast to normal walking the older females did not present with COF 0.15 and had the highest TSR at all COF values.

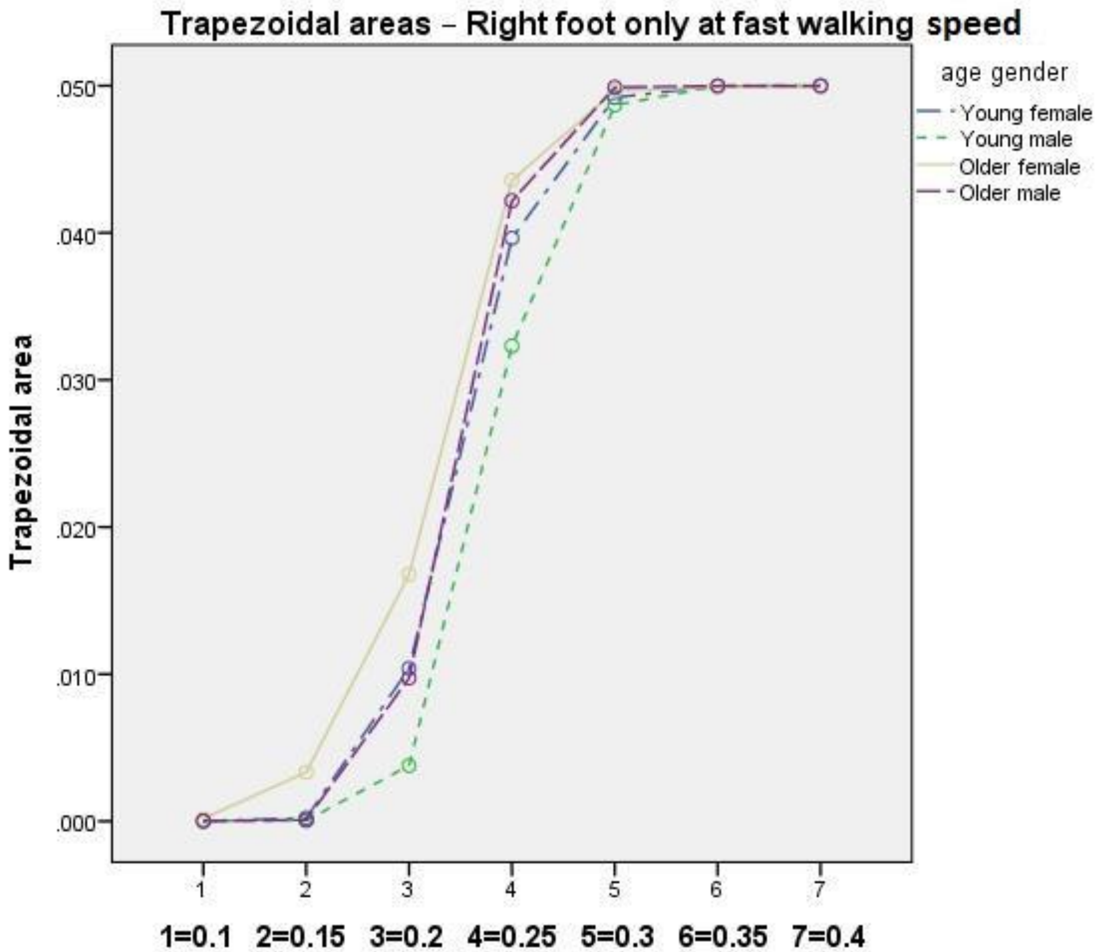


Figure 4.41 Total slipping risk at Fast walking speed (Right limb only) in 7 defined COF zones within the slippery COF rang: 1) 0.0-0.1, 2) 0.11–0.15, 3) 0.16-0.2, 4) 0.21–0.25, 5) 0.26–0.3, 6) 0.31–0.3, 7) 0.36–0.4.

In summary, calculation of trapezoidal area from the probability graphs gives a more detailed analysis of slipping probability allowing exploration of slipping risk in known COF zones. By transforming the graphical information to numeric presentation, quantification of the overall slipping risk can be achieved. Analysis of the individual zones allowed for identification of group differences and performance in the critical slipperiness areas. As in previous analysis, the older females presented as the group with the lowest slipping risk and young adults were more influenced by walking speed with highest slipping risk.

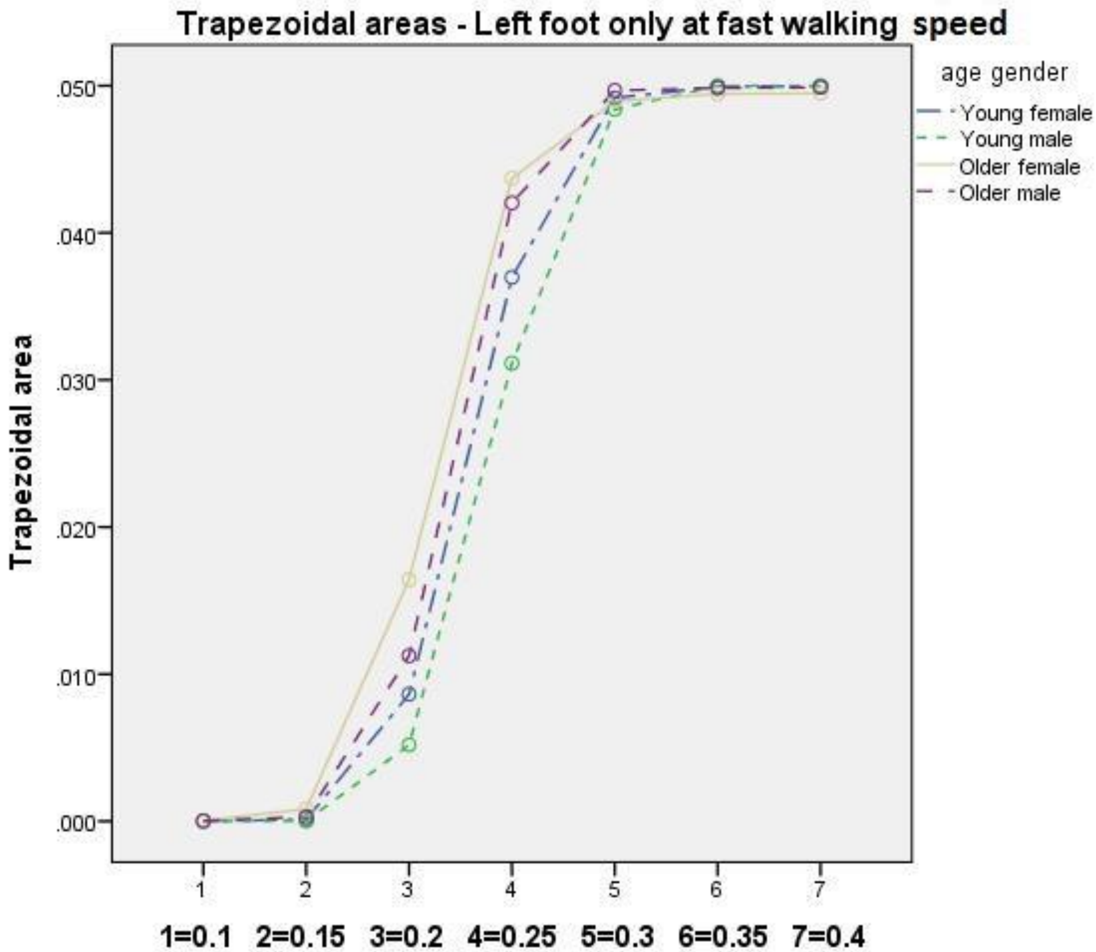


Figure 4.42 Total slipping risk at Fast walking speed (Left limb only) in 7 defined COF zones within the slippery COF range: 1) 0-0.1, 2) 0.11 – 0.15, 3) 0.16-0.2, 4) 0.21 – 0.25, 5) 0.26 – 0.3, 6) 0.31 – 0.3, 7) 0.36 – 0.4.

4.3.4 Individual Case Analysis

Slipping probability functions were characterised by intra-individual variability in all groups. Some individuals' functions were within a narrow range and rapidly increased from 0% to 100% probability, while others presented with a large range and more complexity, as in Figure 4.43. Given such variation, summary statistics do not completely describe the cohort and to fully understand tripping risk at the population level a case study approach to experimental data analysis is highly informative.

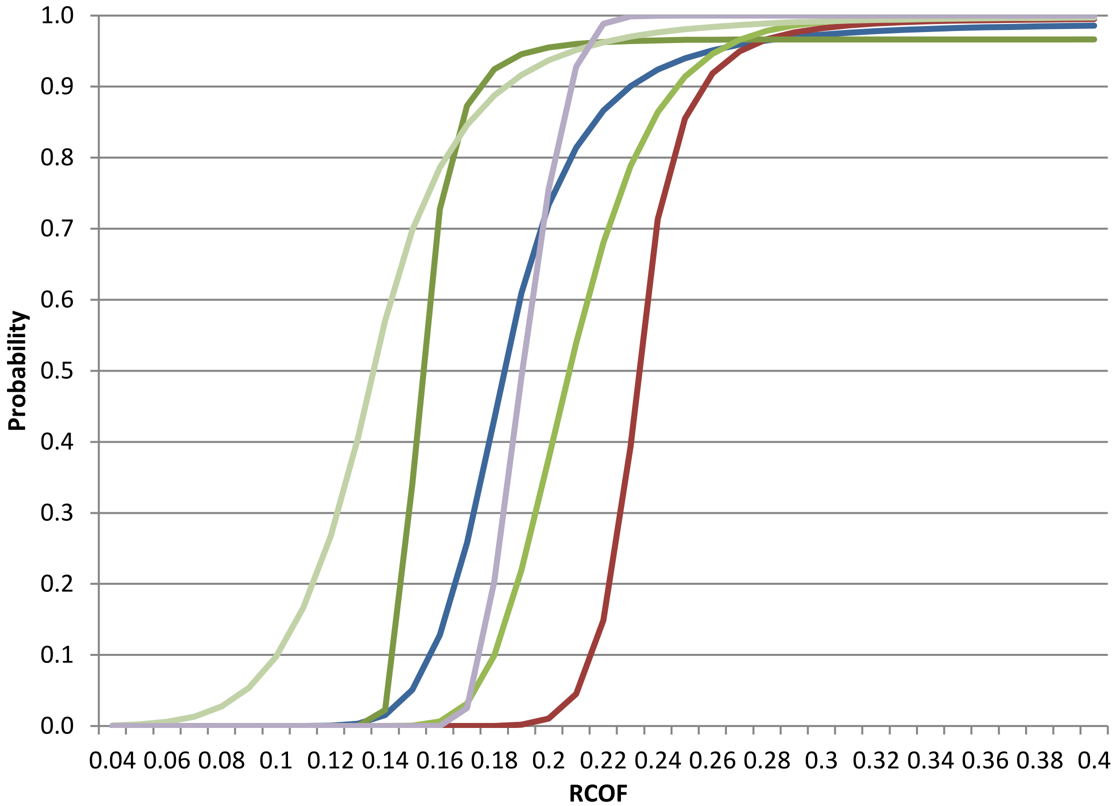


Figure 4.43 A sample PRCOF data for the older females walking at high speed (right limb data only)

Data for nine individuals with complex total slipperiness patterns were selected for further investigation; 3 older females, 2 older males, 2 young females and 2 young males. Their anthropometric and walking speed data are in Table 4.5. Young females had generally low within-group variability but two participants showing most variation were included to represent them.

Two older females were of similar height and mass but their normal and fast speeds were different. The two older males had a 15 cm difference in height and a 20 kg difference in mass. Their normal speed was slightly different but had similar fast speed. The young females had the same height but a 9 kg difference in mass. Older female 1 (OF1) had the smallest change in walking speed with the slowest fast speed and Older Female 3 OF3 had the largest speed increase. The two older males were similar in both speeds and the young females had the fastest normal speed.

Table 4.5 Participants in Case analysis series

	Age (years)	Height (cm)	Mass (kg)	Average Normal speed (m/s)	Average Fast speed (m/s)	Speed difference
OF1	69	152.5	72.6	1.16 + 0.03	1.25 + 0.05	0.09
OF2	68	173.7	72.1	1.4 ± 0.06	1.68 ± 0.09	0.28
OF3	69	155.0	71.5	0.97 + 0.05	1.40 + 0.05	0.43
OM1	66	159.2	55.0	1.09 ± 0.03	1.40 ± 0.08	0.31
OM2	76	175.0	74.1	1.1 + 0.05	1.40 ± 0.05	0.3
YF1	35	167.0	62.5	1.35 + 0.04	1.69 + 0.07	0.34
YF2	31	167.0	53.1	1.4 + 0.05	1.64 + 0.08	0.24
YM1	19	182.0	67.7	1.23 + 0.03	1.40 + 0.03	0.17
YM2	33	182.0	101.0	1.32 + 0.04	1.69 + 0.06	0.37

Table 4.6 Mean and 99th percentile RCOF at normal and fast walking speed

	Normal Speed			
	Mean		99th percentile	
	Right	Left	Right	Left
OF1	0.210	0.208	0.376	0.389
OF2	0.246	0.239	0.266	0.274
OF3	0.212	0.239	0.358	0.520
OM1	0.209	0.247	0.393	0.293
OM2	0.205	0.188	0.404	0.228
YF1	0.158	0.167	0.184	0.207
YF2	0.199	0.206	0.231	0.237
YM1	0.196	0.269	0.230	0.306
YM2	0.195	0.204	0.217	0.223
	Fast Speed			
	Mean		99th percentile	
	Right	Left	Right	Left
OF1	0.193	0.189	0.371	0.234
OF2	0.237	0.254	0.368	0.286
OF3	0.211	0.235	0.289	0.673
OM1	0.219	0.250	0.261	0.277
OM2	0.187	0.229	0.274	1.139
YF1	0.187	0.194	0.211	0.216
YF2	0.213	0.225	0.225	0.225
YM1	0.210	0.271	0.231	0.298
YM2	0.228	0.228	0.251	0.247

Inspection of RCOF in the selected case group (Table 4.6) shows that, as in the RCOF results presented earlier, older adults had greater mean and 99th percentile RCOF at normal speed. At fast speed individual differences can be noted with all older females having lower means for the right limb and most for the left limb.

Investigation of individual participants' mean (Figure 4.44) median (Figure 4.46) standard deviation (Figure 4.45) and interquartile range (Figure 4.47), show greater variability in older people. These descriptive statistics reflect individual ground reaction forces affected by gait biomechanics and body mass.

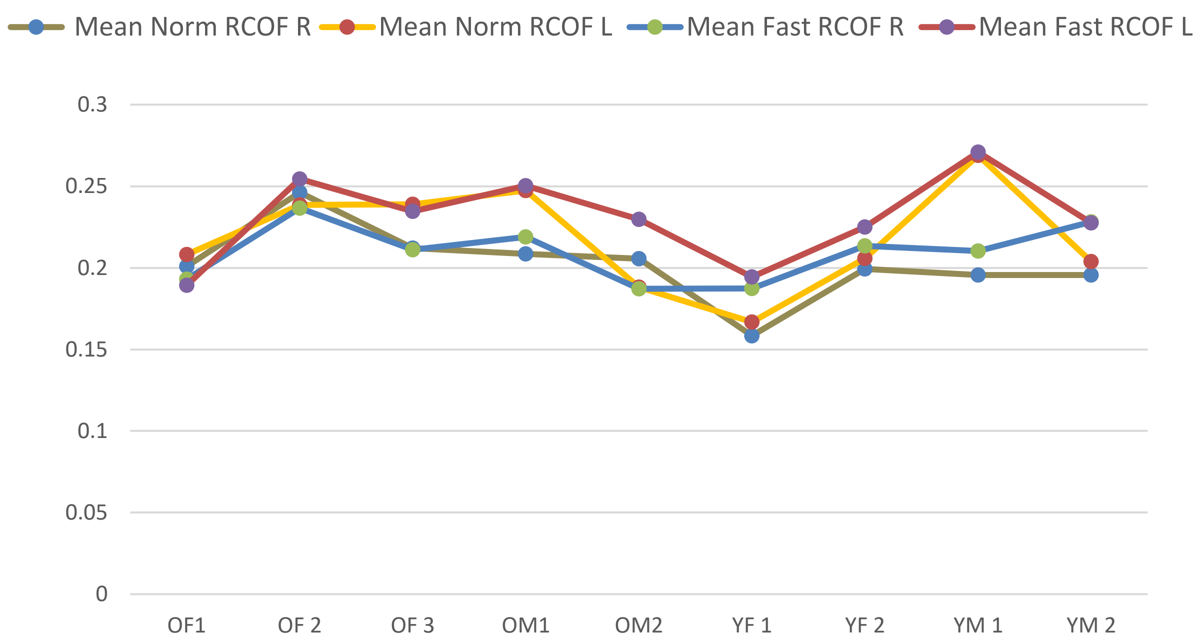


Figure 4.44 Mean RCOF for all participants at normal and fast speed

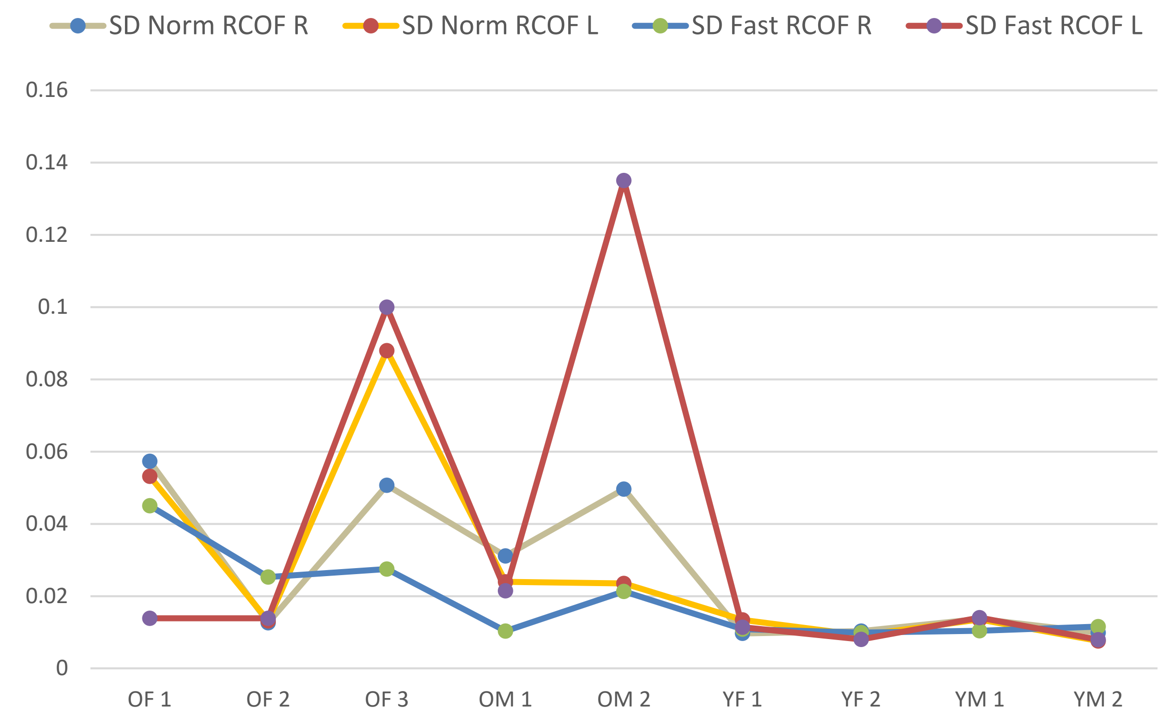


Figure 4.45 Standard Deviations at normal and fast speed

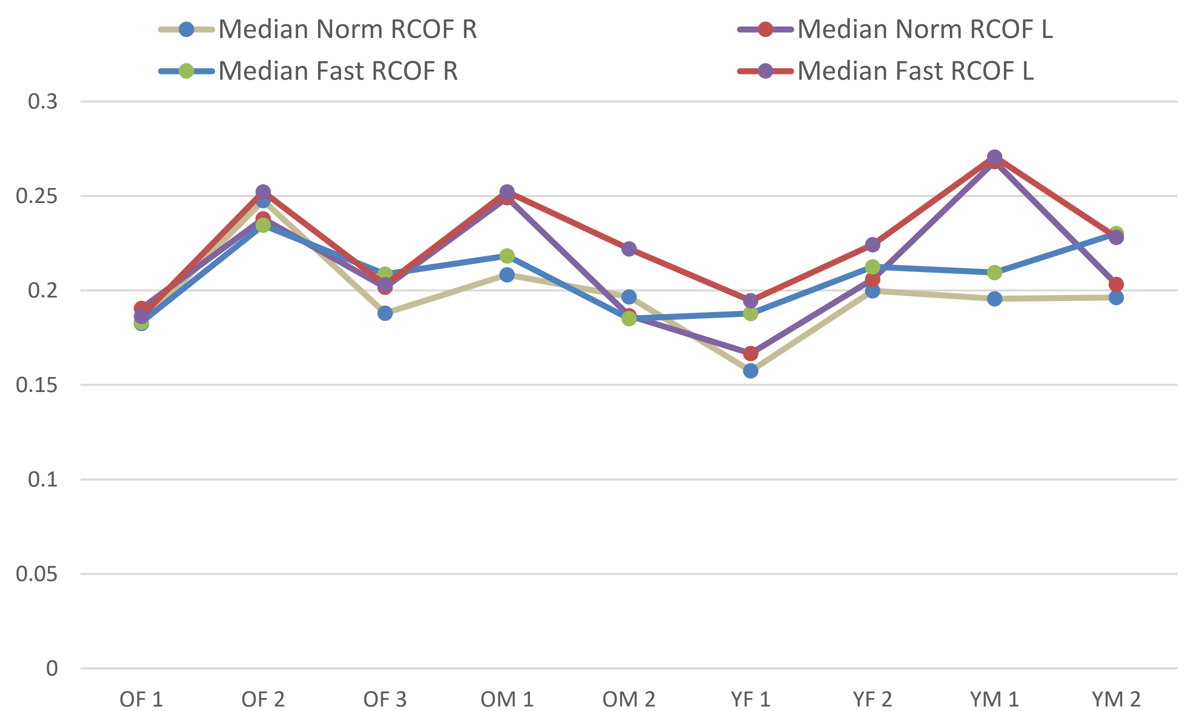


Figure 4.46 Median

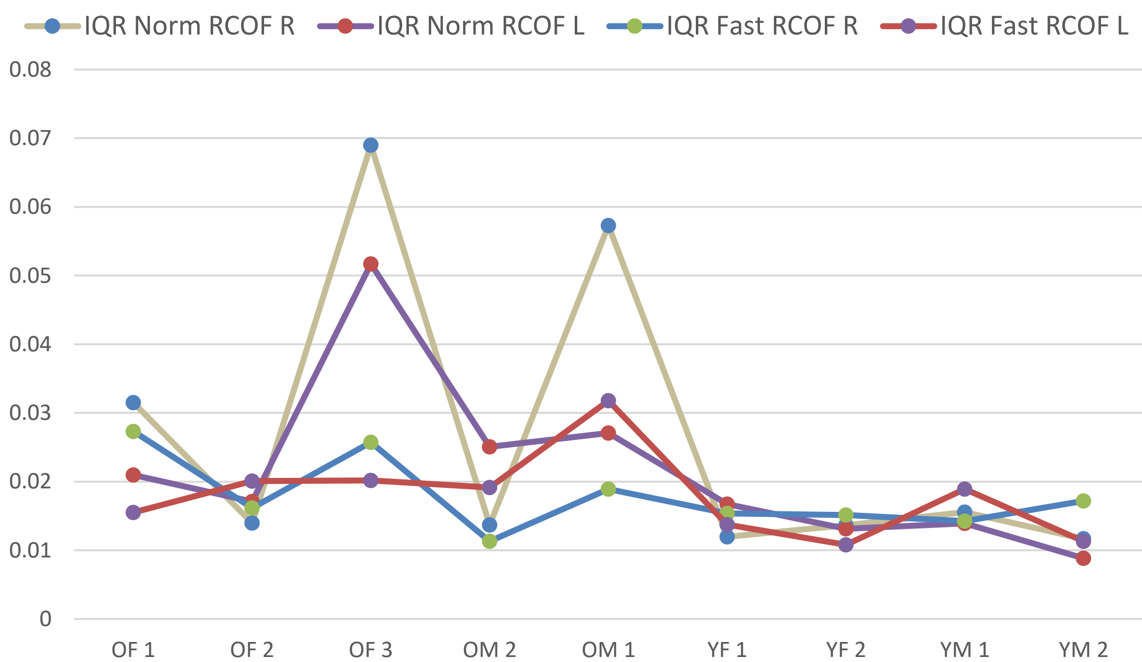


Figure 4.47 Interquartile Range

The previous sections compared RCOF mean and 99th percentile and it was seen that many older people increased RCOF by more than 50% when the larger distribution was considered.

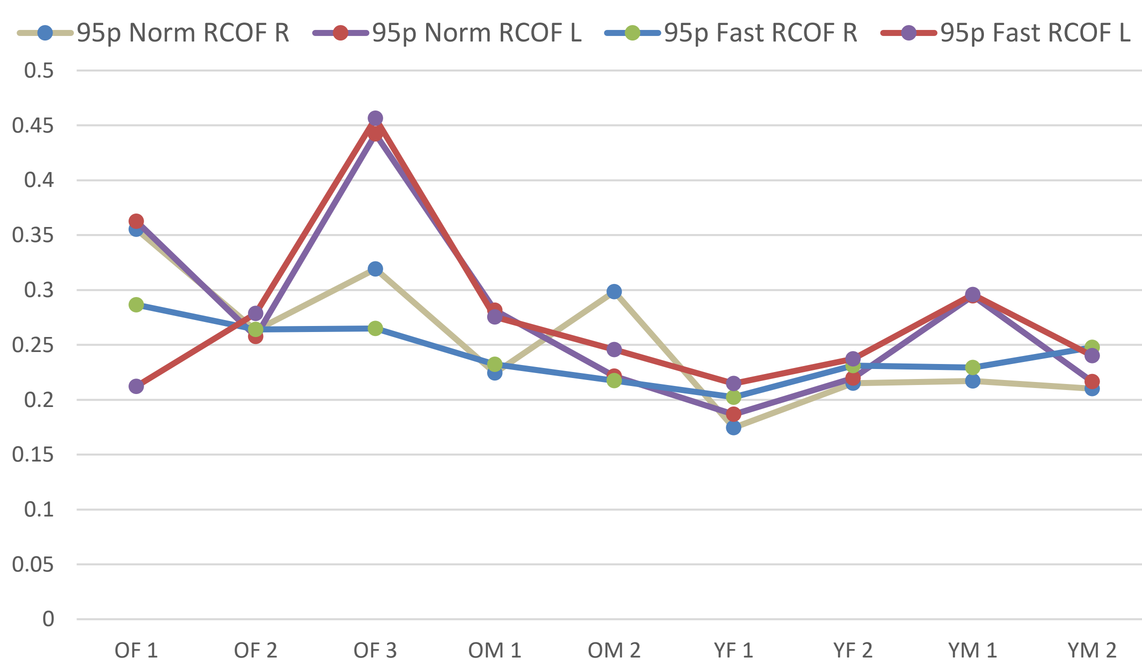


Figure 4.48 95th percentile data

The selected case studies (Figures 4.48 and 4.49) showed more increase from mean to 99th percentile than in young adults overall. Furthermore, the percentile data emphasize walking speed and limb effects in older adults while the 99th percentile was less accentuated in the younger participants.

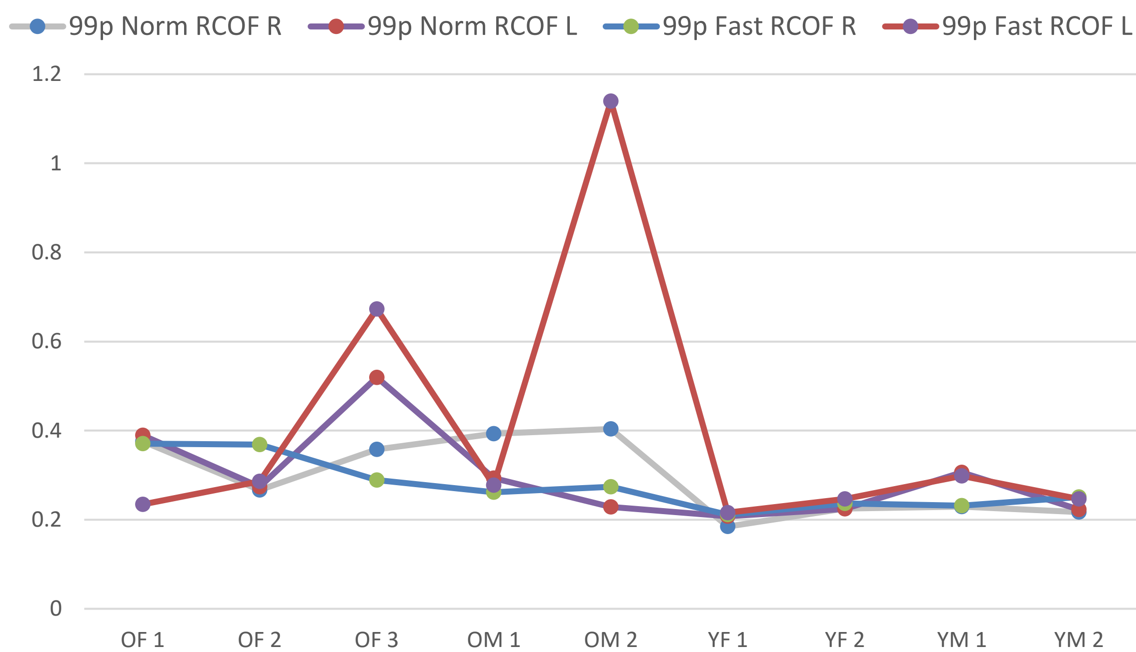


Figure 4.49 99th percentile data

Variability can also be observed by comparing skewness (Figure 4.50) and kurtosis (Figure 4.51). Whilst all young individuals had a relatively normal distribution and values close to zero, non-normality was observed in the older individuals. With four data sets analysed for each participant both positive and negative skew can be observed. Interestingly for OF2, who appeared the most consistent of the older females, her right limb data at normal speed had a positive skew but in fast walking negatively skewed. Interestingly the older female with the most deviation from the descriptive data, OF 3, had less skew than the other older females.

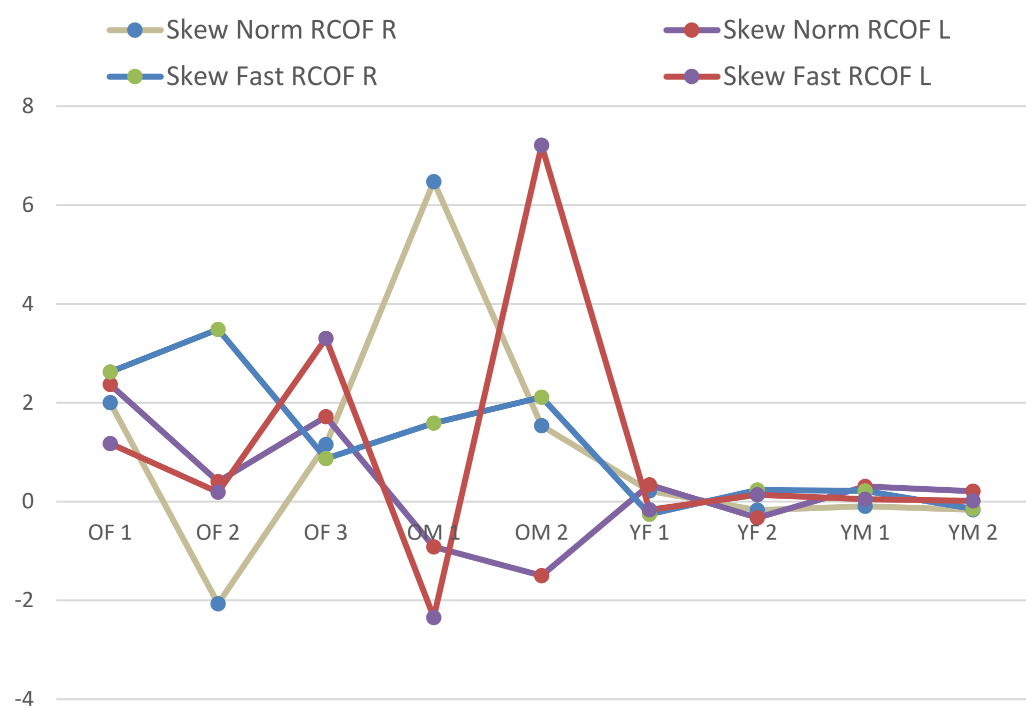


Figure 4.50 Skewness

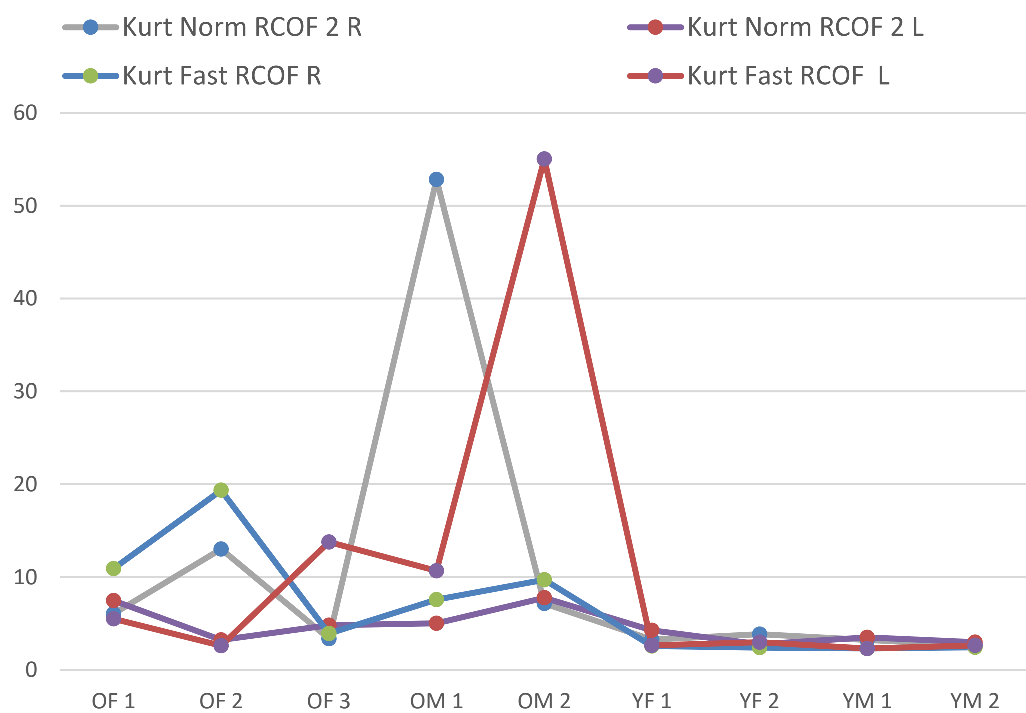


Figure 4.51 Kurtosis

4.3.4.1 Individual Slipping Functions

Analysis of individual probability functions allows for slipping estimation by accommodating non-normality in the distribution. In Figure 4.52, for example, the PROF data graph for Older Female 1 (OF1) at normal and fast speeds for both right and left limb are illustrated and the vertical lines are colour matched with the probability graph (right / left, fast / slow speed) to mark the RCOF mean, 95th and 99th percentile.

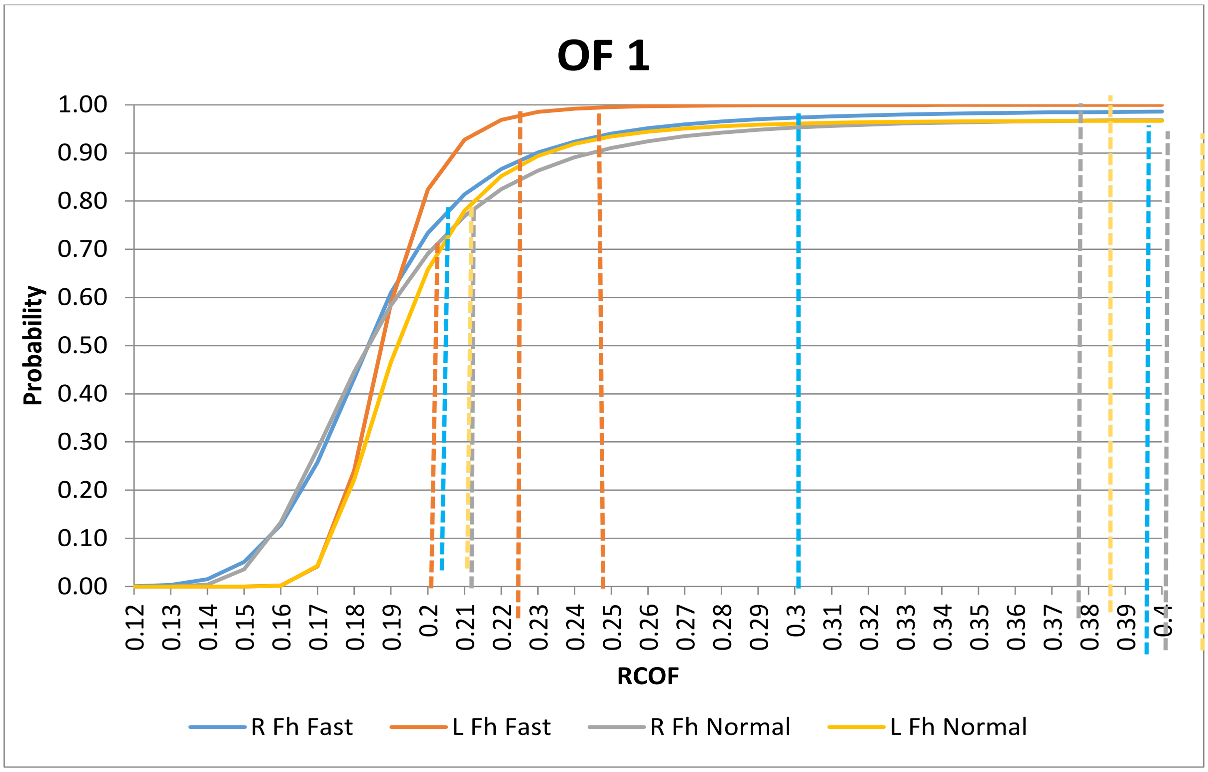


Figure 4.52 PRCOF data for OF 1

In Figure 4.52 asymmetry can be observed at the lower RCOF probability in that the right limb had a lower PRCOF than the left limb but they were similar for normal and fast speeds. The PRCOF function for left limb RCOF at fast walking speed shows a typically safe pattern with a rapid rise and low variability. All other patterns, right limb and normal and fast speeds and left limb and normal speed, had a wide range with 10% - 90% probability in the RCOF range 0.14 to 0.24.

It was also of interest to compare the probability data to the mean, 95th and 99th percentiles as presented by the vertical colour-matched lines. All means represent the 65% - 70% chance of the value appearing, thus a 30 – 35% chance of slipping on a surface COF of that value. In most cases the 95th percentile values have a 95-100% chance of appearing and the probability did not change between the 95th and 99th percentile RCOF. Also, the 99th percentile data are separated from the main probability data. As the probability modelling has accounted for skewness and kurtosis in the RCOF data, the high percentiles, presented as broken lines in the above figures, do not match the probability percentile data, showing the importance of data modelling for a non-normal distribution.

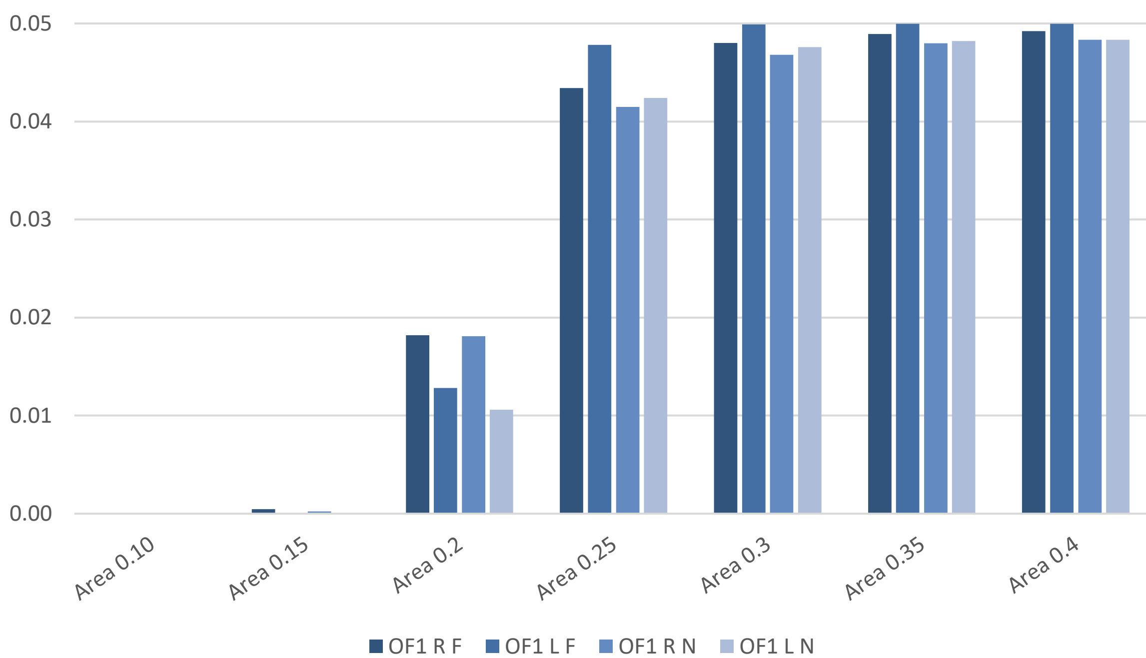


Figure 4.53 The total slipping risk for Case - Older Female 1

Analysis of total slipperiness in Figure 4.53 showed a similar pattern. Between RCOF 0.0-0.15 the area was 0 and thus this individual had a 100% chance of slipping independent of either limb or walking speed. Furthermore, the left limb data, at both normal and fast speeds, had a lower area at RCOF 0.2, representing a higher slipping risk in the very slippery and hazardous area (COF < 0.2). However, the left limb slipping area at fast speed presented highest at RCOF 0.25 and also reached the maximum area, 0.05, thus 100% safety. The right limb total slipping risk was similar at both walking speeds, with only a small increase in area between RCOF 0.25 and 0.3.

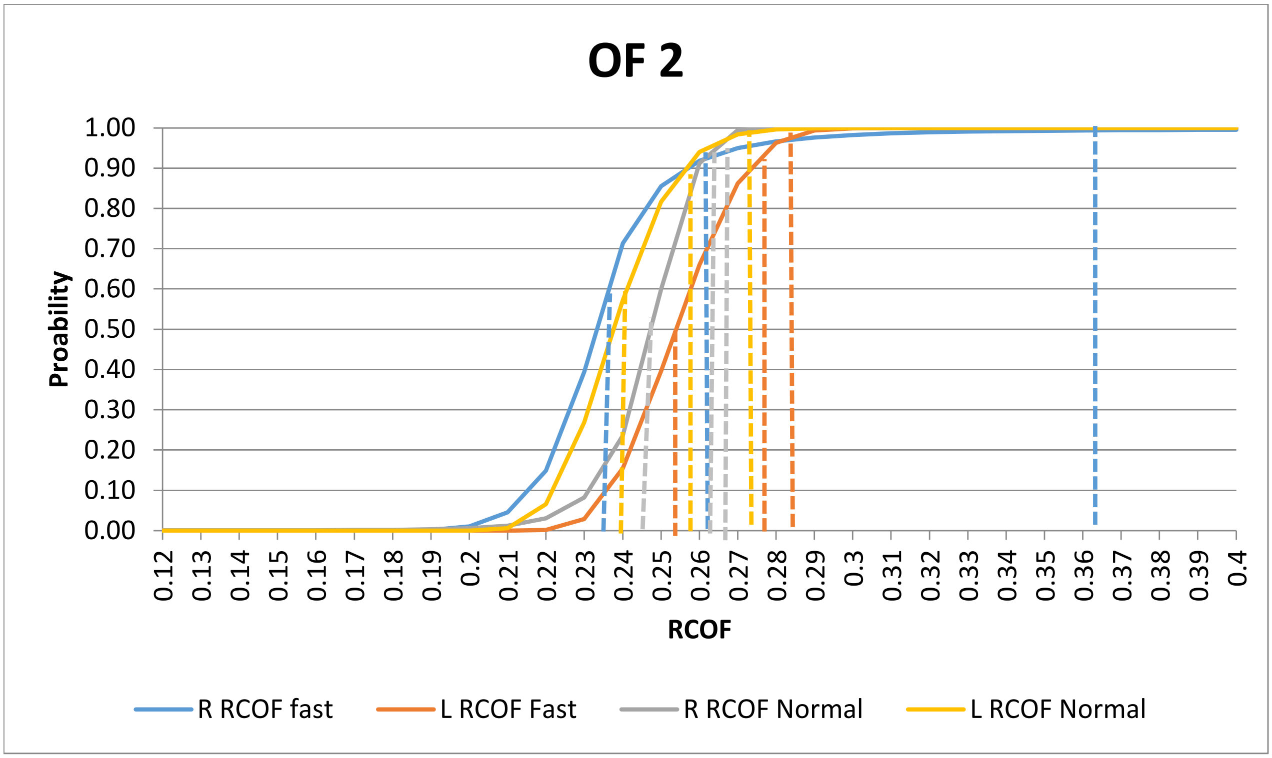


Figure 4.54 The PRCOF data for OF 2

The PRCOF functions of OF2 in Figure 4.54 are similar but in the right limb the PRCOF data increased earlier while the left limb indicated the opposite. The PRCOF data at normal speed started at lower RCOF, representing a safer walking pattern. The safest pattern was for the right limb at fast speed and the highest risk was observed for the left limb at fast speed.

Descriptive data and probability data in OF2 are different from OF1 with all selected values in a small area, matching the percentiles. Only one descriptive data point (right limb fast speed 99th percentile) is outside the main probability graph whilst all other data points are within the main probability graph. The mean of the right normal and left fast speed data had 50% probability with the right fast and left normal speed at 60%. Likewise the 95th and 99th percentile data points fitted the function in a similar manner.

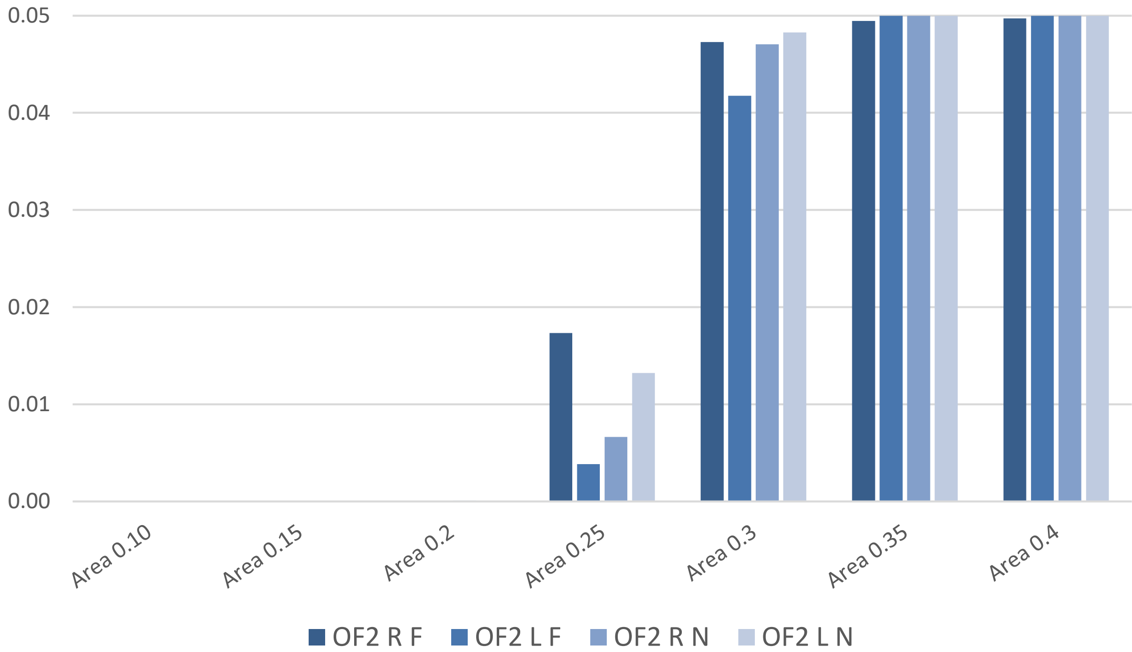


Figure 4.55 Total slipping risk for Case – Older Female 2

Analysis of total slipping risk (Figure 4.55) indicated that this individual was at higher risk on the very slippery and hazardous surface, with COF< 0.2 as the slipperiness area is 0 at that point. As in the probability graph, it can be noted that slipping risk was lower for the right limb at fast speed and highest for the left limb at fast speed. This individual reached the maximum area and 100% safety at RCOF 0.35.

The third older female, OF3, presented a contrasting slipping probability history (Figure 4.56) incorporating a wide range, with different probability patterns for normal and fast walking. The probabilities at normal speed showed a rapid increase and lower values, already having a 10% chance of appearing. Both fast walking speed graphs had a pattern similar to normal speed with lower probabilities initially followed by a gradual increase.

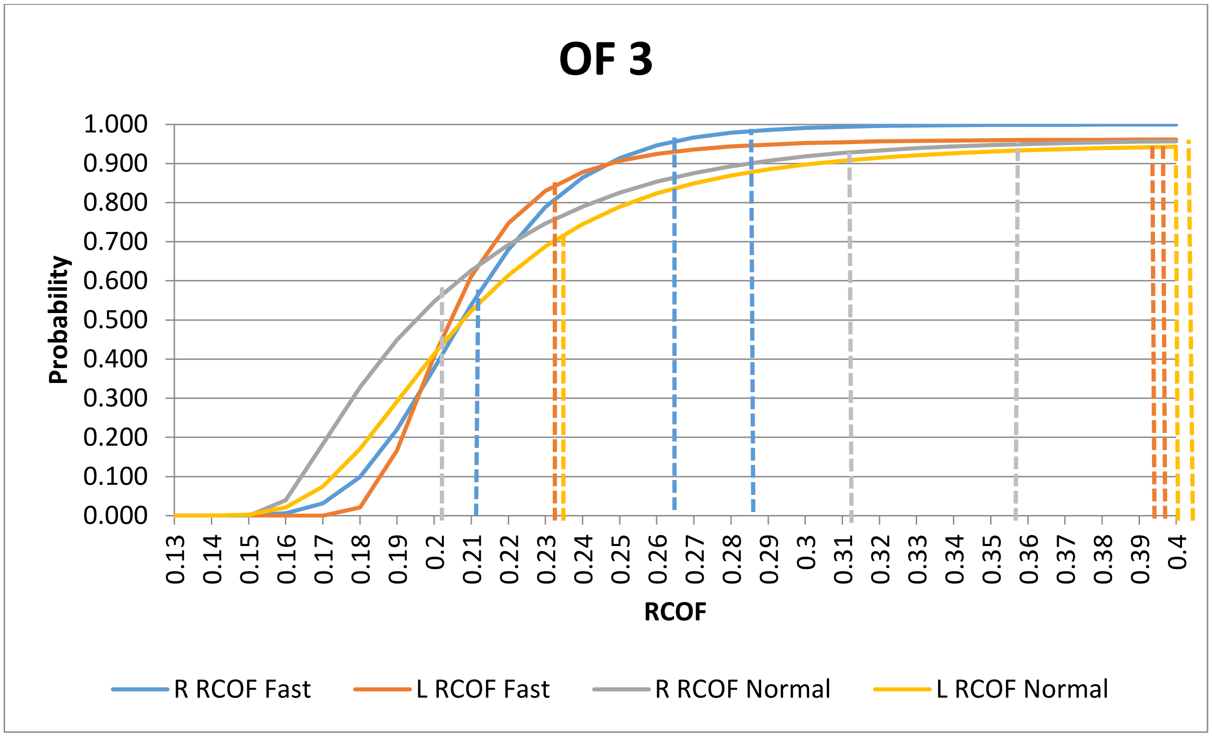


Figure 4.56 The PRCOF data for OF 3

When comparing the probability graph to the descriptive data it can be seen that means for the right limb at both speeds have ~60% chance of appearing and similar values for the left limb appear at 70% and 85% for normal and fast speeds respectively. Many of the 95th and 99th percentile values are beyond the bounds of the probability graph or outside the COF 0.4 safety zone.

The total slipperiness (Figure 4.57) data draw a clear picture of the slipping propensity of this individual, such that with COF 0.15 and less there was 100% chance of slipping. This participant had a gait with high variability and would be at high risk of slipping on a contaminated floor but had passed all screening tests and had no previous falls. Based on these data, however, it would be of interest to undertake a more detailed analysis of their gait function.

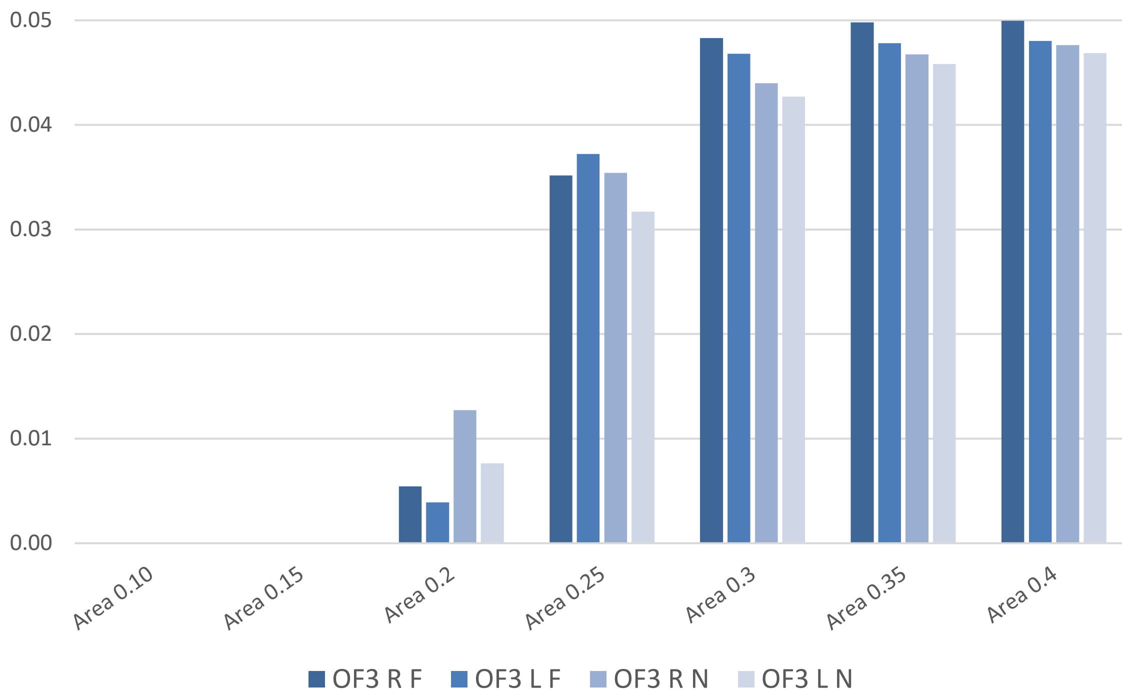


Figure 4.57 Total slipping risk for Case – Older Female 3

The first observation on the slipping function of the first male, OM1, (Figure 4.58) is strong asymmetry. The probability graphs for right and left feet are different in shape and RCOF range, yet the within-limb data are similar at both speeds. Whilst the right limb had a rapid increase from the initial RCOF value, the left side had a slow initial increase.

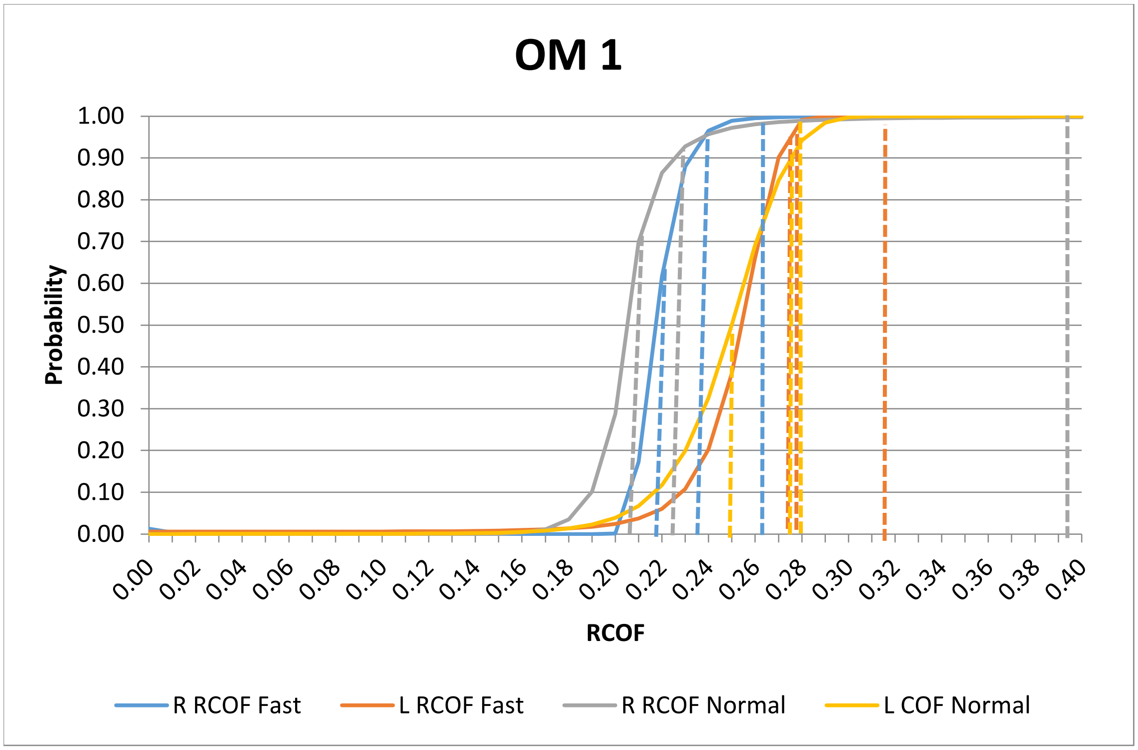


Figure 4.58 The PRCOF data for OM 1

The left limb mean at normal speed had 50% probability with the right side mean for normal speed 70% and fast speed 60%. In the left limb the mean had a 90% chance of appearing. It is also interesting to note that in the left limb fast speed the 99th percentile was similar to the mean and the right limb normal speed 99th percentile value was the only outlier. The total slipperiness data (Figure 4.59) showed that this individual was also at high risk in the very slippery and hazardous zone. The difference between the limbs is also clear with the right side showing a safer gait pattern. On the right side the safe zone was reached at COF 0.3 with the left side reaching the 100% area at COF 0.35.

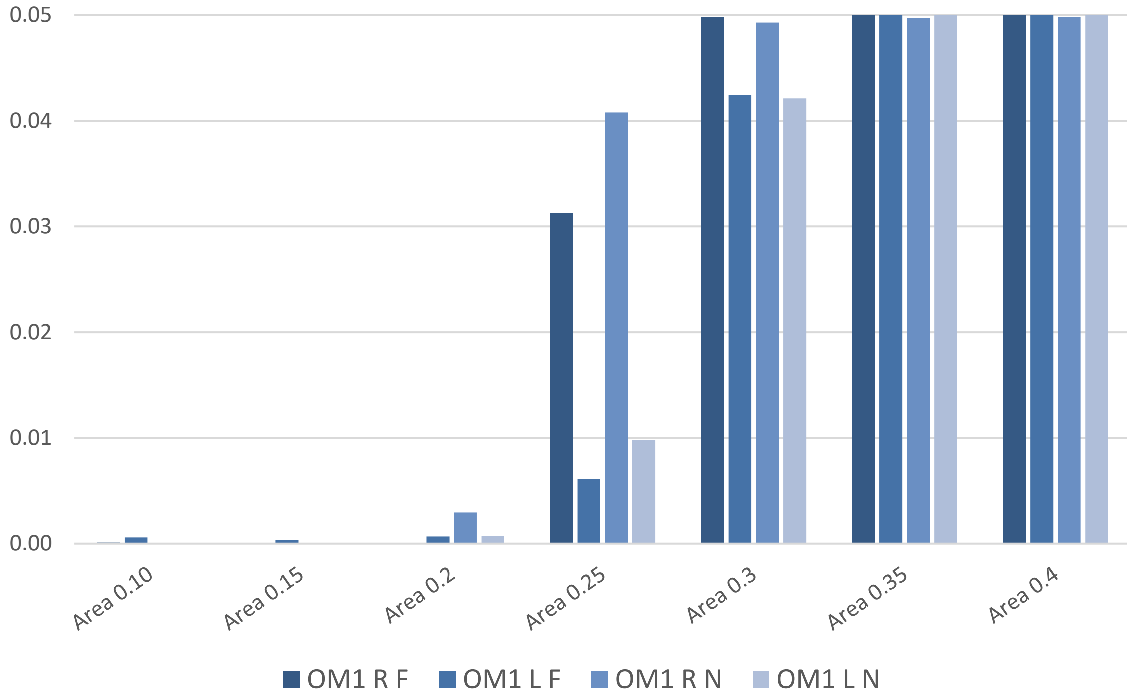


Figure 4.59 Total slipping risk for Case – Older Male 1

In the second older male, OM2, (Figure 4.60) two similar functions are observed but for different limbs and speeds. The right limb fast speed pattern is similar to the left limb normal speed data. These two patterns had a rapid increase in the probability with the mean noted at 50% and 60% for left normal and right fast speeds respectively. The pattern of the right limb at normal speed also had a wide range with initial rapid increase but a slower increase toward the end of the probability graph. The mean value is noted at 55% probability and the 95th percentile at 95% but the 99th percentile is an outlier, outside the probability zone.

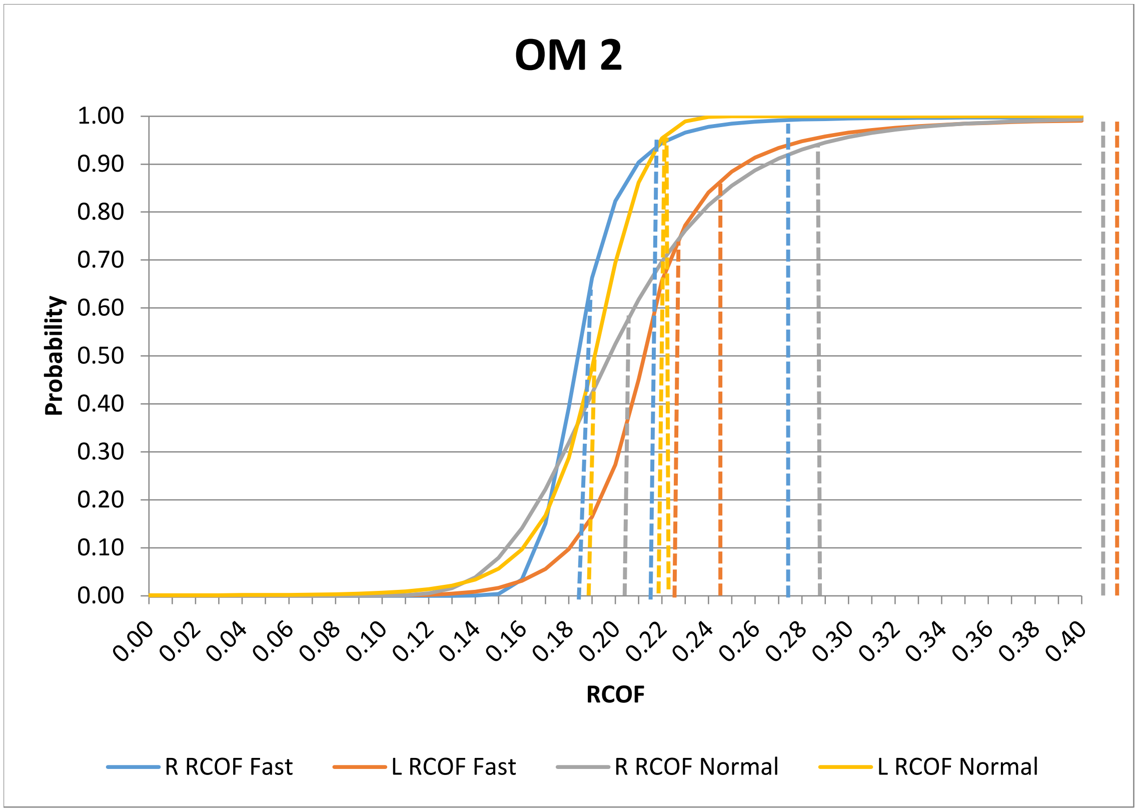


Figure 4.60 The PRCOF data for OM 2

Similarly, the probability data for left limb at fast speed had a large range. Whilst initially the graph showed a slow increase the pattern changed to a wider range towards high RCOF. In the left limb fast walking data, a high value outlier is noted with RCOF = 1.139. The total slipping risk data (Figure 4.61) verified that this individual had a 100% risk of slipping if COF < 0.15. Interestingly the right limb data at fast speed and left limb data at normal speed were similar, reaching 100% safety at COF 0.3. The left limb fast and right limb normal data had a slower increase and reached the 100% safety at COF 0.4

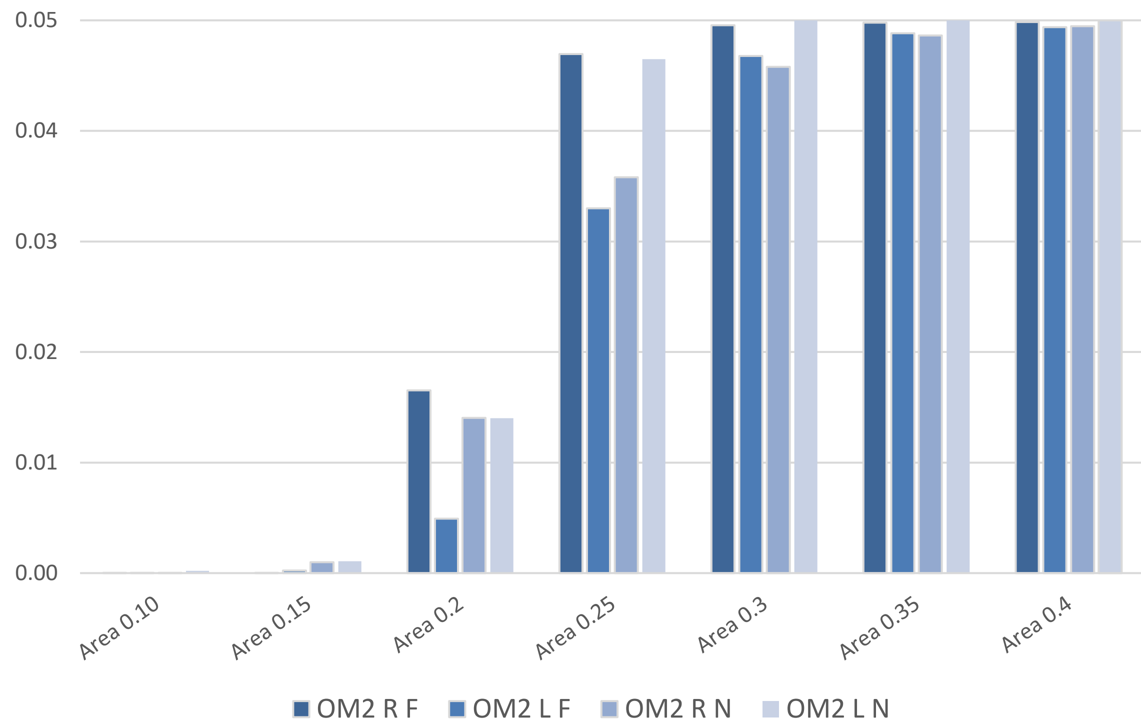


Figure 4.61 Total slipping risk for Case – Older Male 2

Young females were the most homogenous sample with low within-group variability, as well illustrated in the slipping function of YF1 (Figure 4.62). All probability graphs increased rapidly with low range but two sub-groups can be noted based on walking speed. At normal walking speed both feet had a similar pattern with means at 50% and 40% for right and left limbs respectively while during fast walking the limb means appeared at higher probability, 50% and 60% for right and left respectively.

While the PRCOF of YF1 suggest a low variability gait pattern the total slipping risk calculation clearly reveals the effect of walking speed, with the normal speed data increasing rapidly from 0.0 to 0.035-0.04 (70%-80%) between RCOFs 0.15 and 0.25. When walking fast the area at 0.2 was only ~20%. Thus, walking speed influenced this individual's slipping propensity in the very slippery and hazardous zone. The safe area was reached at normal walking speed at RCOF 0.25 and at fast speed at RCOF 0.3. It must also be noted that this individual had similar slipperiness potential in both feet.

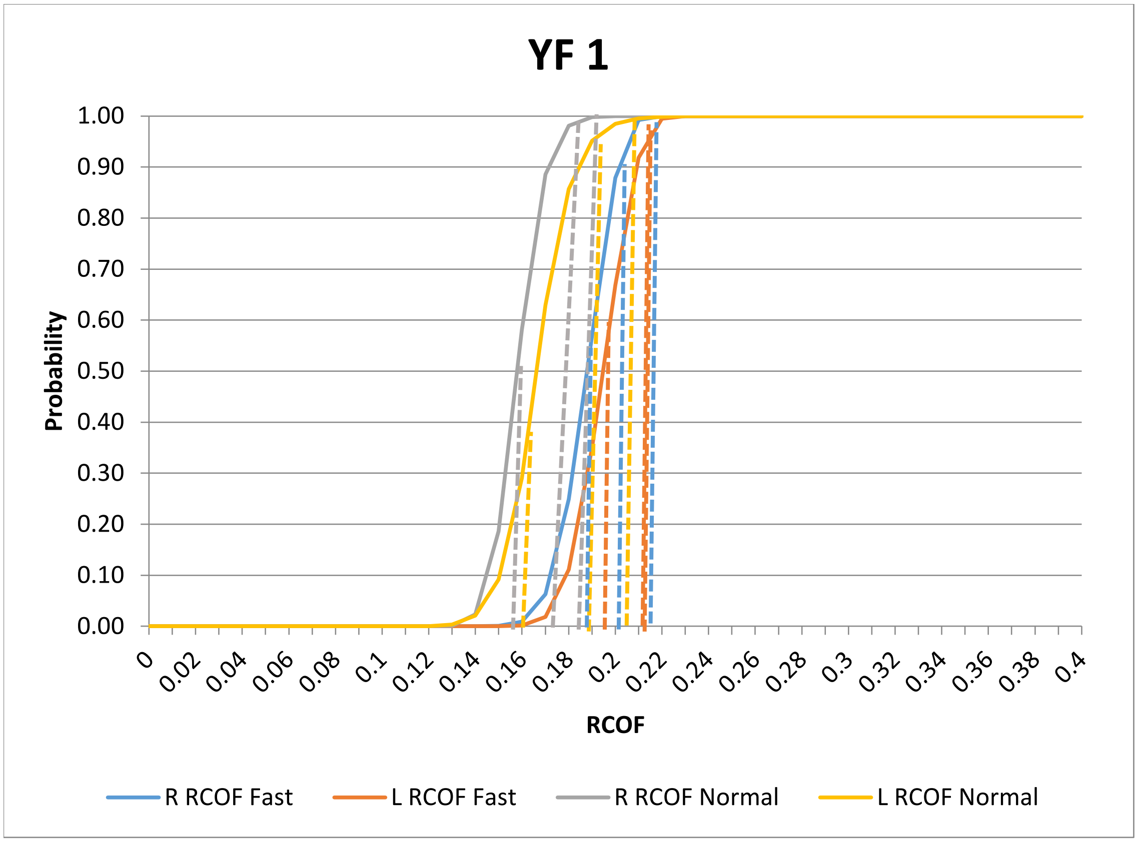


Figure 4.62 The PRCOF data for YF 1

The total slipping risk data (Figure 4.63) verifies that this individual had a 100% risk of slipping if COF < 0.15. At COF 0.2 limb and speed effects can be noted with the right limb having a greater area at both speeds and also a greater area for both limbs in the faster speed condition. At COF 0.25 this individual reached 100% safety at normal speed with a low slipping risk noted at fast speed.

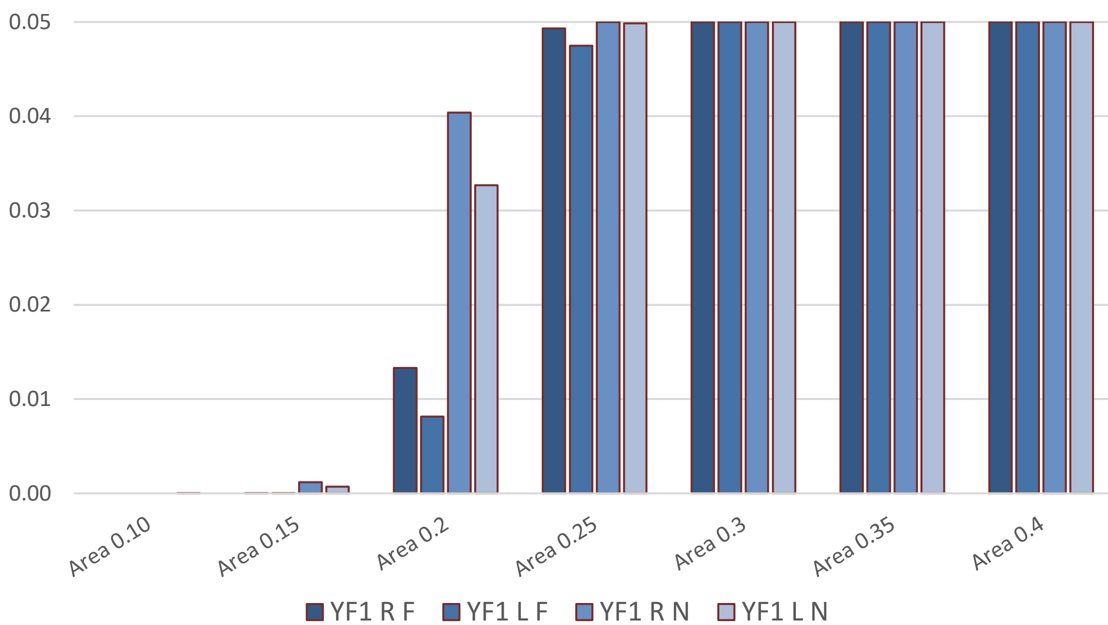


Figure 4.63 Total slipping risk for Case – Young female 1

The PRCOF functions for YF2 (Figure 4.64) were similar to YF 1, i.e., compact within a small range. As for YF 1 all patterns are similar with the lowest values for normal speed data followed by fast speed. The total slipperiness data (Figure 4.65) are similar and again similar to YF1 fast walking data indicated higher slipping risk. For both limbs, this individual had 100% slipping risk in the very slippery and hazardous area. At RCOF 0.25 at normal speed the slipperiness area was already ~90% but by RCOF 0.3 the area was 100% and safety gained.

Observation of the individual PRCOF and total slipperiness data as well as the previously presented population group data described a homogenous group with little variability. However, when combining the total slipperiness graphs, variability in the data can be observed. Whilst the data of YF 1 is characterised by differences between limbs, with increased safety on the right limb, the data for YF 2 were more affected by walking speed.

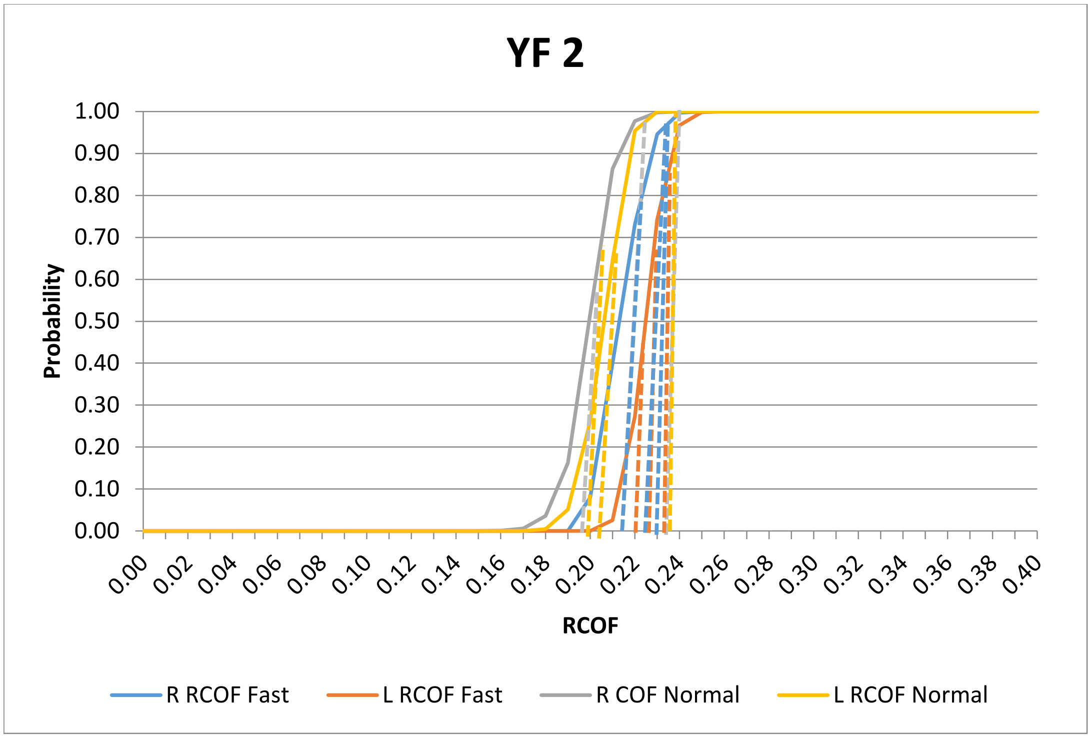


Figure 4.64 The PRCOF data for YF 2

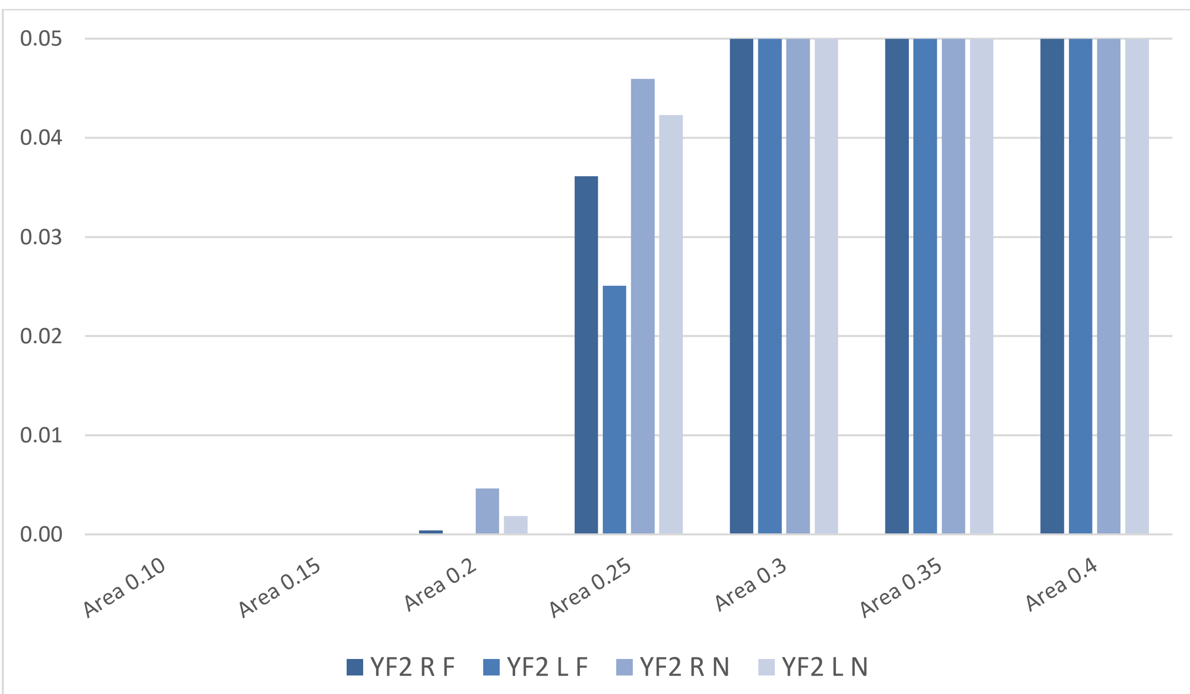


Figure 4.65 Total slipping risk for Case – Young female 2

The last group, the young males, is also represented by two case studies. The first observation on YM1 is the strong limb asymmetry (Figure 4.66). In the left limb, the two probability graphs at fast walking speed are nearly identical with the graphs of the right limb at normal walking speed also presenting with similar patterns, albeit at a lower RCOF range. Despite the clear asymmetry for the RCOF range, these data match the young females with a similar total slipperiness function. In addition, the mean, 95th and 99th percentile values have similar probabilities.

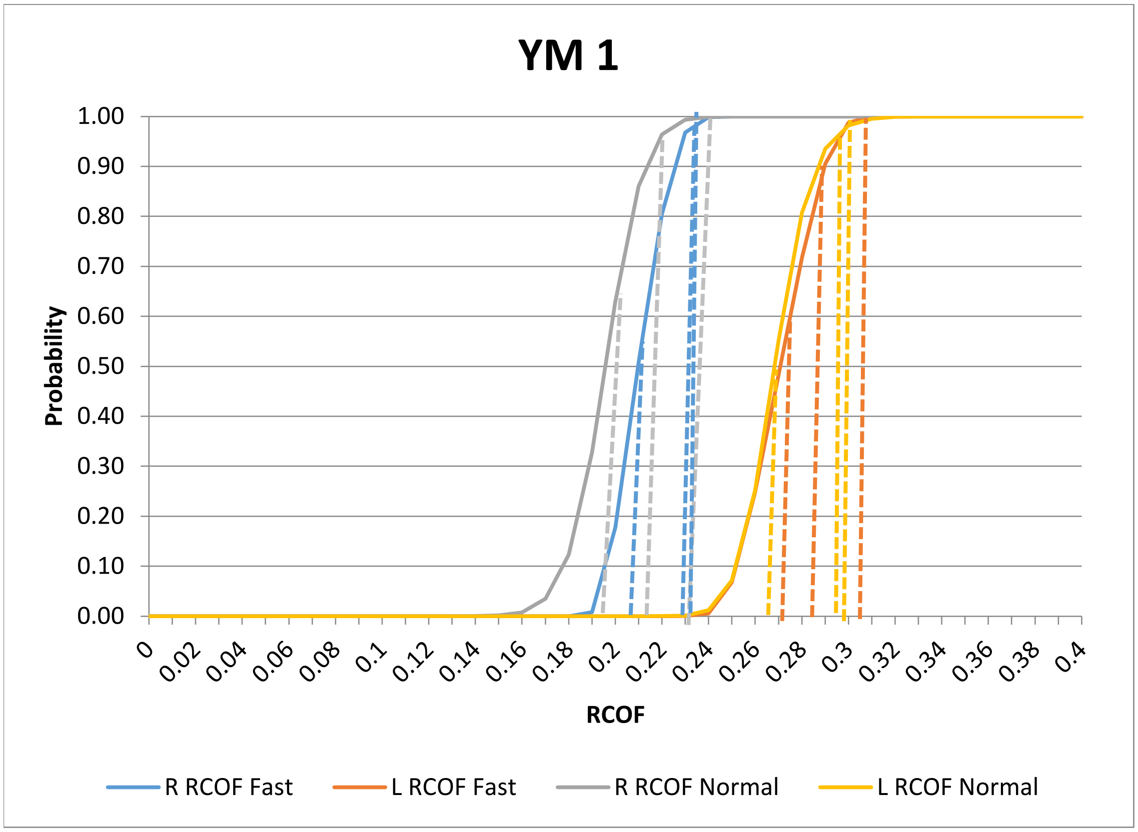


Figure 4.66 The PRCOF data for YM 1

The total slipperiness data (Figure 4.67) also reflect asymmetry; in the left limb walking speed has no effect on slipperiness with both speeds presenting similar functions and 100% slipperiness observed at RCOF 0.25 and the 100% safety zone reached at 0.35. For the right limb, a speed effect can be noted with at normal speed between RCOF 0.15 – 0.2 and at both speeds 100% safety reached at RCOF 0.3.

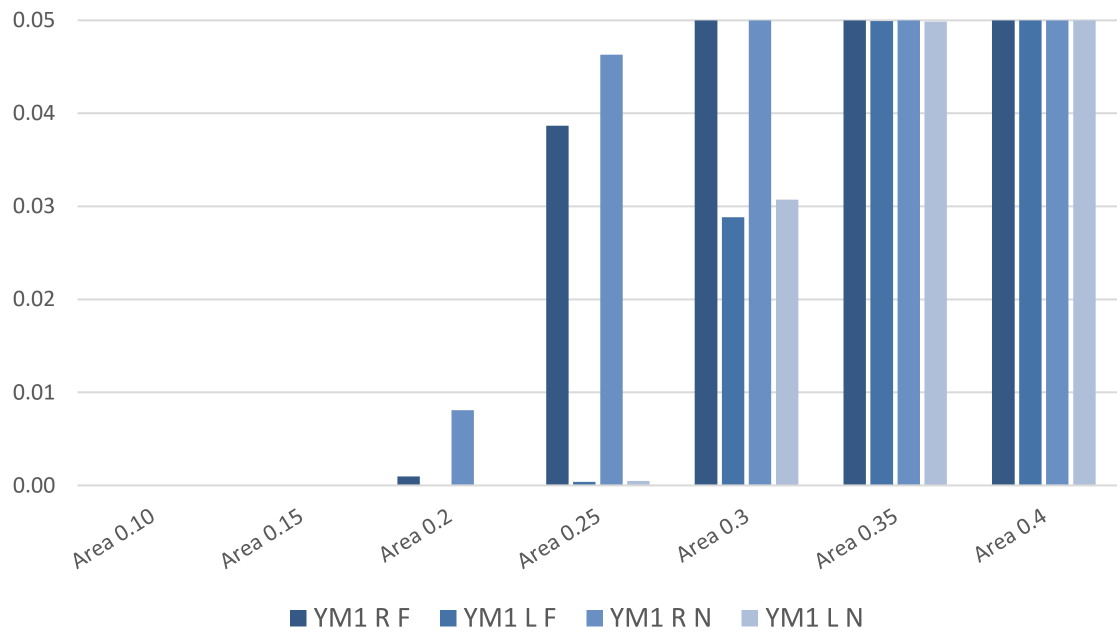


Figure 4.67 Total slipping risk for Case – Young male 1

The slipperiness function for YM 2 (Figure 4.68) is similar to YM 1, with tightly spaced data having a rapid increase from 0% to 100% probability and the RCOF percentile data matching closely. Closer investigation, however, suggests that grouping of the data is driven by walking speed, not by limb asymmetry, and both limbs show safer walking with lower RCOF at normal speed. Analysis of total slipperiness (Figure 4.69) leads to the same conclusion because at fast speed the total slipping risk rose rapidly from 0 at RCOF 0.2 to 100% at RCOF 0.3. Interestingly, the 100% safe zone was reached at the same point for normal speed even though the total area values began to increase at RCOF 0.15 and 0.2 respectively for right and left.

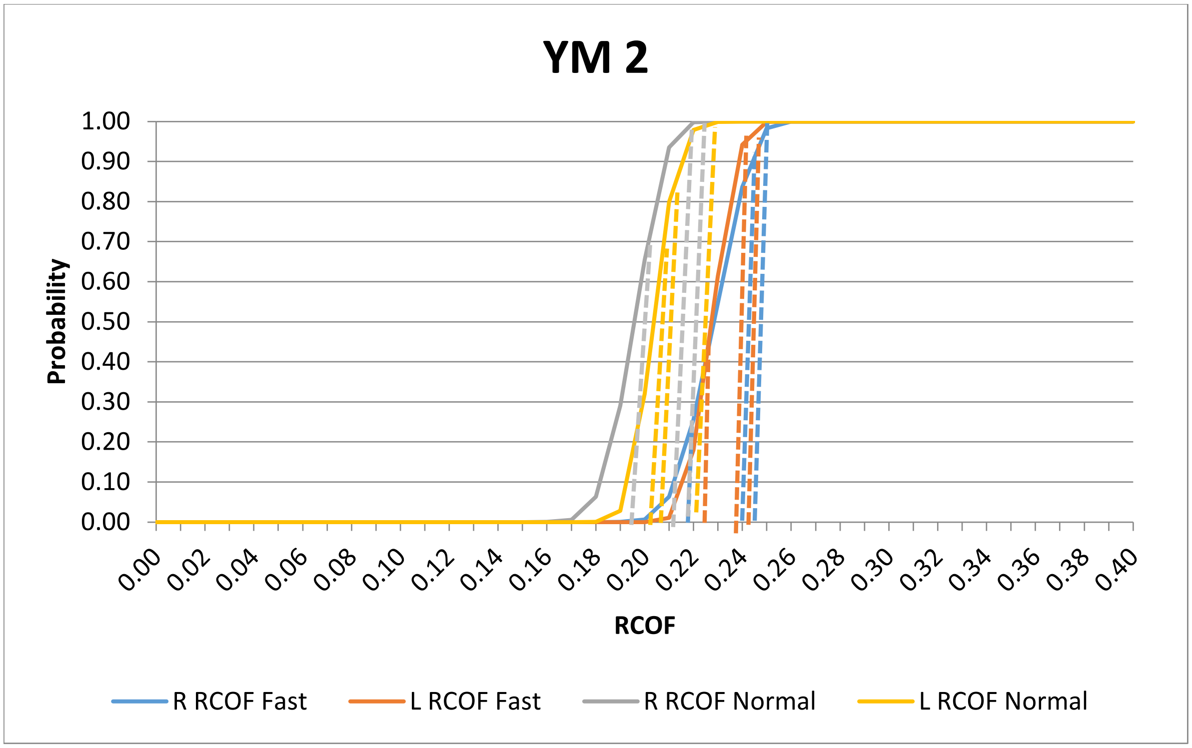


Figure 4.68 The PRCOF data for YM 2

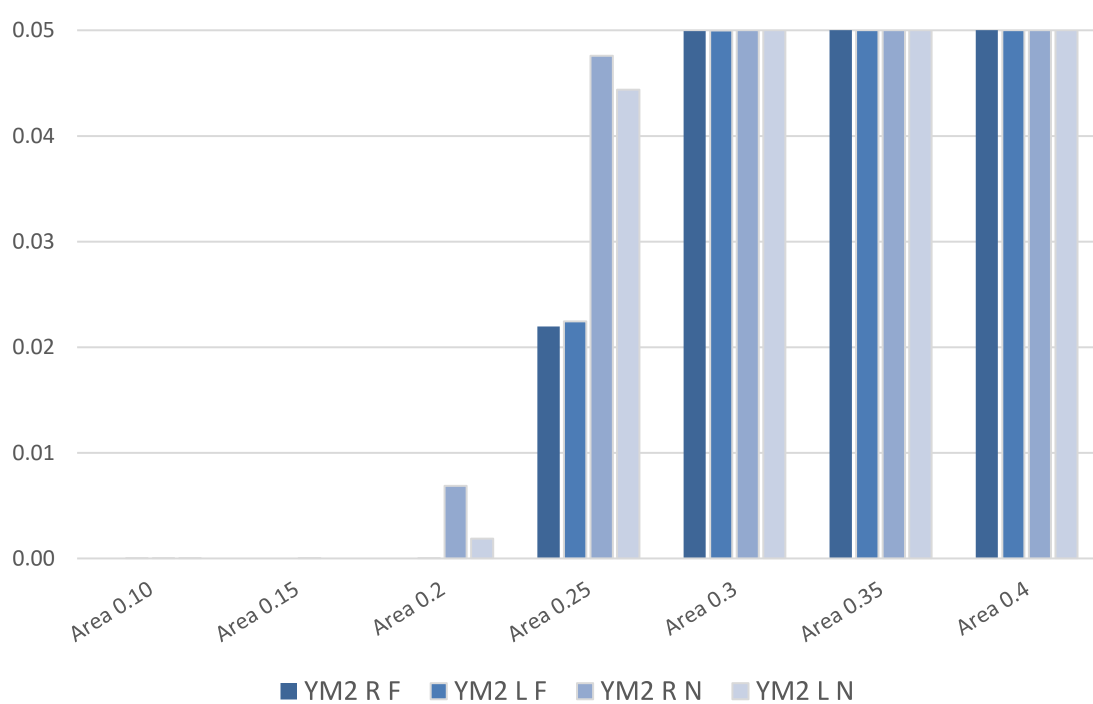


Figure 4.69 Total slipperiness area for Case – Young male 2

4.3.4.2 Case Studies Summary

The individual cases were chosen to represent most differences from the group central tendency. Even though the young females had low within-group variability, two participants were included to reflect the typical pattern for that group.

The older adult cases were characterised by high variability. Often, for example, their percentile data did not match the graphical presentation but in some participants, if the data had low variability and a relatively normal distribution, the percentile data did match the data. In contrast, skewed and kurtotic data with increased variability did not reflect the PRCOF plots, showing the importance of the non-normal data modelling for estimating slipping probability. All young individual cases had clearly defined PRCOF with low range and low variability and the descriptive statistics (mean, 95^{th} and 99^{th} percentile) often produced the same RCOF probability. The young females had similar values but inter-limb asymmetry was observed in the males. Total slipperiness analysis also allowed description of safe zones for the different population groups and revealed that even low variability data can show strong individual differences in safety.

The previous sections discussed the differences between the mean and the 99^{th} percentile. This can also be observed in the individual cases. For example, while the young females had similar values for all descriptive data points, the other individuals showed variability and an increase in RCOF as more data points were included. Comparison of the probability graphs and the descriptive data (mean, 95^{th} and 99^{th} percentile) was instructive in showing that in selected cases with low variability (all young participants) the probability data and the descriptive values closely matched. Likewise, participants with increased variability in their descriptive values did not fit the data. In the previous sections, it was seen that high variability in the walking of older people may preclude using the mean. From the comparisons presented here the mean represents a data value that has a 50% chance of appearing and seems to be a reliable way to compare populations.

4.4 Summary of Results

Figure 4.70 summarises the results relative to the study null hypotheses, as follows.

Hypothesis I: RCOF calculation. A significantly higher RCOF was found with the inclusion of medio-lateral force (F_X).

Hypothesis II: age, gender and speed effects on RCOF. The hypothesised age effect was rejected given a significant difference between age groups at both normal and fast walking speeds. The hypothesised gender effect hypothesis was accepted because there was no RCOF difference between females and males at either normal or fast walking speeds. Walking speed significantly increased RCOF.

Hypothesis III: the probability of slipping. The results confirmed significant age, gender and speed effects on slipping probability and the null hypothesis was rejected.

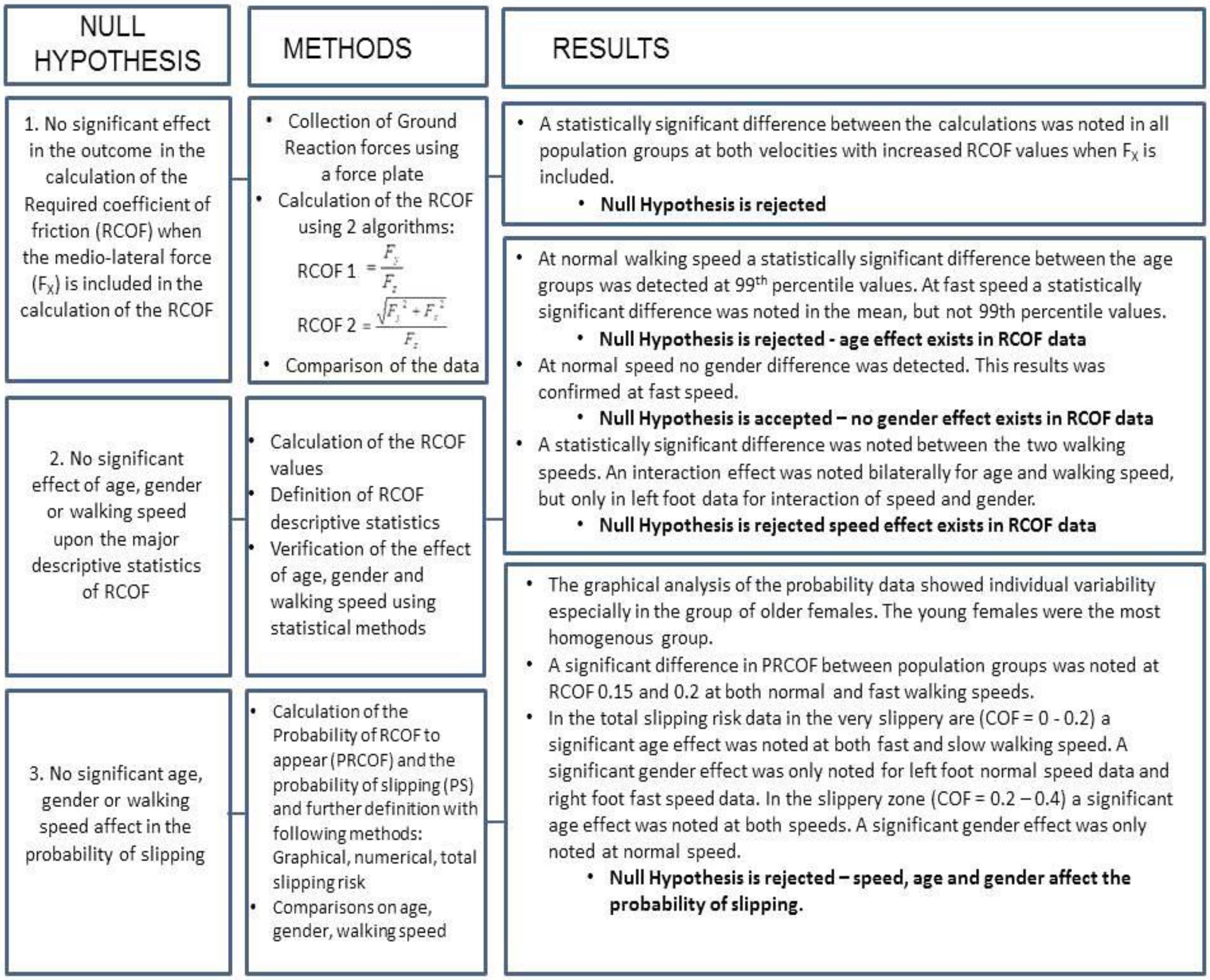


Figure 4.70 Summary of results

5 Discussion

This study investigated the probability of slipping with respect to age and gender by measuring foot-ground reaction forces at normal and fast self-selected walking speeds. The Required Coefficient of Friction (RCOF) was calculated from the three-dimensional foot-ground reaction forces collected during continuous walking and then a mathematical model applied to calculate slipping probability. The results showed that slipping risk was affected by age, gender and walking speed and there was some indication of limb asymmetry in slipping risk. The results also indicated the importance of allowing for individual differences when determining the likelihood of slipping. It may not, therefore, be prudent to generalise from group statistics when assessing the risks posed by walking surfaces with different frictional properties.

This chapter discusses the experimental findings in the following sub-sections: (1) Methodological considerations (2) Age, gender and walking speed effects on RCOF (3) Limb and speed effects on RCOF (4) Slipping probability (5) Individual differences in slipping risk (6) Limitations of the current research and suggestions for future studies.

5.1 Methodological Considerations in Measuring Intrinsic Factors of Slipping Probability

Slipping risk can be evaluated by exploring either intrinsic or extrinsic factors. While tribometric procedures quantify surface friction, intrinsic factors are measured by investigating individuals' walking biomechanics, specifically the ground reaction forces that determine the intrinsic frictional requirement to avoid slipping, the Required Coefficient of Friction (RCOF). Force plates are reliable and precise devices for measuring foot-ground forces during walking but the sampled data may be influenced by methodological considerations, such as sampling frequency and accuracy of limb contact on the force plate, including visually guided targeting. Choice of analysis methods is also important in using force plate data for determining slipping probability.

5.1.1 The Influence of the Medio-Lateral Force (F_X) in the Calculation of the Required Coefficient of Friction (RCOF)

Calculation of the required coefficient of friction (RCOF) was initially presented in the 1950s and further developed in the 1970s to its current forms (Perkins, 1978). Perkins presented RCOF using only anterior-posterior force, excluding the medial-lateral component (F_X) (Perkins, 1978). More recent discussions, however, have suggested the importance of including F_X (Buczek, Cavanagh, Kulakowski, and Pradhan, 1990; Grönqvist, Hirvonen, Rajamäki, and Matz, 2003).

Results of the present experiment confirmed that RCOF increased significantly, by up to 7.5 %, when F_X was included in the calculation. Chang et al. (2011) also studied the effect of F_X on the RCOF calculation and reported that RCOF for young people (18-25 years) increased from .220 to .230 (4.5%) when F_X was included. The young adults in this study had lower mean RCOF values than reported by Chang et al (2011) increasing from .202 and .186 (females and males respectively) to .207 and .194 at normal speed (2.5% and 4.3%) and .219 and .191 (females and males respectively) to .223 and .198 at fast speed (1.8% and 3.7%). For older individuals, 55 years and older, Chang et al. (2011) reported RCOF increasing from .221 to .227 (3.2%). The older adults in this study were older than Chang's group and had RCOF increasing from .195 and .187 (females and males respectively) to .204 and .194 (4.6% and 3.8%) at normal speed and from .218 and .198 (females and males respectively) to .224 and .208 at fast speed (2.8% and 5.1%). In this study the young adults, therefore, increase RCOF less that the participants in Chang's research but the older people increased their RCOF more than Chang reported when F_X was included.

RCOF increase with inclusion of the medio-lateral component is likely to be associated with known ageing effects on gait function. One ageing-related gait adaptation, for example, is increased step width and associated greater medial-lateral force. Indeed, previous literature has reported that a higher risk of falls is related specifically to greater medio-lateral forces (Giakas and Baltzopoulos, 1997).

Older people also tend to walk slower with a shorter step length and higher cadence, features that are also likely to impact RCOF values.

In summary, the findings here suggest that all three GRF components must be included in the RCOF calculation, especially in the populations with decreased medio-lateral stability. The F_X component could also be useful in analysing effects of rehabilitation programs and in addressing whether training medio-lateral stability could reduce slipping propensity. Considerations of medio-lateral stability may also be important when designing measures to prevent slip-induced falls in older people.

5.1.2 Data Presentation

To investigate the effects of statistical treatment methods the mean, median, 95th, 97th and 99th percentile data were computed and compared for all groups at both walking speeds. The results showed that percentile statistics were useful in highlighting condition effects on RCOF, for example in older people walking at normal speed mean RCOF was more than 50% greater than the 99th percentile.

While it is expected that descriptive values increase when more data is included, for example the mean compared to the percentile values, the present findings highlighted differences between the age groups with respect to statistical treatment effects. While the difference between RCOF mean and RCOF99 for all participants was 17% at normal speed and 14% at fast speed, the corresponding values for older adults alone were 52% and 31%. It was also noted that the median was lower than the mean for older adults at both speeds. Other authors have also questioned the more common presentation of mean data, suggesting that information may be lost when presenting the mean only (Matz and Grönqvist, 2001). The results of this study support that view and reinforce the importance of presenting the data using measures in addition to the mean. It must be remembered, however, that while mean values may lose variability information and not account for extreme values, the percentile data may include unrepresentative outliers.

5.1.3 Data Sampling

In gait biomechanics experiments it has been a customary practice to undertake repeated measurements on a short walkway. The number of gait trials in slipping studies has varied, with some authors reporting a single trial only. (Burnfield and Powers, 2002). It has, however, been shown that gait variability is affected by the experimental protocol. Paterson et al. (2009) studied the effect of two protocols on time-distance gait variables, one procedure was continuous overground walking and other ten repeated walking trials. The results showed that walking speed, step length, stride length, step time and stride time were all reduced in the continuous walking manipulation. Both walking speed and step length can impact RCOF and it is reasonable to expect that RCOF profiles would be different in a continuous protocol compared to data collected over repeated trials. Many studies on slipping probability have also used pre-determined walking speeds or employed metronomes to guide walking speed (Burnfield and Powers, 2002; You, Chou, Lin, and Su, 2001). Anderson et al. (2014), however, found that when speed and step length were controlled, no age effect was noted on RCOF.

The present study used a protocol that took into consideration these findings. As the aim was to investigate RCOF simulating everyday normal and fast walking, self-selected walking speeds were requested during an extended continuous walking trial. This protocol allowed for the collection of a large sample (up to 100 strides) allowing analysis of long-term variability. This protocol selection can, however, influence RCOF (via walking speed) and as noted above the RCOF values reported here were lower than those of Chang et al. (2011).

5.2 Age, Gender and Walking Speed Effects on RCOF

Some authors have concluded no significant difference in mean RCOF between young and either middle aged or older adults (Lockhart et al., 2002, 2003). In contrast, there are other reports of increased RCOF in middle aged participants when compared to both young and older participants walking at medium speed (Burnfield and Powers, 2002). Some authors have also studied the causal relationships and suggested that older adults have lower RCOF due to slower walking speed and decreased heel contact velocity (Kim et al., 2005).

This study reported an age effect at normal speed with higher RCOF mean in young adults' right limb only (6.7% increase). In contrast, the comparison of RCOF99 showed that older adults had significantly greater values than their younger counterparts (18% and 21% respectively for right and left limb). At fast speed the young adults presented with significantly greater RCOF mean (10.3% and 10.7% for right and left limbs respectively).

Previous studies on gender effects have indicated that females create larger shear (medio-lateral and anterior-posterior) forces than males (Li et al., 2001; Chao et al., 1983). Some authors have reported that females had higher RCOF at slow speed whilst men had higher RCOF at faster speeds (Burnfield and Powers, 2002). Burnfield and Powers (2002) also suggested that at the lower speeds, females use a longer relative stride than males and thus, using the model of Ekkebus and Killey (1971, 1973), would predict higher RCOF for females. Furthermore, a recent study of barefoot walking found that females had larger RCOF during initial foot-ground contact (Rozin-Kleiner, 2015).

5.3 Limb and Speed Effects on RCOF

Walking speed affects foot-ground impact forces and faster walking is related to increased ground reaction forces (GRF) especially the vertical (F_Z) and anterior-posterior (F_Y) components (Kirtley, 2006). As the RCOF calculation is based on the GRF, walking speed has a direct influence on frictional requirements. The walking speed results were critical to the design of the present study and it was demonstrated that the speed condition instructions to participants were effective in increasing walking speed significantly from normal to fast. Generally, when comparing these results to the literature it can be noted that walking speeds of all groups at both normal and fast gait are lower. This is likely to be due to the continuous walking test protocol in this study, as suggested by studies comparing test protocols (Paterson et al., 2009). Whilst in most studies participants have walked single or multiple trials on a short walkway, in this study data were collected over a longer period, 30 minutes, walking continuously. It is possible that the slower pace in this report was due to the longer, continuous walking trial.

Older adults had lower RCOF than younger participants and also had a smaller RCOF increase from normal to fast walking. When comparing age groups at fast walking speed the RCOF difference was more pronounced, with a statistically significant difference between groups.

With respect to gait symmetry it has been common practice to pool the RCOF data from both feet and represent the data as a single mean RCOF. This study analysed the right and left limb data separately. Whilst asymmetry was not analysed per se, differences in RCOF between the two limbs were noted. Comparison between the right limb and left limb mean RCOF at normal and fast speeds revealed a limb effect approaching significance and a significant limb X gender effect was noted. The right and left limb data were, therefore, examined separately. When comparing mean RCOF across groups while mean RCOF of the right limb was greater at fast speed, the left limb mean RCOF was greater at normal speed. Older adults' left limb RCOF99 was greater than the right limb and also presented with greater variability, as revealed in higher standard deviations. Similarly, older females had a greater mean RCOF for the left limb when compared to the right at normal speed.

It has been frequent practice to pool data from both limbs. The results here demonstrated that it *is* of interest to consider limb effects in quantifying slipping. In future work, it would be informative to investigate limb dominance effects, not determined in the current study.

5.4 Slipping Probability Modelling

Previous sections discussed changes in RCOF due to age, gender and walking speed. It was also shown that the choice of data presentation is affected by variability in both individuals and groups. This variability affects all analysis between groups, especially when including older people who have increased variability in their gait data. The use of a mean value was critiqued and alternative methods were recommended. Using the mean to represent central tendency assumes an approximately normal distribution, therefore, more advanced modelling of data from populations known to have high variability and non-normal distributions is required.

The analysis of slipping probability was based on a calculation that allowed for variability in the data and accounted for skewness and kurtosis. Slipping probability (PS) estimation was based on the probability of an RCOF value (PRCOF) and could take into account different surface frictional properties. The analysis also included estimation of the total slipping risk (TSR) from the integrated PRCOF function. Significant age, gender and speed effects were noted and, most importantly, the calculation enabled reliable estimation of safe friction zones for individuals.

Several authors have estimated the risk of slipping. One of the first studies by Harper et al. (1961) estimated the likelihood of slipping in straight level walking and turning. They used an RCOF calculation excluding F_X and presented the data as a mean value. The study reported mean RCOF of 0.17 (SD 0.04) for men and 0.16 (SD 0.03) for women. The results here suggested considerably higher RCOF for all participant groups, even when excluding F_X. Harper et al. (1961) used Pearson curves and the limited β- function to estimate the RCOF probability and concluded that an able-bodied person had a one in a million chance of slipping when the friction between a level walking surface and footwear was 0.36. Their data set was later re-analysed by Pye (1994) who presented a calculation that showed a 1 in 20 chance of slipping when COF was 0.24. The participants in the present study had a considerably greater chance of slipping at that COF level. The percentage estimates for RCOF = 0.2, for example, were 56% and 41% for older females and males respectively and 41% and 16% for young females and males. This higher probability is consistent with the generally higher RCOF values reported here.

Barnett and Poczynok (2003) discussed floor surface characteristics with respect to biomechanical slipping theories. Their calculation, based on an imaginary surface with COF 0.366, showed that walks of 10 steps caused 10% of the walkers to slip and in a walk of 1000 steps this incremented to 97% slips. Similarly, Besser et al. (Besser, Marpet, and Medoff, 2009) used a logistic regression model to estimate pedestrian safety. In their model, similar graphs to the probability functions reported above were presented. As in the present data a steeper curve implied higher precision. Figure 5.1, for example, illustrates individual PRCOF patterns for older males walking at fast speed.

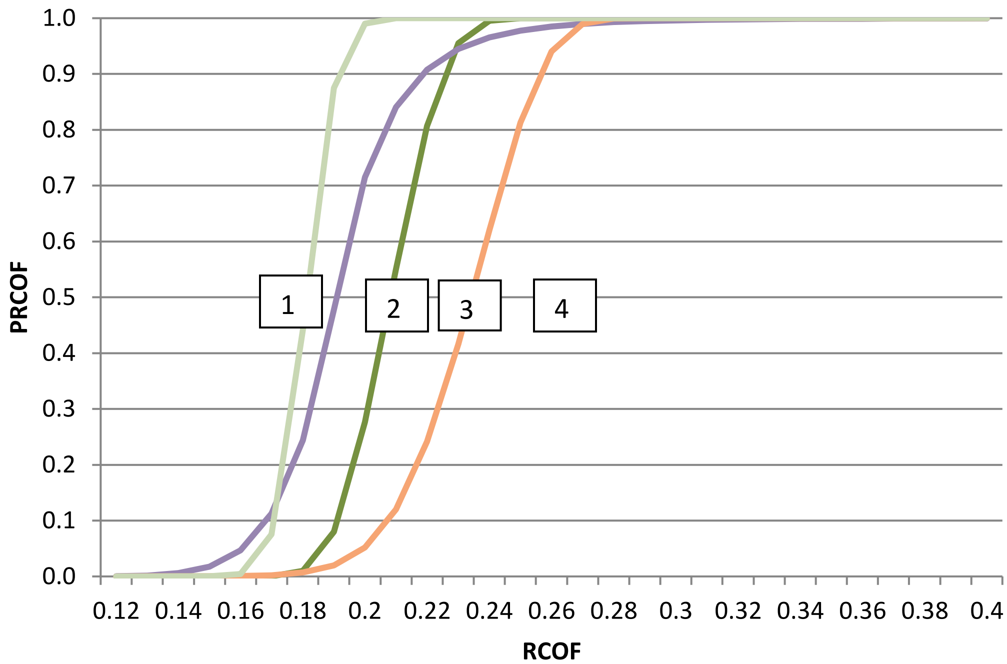


Figure 5.1 Examples of patterns of the probability of slipping data observed in older men walking at fast speed

Graph 1 presents a person who has a steep PRCOF graph with a narrow range: 0.15 (0%) – 0.19 (100%) at a low very RCOF range. This pattern reflects a very safe walking style as the 100% PRCOF, the 0 % PS, is already reached (at COF 0.19) and, therefore, this individual is safe on walking surfaces with COF as low as 0.19. Graph 2 describes data with a larger RCOF range (PRCOF 0.13 and 0.27) showing higher RCOF variability. Whilst this individual has low RCOF, providing safety in the very low COF values, the higher range shows increased variability. This individual is also interesting within the extended high end probability range. The 90% PRCOF (10 % PS) is already reached at RCOF 0.22, the range of the final 10% probability is, therefore, greater than the entire probability range of the individual presented in Graph 1. Graph 3 presented a steep, high accuracy function similar to Graph 1 but with higher RCOF (range 0.18 – 0.24). The comparison between Graphs 1 and 3 provides a clear indication of individual differences. Graph

4 presents an individual with a high RCOF range (0.17 – 0.28) and high variability. Both Graphs 3 and 4 present individuals with higher RCOF, especially at the low range. A 0% RCOF probability at 0.17 equals 100% slipping probability at all surfaces with a COF of less than 0.17. This observation puts both these individuals at a high risk on very slippery and hazardous surfaces (COF 0 – 0.2)

All these probability graphs show individual gait patterns and thus different slipping risk profiles. If the RCOF data of these individuals and groups was presented as mean values only critical information on individual and group variability would have been overlooked and slipping risk assessments would have been misleading.

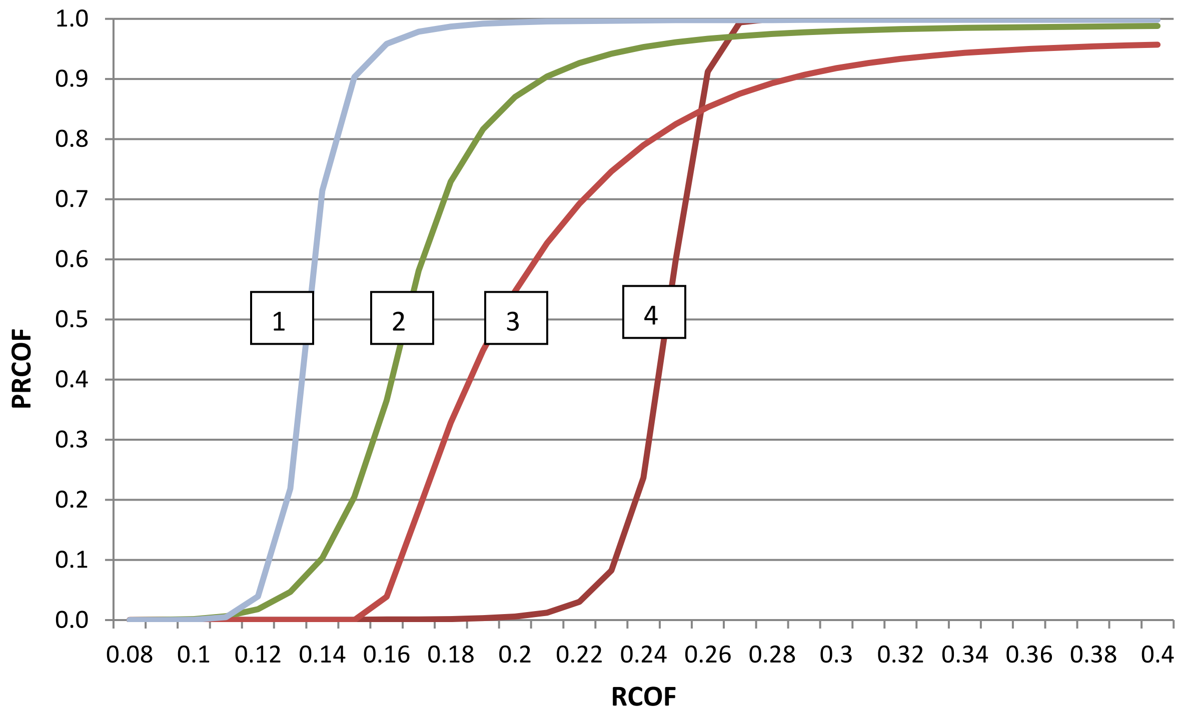


Figure 5.2 Examples of patterns of the probability of slipping data observed in older females walking at normal speed

Figure 5.2 presents examples of older females walking at normal speed. Graphs 1 and 4 are data from individuals with similar PRCOF patterns, with a rapid increase in RCOF probability. Many differences, however, can be seen between the two. Graph 1 presents an individual with PRCOF range of 0.11–0.19. With an extended range within the high percentiles, in must be noted that 90% probability is reached at RCOF 0.14 decreasing the range. With a low range this individual is safe on surfaces considered to be hazardous and slippery (COF 0.2–0.4). Graphs 2 and 3 present individuals with a high range in the PRCOF, with Graph 3 data for an individual with a slipping risk on all surfaces shown as a ”half bell” shaped function. Whilst this individual has low RCOF values, beginning at RCOF 0.145, the total range is 0.145–0.4, with only 95% probability reached at 0.4, thus leaving a 5% PS risk even on surfaces considered safe (COF > 0.4). This type of probability range is of high risk as it is difficult to define a safe zone, rather this individual has some level of slipping risk on most surfaces. Graph 4 also presents a narrow data range 0.2–0.25 and thus low variability, however, as all RCOF are above 0.2, this individual has a 100% PS at the very hazardous and slippery surfaces (COF 0.0–0.2).

If data characteristics including variability, skewness and kurtosis are not included in the analysis, these individual risk profiles cannot be observed. Only a long term data collection protocol, providing sufficient GRF data to capture individual variability, can allow risk to be accurately estimated. The use of this new probability model allows for individual variability to be accounted for when estimating slipping propensity.

5.5 Slipping Risk

It has been claimed that the prevention of slipping can be considered a “wicked problem”. This term was introduced by Rittel and Webber (1973) to describe a problem with the following typical features: There is no definitive formulation of the problem, there is no stopping rule, they are not true or false but good or bad, there is no immediate and no ultimate test of a solution, there is no opportunity to learn by trial and error, rather every attempt counts, they don’t have an enumerable set of potential solutions, they are unique and can be considered to be symptom of another problem. Bowman (Bowman, 2015; Bowman and Graham-Bowman, 2015) eloquently used the term to describe falls prevention. Wicked problems are difficult to define, are socially complex, often have no clear solution, involve a change in behaviour and attempted solutions may lead to unforeseen consequences. When trying to solve the “wicked problems” one must collaborate with others and be innovative in the approaches towards solutions. Intrinsic or biomedical factors have been more researched in proposing slipping-falls prevention measures while environmental factors have been neglected. Furthermore, the term “wicked” may capture an issue highly resistant to solutions requiring action from public policy makers.

In cold climates slipping is a national problem due to slippery outdoor surfaces. As the snow season starts the Finnish National Institute of Health and Welfare has launched a new slipping prevention campaign (Figure 5.3 - National Institute of Health and Welfare, 2015).

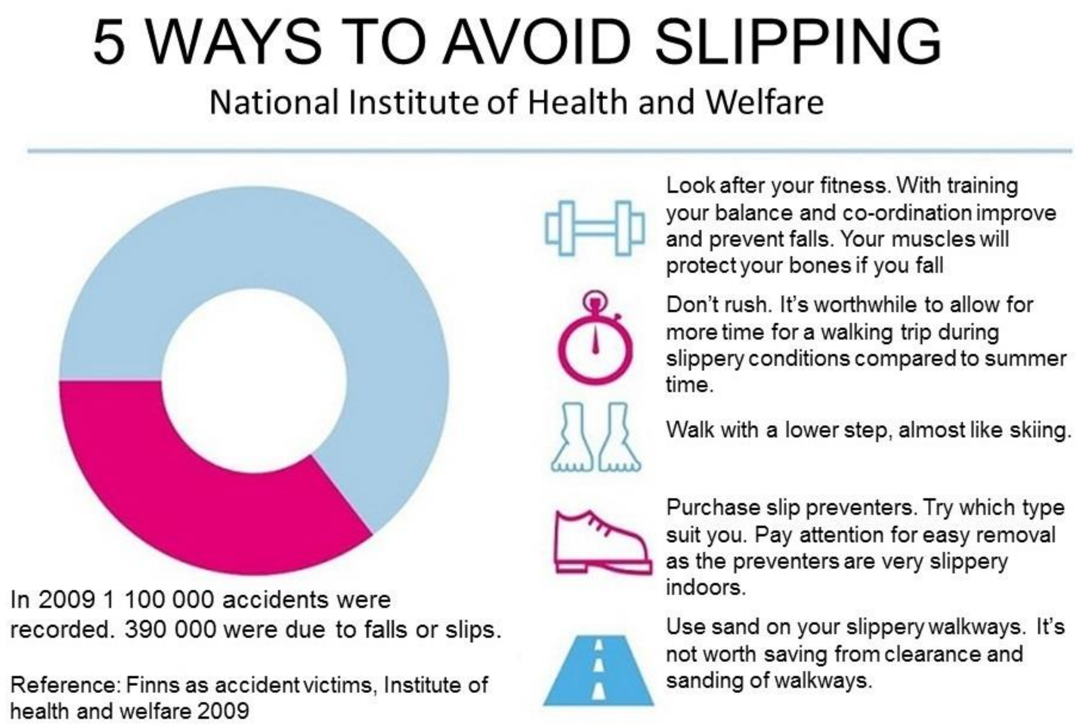


Figure 5.3 5 ways of avoiding slipping (translated by current author from original image (National institute of health and welfare, 2015)

The image above summarises the primary intrinsic and extrinsic causes of slipping and how to prevent them. As a guide to human factors considerations the primary recommendations concern strength and balance, walking pace, and style of walking. For the environmental influences, the frictional properties of footwear and surfaces are central concerns. Snow and/or ice covered surfaces can be treated by applying sand and slipping risk reduced by wearing a “slip preventer”, a device attached to the heel and sole of the shoe to increase friction. Similar advice could be provided to at-risk groups in all climates, especially older generations. Exercise as a tool in falls prevention has been well established and programs implemented but there may be a case for increased community awareness, as reflected in the Finnish example above. At-risk groups could be better informed about the best response to slippery surfaces, such as changing walking style and employing the “skiing type” gait with a low swing phase trajectory, described above.

The results of the present study demonstrate that slipping risk is highly individual-specific. While we can compare cohorts statistically, individual profiles, reflected in RCOF demands influence our probability of slipping. The results of this study suggest that most people are likely to have ground reaction force characteristics producing RCOF values that will meet the international standard of a minimum COF of 0.4 for all walking surfaces.

5.6 Limitations of the Current Research and Suggestions for Future Studies

This study considered a range of intrinsic factors influencing the individual's required coefficient of friction and their probability of slipping. Figure 5.4 summarises recommendations from the results.

When calculating RCOF, all ground reaction force components must be included. The present data verified previous findings showing significant differences between RCOF data sets depending on method of calculation. In characterising central tendency and dispersion in RCOF the mean may not capture important information but percentiles may also misrepresent the data due to outliers. When RCOF data are non-normal mathematical modelling is required to compute slipping probability. Probability analysis can then include graphical presentation, integration of the RCOF functions and analysis of slipping probabilities at selected RCOF. All analyses reflect within-group individuality and while some groups had less variability they all comprised individuals with atypical RCOF characteristics.

The aim of this study was to investigate RCOF properties of young and older people at two walking speeds to determine the probability of slipping based on long term data collection. Future work could, however, incorporate the considerations presented in the following sections.

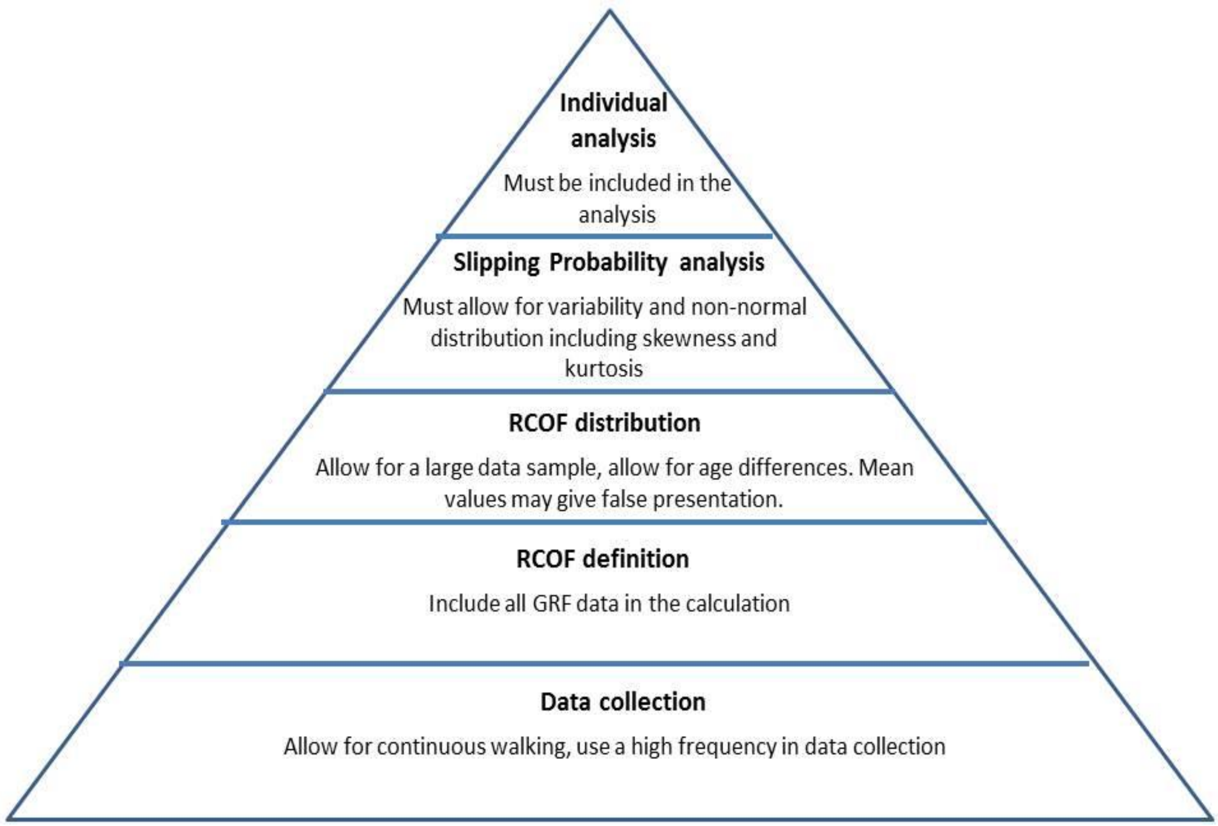


Figure 5.4 Summary of recommendations from the present study

5.6.1 Biomechanical Tests

Time-distance gait parameters such as step length, step width and step time have been linked to RCOF. Both walking speed and step length, for example, influence the three-dimensional GRF and thus RCOF. RCOF increases as step length increases (Burnfield and Powers, 2002; Cooper et al., 2008) and increments with walking speed (Lockhart et al., 2003; Redfern, Cham, Gielo-Perczak, Grönqvist, et al., 2001) also of note, however, is that increased waling speed is associated with greater step length (Powers et al., 2002). This study, however, focussed on ground reaction forces with long term data collection allowing for self–selected normal and fast walking speeds. In future work, it would be of interest to investigate further the gait biomechanics variables influencing required coefficient of friction.

Most authors have pooled right and left foot data but previous reports and the present study demonstrated RCOF differences between limbs. This study did not identify limb dominance that could explain the generally higher RCOF and increased slipping risk in the left limb. This identification would allow a test of the hypothesis that the dominant limb has a lower RCOF. In future studies it would be of interest to test the limb dominance hypothesis and one approach to this problem would be to employ a motor-driven treadmill with embedded force plates. This apparatus would allow extended trial analysis of RCOF with independent manipulations of walking speed, step frequency and step length. While treadmill testing has these advantages, it may be unfamiliar and destabilizing, particularly for older adults.

5.7 Summary

The required coefficient of friction (RCOF) has been used to investigate slipping propensity since the 1950s. As technology has advanced more detailed and accurate biomechanical analysis has followed but possibly the most important advance has been the mathematical models devised to estimate the probability of slipping. This study used a novel modelling approach to investigate slipping probability systematically for the first time.

While the traditional calculation of Required of Coefficient of Friction (RCOF) excluded the medio-lateral force (F_X), this project verified a significant difference between the two calculations in all populations and across walking speeds; confirming the Chang et al. (2011) conclusion that the F_X component has a significant effect on the computed RCOF. Furthermore, it is important to note the RCOF differences across age and gender groups. When calculating RCOF at normal and fast speed the increase in RCOF was higher in the older population groups. This reflects findings by previous authors concerning medio-lateral stability declines with age and the associated increase in medio-lateral stabilizing forces. Even though the older group in this study consisted of healthy older people with no history of falls, it would be of interest to explore the ground reaction force profile and RCOF range for adults with history of falls.

6 Conclusions

This study used a novel modelling approach to calculate and present the coefficient of friction and to compare slipping propensity between young and older females and males when walking at normal and self-selected walking speeds on a level surface.

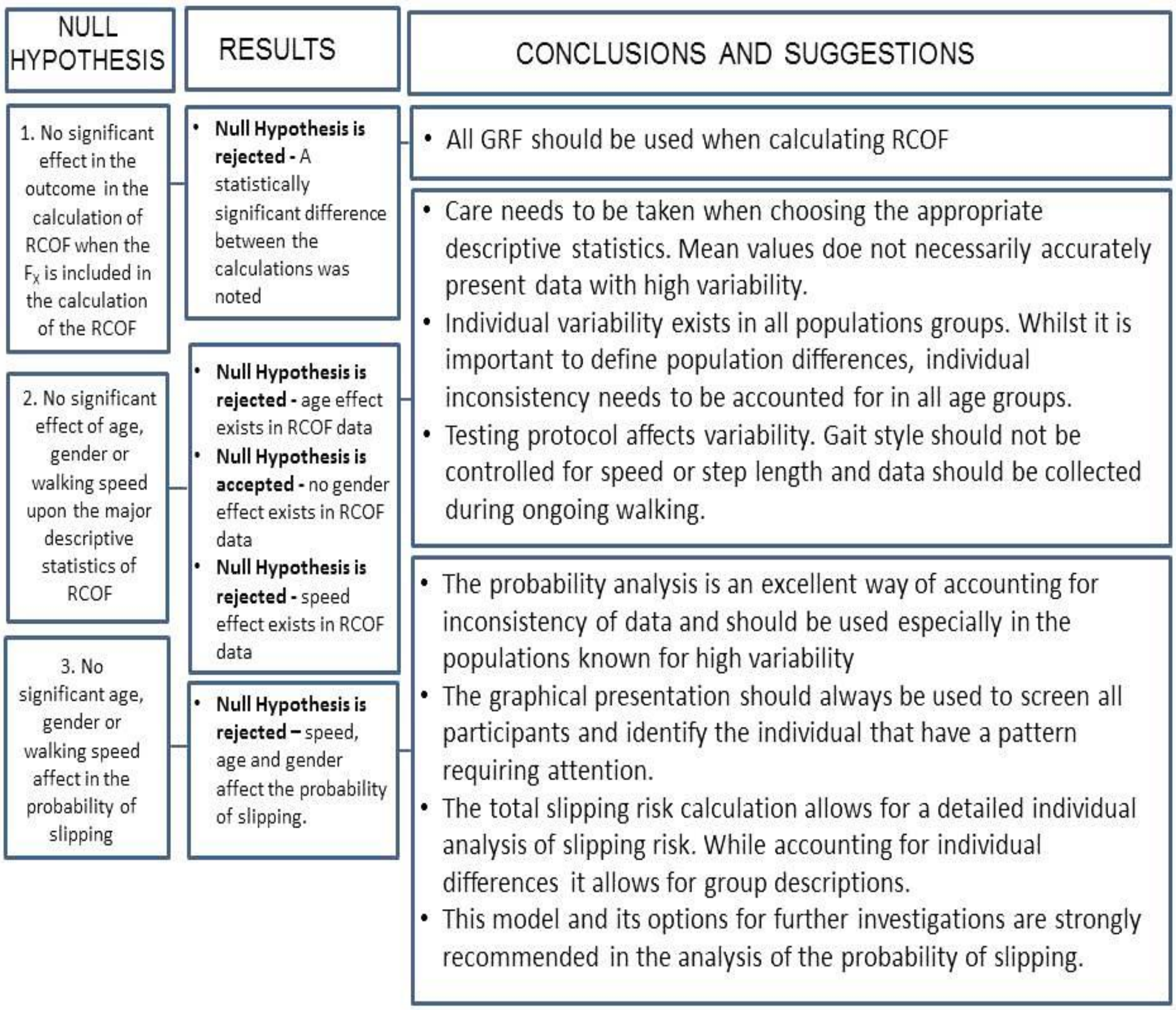


Figure 6.1 Conclusions and suggestions of this study

The results can be summarised as follows:

1) It is important to include the medio-lateral force (F_X) when calculating RCOF because RCOF was significantly greater in all groups with F_X included, setting a higher friction demand for the walking surface. It is also important that the increase in RCOF with F_X included was greater in older people.

2) Using the sample mean RCOF to describe a participant group or individual does not necessarily accurately represent the data. Some individuals and groups (in this study the group of young females) may be highly homogenous in their gait pattern and RCOF range and many individuals have high variability in their ground reaction forces. Comparisons between the descriptive values (mean, median, 95th, 97th and 99th percentile) indicated, in both female and male groups of older people, a difference between the mean and 95th percentile value exceeding 50%, with RCOF increasing as more data points were included.

3) Variability and individuality are key points to understanding intrinsic frictional properties during walking. Comparisons of group data to show overall effects of age, gender and walking speed may mask individual variability, a key finding of the study. Older people in general have higher variability in their RCOF range but an individual’s likelihood of slipping is dependent on their gait mechanics. The importance of individual variability in walking has been evident throughout the investigation and illustrated using case study analysis.

7 References

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Appendices

Appendix A – Participant Information Pack

ATTACHMENT B

Victoria University
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Australia

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301 Flinders Lane
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VICTORIA UNIVERSITY OF TECHNOLOGY

Victoria University

The Probability of Slipping During Level Walking

INFORMATION TO PARTICIPANTS:

Aims:
The aim of the research is to examine the differences between healthy young and healthy elderly female population groups on the frictional properties of the foot-ground interface during walking and further to analyse the probability of slipping probability under different conditions. By comparing the forces produced during walking (Required Coefficient of Friction, RCOF) to the frictional properties of different surfaces the safe limits for walking can be defined.
This study aims to quantify the factors leading to slipping, specifically

(i) To define the RCOF variability
(ii) To estimate the likelihood of RCOF values occurring
(iii) To develop a new mathematical model to analyse the probability of slipping
(iv) To study the effect of walking velocity on frictional properties

Methods:
This research will consist of fifty healthy young participants (age range 18 - 35 years) and fifty healthy elderly participants (age range 65 – 80 years). To be an eligible participant for the research you must be free from disease that might directly affect your walking (mobility and balance) including any neurological, musculoskeletal, cardiovascular, or respiratory disorders; rheumatoid arthritis; or diabetes. Also, there must be no history of any falls in the 24 months prior to participation in the study. A series of screening tests will be carried out: 1) a clearance and general health report from subjects' selected general practitioner (GP); 2) a timed 'up and go' test (time (s) to stand up from a chair, walk 3 meters, turn around, walk back to chair, and sit down; 3) vision acuity.

A general health survey will need to be completed prior to testing along with anthropometric measurements, such as: body height and mass; limb length; ankle, knee and hip range of motion. Following these preliminary tests you will be asked to walk at your self-selected walking velocity on an eight-shaped walkway for thirty minutes. After a few minutes rest, the testing will be repeated while walking at a fast but comfortable velocity for thirty minutes.

Risks and safeguards:
This testing is done while walking on an eight-shaped walkway. If you feel any discomfort during testing, please stop walking. Testing will be constantly supervised and if any discomfort is present the researcher will ask you to stop walking and then you are given the option to withdraw from the testing procedure.
Access to the lab is limited to persons other than the researcher and participants.
The researcher supervising the testing has a first aid certificate and in the unlikely event of an injury the researcher will administer basic first aid. Telephones are located within the facility if further medical attention is needed. Any participants suffering of psychological anxiety after the testing, will be forwarded to Dr. Mark Andersen at Victoria University, school of human movement, recreation and performance for a counselling session.

Any queries about your participation in this project may be directed to the researchers (Name: Mrs. Tuire Karaharju-Huisman, ph. 03-92481133; Dr Russell Best, ph. 03-92481118; Dr Rezaul Begg, ph 03-92481116) Victoria University, PO Box 14428 MC, Melbourne, 8001. If you have any queries or complaints about the way you have been treated, you may contact the Secretary, University Human Research Ethics Committee, Victoria University, PO Box 14428 MC, Melbourne, 8001 (ph. 03-9688 4710). If you require counselling or any other psychological support, you may contact Dr. Mark Andersen (ph. 03 - 9919 5413)

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Victoria University of Technology
The Probability of Slipping During Level Walking

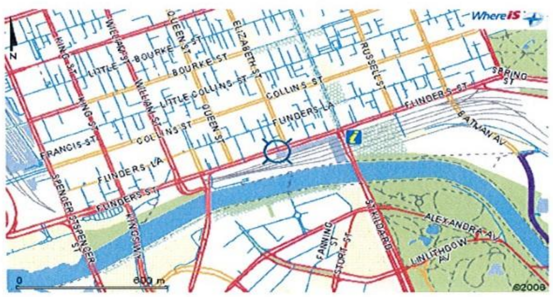
Dear ,

Thank you for your interest in my study and your willingness in participating.

This letter gives you general information on the testing. Please also find attached information on the study and also a health form to be filled by your local General Practitioner. If your GP does not have bulk billing facilities, please bring your receipt with you for reimbursement. Please notify me when you have visited you GP, and we will arrange a suitable testing time. Please have the form with you when coming to the testing.

Where is the testing done?

The testing is done at the Victoria University Biomechanics laboratory, 300 Flinders st. The place is situated opposite to Flinders st. station, next to the Parking Hall at the same address. Left of the "Victoria University" sign and glass doors is a smaller door, with the sign "Biomechanics laboratory" and an arrow pointing to the doorbell. I will meet you at the door!



How to get there?

As the laboratory is situated opposite to the Flinders st. station, all public transport arrives close by. If you prefer to drive in, please park in the parking house at 300 Flinders st and take a lift to the basement level. Your parking fees will be paid. If you prefer to take a taxi, this can be organised as well.

What to take along?

During the testing, you will be walking for 30 at normal velocity and 15 minutes at a faster velocity. Please wear comfortable clothing and your normal walking shoes.

I will be happy to give you more information and answer any possible questions,

Kind regards,

Tuire Karaharju-Huisman, PhD Student
Victoria University, School of Human Movement, Recreation and Performance
Tuire.Karaharju-Huisman@research.vu.edu.au
Tel. 9919 1128

Appendix B – Health check form to General Practitioner

Dear General Practitioner,

_______________________________________ has agreed to volunteer in our study investigating healthy elderly (aged 65 - 80) gait. The aim of the research is to examine the differences between healthy young and healthy elderly populations on the frictional properties of the foot-ground interface during walking and further to analyse the risk of slipping under different conditions. As a safety precaution, we request that participants obtain medical approval from their General Practitioner to ensure there are no underlying cardiorespiratory, or other medical conditions, which might present a health risk.

The study requires participants to walk continuously for a maximum of 30 minutes at a self-selected comfortable walking pace overground and a shorter time at a self selected fast walking velocity. The 30-minute walking task alone has been conducted previously at the University with all elderly participants managing well. All methods have been approved by the Victoria University Human Research Ethics Committee.

Mobility and vision tests will be conducted in the Biomechanics Laboratory at Victoria University. Prior to conducting these screening tests and collecting data, it is essential to ensure all participants are 'healthy' and have no medical conditions (e.g. cardiac condition) that might compromise health and safety during the study. We would appreciate it if you would examine ______________________________ and complete the attached sheet. There is space for you to add any comments if you wish. The patient will return this sheet to us when she/he comes in for testing. If you have any queries, please do not hesitate to contact us on 9919 1133 (Tuire Karaharju-Huisman, PhD candidate) or 9919 1116 (Dr. Rezaul Begg, Principal Supervisor).

Please provide ______________________________ with receipt for this visit, as the university will reimburse costs of this visit.

Thank you for your time.

Regards,

Appendix C – Consent Form

ATTACHMENT A

Victoria University of Technology

Consent Form for Participants Involved in Research

INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study into slipping propensity when walking. The aim of this project is to investigate the factors leading to slipping during walking. You are asked to participate in the testing procedures outlined below. The physical risks associated with the procedures are minimal as the testing is done during normal overground walking. The testing is done on an eight-shaped walkway leading to a potential that you may experience dizziness or fatigue. If this happens, we ask you to stop walking.
All data will be kept confidential and only the researchers named below will have access to the data files. Please be advised that although you are volunteering for this study, you are free to withdraw at anytime.

CERTIFICATION BY PARTICIPANT:

I, ____

of ____

certify that I am at least 18 years old* and that I am voluntarily giving my consent to participate in the experiment entitled: **The probability of slipping during level walking,** being conducted at Victoria University of Technology by: **Dr. Russell Best, Dr. Rezaul Begg and Ms. Tuire Karaharju-Huisman**
I certify that the objectives of the experiment, together with any risks to me associated with the procedures listed hereunder, have been fully explained to me by **Ms. Tuire Karaharju-Huisman.** I freely consent to participating in these procedures.

PROCEDURES:

- Complete the general health survey
- Measurement of body height, mass, leg length, joint range of motion at the hip, knee and ankle
- Performing an up and go test (beginning from a sitting position, standing, walking around a marker 3m away, returning to the chair and sitting)
- Vision acuity test
- Walking on an eight-shaped, 45 m long walkway in the laboratory, first for 5 minutes to familiarise to the situation, for 20 -30 minutes while walking in your normal speed and further for 20 -30 min while walking on a fast speed. A resting period will be allowed between the tests. In case of fatigue, the testing can be separated to two test times. Your walking is recorded by a video camera and the force data is collected by two force plates.

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this experiment at any time and that this withdrawal will not jeopardise me in any way.
I have been informed that the information I provide will be kept confidential.

Signed: .... }

Witness other than the experimenter: } **Date: ....**

....}

Any queries about your participation in this project may be directed to the researcher (Name: Mrs. Tuire Karaharju-Huisman, ph. 040 7524598 or 0392481128). If you have any queries or complaints about the way you have been treated, you may contact the Secretary, University Human Research Ethics Committee, Victoria University of Technology, PO Box 14428 MC, Melbourne, 8001 (telephone no: 03-9688 4710).

Appendix D – Modified Falls Efficiency

Modified Falls Efficacy Scale

Thank you for filling out this questionnaire.

Please fill out as much as you can. When you are finished, please leave it with the investigator.

STATEMENT OF CONFIDENTIALITY

All information that would permit identification of investigators or their participants will be regarded as strictly confidential, will be used only for the purpose of operating and evaluation the study, and will not be disclosed or released for any other purposes without prior consent, except as required by law.

	Not Confident At All (0)	Fairly Confident (5)	Completely Confident (10)
1. Get dressed and undressed			
2. Prepare a simple meal			
3. Take a bath or shower			
4. Get in/out of bed			
5. Answer the door or telephone			
6. Walk around the inside of your house			
7. Reach into cabinets and closet			
8. Light housekeeping			
9. Simple shopping			
10. Using public transport			
11. Crossing Roads			
12. Light gardening or hanging out the washing			
13. Using front or rear steps at home			

Appendix E - Modified mini-mental state examination

Modified Mental Test

Item	Score	Correct
1. Age	1point	
2. Time (to nearest hour)	1point	
3. Address for recall at end of test- this should be repeated by the patient to ensure it has been heard correctly: 42 West Street	1point if fully correct	
4. Year	1point	
5. Name of University	1point	
6. Recognition of two persons (researchers)	1point if fully correct	
7. Date of Birth	1point	
8. Year of first or second world war	1point if fully correct	
8. Name of Prime Minister	1point	
10. Count backwards 20-1	1point if fully correct	
MAXIMUM	10 points	

Appendix F - Subject Details

Subject Details

Name: ____________________________ Birth Date: ________ Age: ______

Test Date: ________________ Height: _______cm Weight: _______kg

<u>Timed Up and Go</u> 1._______s 2._______s 3._______s 4._______s 5.________s

Average: __________s

Vision Test (R/L): _______/_______

Leg Length Measurement	**Right**	**Left**
Trochanter – Lateral femoral epicondyle		
Fibular head – lateral malleoli		
Lateral malleoli – Floor		
Total Leg Legth (cm)		

Slipping History

Have you ever slipped during the past 24 months? Yes No

How many slip-related falls have you had? ____________slip-related falls

How many times did you recover from slips during the past twelve months?____times
How did you recover from those slips?

____

____

____

Medication History

Are there any medical condition or medications that may be affecting your walking / balance

____

____

____

Have you had any orthopaedic / neurological /cardiovascular/ respiratory problems in the past? Yes No
If yes, when did this happen? Have you fully recovered?

____

____

____

____

Appendix G - Matlab code for data file analysis

The code for the analysis of the data files for all people was written to make use of the vector maths provided by MatLab

```
% Program prepared by Tuire Karaharju-Huisman for PhD work in % probability of slipping while walking over a defined surface
% File uses defined trigger points to start the analysis of the files
% Clear to remove any old data values and start from a clean slate clear;
% Define all of the major input parameters for the program to run correctly
% Define the path name to the data files and the group files
path_folder_name = 'E:\Tuire\PHD\Matlab Results\Data\Analyse Data\a_Old Male';
path_name_group = 'E:\Tuire\PHD\Matlab Results\Data\Analyse Data\a_Old Male\a_Normal_Files\extra_percentile\';
% Define constants used in calculations during the execution of analysis
newtons_convert = 0.45359237*9.81;
 % convert to kg from pounds and then convert to newtons
milli_sec = 1/4000*1000;
% record freq 4000 Hz * 1000 to get miliseconds
fp1_trigger_force = 10;  % force plate 1 trigger force in Newtons
fp2_trigger_force = 10;   % force plate 2 trigger force in Newtons
data_end_fp1 = 720;   % from the trigger point fp1 how many data points to analyse to get to 200ms after heal strike
data_end_fp2 = 720; % from the trigger point fp2 how many data points to analyse to get to 200ms after heal strike
ms_after_heal_strike = 80;  % 20ms when recording at 4000 Hz or 0.25ms per recording
which_leg = 200;
% Define the constants for the butter worth filter calculations
cut_off_freq = 36;    % cut off freq for butterworth filter to reduce signal noise
butterworth_order = 4; % order of accuracy of the butterworth filter
sample_frequency = 4000;  % Sample frequency in cycles per second
nyquist_frequency = 2000;   % Nyquist frequency defined as half of the sampling grequency
% define the file path names for readingin the data file and wrigint the results files addpath(path_folder_name);
% Set up the folder path for the first loop
folder_mask = [path_folder_name '\d_*'];
folders_list = dir(folder_mask); % build the list of files *.txt from the path_name directory
num_folders = length(folders_list); % calculate the number of files in the list
```

```
% Collect statistics for all files in a group
   RCOF1_Horiz_all = [];
   RCOF1_Vert_all = [];
   RCOF2_Horiz_all = [];
   RCOF2_Vert_all = [];
% For loop to cycle through folders
for folder_loop = 1:num_folders
% Set up the path for the second loop
   path_name = [path_folder_name '\' folders_list(folder_loop).name '\Normal'];
   addpath(path_name);
   path_and_file = [path_name '\*.txt'];  % build the path string and file extension to read all files
   dir_results = mkdir(path_name, 'extra_percentile'); % create the directory for the results files as path_name\results
   save_path = [path_name, '\extra_percentile\']; % build the path string and file extension to save all files
   save_name_initial = [save_path, folders_list(folder_loop).name, '_RCOF_4000Hz.csv']; % name of the results file for
fp1_trigger_force resutls
   save_name_stats = [save_path, folders_list(folder_loop).name, '_RCOF_4000Hz_stats.csv'];
   save_name_slip = [save_path, folders_list(folder_loop).name, '_RCOF_4000Hz_slip.csv'];
   save_name_initial_RL = [save_path, folders_list(folder_loop).name, '_RCOF_4000Hz_right_left.csv'];
   save_name_stats_RL = [save_path, folders_list(folder_loop).name, '_RCOF_4000Hz_stats_right_left.csv'];
   save_name_slip_RL = [save_path, folders_list(folder_loop).name, '_RCOF_4000Hz_slip_right_left.csv'];
   save_name_group = [path_name_group, folders_list(folder_loop).name, '_RCOF_4000Hz.csv'];   % group location
   save_name_stats_all = [path_name_group, 'RCOF_OMN_all_stats_4000Hz_right_left.csv'];
% define the number of points for the heal strike data analysis
heal_strike_data = 1500; % the number of points required in the analysis for predicting
% the force index of the heal strike
% define the plotting constants
   t = 0:7999;  % default time constant (may not be used) ####
   n = 8096; % number of samples (may notbe used) ####
   % Initialise all vectors that are used during the calculations
   % Initialisations creates an empty vector that we can then use
     % SAve the Loop Number
  Loop_Save = [];
   % Vectors for analysis of the RCOF Force plate 1
   Max_RCof1_Horiz = [];% Stores the maximum Horizontal RCOF values for each file alalysed
   Max_RCof1_Horiz_Index = [];% Stores the indes of the maximum RCOF value
```

```
RCof1_Horiz_Fz_N = [];   % Stores the Fz force at the point of the maximum RCOF

RCof1_Horiz_Fz_msec = [];% Stores the time from heal strike from the maximum RCOF

RCOF1_Horiz_Fx = [];% Value of Fx at the clcluation point

RCOF1_Horiz_foot = [];% Record which foot was on the force plate

Max_RCof1_Vert = [];  % Stores the maximum Vertical RCOF values for each file alalysed

Max_RCof1_Vert_Index = [];  % Stores the indes of the maximum RCOF value

RCof1_Vert_Fz_N = [];% Stores the Fz force at the point of the maximum RCOF

RCof1_Vert_Fz_msec = [];  % Stores the time from heal strike from the maximum RCOF

RCOF1_Vert_Fx = [];% Value of Fx at the clcluation point

RCOF1_Vert_foot = [];  % Record which foot was on the force plate


% Vectors for analysis of the RCOF Force plate 2

Max_RCof2_Horiz = [];% Stores the maximum Horizontal RCOF values for each file alalysed

Max_RCof2_Horiz_Index = [];% Stores the indes of the maximum RCOF value

RCof2_Horiz_Fz_N = [];  % Stores the Fz force at the point of the maximum RCOF

RCof2_Horiz_Fz_msec = [];  % Stores the time from heal strike from the maximum RCOF

RCOF2_Horiz_Fx = [];  % Value of Fx at the clcluation point

RCOF2_Horiz_foot = [];% Record which foot was on the force plate

Max_RCof2_Vert = [];  % Stores the maximum Vertical RCOF values for each file alalysed

Max_RCof2_Vert_Index = [];% Stores the indes of the maximum RCOF value

RCof2_Vert_Fz_N = [];    % Stores the Fz force at the point of the maximum RCOF

RCof2_Vert_Fz_msec = [];  % Stores the time from heal strike from the maximum RCOF

RCOF2_Vert_Fx = [];  % Value of Fx at the clcluation point

RCOF2_Vert_foot = [];  % Record which foot was on the force plate


% Capture all of the statistics for each file and the for all files

% For force place 1 RCOF calculation 1

mean_RCOF1_Horiz = [];

STD_RCOF1_Horiz = [];

median_RCOF1_Horiz = [];

iqr_RCOF1_Horiz = [];

min_RCOF1_Horiz = [];

max_RCOF1_Horiz = [];

skew_RCOF1_Horiz = [];

precentile_RCOF1_Horiz = [];
```

```
precentile97_RCOF1_Horiz = [];

precentile99_RCOF1_Horiz = [];

kurtosis_RCOF1_Horiz = [];


% For force plate 1 RCOF calculation 2

mean_RCOF1_Vert = [];

STD_RCOF1_Vert = [];

median_RCOF1_Vert = [];

iqr_RCOF1_Vert = [];

min_RCOF1_Vert = [];

max_RCOF1_Vert = [];

skew_RCOF1_Vert = [];

precentile_RCOF1_Vert = [];

precentile97_RCOF1_Vert = [];

precentile99_RCOF1_Vert = [];

kurtosis_RCOF1_Vert = [];


% For force place 2 RCOF calculation 1

mean_RCOF2_Horiz = [];

STD_RCOF2_Horiz = [];

median_RCOF2_Horiz = [];

iqr_RCOF2_Horiz = [];

min_RCOF2_Horiz = [];

max_RCOF2_Horiz = [];

skew_RCOF2_Horiz = [];

precentile_RCOF2_Horiz = [];

precentile97_RCOF2_Horiz = [];

precentile99_RCOF2_Horiz = [];

kurtosis_RCOF2_Horiz = [];


% For force plate 2 RCOF calculation 2

mean_RCOF2_Vert = [];

STD_RCOF2_Vert = [];

median_RCOF2_Vert = [];

iqr_RCOF2_Vert = [];
```

```
min_RCOF2_Vert = [];

max_RCOF2_Vert = [];

skew_RCOF2_Vert = [];

precentile_RCOF2_Vert = [];

precentile97_RCOF2_Vert = [];

precentile99_RCOF2_Vert = [];

kurtosis_RCOF2_Vert = [];


% Capture all of the statistics for each file and the for all files for

% when you take into account Right and Left foot hitting the force

% plate


% Vectors for analysis of the RCOF Right/Left Foot


Max_RCof1_Horiz_Value_RL = [];          % Stores the maximum Horizontal RCOF values for each file alalysed

Max_RCof1_Horiz_Index_RL = [];          % Stores the indes of the maximum RCOF value

RCof1_Horiz_Fz_N_RL = [];               % Stores the Fz force at the point of the maximum RCOF

RCof1_Horiz_Fz_msec_RL = [];            % Stores the time from heal strike from the maximum RCOF

RCOF1_Horiz_Fx_RL = [];                 % Value of Fx at the clcluation point

RCOF1_Horiz_foot_RL = [];               % Record which foot was on the force plate

Max_RCof1_Vert_Value_RL = [];           % Stores the maximum Vertical RCOF values for each file alalysed

Max_RCof1_Vert_Index_RL = [];           % Stores the indes of the maximum RCOF value

RCof1_Vert_Fz_N_RL = [];                % Stores the Fz force at the point of the maximum RCOF

RCof1_Vert_Fz_msec_RL = [];             % Stores the time from heal strike from the maximum RCOF

RCOF1_Vert_Fx_RL = [];                  % Value of Fx at the clcluation point

RCOF1_Vert_foot_RL = [];                % Record which foot was on the force plate


% Vectors for analysis of the RCOF Right/Left Foot


Max_RCof2_Horiz_Value_RL = [];          % Stores the maximum Horizontal RCOF values for each file alalysed

Max_RCof2_Horiz_Index_RL = [];          % Stores the indes of the maximum RCOF value

RCof2_Horiz_Fz_N_RL = [];               % Stores the Fz force at the point of the maximum RCOF

RCof2_Horiz_Fz_msec_RL = [];            % Stores the time from heal strike from the maximum RCOF

RCOF2_Horiz_Fx_RL = [];                 % Value of Fx at the clcluation point

RCOF2_Horiz_foot_RL = [];               % Record which foot was on the force plate
```

```
Max_RCof2_Vert_Value_RL = [];                    % Stores the maximum Vertical RCOF values for each file alalysed
Max_RCof2_Vert_Index_RL = [];                    % Stores the indes of the maximum RCOF value
RCof2_Vert_Fz_N_RL = [];                         % Stores the Fz force at the point of the maximum RCOF
RCof2_Vert_Fz_msec_RL = [];                      % Stores the time from heal strike from the maximum RCOF
RCOF2_Vert_Fx_RL = [];                           % Value of Fx at the clcluation point
RCOF2_Vert_foot_RL = [];                         % Record which foot was on the force plate


% For force place 1 RCOF calculation 1
mean_RCOF1_Horiz_RL = [];
STD_RCOF1_Horiz_RL = [];
median_RCOF1_Horiz_RL = [];
iqr_RCOF1_Horiz_RL = [];
min_RCOF1_Horiz_RL = [];
max_RCOF1_Horiz_RL = [];
skew_RCOF1_Horiz_RL = [];
precentile_RCOF1_Horiz_RL = [];
precentile97_RCOF1_Horiz_RL = [];
precentile99_RCOF1_Horiz_RL = [];
kurtosis_RCOF1_Horiz_RL = [];

% For force plate 1 RCOF calculation 2
mean_RCOF1_Vert_RL = [];
STD_RCOF1_Vert_RL = [];
median_RCOF1_Vert_RL = [];
iqr_RCOF1_Vert_RL = [];
min_RCOF1_Vert_RL = [];
max_RCOF1_Vert_RL = [];
skew_RCOF1_Vert_RL = [];
precentile_RCOF1_Vert_RL = [];
precentile97_RCOF1_Vert_RL = [];
precentile99_RCOF1_Vert_RL = [];
kurtosis_RCOF1_Vert_RL = [];

% For force place 2 RCOF calculation 1
```

```
mean_RCOF2_Horiz_RL = [];

STD_RCOF2_Horiz_RL = [];

median_RCOF2_Horiz_RL = [];

iqr_RCOF2_Horiz_RL = [];

min_RCOF2_Horiz_RL = [];

max_RCOF2_Horiz_RL = [];

skew_RCOF2_Horiz_RL = [];

precentile_RCOF2_Horiz_RL = [];

precentile97_RCOF2_Horiz_RL = [];

precentile99_RCOF2_Horiz_RL = [];

kurtosis_RCOF2_Horiz_RL = [];


% For force plate 2 RCOF calculation 2

mean_RCOF2_Vert_RL = [];

STD_RCOF2_Vert_RL = [];

median_RCOF2_Vert_RL = [];

iqr_RCOF2_Vert_RL = [];

min_RCOF2_Vert_RL = [];

max_RCOF2_Vert_RL = [];

skew_RCOF2_Vert_RL = [];

precentile_RCOF2_Vert_RL = [];

precentile97_RCOF2_Vert_RL = [];

precentile99_RCOF2_Vert_RL = [];

kurtosis_RCOF2_Vert_RL = [];


% Build a list of all of the files in the path_and_file and calculate length of that list


dir_list = dir(path_and_file);                % build the list of files *.txt from the path_name directory

num_files = length(dir_list);                 % calculate the number of files in the list


% For each file in the directory read in all of the requried data

% This is columns 1, 2, 3, 7, 8, 9 of each data file

% Store all data in their own vector so that is can be used for alanysis

% to provide the RCOF and associated values for each file
```

```
for loop = 1:num_files                  % For each file in the directory perform the taks that are
                                        % within the loop

  read_matrix = csvread(dir_list(loop).name);   % Read in the complete contents of each column and store them
                                        % the matrix read_matrix
  col_1_raw = read_matrix(:,1);         % Force Plate 1 read data from column 1
  col_2_raw = read_matrix(:,2);         % Force Plate 1 read data from column 2
  col_3_raw = read_matrix(:,3);         % Force Plate 1 read data from column 3
  col_7_raw = read_matrix(:,7);         % Force Plate 1 read data from column 7
  col_8_raw = read_matrix(:,8);         % Force Plate 1 read data from column 8
  col_9_raw = read_matrix(:,9);         % Force Plate 1 read data from column 9

  % Convert the contents of each vector so that it is in Newtons

  col_1 = col_1_raw * newtons_convert;      % Convert column 1 data so that it is in Newtons
  col_2 = col_2_raw * newtons_convert;      % Convert column 2 data so that it is in Newtons
  col_3 = col_3_raw * newtons_convert;      % Convert column 3 data so that it is in Newtons
  col_7 = col_7_raw * newtons_convert;      % Convert column 7 data so that it is in Newtons
  col_8 = col_8_raw * newtons_convert;      % Convert column 8 data so that it is in Newtons
  col_9 = col_9_raw * newtons_convert;      % Convert column 9 data so that it is in Newtons

  % Apply a 4th order butterworth filter to the data
  % Co-efficient for cut off frequency stored in variable Cut_off_freq
  % Normalised to the Nyquist Frequenct
  % Nyquist Frequency is half the smapling rate, 4000Hz / 2 = 2000 Hz

  Wn = cut_off_freq/nyquist_frequency;

  % Calculate the filtering co-efficients

  [b, a] = butter(butterworth_order, Wn);

  % Apply the filter to smooth the data

  but_filter_col_1 = filter(b, a, col_1);     % Apply filter to column 1 data
```

```
but_filter_col_2 = filter(b, a, col_2);        % Apply filter to column 2 data
but_filter_col_3 = filter(b, a, col_3);        % Apply filter to column 3 data
but_filter_col_7 = filter(b, a, col_7);        % Apply filter to column 7 data
but_filter_col_8 = filter(b, a, col_8);        % Apply filter to column 8 data
but_filter_col_9 = filter(b, a, col_9);        % Apply filter to column 9 data

% Calclate the average and standerd deviation of the data to provide an estimate of the
% heal strike which is defined as the average + the standard deviation of the data
% this is done using the Fz data from the first 1500 data points

% Find the point in the graph where the Fz data starts to increase > that the fp1_trigger_force
% When 3 consecutive points are greater than each other then the start index can be said to be found

start_index_1 = 1;
while start_index_1 <= 7998
   if but_filter_col_3(start_index_1) > fp1_trigger_force
      if but_filter_col_3(start_index_1) <=  but_filter_col_3(start_index_1 + 1)
         if but_filter_col_3(start_index_1 + 1) <=  but_filter_col_3(start_index_1 + 2)
            break;
         end;
      end;
   end;
   start_index_1 = start_index_1 + 1;
end;

% Increase the starting point by 50 ms or 200 samples recording at 4000
% Hz or cycles per second

start_index_1_calc = start_index_1 + ms_after_heal_strike;

% Knowing the starting points isolate the number of points specified in data_end_fp1

% column 1 data point selection

filter_col_1 = but_filter_col_1(start_index_1_calc:start_index_1_calc + data_end_fp1);
```

```
% column 2 data point selection

filter_col_2 = but_filter_col_2(start_index_1_calc:start_index_1_calc + data_end_fp1);

% column 3 data point selection

filter_col_3 = but_filter_col_3(start_index_1_calc:start_index_1_calc + data_end_fp1);

% Now do the same for the second force plate fp 2

% Find the point in the graph where the Fz data starts to increase > that the fp1_trigger_force
% When 3 consecutive points are greater than each other then the start index can be said to be found

start_index_2 = 1;
while start_index_2 <= 7998
   if but_filter_col_9(start_index_2) > fp2_trigger_force
      if but_filter_col_9(start_index_2) <=  but_filter_col_9(start_index_2 + 1)
         if but_filter_col_9(start_index_2 + 1) <=  but_filter_col_9(start_index_2 + 2)
            break;
         end;
      end;
   end;
   start_index_2 = start_index_2 + 1;
end;

% Increase the starting point by 50 ms or 200 samples recording at 4000
% Hz or cycles per second

start_index_2_calc = start_index_2 + ms_after_heal_strike;


% Knowing the starting points isolate the number of points specified in data_end_fp2

% column 7 data point selection
```

```
filter_col_7 = but_filter_col_7(start_index_2_calc:start_index_2_calc + data_end_fp2);

% column 8 data point selection

filter_col_8 = but_filter_col_8(start_index_2_calc:start_index_2_calc + data_end_fp2);

% column 9 data point selection

filter_col_9 = but_filter_col_9(start_index_2_calc:start_index_2_calc + data_end_fp2);

% Calculate the RCOF values using the appropriate multiplier for
% vector mltiplicatoin

RCof1_Horiz = abs(filter_col_2./filter_col_3);
RCof1_Vert = abs((sqrt(filter_col_1.^2 + filter_col_2.^2)./filter_col_3));

RCof2_Horiz = abs(filter_col_8./filter_col_9);
RCof2_Vert = abs((sqrt(filter_col_7.^2 + filter_col_8.^2)./filter_col_9));

% Wrap up the maximum values ready to be exported to a csv file
% Storing in the vector the Maximum RCOF, the index position, the Fz at that point and the number of
% milli seconds at that point from the time of heel strike

% Values for FP1 Horizontal

[RCOF1_Horiz_Value, RCOF1_H_Index] = max(RCof1_Horiz);
[RCOF1_Vert_Value, RCOF1_V_Index] = max(RCof1_Vert);
[RCOF2_Horiz_Value, RCOF2_H_Index] = max(RCof2_Horiz);
[RCOF2_Vert_Value, RCOF2_V_Index] = max(RCof2_Vert);

if (((RCOF1_H_Index + ms_after_heal_strike) > 80) andand ((RCOF1_H_Index + ms_after_heal_strike) < 320)) andand (((RCOF1_V_Index + ms_after_heal_strike) > 80) andand ((RCOF1_V_Index + ms_after_heal_strike) < 320)) andand (((RCOF2_H_Index + ms_after_heal_strike) > 80) andand ((RCOF2_H_Index + ms_after_heal_strike) < 320)) andand (((RCOF2_V_Index + ms_after_heal_strike) > 80) andand ((RCOF2_V_Index + ms_after_heal_strike) <320))
```

```
% Save the aray of loop counters
Loop_Save = [Loop_Save, loop];

% Values for FP1 Horizontal

Max_RCof1_Horiz = [Max_RCof1_Horiz , RCOF1_Horiz_Value];
Max_RCof1_Horiz_Index = [Max_RCof1_Horiz_Index, RCOF1_H_Index + ms_after_heal_strike];
RCof1_Horiz_Fz_N = [RCof1_Horiz_Fz_N, filter_col_3(RCOF1_H_Index)];
RCof1_Horiz_Fz_msec = [RCof1_Horiz_Fz_msec , (RCOF1_H_Index + ms_after_heal_strike)*milli_sec];
RCOF1_Horiz_Fx = [RCOF1_Horiz_Fx, filter_col_1(RCOF1_H_Index)];
if filter_col_1(which_leg) < 0
   RCOF1_Horiz_foot = [RCOF1_Horiz_foot, 0];          % 0 if it is the right foot
else
   RCOF1_Horiz_foot = [RCOF1_Horiz_foot, 1];          % 1 if it is the left foot
end;

% Values for FP1 Vertical

Max_RCof1_Vert = [Max_RCof1_Vert , RCOF1_Vert_Value];
Max_RCof1_Vert_Index = [Max_RCof1_Vert_Index, RCOF1_V_Index + ms_after_heal_strike];
RCof1_Vert_Fz_N = [RCof1_Vert_Fz_N, filter_col_3(RCOF1_V_Index)];
RCof1_Vert_Fz_msec = [RCof1_Vert_Fz_msec , (RCOF1_V_Index + ms_after_heal_strike)*milli_sec];
RCOF1_Vert_Fx = [RCOF1_Vert_Fx, filter_col_1(RCOF1_V_Index)];
if filter_col_1(which_leg) < 0
   RCOF1_Vert_foot = [RCOF1_Vert_foot, 0];          % 0 if it is the right foot
else
   RCOF1_Vert_foot = [RCOF1_Vert_foot, 1];          % 1 if it is the left foot
end;

% Values for FP2 Horizontal

Max_RCof2_Horiz = [Max_RCof2_Horiz , RCOF2_Horiz_Value];
Max_RCof2_Horiz_Index = [Max_RCof2_Horiz_Index, RCOF2_H_Index + ms_after_heal_strike];
RCof2_Horiz_Fz_N = [RCof2_Horiz_Fz_N, filter_col_9(RCOF2_H_Index)];
```

```
    RCof2_Horiz_Fz_msec = [RCof2_Horiz_Fz_msec , (RCOF2_H_Index + ms_after_heal_strike)*milli_sec];
    RCOF2_Horiz_Fx = [RCOF2_Horiz_Fx, filter_col_7(RCOF2_H_Index)];
    if filter_col_7(which_leg) < 0
      RCOF2_Horiz_foot = [RCOF2_Horiz_foot, 0];         % 0 if it is the right foot
    else
      RCOF2_Horiz_foot = [RCOF2_Horiz_foot, 1];         % 1 if it is the left foot
    end;

    % Values for FP2 Vertical

    Max_RCof2_Vert = [Max_RCof2_Vert , RCOF2_Vert_Value];
    Max_RCof2_Vert_Index = [Max_RCof2_Vert_Index, RCOF2_V_Index + ms_after_heal_strike];
    RCof2_Vert_Fz_N = [RCof2_Vert_Fz_N, filter_col_9(RCOF2_V_Index)];
    RCof2_Vert_Fz_msec = [RCof2_Vert_Fz_msec , (RCOF2_V_Index + ms_after_heal_strike)*milli_sec];
    RCOF2_Vert_Fx = [RCOF2_Vert_Fx, filter_col_7(RCOF2_V_Index)];
    if filter_col_7(which_leg) < 0
      RCOF2_Vert_foot = [RCOF2_Vert_foot, 0];          % 0 if it is the right foot
    else
      RCOF2_Vert_foot = [RCOF2_Vert_foot, 1];          % 1 if it is the left foot
    end;

  end;

  % This is the end of the analysis of 1 file loop back and complete all files in the directory

end;

  %Now to build up the matrix to take into account Left and right
  %foot depending on which foot lands on the force plate first

  % Find out the length of the data file
  RCOF1_Horiz_Foot_length = length(RCOF1_Horiz_foot);
  RCOF1_Vert_Foot_length = length(RCOF1_Vert_foot);
  RCOF2_Horiz_Foot_length = length(RCOF2_Horiz_foot);
  RCOF2_Vert_Foot_length = length(RCOF2_Vert_foot);
```

```
for rl_loop = 1:RCOF1_Horiz_Foot_length
  if RCOF1_Horiz_foot(rl_loop) == 0
    % Values for FP2 Horizontal
    Max_RCof1_Horiz_Value_RL = [Max_RCof1_Horiz_Value_RL , Max_RCof1_Horiz(rl_loop)];
    Max_RCof1_Horiz_Index_RL = [Max_RCof1_Horiz_Index_RL, Max_RCof1_Horiz_Index(rl_loop)];
    RCof1_Horiz_Fz_N_RL = [RCof1_Horiz_Fz_N_RL, RCof1_Horiz_Fz_N(rl_loop)];
    RCof1_Horiz_Fz_msec_RL = [RCof1_Horiz_Fz_msec_RL , RCof1_Horiz_Fz_msec(rl_loop)];
    RCOF1_Horiz_Fx_RL = [RCOF1_Horiz_Fx_RL, RCOF1_Horiz_Fx(rl_loop)];
    RCOF1_Horiz_foot_RL = [RCOF1_Horiz_foot_RL, RCOF1_Horiz_foot(rl_loop)];

    % Values for FP1 Vertical

    Max_RCof1_Vert_Value_RL = [Max_RCof1_Vert_Value_RL , Max_RCof1_Vert(rl_loop)];
    Max_RCof1_Vert_Index_RL = [Max_RCof1_Vert_Index_RL, Max_RCof1_Vert_Index(rl_loop)];
    RCof1_Vert_Fz_N_RL = [RCof1_Vert_Fz_N_RL, RCof1_Vert_Fz_N(rl_loop)];
    RCof1_Vert_Fz_msec_RL = [RCof1_Vert_Fz_msec_RL , RCof1_Vert_Fz_msec(rl_loop)];
    RCOF1_Vert_Fx_RL = [RCOF1_Vert_Fx_RL, RCOF1_Vert_Fx(rl_loop)];
    RCOF1_Vert_foot_RL = [RCOF1_Vert_foot_RL, RCOF1_Vert_foot(rl_loop)];

    % Values for FP2 Horizontal

    Max_RCof2_Horiz_Value_RL = [Max_RCof2_Horiz_Value_RL , Max_RCof2_Horiz(rl_loop)];
    Max_RCof2_Horiz_Index_RL = [Max_RCof2_Horiz_Index_RL, Max_RCof2_Horiz_Index(rl_loop)];
    RCof2_Horiz_Fz_N_RL = [RCof2_Horiz_Fz_N_RL, RCof2_Horiz_Fz_N(rl_loop)];
    RCof2_Horiz_Fz_msec_RL = [RCof2_Horiz_Fz_msec_RL , RCof2_Horiz_Fz_msec(rl_loop)];
    RCOF2_Horiz_Fx_RL = [RCOF2_Horiz_Fx_RL, RCOF2_Horiz_Fx(rl_loop)];
    RCOF2_Horiz_foot_RL = [RCOF2_Horiz_foot_RL, RCOF2_Horiz_foot(rl_loop)];

    % Values for FP2 Vertical

    Max_RCof2_Vert_Value_RL = [Max_RCof2_Vert_Value_RL , Max_RCof2_Vert(rl_loop)];
    Max_RCof2_Vert_Index_RL = [Max_RCof2_Vert_Index_RL, Max_RCof2_Vert_Index(rl_loop)];
    RCof2_Vert_Fz_N_RL = [RCof2_Vert_Fz_N_RL, RCof2_Vert_Fz_N(rl_loop)];
    RCof2_Vert_Fz_msec_RL = [RCof2_Vert_Fz_msec_RL , RCof2_Vert_Fz_msec(rl_loop)];
```

```
    RCOF2_Vert_Fx_RL = [RCOF2_Vert_Fx_RL, RCOF2_Vert_Fx(rl_loop)];
    RCOF2_Vert_foot_RL = [RCOF2_Vert_foot_RL, RCOF2_Vert_foot(rl_loop)];

elseif RCOF1_Horiz_foot(rl_loop) == 1
    % Values for FP2 Horizontal
    Max_RCof1_Horiz_Value_RL = [Max_RCof1_Horiz_Value_RL , Max_RCof2_Horiz(rl_loop)];
    Max_RCof1_Horiz_Index_RL = [Max_RCof1_Horiz_Index_RL, Max_RCof2_Horiz_Index(rl_loop)];
    RCof1_Horiz_Fz_N_RL = [RCof1_Horiz_Fz_N_RL, RCof2_Horiz_Fz_N(rl_loop)];
    RCof1_Horiz_Fz_msec_RL = [RCof1_Horiz_Fz_msec_RL , RCof2_Horiz_Fz_msec(rl_loop)];
    RCOF1_Horiz_Fx_RL = [RCOF1_Horiz_Fx_RL, RCOF2_Horiz_Fx(rl_loop)];
    RCOF1_Horiz_foot_RL = [RCOF1_Horiz_foot_RL, RCOF2_Horiz_foot(rl_loop)];

    % Values for FP1 Vertical

    Max_RCof1_Vert_Value_RL = [Max_RCof1_Vert_Value_RL , Max_RCof2_Vert(rl_loop)];
    Max_RCof1_Vert_Index_RL = [Max_RCof1_Vert_Index_RL, Max_RCof2_Vert_Index(rl_loop)];
    RCof1_Vert_Fz_N_RL = [RCof1_Vert_Fz_N_RL, RCof2_Vert_Fz_N(rl_loop)];
    RCof1_Vert_Fz_msec_RL = [RCof1_Vert_Fz_msec_RL , RCof2_Vert_Fz_msec(rl_loop)];
    RCOF1_Vert_Fx_RL = [RCOF1_Vert_Fx_RL, RCOF2_Vert_Fx(rl_loop)];
    RCOF1_Vert_foot_RL = [RCOF1_Vert_foot_RL, RCOF2_Vert_foot(rl_loop)];

    % Values for FP2 Horizontal

    Max_RCof2_Horiz_Value_RL = [Max_RCof2_Horiz_Value_RL , Max_RCof1_Horiz(rl_loop)];
    Max_RCof2_Horiz_Index_RL = [Max_RCof2_Horiz_Index_RL, Max_RCof1_Horiz_Index(rl_loop)];
    RCof2_Horiz_Fz_N_RL = [RCof2_Horiz_Fz_N_RL, RCof1_Horiz_Fz_N(rl_loop)];
    RCof2_Horiz_Fz_msec_RL = [RCof2_Horiz_Fz_msec_RL , RCof1_Horiz_Fz_msec(rl_loop)];
    RCOF2_Horiz_Fx_RL = [RCOF2_Horiz_Fx_RL, RCOF1_Horiz_Fx(rl_loop)];
    RCOF2_Horiz_foot_RL = [RCOF2_Horiz_foot_RL, RCOF1_Horiz_foot(rl_loop)];

    % Values for FP2 Vertical

    Max_RCof2_Vert_Value_RL = [Max_RCof2_Vert_Value_RL , Max_RCof1_Vert(rl_loop)];
    Max_RCof2_Vert_Index_RL = [Max_RCof2_Vert_Index_RL, Max_RCof1_Vert_Index(rl_loop)];
    RCof2_Vert_Fz_N_RL = [RCof2_Vert_Fz_N_RL, RCof1_Vert_Fz_N(rl_loop)];
```

```
        RCof2_Vert_Fz_msec_RL = [RCof2_Vert_Fz_msec_RL , RCof1_Vert_Fz_msec(rl_loop)];
        RCOF2_Vert_Fx_RL = [RCOF2_Vert_Fx_RL, RCOF1_Vert_Fx(rl_loop)];
        RCOF2_Vert_foot_RL = [RCOF2_Vert_foot_RL, RCOF1_Vert_foot(rl_loop)];
    end;
  end;

% Collect all the data that is to be collected for all files
RCOF1_Horiz_all = [RCOF1_Horiz_all, Max_RCof1_Horiz];
RCOF1_Vert_all = [RCOF1_Vert_all, Max_RCof1_Vert];
RCOF2_Horiz_all = [RCOF2_Horiz_all, Max_RCof2_Horiz];
RCOF2_Vert_all = [RCOF2_Vert_all, Max_RCof2_Vert];

% Calclulate the statistics for this file for FP1 and FP2 independant
% of which foot hits the force plate first
mean_RCOF1_Horiz = [mean_RCOF1_Horiz, mean(Max_RCof1_Horiz)];
STD_RCOF1_Horiz = [STD_RCOF1_Horiz, std(Max_RCof1_Horiz)];
median_RCOF1_Horiz = [median_RCOF1_Horiz, median(Max_RCof1_Horiz)];
iqr_RCOF1_Horiz = [iqr_RCOF1_Horiz, iqr(Max_RCof1_Horiz) ];
min_RCOF1_Horiz = [min_RCOF1_Horiz, min(Max_RCof1_Horiz)];
max_RCOF1_Horiz = [max_RCOF1_Horiz, max(Max_RCof1_Horiz)];
skew_RCOF1_Horiz = [skew_RCOF1_Horiz, skewness(Max_RCof1_Horiz)];
precentile_RCOF1_Horiz = [precentile_RCOF1_Horiz, prctile(Max_RCof1_Horiz,95)];
precentile97_RCOF1_Horiz = [precentile97_RCOF1_Horiz, prctile(Max_RCof1_Horiz,97)];
precentile99_RCOF1_Horiz = [precentile99_RCOF1_Horiz, prctile(Max_RCof1_Horiz,99)];
kurtosis_RCOF1_Horiz = [kurtosis_RCOF1_Horiz, kurtosis(Max_RCof1_Horiz)];

mean_RCOF1_Vert = [mean_RCOF1_Vert, mean(Max_RCof1_Vert)];
STD_RCOF1_Vert = [STD_RCOF1_Vert, std(Max_RCof1_Vert)];
median_RCOF1_Vert = [median_RCOF1_Vert, median(Max_RCof1_Vert)];
iqr_RCOF1_Vert = [iqr_RCOF1_Vert, iqr(Max_RCof1_Vert) ];
min_RCOF1_Vert = [min_RCOF1_Vert, min(Max_RCof1_Vert)];
max_RCOF1_Vert = [max_RCOF1_Vert, max(Max_RCof1_Vert)];
skew_RCOF1_Vert = [skew_RCOF1_Vert, skewness(Max_RCof1_Vert)];
precentile_RCOF1_Vert = [precentile_RCOF1_Vert, prctile(Max_RCof1_Vert,95)];
precentile97_RCOF1_Vert = [precentile97_RCOF1_Vert, prctile(Max_RCof1_Vert,97)];
```

```
precentile99_RCOF1_Vert = [precentile99_RCOF1_Vert, prctile(Max_RCof1_Vert,99)];
kurtosis_RCOF1_Vert = [kurtosis_RCOF1_Vert, kurtosis(Max_RCof1_Vert)];

% Calclulate the statistics for this file for FP1 and FP2 independant
% of which foot hits the force plate first
mean_RCOF2_Horiz = [mean_RCOF2_Horiz, mean(Max_RCof2_Horiz)];
STD_RCOF2_Horiz = [STD_RCOF2_Horiz, std(Max_RCof2_Horiz)];
median_RCOF2_Horiz = [median_RCOF2_Horiz, median(Max_RCof2_Horiz)];
iqr_RCOF2_Horiz = [iqr_RCOF2_Horiz, iqr(Max_RCof2_Horiz) ];
min_RCOF2_Horiz = [min_RCOF2_Horiz, min(Max_RCof2_Horiz)];
max_RCOF2_Horiz = [max_RCOF2_Horiz, max(Max_RCof2_Horiz)];
skew_RCOF2_Horiz = [skew_RCOF2_Horiz, skewness(Max_RCof2_Horiz)];
precentile_RCOF2_Horiz = [precentile_RCOF2_Horiz, prctile(Max_RCof2_Horiz,95)];
precentile97_RCOF2_Horiz = [precentile97_RCOF2_Horiz, prctile(Max_RCof2_Horiz,97)];
precentile99_RCOF2_Horiz = [precentile99_RCOF2_Horiz, prctile(Max_RCof2_Horiz,99)];
kurtosis_RCOF2_Horiz = [kurtosis_RCOF2_Horiz, kurtosis(Max_RCof2_Horiz)];

mean_RCOF2_Vert = [mean_RCOF2_Vert, mean(Max_RCof2_Vert)];
STD_RCOF2_Vert = [STD_RCOF2_Vert, std(Max_RCof2_Vert)];
median_RCOF2_Vert = [median_RCOF2_Vert, median(Max_RCof2_Vert)];
iqr_RCOF2_Vert = [iqr_RCOF2_Vert, iqr(Max_RCof2_Vert) ];
min_RCOF2_Vert = [min_RCOF2_Vert, min(Max_RCof2_Vert)];
max_RCOF2_Vert = [max_RCOF2_Vert, max(Max_RCof2_Vert)];
skew_RCOF2_Vert = [skew_RCOF2_Vert, skewness(Max_RCof2_Vert)];
precentile_RCOF2_Vert = [precentile_RCOF2_Vert, prctile(Max_RCof2_Vert,95)];
precentile97_RCOF2_Vert = [precentile97_RCOF2_Vert, prctile(Max_RCof2_Vert,97)];
precentile99_RCOF2_Vert = [precentile99_RCOF2_Vert, prctile(Max_RCof2_Vert,99)];
kurtosis_RCOF2_Vert = [kurtosis_RCOF2_Vert, kurtosis(Max_RCof2_Vert)];

% Calclulate the statistics for this file for rIght and Left foots
mean_RCOF1_Horiz_RL = [mean_RCOF1_Horiz_RL, mean(Max_RCof1_Horiz_Value_RL)];
STD_RCOF1_Horiz_RL = [STD_RCOF1_Horiz_RL, std(Max_RCof1_Horiz_Value_RL)];
median_RCOF1_Horiz_RL = [median_RCOF1_Horiz_RL, median(Max_RCof1_Horiz_Value_RL)];
iqr_RCOF1_Horiz_RL = [iqr_RCOF1_Horiz_RL, iqr(Max_RCof1_Horiz_Value_RL) ];
min_RCOF1_Horiz_RL = [min_RCOF1_Horiz_RL, min(Max_RCof1_Horiz_Value_RL)];
```

```
max_RCOF1_Horiz_RL = [max_RCOF1_Horiz_RL, max(Max_RCof1_Horiz_Value_RL)];

skew_RCOF1_Horiz_RL = [skew_RCOF1_Horiz_RL, skewness(Max_RCof1_Horiz_Value_RL)];

precentile_RCOF1_Horiz_RL = [precentile_RCOF1_Horiz_RL, prctile(Max_RCof1_Horiz_Value_RL,95)];

precentile97_RCOF1_Horiz_RL = [precentile97_RCOF1_Horiz_RL, prctile(Max_RCof1_Horiz_Value_RL,97)];

precentile99_RCOF1_Horiz_RL = [precentile99_RCOF1_Horiz_RL, prctile(Max_RCof1_Horiz_Value_RL,99)];

kurtosis_RCOF1_Horiz_RL = [kurtosis_RCOF1_Horiz_RL, kurtosis(Max_RCof1_Horiz_Value_RL)];


mean_RCOF1_Vert_RL = [mean_RCOF1_Vert_RL, mean(Max_RCof1_Vert_Value_RL)];

STD_RCOF1_Vert_RL = [STD_RCOF1_Vert_RL, std(Max_RCof1_Vert_Value_RL)];

median_RCOF1_Vert_RL = [median_RCOF1_Vert_RL, median(Max_RCof1_Vert_Value_RL)];

iqr_RCOF1_Vert_RL = [iqr_RCOF1_Vert_RL, iqr(Max_RCof1_Vert_Value_RL) ];

min_RCOF1_Vert_RL = [min_RCOF1_Vert_RL, min(Max_RCof1_Vert_Value_RL)];

max_RCOF1_Vert_RL = [max_RCOF1_Vert_RL, max(Max_RCof1_Vert_Value_RL)];

skew_RCOF1_Vert_RL = [skew_RCOF1_Vert_RL, skewness(Max_RCof1_Vert_Value_RL)];

precentile_RCOF1_Vert_RL = [precentile_RCOF1_Vert_RL, prctile(Max_RCof1_Vert_Value_RL,95)];

precentile97_RCOF1_Vert_RL = [precentile97_RCOF1_Vert_RL, prctile(Max_RCof1_Vert_Value_RL,97)];

precentile99_RCOF1_Vert_RL = [precentile99_RCOF1_Vert_RL, prctile(Max_RCof1_Vert_Value_RL,99)];

kurtosis_RCOF1_Vert_RL = [kurtosis_RCOF1_Vert_RL, kurtosis(Max_RCof1_Vert_Value_RL)];


% Calclulate the statistics for this file for Right and Left foots

mean_RCOF2_Horiz_RL = [mean_RCOF2_Horiz_RL, mean(Max_RCof2_Horiz_Value_RL)];

STD_RCOF2_Horiz_RL = [STD_RCOF2_Horiz_RL, std(Max_RCof2_Horiz_Value_RL)];

median_RCOF2_Horiz_RL = [median_RCOF2_Horiz_RL, median(Max_RCof2_Horiz_Value_RL)];

iqr_RCOF2_Horiz_RL = [iqr_RCOF2_Horiz_RL, iqr(Max_RCof2_Horiz_Value_RL) ];

min_RCOF2_Horiz_RL = [min_RCOF2_Horiz_RL, min(Max_RCof2_Horiz_Value_RL)];

max_RCOF2_Horiz_RL = [max_RCOF2_Horiz_RL, max(Max_RCof2_Horiz_Value_RL)];

skew_RCOF2_Horiz_RL = [skew_RCOF2_Horiz_RL, skewness(Max_RCof2_Horiz_Value_RL)];

precentile_RCOF2_Horiz_RL = [precentile_RCOF2_Horiz_RL, prctile(Max_RCof2_Horiz_Value_RL,95)];

precentile97_RCOF2_Horiz_RL = [precentile97_RCOF2_Horiz_RL, prctile(Max_RCof2_Horiz_Value_RL,97)];

precentile99_RCOF2_Horiz_RL = [precentile99_RCOF2_Horiz_RL, prctile(Max_RCof2_Horiz_Value_RL,99)];

kurtosis_RCOF2_Horiz_RL = [kurtosis_RCOF2_Horiz_RL, kurtosis(Max_RCof2_Horiz_Value_RL)];


mean_RCOF2_Vert_RL = [mean_RCOF2_Vert_RL, mean(Max_RCof2_Vert_Value_RL)];

STD_RCOF2_Vert_RL = [STD_RCOF2_Vert_RL, std(Max_RCof2_Vert_Value_RL)];

median_RCOF2_Vert_RL = [median_RCOF2_Vert_RL, median(Max_RCof2_Vert_Value_RL)];
```

```
iqr_RCOF2_Vert_RL = [iqr_RCOF2_Vert_RL, iqr(Max_RCof2_Vert_Value_RL) ];
min_RCOF2_Vert_RL = [min_RCOF2_Vert_RL, min(Max_RCof2_Vert_Value_RL)];
max_RCOF2_Vert_RL = [max_RCOF2_Vert_RL, max(Max_RCof2_Vert_Value_RL)];
skew_RCOF2_Vert_RL = [skew_RCOF2_Vert_RL, skewness(Max_RCof2_Vert_Value_RL)];
precentile_RCOF2_Vert_RL = [precentile_RCOF2_Vert_RL, prctile(Max_RCof2_Vert_Value_RL,95)];
precentile97_RCOF2_Vert_RL = [precentile97_RCOF2_Vert_RL, prctile(Max_RCof2_Vert_Value_RL,97)];
precentile99_RCOF2_Vert_RL = [precentile99_RCOF2_Vert_RL, prctile(Max_RCof2_Vert_Value_RL,99)];
kurtosis_RCOF2_Vert_RL = [kurtosis_RCOF2_Vert_RL, kurtosis(Max_RCof2_Vert_Value_RL)];

% Statistics files building for writing
stats_RCof1_horiz = [mean_RCOF1_Horiz, STD_RCOF1_Horiz, median_RCOF1_Horiz, iqr_RCOF1_Horiz, min_RCOF1_Horiz, max_RCOF1_Horiz, skew_RCOF1_Horiz, precentile_RCOF1_Horiz, precentile97_RCOF1_Horiz, precentile99_RCOF1_Horiz, kurtosis_RCOF1_Horiz ];
stats_RCof1_Vert = [mean_RCOF1_Vert, STD_RCOF1_Vert, median_RCOF1_Vert, iqr_RCOF1_Vert, min_RCOF1_Vert, max_RCOF1_Vert, skew_RCOF1_Vert, precentile_RCOF1_Vert, precentile97_RCOF1_Vert, precentile99_RCOF1_Vert, kurtosis_RCOF1_Vert];
stats_RCof2_horiz = [mean_RCOF2_Horiz, STD_RCOF2_Horiz, median_RCOF2_Horiz, iqr_RCOF2_Horiz, min_RCOF2_Horiz, max_RCOF2_Horiz, skew_RCOF2_Horiz, precentile_RCOF2_Horiz, precentile97_RCOF2_Horiz, precentile99_RCOF2_Horiz, kurtosis_RCOF2_Horiz];
stats_RCof2_Vert = [mean_RCOF2_Vert, STD_RCOF2_Vert, median_RCOF2_Vert, iqr_RCOF2_Vert, min_RCOF2_Vert, max_RCOF2_Vert, skew_RCOF2_Vert, precentile_RCOF2_Vert, precentile97_RCOF2_Vert, precentile99_RCOF2_Vert, kurtosis_RCOF2_Vert];

stats_RCof1_horiz_RL = [mean_RCOF1_Horiz_RL, STD_RCOF1_Horiz_RL, median_RCOF1_Horiz_RL, iqr_RCOF1_Horiz_RL, min_RCOF1_Horiz_RL, max_RCOF1_Horiz_RL, skew_RCOF1_Horiz_RL, precentile_RCOF1_Horiz_RL, precentile97_RCOF1_Horiz_RL, precentile99_RCOF1_Horiz_RL, kurtosis_RCOF1_Horiz_RL ];
stats_RCof1_Vert_RL = [mean_RCOF1_Vert_RL, STD_RCOF1_Vert_RL, median_RCOF1_Vert_RL, iqr_RCOF1_Vert_RL, min_RCOF1_Vert_RL, max_RCOF1_Vert_RL, skew_RCOF1_Vert_RL, precentile_RCOF1_Vert_RL, precentile97_RCOF1_Vert_RL, precentile99_RCOF1_Vert_RL, kurtosis_RCOF1_Vert_RL];
stats_RCof2_horiz_RL = [mean_RCOF2_Horiz_RL, STD_RCOF2_Horiz_RL, median_RCOF2_Horiz_RL, iqr_RCOF2_Horiz_RL, min_RCOF2_Horiz_RL, max_RCOF2_Horiz_RL, skew_RCOF2_Horiz_RL, precentile_RCOF2_Horiz_RL, precentile97_RCOF2_Horiz_RL, precentile99_RCOF2_Horiz_RL, kurtosis_RCOF2_Horiz_RL];
stats_RCof2_Vert_RL = [mean_RCOF2_Vert_RL, STD_RCOF2_Vert_RL, median_RCOF2_Vert_RL, iqr_RCOF2_Vert_RL, min_RCOF2_Vert_RL, max_RCOF2_Vert_RL, skew_RCOF2_Vert_RL, precentile_RCOF2_Vert_RL, precentile97_RCOF2_Vert_RL, precentile99_RCOF2_Vert_RL, kurtosis_RCOF2_Vert_RL];
```

```
% To correctly build the result file we want all results to appear ina matrix of result columns

% For this to happen we need to transpose the vectors from being 1 x n to n x 1

stats_RCof1_horiz = stats_RCof1_horiz';
stats_RCof1_Vert = stats_RCof1_Vert';
stats_RCof2_horiz = stats_RCof2_horiz';
stats_RCof2_Vert = stats_RCof2_Vert';

stats_RCof1_horiz_RL = stats_RCof1_horiz_RL';
stats_RCof1_Vert_RL = stats_RCof1_Vert_RL';
stats_RCof2_horiz_RL = stats_RCof2_horiz_RL';
stats_RCof2_Vert_RL = stats_RCof2_Vert_RL';

Loop_Save = Loop_Save';

Max_RCof1_Horiz = Max_RCof1_Horiz';
Max_RCof1_Horiz_Index = Max_RCof1_Horiz_Index';
RCof1_Horiz_Fz_N = RCof1_Horiz_Fz_N';
RCof1_Horiz_Fz_msec = RCof1_Horiz_Fz_msec';
RCOF1_Horiz_Fx = RCOF1_Horiz_Fx';
RCOF1_Horiz_foot = RCOF1_Horiz_foot';
Max_RCof1_Vert = Max_RCof1_Vert';
Max_RCof1_Vert_Index = Max_RCof1_Vert_Index';
RCof1_Vert_Fz_N = RCof1_Vert_Fz_N';
RCof1_Vert_Fz_msec = RCof1_Vert_Fz_msec';
RCOF1_Vert_Fx = RCOF1_Vert_Fx';
RCOF1_Vert_foot = RCOF1_Vert_foot';

Max_RCof2_Horiz = Max_RCof2_Horiz';
Max_RCof2_Horiz_Index = Max_RCof2_Horiz_Index';
RCof2_Horiz_Fz_N = RCof2_Horiz_Fz_N';
RCof2_Horiz_Fz_msec = RCof2_Horiz_Fz_msec';
RCOF2_Horiz_Fx = RCOF2_Horiz_Fx';
RCOF2_Horiz_foot = RCOF2_Horiz_foot';
```

```
Max_RCof2_Vert = Max_RCof2_Vert';

Max_RCof2_Vert_Index = Max_RCof2_Vert_Index';

RCof2_Vert_Fz_N = RCof2_Vert_Fz_N';

RCof2_Vert_Fz_msec = RCof2_Vert_Fz_msec';

RCOF2_Vert_Fx = RCOF2_Vert_Fx';

RCOF2_Vert_foot = RCOF2_Vert_foot';


Max_RCof1_Horiz_Value_RL = Max_RCof1_Horiz_Value_RL';

Max_RCof1_Horiz_Index_RL = Max_RCof1_Horiz_Index_RL';

RCof1_Horiz_Fz_N_RL = RCof1_Horiz_Fz_N_RL';

RCof1_Horiz_Fz_msec_RL = RCof1_Horiz_Fz_msec_RL';

RCOF1_Horiz_Fx_RL = RCOF1_Horiz_Fx_RL';

RCOF1_Horiz_foot_RL = RCOF1_Horiz_foot_RL';

Max_RCof1_Vert_Value_RL = Max_RCof1_Vert_Value_RL';

Max_RCof1_Vert_Index_RL = Max_RCof1_Vert_Index_RL';

RCof1_Vert_Fz_N_RL = RCof1_Vert_Fz_N_RL';

RCof1_Vert_Fz_msec_RL = RCof1_Vert_Fz_msec_RL';

RCOF1_Vert_Fx_RL = RCOF1_Vert_Fx_RL';

RCOF1_Vert_foot_RL = RCOF1_Vert_foot_RL';


Max_RCof2_Horiz_Value_RL = Max_RCof2_Horiz_Value_RL';

Max_RCof2_Horiz_Index_RL = Max_RCof2_Horiz_Index_RL';

RCof2_Horiz_Fz_N_RL = RCof2_Horiz_Fz_N_RL';

RCof2_Horiz_Fz_msec_RL = RCof2_Horiz_Fz_msec_RL';

RCOF2_Horiz_Fx_RL = RCOF2_Horiz_Fx_RL';

RCOF2_Horiz_foot_RL = RCOF2_Horiz_foot_RL';

Max_RCof2_Vert_Value_RL = Max_RCof2_Vert_Value_RL';

Max_RCof2_Vert_Index_RL = Max_RCof2_Vert_Index_RL';

RCof2_Vert_Fz_N_RL = RCof2_Vert_Fz_N_RL';

RCof2_Vert_Fz_msec_RL = RCof2_Vert_Fz_msec_RL';

RCOF2_Vert_Fx_RL = RCOF2_Vert_Fx_RL';

RCOF2_Vert_foot_RL = RCOF2_Vert_foot_RL';



% Build the results matrix before writing them to the results directory
```

```
    results_matrix = [Loop_Save, Max_RCof1_Horiz, Max_RCof1_Horiz_Index, RCof1_Horiz_Fz_N, RCof1_Horiz_Fz_msec, RCOF1_Horiz_Fx,RCOF1_Horiz_foot, Max_RCof1_Vert, Max_RCof1_Vert_Index, RCof1_Vert_Fz_N, RCof1_Vert_Fz_msec, RCOF1_Vert_Fx,RCOF1_Vert_foot, Max_RCof2_Horiz, Max_RCof2_Horiz_Index, RCof2_Horiz_Fz_N, RCof2_Horiz_Fz_msec, RCOF2_Horiz_Fx, RCOF2_Horiz_foot, Max_RCof2_Vert, Max_RCof2_Vert_Index, RCof2_Vert_Fz_N, RCof2_Vert_Fz_msec, RCOF2_Vert_Fx, RCOF2_Vert_foot];
    results_stats = [stats_RCof1_horiz, stats_RCof1_Vert, stats_RCof2_horiz, stats_RCof2_Vert];
    results_RCOF_slip = [Max_RCof1_Horiz, Max_RCof1_Vert, Max_RCof2_Horiz, Max_RCof2_Vert];

    % Build the results matrix for the left and right cases

    results_matrix_RL = [Loop_Save, Max_RCof1_Horiz_Value_RL, Max_RCof1_Horiz_Index_RL, RCof1_Horiz_Fz_N_RL, RCof1_Horiz_Fz_msec_RL, RCOF1_Horiz_Fx_RL,RCOF1_Horiz_foot_RL, Max_RCof1_Vert_Value_RL, Max_RCof1_Vert_Index_RL, RCof1_Vert_Fz_N_RL, RCof1_Vert_Fz_msec_RL, RCOF1_Vert_Fx_RL,RCOF1_Vert_foot_RL, Max_RCof2_Horiz_Value_RL, Max_RCof2_Horiz_Index_RL, RCof2_Horiz_Fz_N_RL, RCof2_Horiz_Fz_msec_RL, RCOF2_Horiz_Fx_RL, RCOF2_Horiz_foot_RL, Max_RCof2_Vert_Value_RL, Max_RCof2_Vert_Index_RL, RCof2_Vert_Fz_N_RL, RCof2_Vert_Fz_msec_RL, RCOF2_Vert_Fx_RL, RCOF2_Vert_foot_RL];
    results_stats_RL = [stats_RCof1_horiz_RL, stats_RCof1_Vert_RL, stats_RCof2_horiz_RL, stats_RCof2_Vert_RL];
    results_RCOF_slip_RL = [Max_RCof1_Horiz_Value_RL, Max_RCof1_Vert_Value_RL, Max_RCof2_Horiz_Value_RL, Max_RCof2_Vert_Value_RL];

    % Write to a CSV file in the results directory and group directory
    csvwrite(save_name_initial, results_matrix);
    csvwrite(save_name_stats, results_stats);
    csvwrite(save_name_slip, results_RCOF_slip);

    csvwrite(save_name_initial_RL, results_matrix_RL);
    csvwrite(save_name_stats_RL, results_stats_RL);
    csvwrite(save_name_slip_RL, results_RCOF_slip_RL);

    %csvwrite(save_name_group, results_matrix);
    csvwrite(save_name_group, results_matrix);

end;

% To correctly build the result file we want all results to appear ina matrix of result columns
```

```
% For this to happen we need to transpose the vectors from being 1 x n to n x 1
RCOF1_Horiz_all = RCOF1_Horiz_all';
RCOF1_Vert_all = RCOF1_Vert_all';
RCOF2_Horiz_all = RCOF2_Horiz_all';
RCOF2_Vert_all = RCOF2_Vert_all';

results_stats_all = [RCOF1_Horiz_all, RCOF1_Vert_all, RCOF2_Horiz_all, RCOF2_Vert_all];

% Write to a CSV file in the results directory and group directory
csvwrite(save_name_stats_all, results_stats_all);

% Clean up for next run
rmpath(path_name);
rmpath(path_folder_name);
```