Age effects on the gait kinematics to negotiate surface height changes

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"*Fortitudine vincimus*"

"*By endurance we conquer*"

ABSTRACT

The primary aim of this study was to ascertain the biomechanical mechanisms or reasons for the high rate of falling behaviour exhibited by the elderly adult female population in terrain containing surface height changes. As such, this study specifically: (1) focused upon elderly (n = 48, age = 67 ± 5.4 yrs.) and young adult females (n = 48, age = 20 ± 2.4 yrs.); (2) examined the gait adjustments (spatio-temporal characteristics) made to approach (over distance) and accommodate (descend and ascend) terrain representative of a single step, kerb or door threshold (height: 15 cm). The walkways employed in this investigation consisted of a raised surface or platform (height: 15 cm; width: 1 m) fixed to a 22 m level walkway. In the ascent task, the raised surface was 9 m long, whereas in the descent task the raised surface was 15 m long; (3) ascertained the effect of walking velocity ("hurrying") upon a person's ability to safely accommodate this terrain. Walking velocities were comfortable and fast; and, (4) employed a multiple camera setup to record the participants' motion along the walkway. Variables of interest (i.e. linear and angular spatio-temporal variables) were extracted by a Peak Motus Measurement System and computer software programs (C language) written by the author. Data analysis procedures involved multivariate techniques such as MANOVA, discriminant and cluster analyses.

As part of this investigation, an instrument reliability study was conducted in order to ascertain the experimental setup (camera location and field of view) needed to minimize the effects of perspective, parallax and digitization error

associated with 2D planar analyses. The setup found to be the most suitable and reliable for the main phase of this investigation (step tasks) involved: (1) four cameras; (2) a camera location of 10 m from the 2D measurement plane; (3) a 2.5 to 3 m (width) camera field of view; and, (4) a 20 cm camera field of view overlap (width). On average, this setup was associated with the least error or about 4 mm and 0.5° for linear and angular spatial data respectively.

The step tasks (particularly descent) were found to perturb the gait of the elderly adult females (EA) more than the young adult females (YA). Essentially, they exerted more control, or were more cautious, since they: (1) made large step adjustments (up to $2\frac{1}{2}$ times the magnitude of the YA); (2) primarily employed a short step strategy (EA = 60%, YA = 19%); (3) exhibited less footfall variability ($p < .05$) and targeted a narrow region near the step; (4) moved slower ($p < .001$); (5) landed with less vertical velocity in descent ($p < .001$); (6) spent a longer time in double foot support in ascent ($p < .001$); (7) preferred to land on the forefoot, as opposed to the heel region, in descent ($p < .001$). This action or response allows greater attenuation of impact forces; (8) increased the time available to deal with a trip ($p < .05$); and, (9) minimized the chance of a slip (particularly in descent) by reducing the horizontal landing velocity of the lead foot ($p < .001$). This study also found the elderly to be a greater risk of a misstep or trip. The elderly placed the feet close to the step, cleared it by a lesser margin ($p < .001$) and exhibited less smoothness in the trajectory of the lead limb endpoint ($p < .001$).

The fast walking velocity conditions primarily elicited reductions in measures associated with dynamic stability. Essentially, the chance of a slip increased ($p < .001$) as a result of higher horizontal velocities of the lead foot upon landing, greater vertical momentum (descent) had to be attenuated upon landing ($p < .001$) and less time was available to regain balance should a trip occur ($p < .001$).

Lastly, this study found evidence of a "visual switch point" occurring at the 3rd-last footfall prior to the step. This provides evidence of a ubiquitous strategy (regulated by the visual system) employed by healthy adult females to approach and accommodate terrain containing surface height changes.

In conclusion, this study found evidence to suggest that elderly adult females are at greater risk (compared to young adult females) of a fall in terrain containing surface height changes. Stair or step descent appears to be particularly hazardous (especially when walking fast) since foot clearances are small and foot placement is close to the step edge. Both of these actions increase the chance of a stumble or trip-induced fall. These actions appear to be directly related to the short crossing step employed by elderly adult females. Any decline in step length capacity (due to the ageing process) may indicate a heightened risk of a fall on a stair or step. Finally, future work in this field would gain profitably by focusing on issues such as: (1) the likelihood of a misstep (partial foot support on a step or failure to ground the foot on a step) in terrain containing surface height changes; (2) the probability of limb collapse due to inadequate foot support on a step; and, (3) minimum lower limb strength and power required to prevent limb collapse or regain balance on a step should the foot be inadequately supported.

Once this information is acquired, exercise-based intervention programs could be developed and administered to large groups of at-risk elderly female adults in order to minimise falling behaviour.

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CHAPTER 1 INTRODUCTION

Natural or manufactured environments encountered in "everyday" activity rarely afford an even or unobstructed travel path (Patla, 1991). As such, safe or successful transport of the body requires the basic gait pattern to be adapted in order to avoid or accommodate obstacles such as a pothole or step. Any decline in a person's gait may diminish their capacity to live independently or move freely within the community. Gait impairments, for example, may heighten the risk of a trip-induced fall or may cause a person to avoid terrain such as a staircase or step. As such, gait analysis is important since it provides information about: (1) the adjustments required to move safely through or over "everyday" terrain; (2) the level of gait impairment or dysfunction that may occur in populations such as the elderly; and, (3) the value of intervention programs designed to prevent, alleviate or correct impairment; that is, the degree or extent of departure from "normal" gait (unobstructed and obstructed) can be determined and the progressive changes resulting from intervention strategies (e.g., fall prevention programs) can be assessed.

Human gait matures at about seven years of age and remains essentially unchanged until at least the 7th decade (Smidt, 1990; Whittle, 1991; Prince, Corriveau, Hebert & Winter, 1997). At around 60 to 70 years of age, however, gait impairments become increasingly evident in the elderly population. Typical impairments include reductions in step length, cadence and walking speed, and an increase in step width (e.g., Hageman & Blanke, 1986; Blanke & Hagemann, 1989; Smidt, 1990; Whittle, 1991; Öberg, Karsznia & Öberg, 1993; Öberg, Karsznia & Öberg, 1994). The most significant impairment is a reduction in the ability to deal with perturbed environments. This is demonstrated by the steady age-related rise in serious injuries resulting from pedestrian accidents, and the high incidence of stumbling, tripping and falling behaviours exhibited by the elderly (Campbell, Reinken, Allan & Martinez, 1981; Prudham & Evans, 1981; Nickens, 1985; Tinetti, Williams & Mayewski, 1986; Australian Bureau of Statistics, 1992; 1995a; 1998; Fildes, 1994; Carter, Kannus & Khan, 2001).

Stumbling, tripping and falling behaviours are the manifestation of a reduced ability to pro-actively deal with, or recover from, known and unexpected perturbations. Failure to achieve adequate foot clearance of an obstacle in the path of travel or maintain adequate foot-ground clearance, for example, may result in a stumble or trip. Stumbles or trips become falls if (1) the corrective response occurs too late, (2) the selected response is incorrect, or (3) the corrective response is inadequately executed (Grabiner & Jahnigen, 1992).

Numerous age-related physiological and neurological changes have been identified as contributing to stumbling, tripping and falling behaviours. These include: (1) reduced muscle strength and speed of muscular contraction in the lower limbs; (2) loss of shock-absorbing capability by ligaments, tendons and joint surfaces in the lower limbs; (3) reduced aerobic capacity; (4) reduced lower limb joint range of motion; (5) longer reaction times; (6) increased rate of brain loss; (7) reduced level of neurotransmitter production; and, (8) a decreased acuity of the visual, auditory, vestibular and somatosensory systems

(Payton & Poland, 1983; Whipple, Wolfson & Amerman, 1987; Morse, Tylko & Dixon, 1987; Robbins, Rubenstein, Josephson, Schulman, Osterweil & Fine, 1989; Gehlsen & Whaley, 1990; Smidt, 1990; Wolfson, Whipple, Amerman & Tobin, 1990; Patla, 1997; Prince et al., 1997; Thelen, Wojcik, Schultz, Ashton-Miller, & Alexander, 1997; Startzell, Owens, Mulfinger & Cavanagh, 2000; Carter et al., 2001).

The most common cause of an accident in Australian households is a fall (Australian Bureau of Statistics, 1992; 1998). Fourty-three percent of all accidents have been directly attributed to a fall, and account for the majority of accidents to older adults. About a third of community dwelling persons over the age of 65 fall each year, with this proportion increasing to about half for elderly people aged 80 years or more (Campbell et al., 1981; Prudham & Evans, 1981; Nelson, Murlidhar & Amin, 1990; Lilley, Arie & Chilvers, 1995; Hill, Schwarz, Flicker & Carroll, 1999; Martin & Grabiner, 1999). In 10 to 15 percent of falls, serious injuries such as hip fracture or fracture to other bones occur. Interestingly, women fall more often than men until the age of 75 years after which the frequency is similar in both sexes (Gryfe, Amies & Ashley, 1977; Campbell et al., 1981; Campbell, Borrie, Spears, Jackson, Brown & Fitzgerald, 1990; Nickens, 1985; Tinetti, Speechley & Ginter, 1988; Schultz, Ashton-Miller & Alexander, 1997; Lord, Sherrington & Menz, 2001; Asakawa, Takahashi & Kagawa, 2001).

Falls are a major cause of morbidity in the elderly population (Tinetti et al., 1988; Tinetti & Speechley, 1989; Lilley et al., 1995), and have also been directly linked to a reduction in physical activity levels, mobility and "living" independence (Legters, 2002). The physical injury and/or psychological trauma associated with a fall may cause a person to negotiate "everyday" terrain with extra caution, or to simply avoid it. Such behavioural changes may serve to reduce a person's capacity to safely and efficiently negotiate such terrain (Albarede, Lemieux, Vellas & Groulx 1989; Maki, Holliday & Topper, 1991; Tinetti, 1994; Lilley et al., 1995).

Tripping on a level surface or over an object is one of the most frequently reported causes of a fall in the elderly (Blake, Morgan, Bendall, Dallosso, Ebrahim, Arie, Fentem & Bassey, 1988; Tinetti & Speechley, 1989; Campbell et al., 1990; Berg, Alessio, Mills & Tong, 1997; Lord et al., 2001). Trips are commonly caused by unexpected toe contact (lead limb) with the ground or an obstacle. Heel contact however, tends to cause a stumble rather than a trip (Chen, Ashton-Miller, Alexander & Schultz, 1991). Slips, misplaced steps (e.g., stepping into a hole), a sudden loss of balance and hurrying have also been linked to falls in the elderly (Berg et al., 1997).

Between one-third and a half of all falls experienced by the elderly in the community have been attributed to environmental factors (Lilley et al., 1995; Berg et al., 1997; Lord et al., 2001). In public places, stairs, mats, kerbs, and footpath irregularities have been identified as major sites of falling (Sheldon, 1960; Nickens, 1985; Lilley et al., 1995). The largest proportion of falls occur on steps, and approximately 80% of these occur when stepping down (Svanstrom, 1974; Tinetti et al., 1988; National Safety Council, 1985; 1994;

Simoneau, Cavanagh, Ulbrecht, Leibowitz & Tyrell, 1991; Australian Bureau of Statistics, 1995a; Startzell et al., 2000). Berg et al. (1997), however, found most falls occurred on level or bumpy ground, with an equal number of falls occurring during stair descent and ascent. In the home environment, objects such as flooring, carpet edges and joins, electrical cords and door thresholds have been associated with trip-induced falls (Chen et al., 1991).

In Australia, the elderly as a group represent a large and growing proportion of the population (Clare & Tupole, 1994; Australian Bureau of Statistics, 2000). As such, it has now become more important to identify critical markers, or quantitative measures, that provide accurate and reliable information about the integrity of the locomotor system. This information may assist professionals to ascertain a person's likelihood of a fall, and if necessary provide appropriate intervention.

Recently, investigators have begun to examine the biomechanical characteristics of the visually-guided gait adjustments made by people to deal with and recover from perturbations (e.g., Chen et al., 1991; Simoneau et al., 1991; McFadyen, Magnan & Boucher, 1993; Patla & Rietdyk, 1993; Chen, Ashton-Miller, Alexander & Schultz, 1994a; 1994b; Eng, Winter & Patla, 1994; Sparrow, Shinkfield, Chow & Begg, 1996; Patla, Rietdyk, Martin & Prentice, 1996; Begg, Sparrow & Lythgo, 1998; Austin, Garrett & Bohannon, 1999; McFadyen & Prince, 2002; Sorensen, Hollands & Patla, 2002). These studies have examined the gait adjustments made by young and elderly adults to: (1) regulate step length and width; (2) to step over, on and around obstacles of varying dimensions, proximity and fragility; and, (3) to recover from unexpected obstructions and unwanted foot contact with an object. Many of these studies have also examined the performance of these tasks under time critical conditions (reduced available response time). In general, these investigations have contributed to a better understanding of the circumstances surrounding falls. Studies have shown older adults (particularly females) are less able to regain balance after the onset of an unexpected perturbation or to avoid an obstacle under time-critical conditions. Furthermore, studies suggest the elderly are at greater risk of a misstep (accidentally stepping on an object) and unwanted foot-ground-contact in terrain containing stairs or steps.

To date, the majority of studies of obstructed gait have primarily focused on the adjustments made by young adults to step over a fixed object (e.g., Chen et al., 1991; Patla & Rietdyk, 1993; Patla et al., 1996; Chou, Kaufman, Brey & Draganich, 2001; McFadyen & Prince, 2002). Few studies have directly compared the gait adjustments made by young and elderly adults to accommodate terrain containing surface height changes. Furthermore, studies involving older adults have lacked a degree of ecological validity since harness-support devices and virtual obstacles or light-beams were used (e.g., Chen et al., 1994a; 1994b; Chen, Schultz, Ashton-Miller, Giordani, Alexander & Guire, 1996). Recent studies suggest that devices such as these may evoke atypical gait responses (Patla et al., 1996; Rietdyk & Patla, 1998).

It is important to learn more about the gait adjustments made by populations such as the elderly to perform "everyday" tasks such as climbing a step or kerb

(Prince et al., 1997; Startzell et al., 2000). These sites have been directly associated with falls that have resulted in serious injury. Disappointingly, however, few studies of obstructed gait have reported significant age differences despite the fact that terrain containing surface height changes perturbs the gait of elderly females more than young adult females. The primary aim of this study, therefore, was to acquire knowledge in order to better understand the biomechanical mechanisms or reasons for the high rate of falling behaviour exhibited by the elderly adult female population in terrain containing surface height changes. Such information is important in helping the community understand why the elderly fall. Furthermore, it assists professionals to: (1) better monitor age-related changes in gait; (2) assess a person's propensity to fall; (3) understand circumstances surrounding falls; and, (4) provide, where necessary, appropriate intervention.

In summary, this project extended work in the field of obstructed gait by: (1) focusing upon terrain directly linked to falls (e.g., a single step, kerb and door threshold); (2) examining the approach (over distance) and crossing phases (descent and ascent tasks) in order to ascertain the likelihood of a misstep or fall; (3) involving young and elderly adult females so as to explore the biomechanical mechanisms or reasons (spatio-temporal aspects) for the high rate of falling behaviour found in the elderly adult female population; and, (4) ascertaining the effect of walking velocity ("hurrying") upon a person's ability to safely accommodate a step. As part of this process, an instrument reliability study was conducted in order to establish the experimental set-up needed to minimize error associated with 2D planar analyses.

CHAPTER 2 REVIEW OF LITERATURE

The format of this chapter is as follows. There are three major sections where the literature pertaining to (1) falling behaviour (incidence and nature), (2) normal gait (unobstructed) and (3) adaptive gait (obstructed) is reviewed. Within each section, the literature pertaining to sub-sections of these areas has been examined.

Critical comment of the literature is found in summary sections located at the end of a section and/or sub-section. Principally, these summaries critically assess the current knowledge base and address the worth of this project.

Throughout this thesis the term normal or basic gait refers to the walking pattern exhibited by a healthy adult moving at self-selected velocity along a straight, flat and unobstructed path. The term adaptive or obstructed gait refers to the walking pattern exhibited by a healthy adult traversing terrain that may be, or needs to be, avoided (e.g., stepped over) or accommodated (i.e. stepped upon). The Australian Bureau of Statistics (1995a; 1998) definition of a fall will be used. A fall is defined as an accidental loss of balance where a person drops to the ground after a trip or slip.

2.1 Falling behaviour

2.1.1 Fall incidence

At around 60 to 70 years of age, gait dysfunctions become increasingly evident and begin to reduce a person's ability to pro-actively deal with, or recover from, known and unexpected perturbations. This is demonstrated by the steady age-related rise in serious injuries resulting from pedestrian accidents, and the high incidence of stumbles, trips and falls exhibited by the elderly from age 65 onwards (Campbell et al., 1981; Prudham & Evans, 1981; Nickens, 1985; Tinetti et al., 1986; Australian Bureau of Statistics, 1992; 1995a; 1998; Fildes, 1994; Carter et al., 2001).

Falls have been identified (Australian Bureau of Statistics, 1992; 1998) as the most common cause of an accident (43% of accidents) in Australian households, and are cited as the most frequent cause of injury among females (39%) and the second most common cause among males (27%). Falls account for the majority of injuries to adults aged 65 years or more. About a third of community dwelling persons over the age of 65 fall at least once a year, with about half of them doing so recurrently (Prudham & Evans, 1981; Campbell et al., 1981; Blake et al., 1988; Nelson et al., 1990; Lilley et al., 1995; Hill et al., 1999; Martin & Grabiner, 1999).

Falling rates have been found to be higher in older women (≈ 40%) than in older men (≈ 28%) and continue to rise with age from 65 years (Gryfe et al., 1977; Campbell et al., 1981; Campbell, Borrie & Spears, 1989; Campbell et al., 1990; Nickens, 1985; Tinetti et al., 1988; Schultz et al., 1997; Lord et al., 2001). In 1995, a survey of fall risk factors by the Australian Bureau of Statistics found 23.9% of all women (91,700 cases), compared to 15.5% of all men (47,800 cases), fell in the previous twelve months. In the 70 years or more age group, 28% of all females fell, whereas the male proportion remained essentially unchanged (15.6%). In a recent study, Asakawa et al. (2001) found women aged 65 or more fell almost twice as often (1.9 times) as men in this age group.

Lord (1990) found hospital admissions due to injuries sustained from falls to be consistently higher for older women aged 60 years or more (refer to Figure 2.1.1.1). In addition, Fildes (1994) concluded that older women are roughly twice as likely to injure themselves in a fall than are their male counterparts.

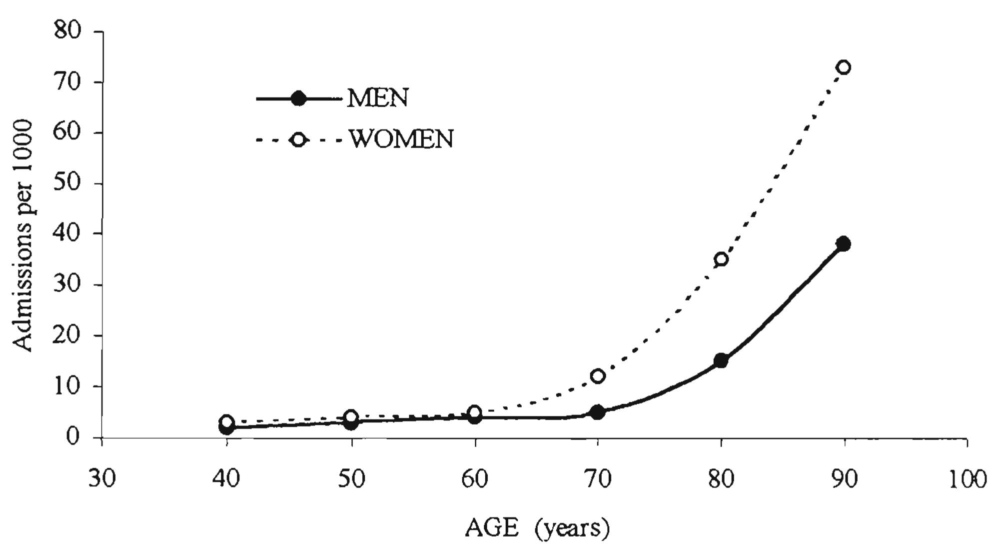


Figure 2.1.1.1 Hospital admissions for falls according to age and gender (taken from Lord, 1990, p.118).

2.1.2 Fall risk factors

Over one-hundred and thirty different factors have been directly linked to falling behaviour in the elderly population (Myers, Young & Langlois, 1996). In an attempt to better understand this behaviour, investigators have classified risk factors as either intrinsic or extrinsic (Nickens, 1985; Davis, Ross, Nevitt & Wasnich, 1999). Intrinsic risk factors have been described as host factors (e.g., physiological and neurological) that increase a person's liability to fall, whereas extrinsic factors have been described as environmental hazards that increase the opportunity to fall (Carter et al., 2001).

Carter et al. (2001) have produced a particularly useful model (refer to Figure 2.1.2.1) that illustrates the interplay of risk factors (intrinsic and extrinsic) in falling behaviour. In order to better understand this model, it is important to define key terms such as impairment and disability. The World Health Organisation (1980) has defined impairment to be any loss or abnormality of psychological, physiological or anatomical structure or function. Disability has been defined (Schuntermann, 1996) as any restriction or lack (resulting from impairment) of ability to perform an activity in the manner or within the range considered normal for a human being.

It is evident from the model of Carter et al. (2001) that age-related host factors (e.g., physiological and neurological changes) lead to impairments/disabilities that predispose a person to a fall. Some host factors reported by Carter et al. and other investigators (see below) are: (1) reduced muscle strength and velocity of muscular contraction in the lower limbs; (2) loss of shock-absorbing capability by ligaments, tendons and joint surfaces in the lower limbs; (3) reduced aerobic capacity; (4) reduced lower limb joint range of motion; (5) longer reaction times; (6) increased rate of brain loss; (7) reduced level of neurotransmitter production; and, (8) a decreased acuity of the visual, auditory, vestibular and somatosensory systems (Payton & Poland, 1983; Morse et al., 1987; Whipple et al., 1987; Robbins et al., 1989; Gehlsen & Whaley, 1990; Smidt, 1990; Wolfson et al., 1990; Whittle, 1991; Patla, 1997; Prince et al., 1997; Thelen et al., 1997; Startzell et al., 2000).

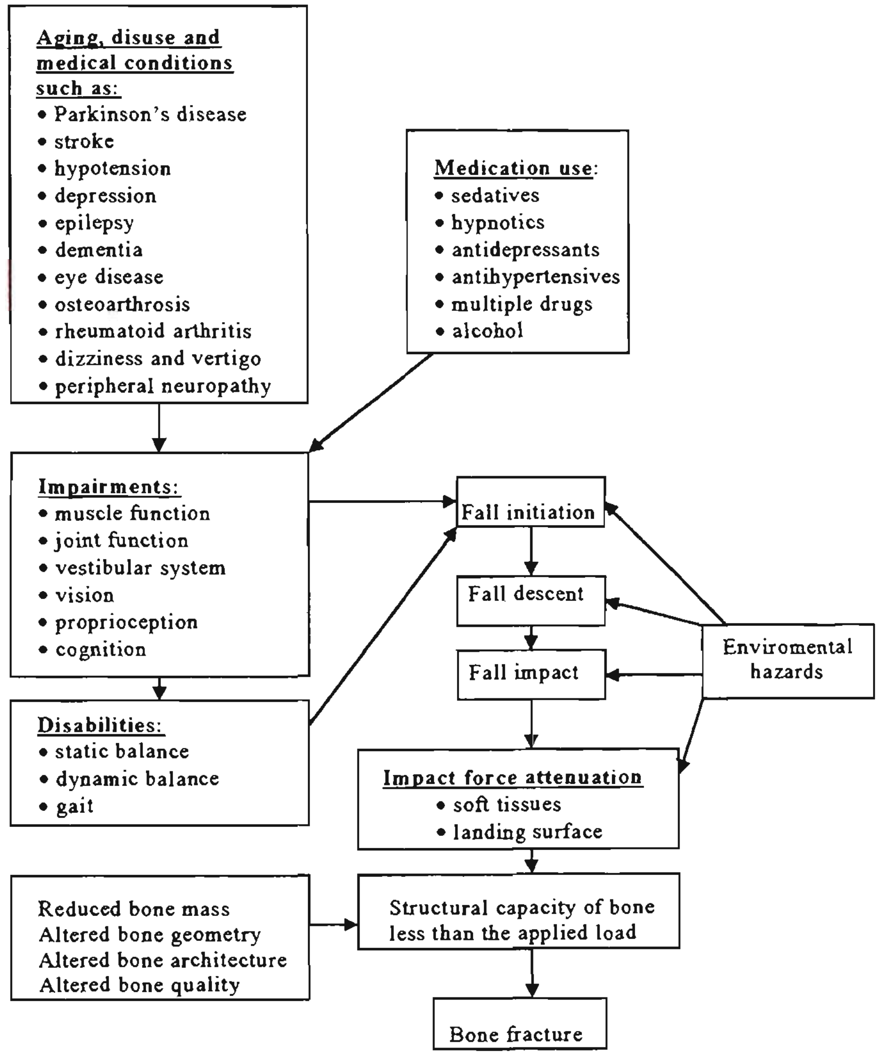


Figure 2.1.2.1 Intrinsic impairments and disabilities that interplay with environmental hazards and predispose individuals to falls and fractures (taken from Carter et al., 2001, p. 430).

Intrinsic factors affect a person's ability to pro-actively deal with, or recover from, known and unexpected perturbations. Failure to achieve adequate foot-ground or foot-obstacle clearance due to lower limb muscular weakness, for example, can result in a stumble or trip. Stumbles or trips become falls if (1) the corrective response occurs too late, (2) the selected response is incorrect, or (3) the corrective response is inadequately executed (Grabiner & Jahnigen, 1992).

To date, medical fall-prevention programs have predominantly focused on intrinsic risk factors (Carter et al., 2001). It has been reported, however, that between one-third and a half of all falls experienced by the elderly are due to environmental factors (Lilley et al., 1995; Australian Bureau of Statistics, 1995a; Berg et al., 1997). The Australian Bureau of Statistics (1995a) found 34.9% of all persons who fell stated that a surface (e.g., uneven terrain) contributed to their fall. Moreover, 33.8% of all persons who fell stated that an object (e.g., step or stair) contributed to their fall.

Tripping with the ground or over an object are the most frequently reported causes of a fall in the elderly (Blake et al., 1988; Tinetti & Speechley, 1989; Campbell et al., 1990; Australian Bureau of Statistics, 1995a; Berg et al., 1997). Other major causes include misplaced steps (e.g., stepping into a hole), slips, and a sudden loss of balance. Pauls (1985), for example, has suggested that about half of all stair descent accidents are due to overstepping. Significant reasons cited by fallers include hurrying too much, not looking where one was going, tripping over something and slipping on a wet or slippery surface (Australian Bureau of Statistics, 1995a; Berg et al., 1997).

In the elderly, about 50% of falls occur in the home or immediate home surroundings on both level and uneven surfaces (Campbell et al., 1990; Luukinen, Koski, Hiltunen & Kivela, 1994; Australian Bureau of Statistics, 1995a). Objects associated with trip-induced falls in or about the home include steps, flooring, carpet edges and joins, electrical cords, door thresholds, garden objects, garage items and pathways (Chen et al., 1991; Fildes, 1994; Australian Bureau of Statistics, 1995a; Berg et al., 1997; Lord et al., 2001).

In public places, falls have been reported to occur on sites such as level ground, steps, mats, kerbs, footpath irregularities, construction works, uneven ground and slippery surfaces (Sheldon, 1960; Nickens, 1985; Australian Bureau of Statistics, 1995a; Lilley et al., 1995; Berg et al., 1997; Lord et al., 2001). Investigations suggest the most common objects associated with a fall to be steps and stairs ($\approx$ 34%) with approximately eighty percent of falls occurring when stepping down (Svanstrom, 1974; Tinetti et al., 1988; Templer, 1992; National Safety Council, 1985; 1994; Simoneau et al., 1991; Australian Bureau of Statistics, 1995a; Startzell et al., 2000). Berg et al. (1997), however, reported an equal number of falls occurring in stair descent and ascent; this proportion was obtained from falls recorded on stairs in both the home and public environment.

In recent years, investigators have begun to examine the gait adjustments made by adults to deal with extrinsic fall-related risk factors (e.g., Chen et al., 1991; Simoneau et al., 1991; McFadyen et al., 1993; Patla & Rietdyk, 1993; Eng et al., 1994; Crosbie, 1996; Begg et al., 1998; Austin et al., 1999; McFadyen & Prince, 2002; Sorensen et al., 2002). Studies have examined gait adjustments made by young and elderly adults to regulate step length and width, to step over, on and around objects of varying dimensions and proximity, and to recover from unexpected foot contacts with an object. Many of the studies also examined the performance of these tasks under time critical conditions (reduced available response time). The objects used in these studies were predominantly rods, light-bands, stairs and barriers of varying proximity, height and width. For a detailed review of findings the reader is referred to the section on adapted gait (section 2.3).

In general, the emergent research body focusing upon fall-related extrinsic risk factors has provided a better understanding of the impact of age-related gait dysfunctions upon safe and purposeful travel in "everyday" terrain. Research, for example, has found the elderly: 1) need more time (at least two step durations) to deal with perturbations or avoid environmental objects (e.g., Chen et al., 1994a; 1994b; Cao, Schultz, Ashton-Miller & Alexander, 1997; 1998a; 1998b; Sorensen et al., 2002); 2) experience a marked reduction in the ability to avoid an obstacle when attention is divided (e.g., Chen et al., 1996); 3) adopt a foot placement strategy that reduces the time available to deal with an obstacle (e.g., Begg & Sparrow, 2000); 4) exhibit greater foot clearances when stepping on a raised platform than stepping off (e.g., Begg & Sparrow, 2000); and, 5) exhibit different foot orientations when accommodating a raised platform (Lythgo & Begg, 1999a). Other investigators (e.g., Thelen et al., 1997; Wojcik, Thelen, Schultz, Ashton Miller & Alexander, 1999) have reported age and gender-related (females) reductions in the ability to regain balance from a simple leaning task.

2.1.3 Fall outcomes

Literature on the total cost of falls is scant. Of the few studies conducted, however, the financial cost of fall-related injuries or deaths appears to be high. In the United States of America, for example, annual costs associated with fall-related fractures have been estimated to be $US10 billion (Khan, McKay, Kannus, Bailey, Wark & Bennell, 2001), whereas in the United Kingdom (year of costing 2000) the estimated total direct hospital costs associated with hip fractures alone were £1.3 billion (Torgerson & Dolan, 2000). In Australia, the annual cost of fall-related injuries or deaths has been estimated to be $2.5 billion (Fildes, 1994).

Falls are a major cause of serious injury in the elderly population (Tinetti et al., 1988; Tinetti & Speechley, 1989; Lilley et al., 1995; Australian Bureau of Statistics, 1995a; 1998). Over ninety-percent of hip fractures result from falls, and in 12 to 20% of these cases the outcome is fatal (Grisso, Kelsey, Strom, Chiu, Maislin, O'Brien, Hoffman & Kaplan, 1991; Nyberg, Gustafson, Berggren, Brännström & Bucht, 1996; Parkkari, Kannus, Palvanen, Natri, Vainio, Aho, Vuori & Jarvinen, 1999; Lord et al., 2001).

Falls have also been directly linked to a reduction in physical activity levels, mobility and "living" independence (Albarede et al., 1989; Maki et al., 1991; Tinetti, 1994; Lilley et al., 1995; Legters, 2002). It has also been suggested that the physical injury and/or psychological trauma associated with a fall causes a person to traverse "everyday" terrain with extra caution, or to simply avoid it

(Yardley & Smith, 2002). This behaviour reduces a person's ability to safely and efficiently traverse such terrain, or simply enjoy "everyday" life activity.

2.1.4 Summary

In Australia, as throughout most of the world, the elderly as a group represent a large and growing proportion of the population (Clare & Tupole, 1994; Australian Bureau of Statistics, 2000; Carter et al., 2001). It is well documented that this group, after the age of 65 years, experience a dramatic rise in falling behaviour with elderly women exhibiting the highest rate of falls (e.g., Gryfe et al., 1977; Campbell et al., 1981; Campbell et al., 1990; Nickens, 1985; Tinetti et al., 1988; Schultz et al., 1997; Lord et al., 2001).

The rising number of falls in the elderly adult population has begun to place a significant financial burden on the community (Fildes, 1994; Torgerson & Dolan, 2000; Khan et al., 2001). Additionally, falls have been found to reduce a person's quality of life or may even cause death (e.g., Grisso et al., 1991; Parkkari et al., 1999). Falls, for example, have been directly associated with a reduction in physical activity levels, functional mobility, "living" independence and socio-economic status.

Investigations have contributed to a better understanding of the circumstances surrounding falls. For instance, over one-hundred and thirty risk factors (intrinsic and extrinsic) have been directly linked to falling behaviour in the elderly (Myers et al., 1996). Despite the recognised importance of extrinsic risk factors however (e.g., environmental hazards), medical fall-prevention programs have predominantly focused on intrinsic risk factors such as changes in physiological and neurological processes (Carter et al., 2001).

Emergent research has begun to examine the gait adjustments made by adults to deal with extrinsic fall-related risk factors (e.g, Chen et al, 1991; 1994a; 1994b; Austin et al., 1999). The majority of these studies, however, have focused upon the young adult population and have used obstacles (e.g., rods and light-bands) not typically found in "everyday" terrain.

Despite research efforts, investigations have not provided a comprehensive quantitative model that predicts the likelihood of a fall in the elderly. There is a need, therefore, to identify critical markers or quantitative measures that provide accurate and reliable information about the integrity of the locomotor system in perturbed environments. The acquirement of such knowledge assists professionals to: (1) better monitor age-related changes in the locomotor system; (2) more accurately assess a person's likelihood of a fall; (3) understand circumstances surrounding the high incidence of falls in the elderly; and, (4) provide, where necessary, appropriate intervention.

There is a need to learn more about the gait adjustments made by elderly females to perform "everyday" tasks such as climbing (ascent and descent) a kerb or door threshold. The literature (e.g., Pauls, 1985; Lilley et al., 1995; Berg et al., 1997) suggests this group experience a high rate of falls on these sites from misplaced steps and hurrying. Furthermore, little information exists as to whether an ascent or descent task is more dangerous. These tasks, therefore, need to be more comprehensively examined and compared.

This project examines several of the issues raised in this section. Specifically, the gait adjustments made by young and elderly adult females to approach and accommodate (ascent and descent) a raised surface (representing a single step, kerb or door threshold) at self-selected walking velocity and whilst hurrying.

2.2 The characteristics of normal gait

This section examines age-related differences in normal gait. The main focus being to identify those differences that have been, or may be, associated with the higher falling behaviour exhibited by the elderly. It was not the aim to present a comprehensive review of the kinematic and kinetic characteristics of normal gait. This was considered beyond the scope of this project. The reader is referred to Whittle (1991) for an in-depth analysis.

2.2.1 Gait cycle description

Normal walking requires the stance limb to be in contact with the ground for the full duration of the step, and the swing limb to be airborne for the major part of the step (Patla, 1991). The characteristics of normal gait are primarily determined by the modulation of the swing limb's trajectory and foot placement. Such modulation can be achieved in several phases of the step cycle. These phases have been defined by Inman, Ralston and Todd (1994) to be (1) late stance or double support, (2) early swing, and (3) late swing (refer to Figure 2.2.1.1).

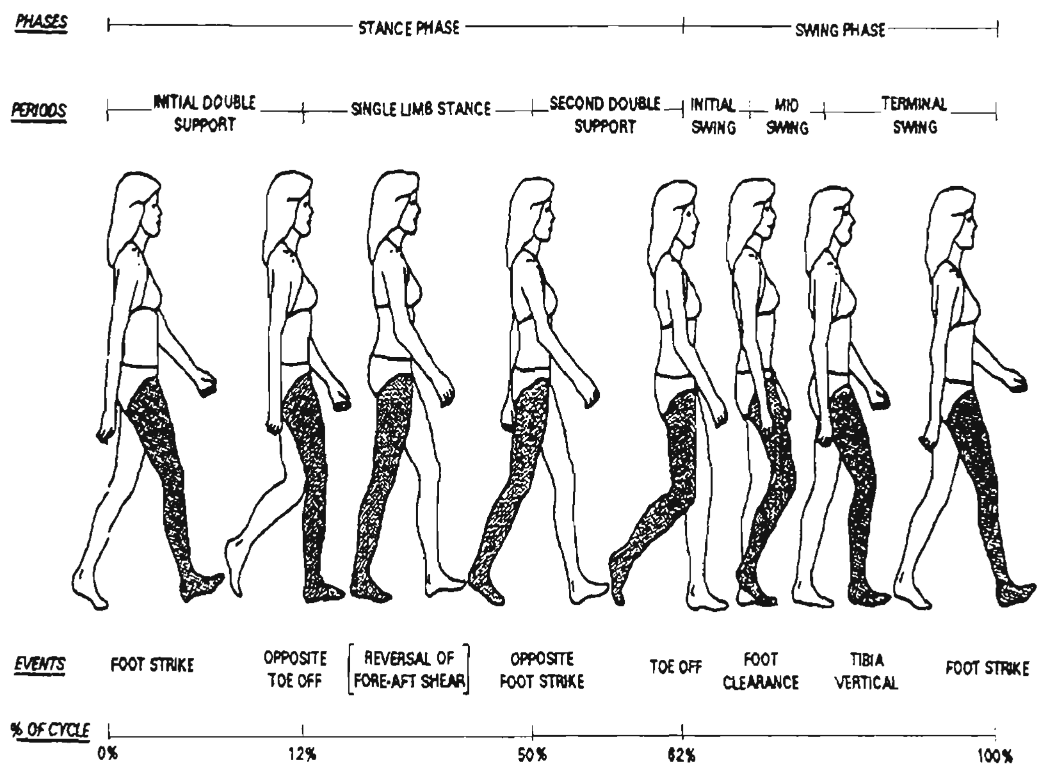


Figure 2.2.1.1 A typical normal walk cycle illustrating the events of gait (taken from Rose and Gamble, 1994, p. 26).

In the late stance phase, the final push-off action takes place in order to propel the body forward (Inman et al., 1994). In this phase the plantar-flexors actively extend the ankle, while hamstrings activity results in knee flexion to lift the foot off the ground. During the early swing phase, the limb is actively pulled up primarily through the action of the rectus femoris, whilst the biceps femoris actively flexes the knee joint. Later on, the knee joint begins to extend and dorsiflexor activity (beginning at toe-off) flexes the foot to ensure ground clearance. In the late swing phase, the limb movements are decelerated and the foot is readied for contact with the ground. The hamstring activity in this phase decelerates knee extension and hip flexion, and ankle activity prepares the foot for heel contact (Inman et al., 1994).

2.2.2 Toe-ground-clearance

The lead foot has been described as the last segment in a multi-segment chain (Figure 2.2.2.1) starting with the stance foot up to the pelvis, across the pelvis and down the swing limb (Winter, 1991). This segment is considered by Winter to be only one segment in a chain that is seven segments long with at least 12 major joint angular degrees of freedom, 3 at each hip, one at each knee, and 2 at each ankle. During the swing phase a relatively small change in a number of these angular degrees of freedom can strongly influence the end-point trajectory of the lead heel and toe. Toe clearance, for example, can be controlled by the plantar/dorsiflexion of the swing ankle or equally well controlled by four other joints in the 7-segment chain (refer to figure 2.2.2.1). Locomotor actions that affect foot clearance include swing knee flexion, stance hip abduction/adduction, stance knee flexion and stance ankle plantar/dorsiflexion.

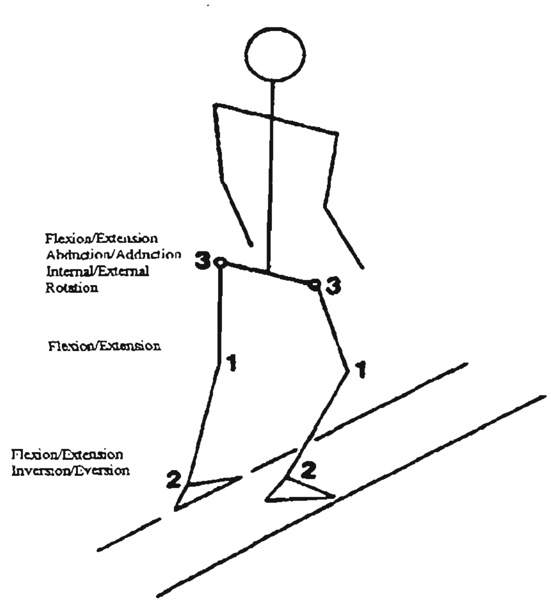


Figure 2.2.2.1 Stick diagram of link chain system of 7 segments of the support limb, pelvis and swing limb involved in the control of the toe and heel trajectories. The 12 major degrees of freedom at the 6 joints that influence those trajectories are also shown (taken from Winter, 1992, p. 46).

Toe clearance of the ground has been found to be small in normal gait (Winter, Patla, Frank & Walt, 1990; Winter, 1991; 1992; Karst, Hageman, Jones & Bunner, 1999). In the early swing phase, for example, the toe rises to no more than 2.5 cm above the ground and then drops to about 1 cm clearance at midswing (Figures 2.2.2.2 and 2.2.2.3). Winter (1991) found lower toe clearances at midswing for a group of elderly adults (1.12 cm) compared to a group of young adults (1.29 cm).

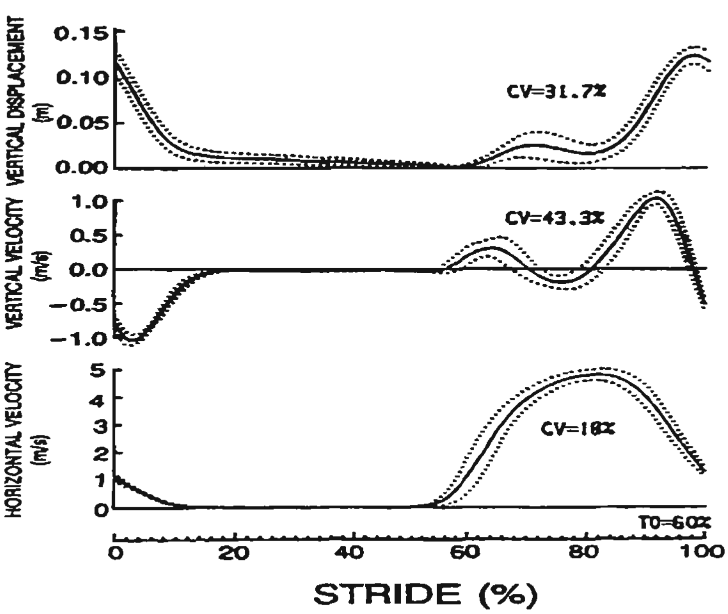


Figure 2.2.2.2 Ensemble averaged displacement and velocity profiles of the toe over one stride of 11 subjects walking at their natural cadence. Heel contact is 0% and 100% of stride, and toe-off (*TO*) is at 60% of stride. Minimum toe vertical displacement was set at zero when the toe pressed downward into the floor immediately before *TO*. *CV* = coefficient of variation (taken from Winter, 1992, p. 47).

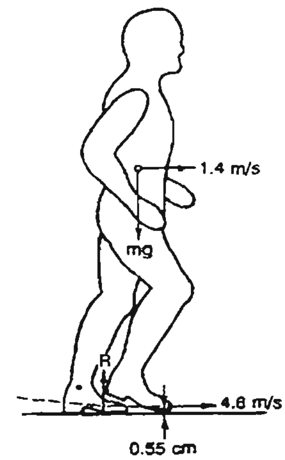


Figure 2.2.2.3 Position of the body at the instant of minimum toe clearance for one representative walking trial showing the high forward toe velocity (4.6 $m \cdot s^{-1}$) and centre of gravity of the head, arms and trunk located ahead of the stance foot; *R* represents the ground reaction force; *mg* represents the body's centre of gravity vector (taken from Winter, 1992, p. 47).

At midswing (Winter, 1991), the body is inherently unstable since the body's centre of mass (*COM*) is forward of the base of support and the toe's horizontal velocity ($\approx$ 4.5 $m \cdot s^{-1}$) is greatest (Winter, 1991). At this point, toe contact with the ground is dangerous since it may cause a trip-induced fall. In contrast, heel or midsole contact tends to cause a stumble, ankle plantarflexion and possible forward sliding of the foot, rather than a trip (Chen et al., 1991).

After midswing the knee extends and the foot dorsiflexes (Winter, 1991). These actions elevate the toe to a maximum height of about 13 cm in preparation for a heel landing. A gentle heel (low velocity) landing is necessary in order to prevent a dangerous skid or slip on a compliant or slippery surface.

2.2.3 Joint angle profiles

Toe-ground-clearance is significantly affected by lower limb joint motion (hip, knee and ankle). Typical plots of lower limb joint motion are shown in figure 2.2.3.1. These plots show hip motion to range from about -20° to 20°, knee motion to range from about 2° to 60°, and ankle motion to range from about 10° to -20° (Winter, 1991).

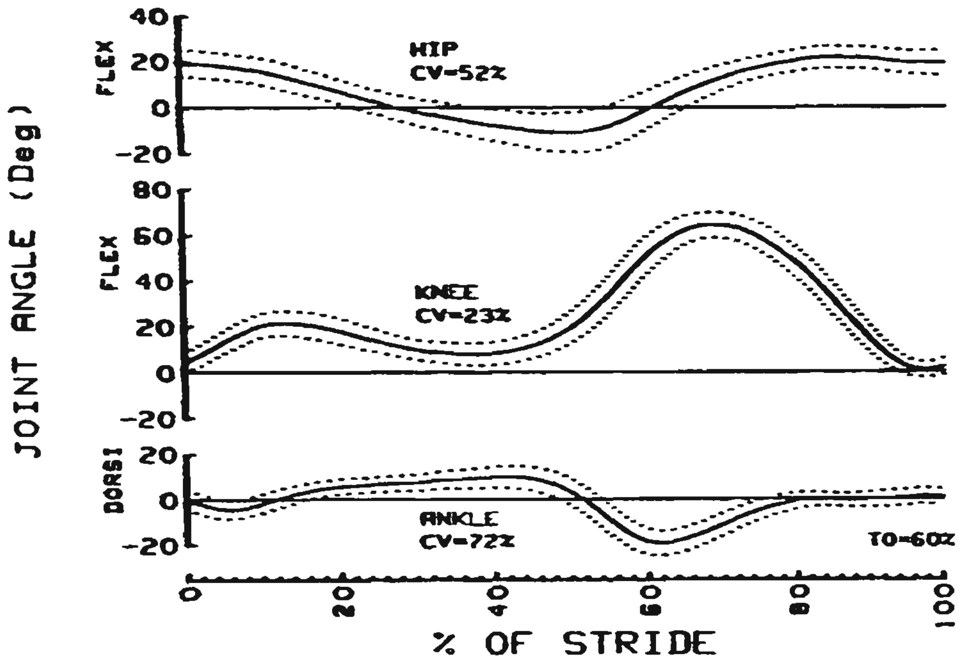


Figure 2.2.3.1 Typical plots of lower limb joint motion (taken from Winter, 1991, p. 28).

Other joint angle profiles reported for normal gait include trunk and head rotation (pitch) in the sagittal plane, and trunk roll motion in the frontal plane. Little agreement exists on the amount of trunk rotation that occurs during walking. Trunk flexion values (with respect to the earth vertical) ranging from 2 to 12° have been reported (Pozzo, Berthoz & Lefort, 1990; Krebs, Wong, Jevsevar, O'Riley & Hodge, 1992; Prince, Winter, Stergiou & Walt, 1994;

Sartor, Alderink, Greenwald & Elders, 1999). Trunk flexion peaks have been observed near each heel strike, with maximum trunk extension occurring during single limb support (Krebs et al., 1992). Murray, Drought and Kory (1964) found the transverse rotation of the trunk of 60 males to be about 6.9 ± 1.9° in normal gait. Opila-Correia (1990) reported the average trunk kinematics of 14 females in normal gait to be: trunk flexion-extension = 11.1°, abduction-adduction = 12.6°, and medial-lateral total angular excursions relative to the pelvis = 17.5°.

Head pitch motion in the sagittal plane has been measured to be about 11° (Pozzo et al., 1990) and trunk roll movements have been found to show a cyclical pattern less than ± 3° (Patla, Adkin & Ballard, 1999). Pozzo et al. (1990) also found pitch rotation and vertical displacement of the head to co-vary (in the sagittal plane) in the normal gait of a small group of 10 adults aged 20-45 years; that is, the head always rotated in the opposite direction from its translation along the vertical axis: a downward rotation of the head was accompanied by an upward movement, and vice versa (refer to figure 2.2.3.2). The predominant frequencies of head pitch rotation and translation were reported to fall between 0.2 - 1.0 Hz.

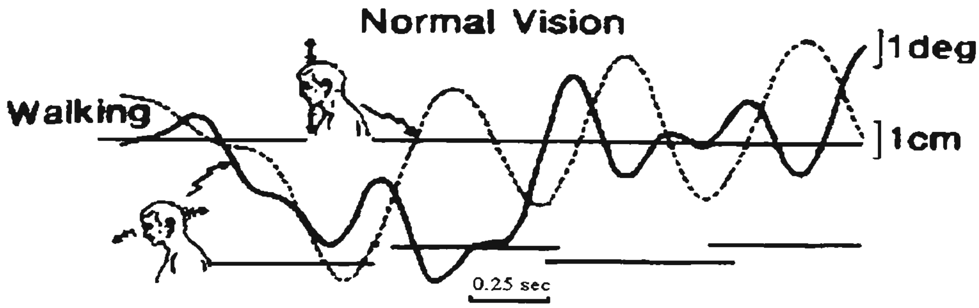


Figure 2.2.3.2 Head translation along the vertical axis (dotted line) and rotation in the sagittal plane (solid line) during free walking (taken from Pozzo et al., 1990, p. 101).

2.2.4 The role of vision

The precise detection of sensory information is necessary for safe and purposeful travel. Visual information plays an important role in the pro-active control of gait, whereas kinesthetic and vestibular information is important in the reactive control of balance should unexpected foot contact with the ground or an object occur (Patla, 1997).

Deterioration of the body's perceptual systems can have a dramatic affect on a person's ability to pro-actively deal with, or recover from, perturbations. Accurate estimation of self-motion and limb position, for example, is important in the maintenance of dynamic stability. Errors in its estimation may be dangerous since it may reduce the time available to react to known or unexpected perturbations.

An early investigation (Patla, Robinson, Samways & Armstrong, 1989) found that visual information is most useful in the planning stage of locomotion, or when the foot to be repositioned is still on the ground. The period of visual sampling was also found to be dependent on the amplitude or complexity of the adjustment required; the greater the adjustment, the longer the time that is needed.

More recently, Patla, Adkin, Martin, Holden and Prentice (1996) found vision to play a minor role in the normal gait of young adults. Its role, however, was observed to become increasingly important in perturbed environments (e.g., a winding path or a path containing obstacles). This study, for example, found straight path locomotion over even terrain only required a person to visually sample the environment for less than 10% of the travel time. In the perturbed environments, however, sampling time increased to about 30%.

Perturbations experienced by the head during locomotion may threaten the accuracy of the sensory information required for safe and purposeful travel (Grossman, Leigh, Abel, Lanska & Thurston, 1988; Patla, 1997). Various volitional and reflexive mechanisms are used to ensure the quality of this information (Grossman et al., 1988; Pozzo et al., 1990; Winter, 1991; Patla, 1997). The spinal column, for example, dampens the effect of pelvic acceleration in order to attenuate anteroposterior movement of the head. Winter (1991) has reported the anteroposterior acceleration of the head to be about a third of that experienced at the hip; this prevents blurring of the image on the retina and affords a stable gravitational reference for the vestibular system (Winter, 1991).

2.2.5 Age-related differences

Age-related gait dysfunctions become increasingly evident in the 7^{th} decade of life (Smidt, 1990; Whittle, 1991; Prince et al., 1997). The most common manifestations of a failing gait pattern include reductions in measures such as walking velocity, step length and cadence, coupled with an increase in step width (Hageman & Blanke, 1986; Blanke & Hageman, 1989; Smidt, 1990; Whittle, 1991; Öberg et al., 1993; 1994; Ostrosky, VanSwearingen, Burdett & Gee, 1994; McGibbon & Krebbs, 2001).

McGibbon & Krebs (2001) reported that in normal gait the elderly lead with the trunk, whereas the young lead with the pelvis. The authors proposed that a trunk-leading strategy may be a response to lower extremity weakness. Essentially, they suggested that the musculature of the pelvis and trunk is used to advance, or pull, the leg into the swing phase when the lower extremity muscles (ankle plantarflexors and knee extensors) are weakened from aging.

Winter (1991) found the minimum toe-ground clearance of a group of elderly adults (1.12 cm; n = 18) to be less than a group of young adults (1.29 cm; n = 11) in normal gait; these clearances were not found to be significantly different. In addition, the horizontal landing velocity of the heel of the older adults (1.15 $m \cdot s^{-1}$) was found to be significantly greater ($p < .01$) than the young adults (0.87 $m \cdot s^{-1}$). Low foot-ground-clearances increase the chance of a trip or stumble, whereas high foot landing velocities (horizontal) increase the chance of a slip-induced fall on a compliant or slippery surface.

Karst et al. (1999) reported a mean minimum toe-ground clearance of 1.29 cm for a group (n = 16) of elderly adults in normal gait. Interestingly, the investigators found a reduction in this variable (1.05 cm) when the elderly adults walked at a fast velocity or about 25% faster than their normal velocity. In addition, the horizontal landing velocity of the heel was found to be less (0.330 $m \cdot s^{-1}$) in the normal velocity condition compared to the fast velocity condition (0.491 $m \cdot s^{-1}$). Disappointingly, statistical comparison tests were not conducted on these variables.

Other age-related gait changes have been found in joint angle profiles during normal gait (Hageman & Blanke, 1986; Smidt, 1990; Whittle, 1991; Öberg et al., 1994; Nigg, Fisher & Ronsky, 1994; Ostrosky et al., 1994; Judge, Davis and Ounpuu, 1996; Crosbie, Roongtiwa & Smith, 1997a; 1997b; McGibbon & Krebs, 2001). Typically, these have involved reductions in: (1) low-back (trunk relative to pelvis) motion; (2) hip motion (flexion and extension); (3) knee motion - flexion in the swing phase, and extension at the end of the swing phase; (4) ankle motion (plantar/dorsiflexion); (5) peak ankle plantarflexion at toe-off; and, (6) transverse rotation of the pelvis. Increases in foot placement angle (toe-out) and knee extension angle at midstance have also been reported in the elderly. Most of these changes have been directly attributed to the age-related reduction in step length.

Whittle (1991) reported the vertical movement of the head to decrease and its lateral movement to increase with age. These age-related changes most likely result from a reduction in step length and an increase in step width respectively.

Significant age–related differences in head and hip horizontal acceleration have been reported by Winter (1991). Lower hip acceleration was found in the elderly (1.54 $m \cdot s^{-2}$) compared to the young (1.91 $m \cdot s^{-2}$), while greater head acceleration was found in the elderly (elderly = 0.621 $m \cdot s^{-2}$, young = 0.475 $m \cdot s^{-2}$, $p < .05$). These results show the elderly were able to reduce their horizontal head acceleration, relative to horizontal hip acceleration, by about 58% compared with 77% for the young ($p < .02$). It was suggested that this difference may be caused by a degeneration in the control of the trunk or a reduced gain in the vestibular system of the elderly. A reduction in the gain of the vestibular system requires larger acceleration input in order to monitor head accelerations. Patla (1997) has also suggested that such constant jarring of the head, if uncorrected, is undesirable because it may cause distortion of the visual image on the retina.

To date, few investigations have examined age-related differences in the role of vision in gait. In a recent investigation, Anderson, Nienhuis, Mulder and Hulstijn (1998) found that a group of older adults ($n = 19$) looked at the ground more often than a group of young adults ($n = 10$) whilst walking free of restriction (full visual field) and walking with a restricted visual field. In the restricted condition, visual information from the floor in front of the subject's feet was blocked. The authors concluded that older adults are more dependent on visual input to regulate the velocity of gait.

Few age-related differences in the kinetics of free walking have been found (Chao, Laughman, Schneider & Stauffer, 1983; Winter, 1991; Nigg et al., 1994; Eng & Winter, 1995; Judge et al., 1996). The most consistent finding being a reduction in ankle plantarflexor power during the push-off phase. Compared to young adults, elderly adults have been found to exhibit less horizontal reaction force at push-off (Winter, 1991). This reduction is directly related to the shortened step length observed in the elderly.

2.2.6 Summary

To date, studies have provided valuable information about the characteristics of normal gait. In order to achieve safe, efficient and/or purposeful travel, numerous tasks must be executed (Winter, 1989). The most important of these tasks are: (1) the control of foot trajectory so as to achieve ground clearance and a gentle heel or toe landing (i.e. prevent a stumble, trip or slip that may bring about a fall); (2) the maintenance of upright posture and balance (i.e. prevent a fall in the antero-posterior or lateral directions); (3) the maintenance of support of the upper body against gravity during stance (i.e. prevent lower limb collapse); and, (4) the precise detection of sensory information (visual, kinesthetic and vestibular). Accurate estimation of self-motion and limb position is necessary so that pro-active and reactive control of gait may be achieved. Any distortion of this information may jeopardize dynamic stability or lead to a stumble, trip or fall (Patla, 1997).

There is strong evidence of age-related differences in normal gait. Studies (e.g., Öberg et al., 1994; Ostrosky et al., 1994; McGibbon & Krebbs, 2000) have reported age-related reductions in: (1) step length, cadence and walking velocity; (2) foot-ground-clearance (age and gait velocity-related); (3) most joint angle ranges of motion; (4) vertical movement of the head; (5) the capacity to lead with the pelvis; and, (6) the ability to attenuate horizontal head acceleration.

Furthermore, studies (e.g., Whittle, 1991; Winter, 1991; Anderson et al., 1998) have reported increases in: (1) step width; (2) horizontal foot landing velocity; (3) lateral movement of the head; (4) horizontal hip acceleration; and, (5) visual sampling time.

Although studies have provided valuable information about normal gait, more research focussing upon age-related differences is needed so as to better understand the high incidence of falling behaviour exhibited by elderly adults. Many questions still remain about issues pertaining to the achievement and maintenance of dynamic stability. For instance, few investigations have examined the effect of gait velocity (e.g., comfortable versus fast) upon important parameters such as foot-ground-clearance or foot landing velocity (horizontal). Interestingly, Karst et al. (1999) reported a reduction in foot-ground-clearance and an increase in foot-landing velocity when walking fast. These changes could place a person at greater risk of a serious fall as a result of foot contact with an object or the ground.

In elderly gait, no studies have examined head pitch motion. Greater motion however, probably distorts the visual image on the retina leading to a reduction in the quality of visual information. There is also ambiguity (Winter, 1991; Karst et al., 1999) as to the extent of age-related differences in the horizontal velocity of the landing foot. Compared to young adults, Winter (1991) found greater velocities for a group of elderly adults, whereas Karst et al. (1999) found elderly adults to have a landing velocity half the magnitude of Winter's young adults. This parameter is important since literature suggests that high landing velocities increase the chance of a slip-induced fall on a compliant or slippery surface (e.g., Winter, 1991).

Further comparisons of young and elderly gait are needed. There are still many aspects of the gait changes associated with ageing that need to be confirmed or explored. As such, this project examines several of the issues raised in this section. Specifically, the effect of age and gait velocity upon important parameters such as foot-ground-clearance, foot-landing velocity, head pitch motion and trunk motion.

2.3 The characteristics of adaptive gait

Traditionally, gait studies have mainly involved walking at self-selected speed along a straight, flat and unobstructed path. These investigations have provided a large database on the characteristics of basic gait but have not provided much insight into the characteristics of obstructed or adaptive gait.

Recently, researchers have begun to examine the gait adjustments made to meet the demands of terrain that is uneven or winding, or contains objects such as a step or low barrier. These adjustments (Patla, 1991) represent a complex re-organisation of the basic gait pattern and involve either an avoidance (step around or over), recovery (regain balance) or accommodation strategy (step on).

Investigations of obstructed gait are important since the literature shows that older adults (particularly older females) fall in terrain containing surface height changes (e.g., a single step, kerb or door threshold). Tripping on a level surface or over an object, for example, is the most frequently reported cause of a fall in the elderly population (e.g., Campbell et al., 1990; Berg et al., 1997). Reasons cited by fallers include hurrying, not looking at the travel path, accidental foot contact with the ground or an obstacle, a misplaced step and slipping (Berg et al., 1997).

In the obstructed gait literature, the first limb to negotiate or cross an obstacle is often referred to as the ipsilateral or lead limb, and the trailing limb is often referred to as the contralateral or stance limb. These terms, therefore, are interchangeable and are used throughout this review.

2.3.1 Avoidance strategies

Avoidance strategies have been defined by Patla (1991) to include all the modifications that are made to avoid stepping on a particular surface perceived to be unsafe or detrimental to travel. A pothole or a sharp obstacle, for example, represent inappropriate surfaces for stepping. To avoid such surfaces, one can regulate step length, step width and foot-ground clearance to go over an obstacle, change direction to go around an obstacle, or stop.

2.3.1.1 Steering control

Studies have provided important information about the gait adjustments made to suddenly turn or stop (steering control). Steering control studies, for example, involving young adults (Patla et al., 1991; Patla et al., 1999; Vallis, Patla & Adkin, 2001) have shown that: 1) turns or direction changes cannot be achieved in the ongoing step, whereas stance width can be changed in this step. Patla et al. (1991) claimed these results provide evidence that direction change within the same step is not limited by reaction time but by the inability of lower limb musculature (stance limb rotators and invertors-evertors) to generate the forces required to change direction; 2) the order of control for a steering task is head and trunk re-orientation followed by movement of the centre of mass (*COM*) in the direction of travel; that is, looking at your travel path is critical for steering;

3) foot-placement and trunk-roll-motion mechanisms are used to move the *COM* towards the new travel path; 4) when steering is compromised the central nervous system delays committing the movement of the *COM* until it has acquired visual information about the new path; and, 5) when time is at premium, a cross-over strategy cannot be safely used to change direction. A cross-over occurs when a person moves to the contralateral side with their ipsiplateral limb. Movement to the right side, for example, is made with the left limb (cross-over) whilst the right limb is in stance.

Investigations have examined the ability of adults to suddenly turn or stop (Cao et al., 1997; 1998a; 1998b). Elderly females were found to be less successful ($p < .05$) than elderly males or young adults. Both the elderly females and males, however, needed more time ($\approx$ 28 to 43 ms longer, $p < .001$) than the young to arrest forward momentum.

Cao et al. (1997; 1998a; 1998b) suggested the observed age and gender differences in the ability to suddenly stop or turn were due to the way in which muscle contraction processes, and perhaps pre-motor processes, occur. They proposed the lower rates of success exhibited by the elderly adult females were due to their reduced capacity to rapidly generate torques at the ankle. Such a finding is important since it suggests that the dynamic stability of older females may be compromised when hurrying to cross (descend or ascend) a step or kerb. Since the lower limb musculature plays a key role in maintaining dynamic stability in such terrain, any decline in the capacity of the lower limb musculature to accept weight rapidly may predispose a person to a fall.

2.3.1.2 Stepping over obstacles

The majority of obstacle avoidance studies have focused on the gait adjustments made by young adults to step over a fixed object. The objects used in these studies were rods placed across adjustable stands, light-bands, and barriers of varying proximity, height and width. In several studies, the object appeared suddenly on a walkway so as to examine the young adult's ability to deal with an obstacle under time critical conditions.

Studies have primarily focused upon the spatio-temporal aspects of obstructed gait (e.g., Chen et al., 1991; Chou et al., 2001; McFadyen & Prince, 2002). Typically, gait measures such as step length and time, foot-obstacle clearance, foot placement, crossing and landing velocities (foot and hip), trunk and lower-limb joint angular motions have been examined. Some of these variables are shown in figure 2.3.1.2.1. In addition, some studies have examined the trajectory of the foot in the crossing step (e.g., Patla & Rietdyk, 1993; Patla et al., 1996).

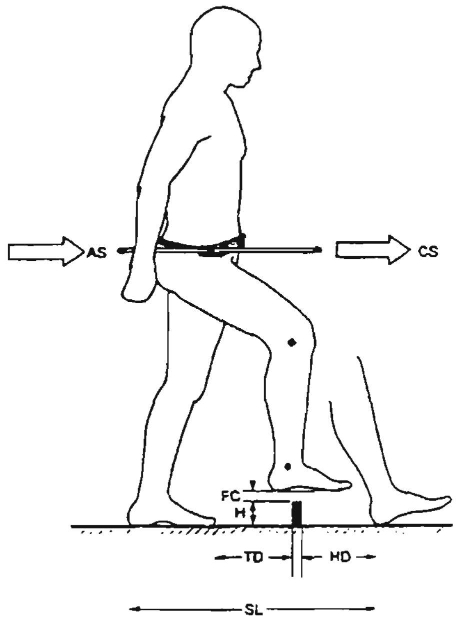


Figure 2.3.1.2.1 Schematic drawing showing spatio-temporal measures collected by Chen et al. 1991 (taken from Chen et al., 1991, p. 197). AS: approach speed; CS: crossing speed; FC: foot clearance; H: obstacle height; HD: heel-obstacle-distance; TD: toe-obstacle-distance; SL: step length.

An early study conducted by Chen et al. (1991) appears to be the first major investigation into the effect of age upon obstructed gait (solid object). Watanabe and Miyakawa (1991) similarly examined this issue but the investigation involved low subject numbers coupled with only a few outcome measures. Only 14 adults participated (4 were elderly) in the latter study, whereas 48 adults (24 were elderly) participated in Chen et als' study. In fact, compared to other obstructed gait studies, Chen et als' study is notable for the involvement of large subject numbers. Typically, obstructed gait studies have involved subject numbers of 12 or less. Patla and Prentice (1995) and Chou et al. (2001), for example, only used six subjects.

Chen et al. (1991) used four obstacle-height conditions of 0, 2.5, 5.2, and 15.2 cm (depth: 2.5 cm). Subjects demonstrated no change in approach speed with increased obstacle-height, but significant decreases in crossing speed and increases in foot-clearance were observed ($p < .0001$). The minimum foot-clearances (lowest point of the heel, toe or sole), for example, found across all subjects for the 2.5 cm and 15.2 cm obstacles were 6.4 cm and 11.9 cm respectively. Watanabe and Miyakawa (1991) similarly found foot-clearance to increase with obstacle height. Obstacle heights of 0, 4, 8 and 12 cm (depth: 2.5 cm) were employed in this study. Foot-clearance was found to increase significantly ($p < .05$) from about 7 cm for the lowest obstacle to about 13.5 cm for the highest obstacle. Interestingly, significant age-related differences in foot-clearance measures were not found in these studies.

Chen et al. (1991) found the sole of the lead foot to be essentially horizontal at the time it crossed the obstacle. Toe-obstacle-distance and heel-obstacle-distance were found to be approximately equal for each obstacle condition; typical values for these measures ranged between 19 and 25 cm. This shows the participants crossed the obstacles in mid-step. Significant decreases with age were found for crossing speed ($p < .0001$), crossing step length ($p < .0001$), heel-obstacle-distance ($p < .0001$), and step width ($p < .003$). Interestingly, the authors concluded that the age-related reductions in measures such as crossing step length or heel-obstacle-distance actually increased the risk of stepping on the light-band. This was supported by the fact that 4 of the 24 elderly adults contacted the obstacle with the heel, whereas none of the young adults made contact.

In Chen et als' study, the lead limb was defined as the limb subjects were observed to use to kick an object after a 4 m approach. The adoption of this protocol may have compromised the ecological validity of this study since subjects were constrained to use a pre-determined lead limb. This practice may have confounded outcomes since non-typical crossing patterns may have been adopted. Other obstructed gait studies have adopted similar protocols where participants have been constrained to use a pre-determined lead limb such as the right limb (e.g., McFadyen et al., 1993; Patla & Prentice, 1995; Chou & Draganich, 1997; Austin et al., 1999). A superior method involves the practice of allowing subjects to naturally select the lead limb when avoiding an obstacle, as opposed to forcing them to use the same limb or some arbitrarily identified lead limb. Importantly, recent studies have begun to adopt such a lead limb protocol (e.g., Begg, et al., 1998; Chou et al., 2001).

Some studies have examined the ability (rate of success) of adults to avoid stepping on objects that have suddenly appeared on a walkway (Patla et al., 1991; Chen et al., 1994a; 1996; Patla, Prentice, Rietdyk, Allard & Martin, 1999). The objects were light-bands or light-patches projected onto the walkway at predicted footfall positions (refer to figure 2.3.1.2.2) and a 'pop-up" solid barrier placed at varying positions within the step cycle that dropped to the floor if it was struck by a subject (refer to figure 2.3.1.2.3).

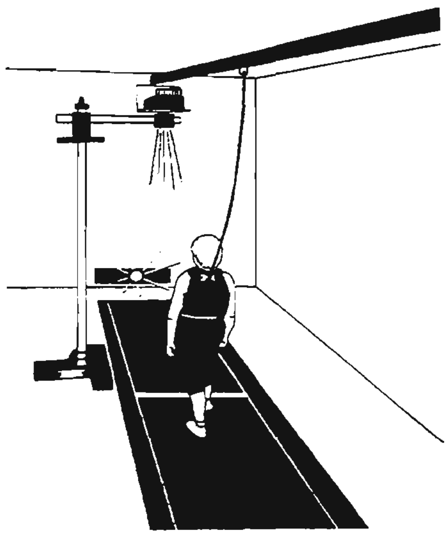


Figure 2.3.1.2.2 Schematic diagram of the experimental apparatus used by Chen et al. (1994a; 1994b; 1996). A light-band (3 cm depth) was projected onto the walkway (taken from Chen et al., 1996, p. 117).

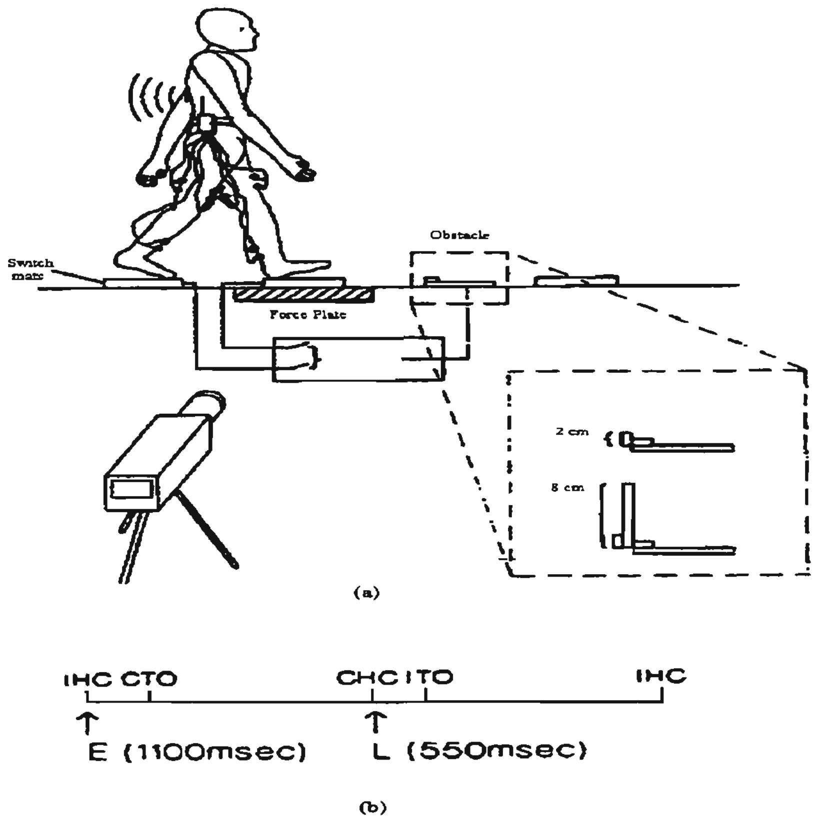


Figure 2.3.1.2.3 Part (a) is a schematic diagram of the obstacle avoidance experimental setup used by Patla et al. (1991). The subject goes over the obstacle (apparatus shown in detail in the inset) with the right (ipsilateral) limb first. Part (b) is a diagram showing when the obstacles were triggered, superimposed on the temporal structure of a normal stride (*IHC* denotes ipsilateral heel contact; *CHC* denotes contralateral heel contact; *ITO* denotes ipsilateral toe-off; and *CTO* denotes contralateral toe-off.

A study by Patla et al. (1991) found young adults need an available response time (*ART*) of about 1000 ms or more (two step durations) in order to safely step over a solid object (height: 8 cm); that is, in order to avoid the object, the subjects needed to see it at least two step durations (≈ 1000 ms) ahead. A 100% success rate was found for lower object heights (0 and 2 cm) when the *ART* was equivalent to one step duration (≈ 500 ms). This demonstrates that young adults can modify limb trajectory within a step cycle and step over objects of a reasonable size.

Chen et al. (1994a; 1996) has shown that older adults are more likely to contact a virtual obstacle (light-band) under time critical conditions. In particular, a sudden obstacle presentation coupled with a simple divided-attention task (e.g., responding vocally to a light cue) was found to significantly reduce ($p < .01$) the rate of success of the elderly adults compared to the young adults.

In a subsequent paper, Chen et al. (1994b) examined the stepping strategies employed in the previous study (1994a). Subjects were found to either shorten their normal step length (*SSS*) and then take an extra crossing step, or take a longer crossing step (*LSS*) to avoid the light-band (refer to Figure 2.3.1.2.4). No significant age differences were found in the choice of strategy; that is, both the young and the elderly exhibited similar *SSS* and *LSS* frequencies across *ART* conditions. Both age groups were found to use the *SSS* more often (*SSS* ≈ 56%) in the *ART* conditions of 350 ms or less, compared to *ART* conditions of 400 ms or more (*SSS* ≈ 36%). It was suggested that this strategy is physically easier to implement under short *ART* conditions but is inherently dangerous since the body may be placed in an unstable position where the *COM* is further forward of the base of support. The chance of a misstep may also be greater for this strategy since this study found the foot to be placed closer to the obstacle in *SSS* (≈ 9 cm) compared to the *LSS* strategy (≈ 16 cm).

Chen et al. found the elderly ($p < .001$) failed to achieve a 100% success rate even when the obstacle was presented two step durations ahead (≈ 1000 ms), whereas the young successfully stepped over it every time. This is an important finding since it shows that the elderly are a greater risk of obstacle contact even when the obstacle is presented two step durations ahead. Interestingly, the earliest the young were found to adjust their step length whilst approaching the obstacle was less than three steps ahead, whereas the elderly were found to adjust their stepping pattern one step earlier. This suggests the elderly may need more than two step durations in order to avoid an obstacle that appears suddenly.

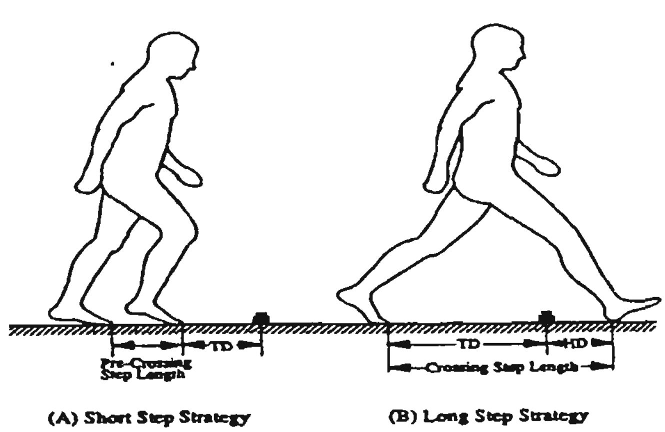


Figure 2.3.1.2.4 (a) Short step (*SSS*), and (b) long step (*LSS*) strategies used by Chen et al. (1994b) (taken from Chen et al., 1994b, p. 141).

Chen et al. found three of the older adults and one of the young adults to completely lose balance and fall. All falls involved faster than normal walking speed and occurred at obstacle presentation times of 450 ms or less. Two of the falls were associated with a sudden shortening of the pre-crossing step. The two subjects involved (a young and old adult) shortened their pre-crossing step to a point where their *COM* was so far forward of their base of support that they could not recover balance by taking additional steps. The other two falls involved older adults who began to step on the obstacle and, in a belated avoidance manoeuvre, tried to avoid lowering the foot onto it. This caused them to fall in an antero-lateral direction. The falls occurred, after footstrike, when they tried to avoid lowering the forefoot or heel onto the obstacle.

Some methodological limitations are evident in the studies conducted by Chen et al. (1994a; 1994b). Only four normal walking trials (unobstructed walking), for example, were included in each of the three identical blocks of trials. The probability, therefore, of the virtual obstacle appearing was high; that is, 14 out of 18 chances. Subjects may have anticipated the appearance of the virtual obstacle and employed some anticipatory locomotor adjustments prior to its appearance. This is supported by studies conducted by Maki, McIlroy and Perry (1994) and McIlroy and Maki (1995) who found that predictability of a perturbation brings about anticipatory movements that place the body in a more stable position to deal with it. It has also has been suggested that the first response to a perturbation (e.g., a novel travel path) is fundamentally different from subsequent responses (Thomson, 1983; Maki et al, 1994; McIlroy & Maki, 1995; Patla et al., 1996). This idea, coupled with the previous findings, support the notion that clinical or experimental assessment of obstructed locomotion is most likely confounded by adaptive changes that occur during repeated or blocked testing methods adopted by studies such as Chen et al. (1991; 1994a; 1994b; 1996). Studies, therefore, may profitably gain by focusing more upon the first compensatory responses to the novel travel path or disturbance.

The studies conducted by Chen et al. (1994a; 1994b; 1996) also used a safety-harness device in order to protect participants from injury. A question remains, however, as to what influence harness-support devices have upon an avoidance or recovery response. For instance, Rietdyk and Patla (1998) have suggested these devices allow a person to modify the recovery response since the nervous system is able to perceive the increase in stability offered by the device. Furthermore, they suggested toe-clearances are probably lower when harness-support devices are employed since the consequences of foot contact with an obstacle are not as serious.

The suggestion put forward by Rietdyk and Patla is partly supported by an earlier study (Patla et al., 1996) which found evidence of more cautious behaviour when stepping over a fragile obstacle (refer to figure 2.3.1.2.5). Lead toe clearance ($\approx$ 14.6 cm), vertical position of the lead hip, and lead hip vertical velocity, for example, were found to increase significantly ($p < .05$) for at least 4 of the 6 young adult participants when going over a fragile obstacle compared to a solid obstacle (toe clearance $\approx$ 11.8 cm). It was proposed that these differences represented a cautious response influenced by the consequences of error. If a subject were to accidentally hit the cylinders, the rolling cylinders would pose a far greater hazard to travel than the solid obstacle would in similar circumstances. Added precaution, therefore, would be natural; that is, the participants modified their response because of the increased penalty of contact with the fragile obstacle.

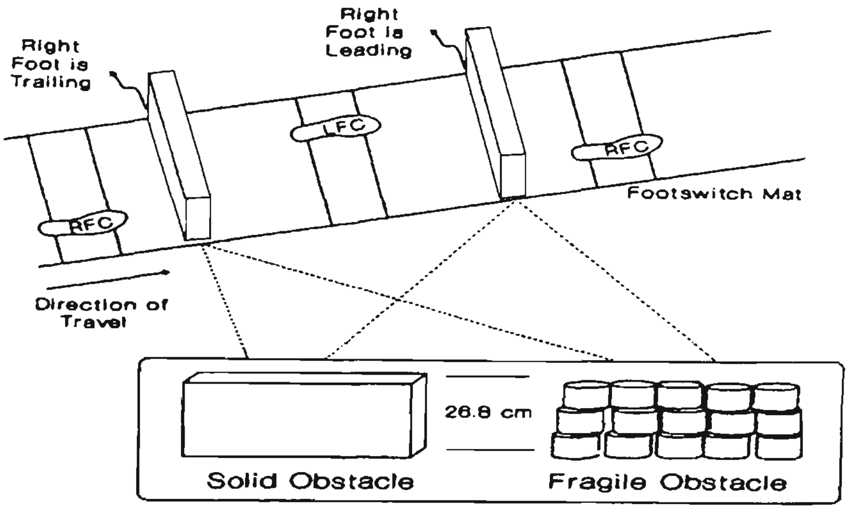


Figure 2.3.1.2.5 A schematic diagram of the experimental setup used by Patla et al. (1996). The obstacle position when the right limb is leading or trailing are shown. *RFC* = right foot contact; *LFC* = left foot contact (taken from Patla et al., 1996, p. 37).

Interestingly, Patla et al. (1996) found the trail limb to be unaffected by obstacle fragility, nor were any differences found between the toe clearances of the lead and trail limbs. Differences, however, in the trajectories and velocities of the trail and lead limbs were observed. The trail limb moved upward while going over the obstacle, whereas the lead limb began its descent at this point. The vertical toe velocity was significantly higher for the trail limb ($p < .05$), whereas the horizontal toe velocity was significantly higher for the lead limb ($p < .05$). The lead limb had a higher vertical velocity at landing with the limb moving backward at foot contact: no significant difference was found in this measure. The authors concluded these actions were representative of an attempt to reduce the dangers of a trip when crossing the obstacle or a slip upon landing.

In a recent study involving an obstacle (length: 122 cm; depth 5 cm; height: 11.75 cm) avoidance task, McFadyen and Prince (2002) found age-related reductions ($p < .05$) in the following outcome variables: (1) foot-obstacle-clearance (elderly adults ≈ 8 cm, young adults ≈ 10 cm); (2) crossing speed; (3) stride length; and, (4) lead foot-heel-placement past the obstacle (elderly adults ≈ 28 cm, young adults ≈ 35 cm). No age difference was found in trail-toe-obstacle distance (≈ 30 cm). In general, these findings are in agreement with earlier work conducted by Chen et al. (1991). Chen et al., however, did not find a significant age-related difference in foot-obstacle-clearance but reported similar magnitudes.

Other studies of obstructed gait have primarily involved small numbers of young adults (McFadyen et al., 1993; Patla & Prentice, 1995; Liu, Patla, Sparrow, Charlton & Adkin, 1996; 1997; Chou, Draganich & Song 1997; Chou & Draganich, 1996; 1997; 1998a; 1998b; Austin et al., 1999; Begg et al., 1998; Patla et al., 1999; Chou et al., 2001; Krell & Patla, 2002). The objects used in these studies were rods or elastic bands placed across adjustable stands, barriers and light-patches.

In general, more cautious behaviour has been reported for obstacle avoidance tasks: (1) compared to level walking, the horizontal velocity of the lead toe (crossing and landing) is less ($p < .0001$) when stepping over an object (Patla &

Rietdyk, 1993); (2) the hip and *COM* are "held back" or behind the location of the toe of the support foot until the lead toe reaches the top of an obstacle (Patla & Rietdyk, 1993; Liu et al., 1996); (3) greater knee flexion and dorsiflexion of the lead foot (McFadyen et al., 1993) are exhibited when an object is placed close to the stance foot (trail limb); (4) trail limb support time, compared to lead limb support time, is significantly longer ($p < .01$) when stepping over obstacles (Begg et al., 1998); and, (5) lead limb crossing time and crossing speed reduce ($p < .001$) as the height of an obstacle increases (Sparrow et al., 1996; Begg et al., 1998). No changes in crossing step/stride length or walking base, however, have been found with increases in obstacle height (Begg et al., 1998; Chou et al., 2001).

Two strategies have been observed to provide the lead limb elevation needed to clear an obstacle (Patla & Rietdyk, 1993). These include: (1) an upward bias provided by the stance limb (greater vertical push-off); and, (2) alteration of the limb trajectory (dominant strategy) through greater knee and hip flexion. Lead limb knee and hip flexion have been shown to increase ($p < .0001$) with obstacle height.

Similar magnitudes of toe-obstacle-clearance ($\approx$ 10 cm) have been reported for the lead and trail foot (e.g., Patla & Rietdyk, 1993; Patla & Prentice, 1995; Patla et al., 1996; Austin et al., 1999). Trail foot heel-obstacle-clearance ($\approx$ 30 to 45 cm), however, has been found to be greater (Sparrow et al., 1996) than lead foot heel-obstacle-clearance ($\approx$ 10 to 15 cm) and increases with obstacle height.

Lead toe-obstacle-clearance has also been found to increase with obstacle height ($p < .001$).

Significant reductions ($p < .01$) in trail limb toe-obstacle-clearance (young adults only) have been found with reductions in toe-obstacle-distance from an object (Chou & Draganich, 1998a; 1998b). In fact, a reduction in toe-obstacle-distance coupled with an increase in obstacle height resulted in more foot contacts (refer to figure 2.3.1.2.6) with an obstacle (Chou and Draganich, 1998a). This finding is important since it suggests that populations such as the elderly may be at greater risk, compared to young adults, of a fall resulting from trail foot contact. Age-related reductions in vision, for example, may cause the trail foot to be positioned too close to an obstacle. This action, coupled with a reduction in lower extremity strength, may reduce the capacity of an elderly person to achieve safe elevation of the limb or recover balance should foot contact occur. Investigations involving young adults, however, have not found lead or trail toe-obstacle-distances to change with obstacle height or proximity (Sparrow et al., 1996; Chou et al., 2001; Krell & Patla, 2002). In fact, this parameter has been found to remain essentially invariant.

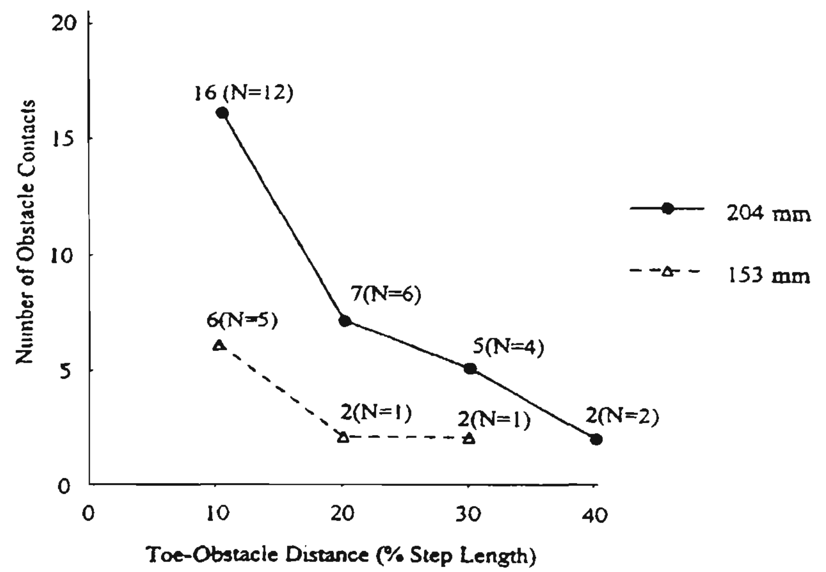


Figure 2.3.1.2.6 Reducing the toe-obstacle distance of the trailing limb results in contact of the trailing foot with the obstacle of 153 and 204 mm heights. The total number of obstacle contacts increased with obstacle height and with decreasing toe-obstacle distance. Numbers given at the data points represent the total number of contacts for all subjects and for the number of subjects contacting the obstacle. For example, 16 (n = 12) indicates that there were a total of 16 obstacle contacts for the group of subjects with 12 of the subjects contacting the obstacle of 204 mm height at a distance of 10 % (taken from Chou and Draganich, 1998a, p. 688).

In all, the methods adopted by the studies were appropriate. Some, however, show limitations. Firstly, many of the studies used a pre-determined lead limb method (e.g., Patla & Prentice, 1995; Chou & Draganich, 1997; 1998a; 1998b; Chou et al., 1997) and some adopted blocked trial methods (e.g., McFadyen et al., 1993). The limitations of these methods have been previously discussed. Secondly, the average walkway length was about 9 m with the longest being 12 m (e.g., Patla et al., 1999) and the shortest 4 m (Austin et al., 1999). The short walkways most likely constrained the subject's gait (stepping pattern) since they may not have achieved a transport phase in the approach (2 m approach) to the obstacle or departure from it (2 m departure); that is, they were probably adjusting their gait pattern as soon as they began walking towards the obstacle (and after crossing it) due to limited walkway space. The average step length of an adult female, for example, is about 60 cm (Öberg et al., 1993), therefore a 4 m walkway only allows 3-4 steps to the object.

Further comparisons of the ability of the young and elderly to avoid an obstacle are needed. There are still many age-related changes in gait to be explored or confirmed. Only one investigation, for example, appears to have examined the effect of speed on the ability of a person to step over an obstacle (Liu et al., 1996). Hurrying too much has been associated with falls (Australian Bureau of Statistics, 1995a).

In brief, this project aimed to improve and extend work in the field of obstructed gait by; 1) focusing on the first response to an obstacle; 2) allowing subjects to choose the lead limb; 3) increasing participant numbers in order to improve the power of comparison tests; 4) examining the effect of hurrying; 5) improving ecological validity by not employing a harness-support device; and, 6) extending the length of the walkway so as to ensure the integrity of the gait responses in approach and departure.

2.3.2 Recovery strategies

Important information has been provided by studies about the gait adjustments made by adults to regain balance control after perturbations such as a trip or unexpected release from a leaning position. Studies of young adults involving tripping perturbations, for example, have shown: 1) increases in trunk ($\approx 5°$ to

18°), hip (≈ 17° to 21°), knee (≈ 13° to 29°) and ankle (≈ 6° of dorsiflexion) flexion as a result of an unexpected trip (e.g., Grabiner, Koh, Lundin & Jahnigen, 1993; Eng et al., 1994). Grabiner et al. found the increase in maximum trunk flexion to be significantly related to pre-perturbation walking speed ($p < .05$); 2) the recovery strategy employed (elevating, lowering, and reaching of the perturbed lower limb) to be dependent upon the location (early or late in the swing phase) of the perturbation (Eng et al., 1994). For instance, an elevating response was found to be commonly used when the limb is obstructed in early swing (20% of the swing phase); a lowering response was predominantly used when the limb was obstructed in late swing (60% of the swing phase); and a reaching strategy was employed by some subjects during late swing; 3) balance corrections to be triggered by proximally located signals that are most likely located within the lower trunk or pelvis (Allum, Bloem, Carpenter, Hulliger & Hadders-Algra, 1998); 4) trip and step-down disturbances (floor collapse) generally result in a forward fall and abdominal pelvis impact with the ground (Smeesters, Hayes & McMahon, 2001a); forward falls may also result from a slip or faint when hurrying. At normal and slow walking speeds, slips usually result in sideways or backward falls with the hip or buttocks impacting with the ground (Smeesters et al). The act of fainting predominantly results in sideways falls and hip impact with the ground (Smeesters et al.); 5) the average trip duration (i.e. foot restraint) from which balance cannot be regained (within a single step) to be 681 ± 169 ms (Smeesters Hayes & McMahon, 2001b); and, 6) trip-induced falls may be due to slower reaction times and/or reduced lower extremity strengths (Smeesters et al., 2001b).

An investigation by Rietdyk and Patla (1998) warrants more detailed discussion. They examined recovery from lower limb obstruction (within a step) whilst in unilimb and trilimb support conditions (refer to Figure 2.3.2.1). Five young adult males participated in this investigation. The perturbation apparatus consisted of a thin, flexible metal strip (8 cm width, 1 m length) positioned on the ground immediately behind the left foot. The strip lay on the ground (flat) across the walkway and was manually triggered by the experimenter. The positioning of the apparatus ensured that the perturbation was always applied at the same position and phase (i.e. early swing). Nine percent of the 138 trials were obstructed and completely randomised.

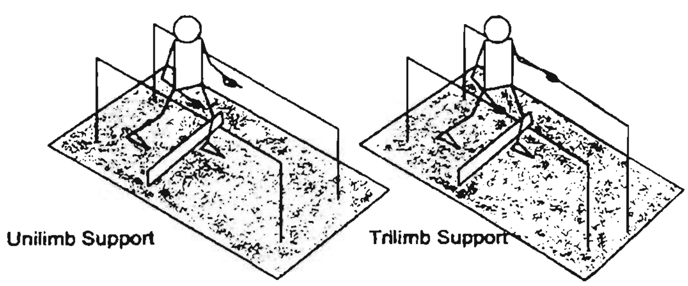


Figure 2.3.2.1 The experimental setup adopted by Rietdyk and Patla (1998) (taken from Rietdyk and Patla, 1998, p. 252).

The study by Rietdyk and Patla (1998) produced some notable outcomes. For instance, a greater reflex gain (greater dependence on the muscles of the stance limb) was found for unilimb support compared to trilimb support. This led the investigators to conclude that the availability of the arms for balance recovery, or the haptic information provided by the arms, was enough to reduce the control system's dependence on the stance limb for support. Basically, the nervous system perceived the increase in stability provided by the arms and pro-actively modified the response.

According to Rietdyk and Patla (1998), this finding has important implications for harness-supported testing. Essentially, the use of support devices may confound outcomes since the body's control system is able to accurately perceive a change in the threat to stability and modify the response accordingly. This notion is further supported by the differing voluntary lower limb reaction times reported in two studies (Thelen et al., 1997; Wojcik et al., 1999). In a balance recovery task involving a harness-support system, Wojcik et al. found reaction time to fall around 60 to 70 ms. In contrast, Thelen et al. (1997) reported reaction time in the absence of a harness-support system to be about 150 ms. Wojcik et al. proposed that the shorter reaction times probably resulted from the harness activating pressure receptors in the abdominal and lumbar region.

Several studies have focused on age and gender-related differences in the ability of adults to regain balance after a trip or unexpected release from a forward leaning position. These studies found: 1) the mean maximum forward lean (16.2°) from which older females can regain balance (within a single step) is significantly smaller ($p < .05$) than that (average = 29.1°) for young females, young males and older males (Thelen et al., 1997; Wojcik et al., 1999); 2) older females exhibit the lowest step velocity and longest reaction times ($\approx$ 20 ms longer) when recovering from an unexpected release from a forward leaning position (Wojcik et al., 1999); 3) compared to older males, older females (in particular women aged 65-69 years) exhibited the highest incidence of falls (older males = 7%, older females = 36%) when the lead limb was unexpectedly obstructed by an obstacle in mid to late swing (Pavol, Owings, Foley & Grabiner, 1999). The likelihood of falling from a trip appears to be linked to faster walking speed ($\approx$ 1.31 $m{\cdot}s^{-1}$), shorter step time, and longer step lengths; 4) during and after-step falls (trip-induced) are directly linked to fast walking speed in the elderly (Pavol, Owings, Foley & Grabiner, 2001); 5) young adults exhibit larger stepped-leg joint torques when regaining balance from an unexpected release from a forward lean (Wojcik, Thelen, Schultz, Ashton-Miller & Alexander, 2001). Compared to men, women use near maximal joint torques to recover balance; 6) older adults, and in particular those who fall, exhibit greater head movement and slower onset times than young adults when a standing platform is suddenly translated (Wu, 2001); 7) in order to regain balance after an obstacle-induced trip, an elderly person needs to contact the ground before the trunk angle exceeds 23° to 26° (van den Bogert, Pavol & Grabiner, 2002). Interestingly, this value exceeds the maximum forward lean (16.2°) from which elderly adults could regain balance from an unexpected release (Wojcik et al., 1999). This difference is most likely due to the forward lean task requiring a full step to be completed, whereas an unexpected tripping task only requires the limb endpoint trajectory to be changed. Put simply, more time is required to regain balance in the forward lean task; and, 8) response time is probably the most important parameter (especially for the elderly) in order to regain balance after a trip (van den Bogert et al., 2002).

Overall, the methods adopted by the studies were appropriate. Participant numbers ranged from 7 to 79, some studies focused upon the first response trial and did not constrain the selection of the lead limb, and the walkway length ranged from 7 to 11 m. Some of the studies, however show and recognized limitations. Firstly, the tripping device (spool of braided nylon cable attached to the ankle) used by Smeesters et al. (2001a; 2001b) lacks ecological validity (refer to figure 2.3.2.2). When activated the device restrained any forward movement of the ankle for durations of 100 ms and more. Such restraint of the limb is not representative of a trip that occurs in "everyday" activity. Any limb response, for example, that involved a vertical or mediolateral movement of the ankle after the device was activated probably resulted in the cable pulling the ankle backwards. Such an action does not occur when a person is tripped in "everyday" activity.

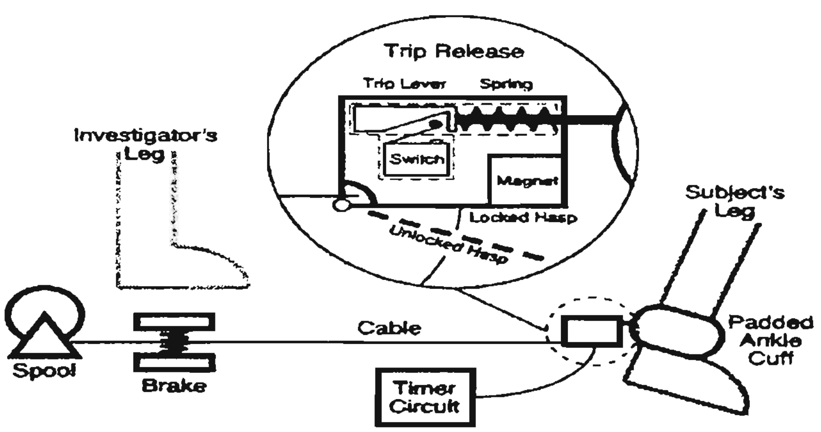


Figure 2.3.2.2 Trip device used by Smeesters et al. (2001a; 2001b). Trips were induced by suddenly interrupting the spooling of the cabling attached to the padded ankle cuff. When it occurred, the trip lever activated the switch in the trip release device, triggering the trip duration countdown on the timer circuit. Once the time had elapsed, the magnet, which locked the cable in place, was deactivated, releasing the cable and ending the trip (taken from Smeesters et al., 2001b, p. 591).

Another possible limitation of the studies conducted by Smeesters et al. (2001a; 2001b) involves the use of a metronome to dictate walking velocity. The metronome most likely divided the participants' attention which may have affected their ability to respond. A study by Chen et al. (1996) suggests that attention division tasks may increase the risk of a fall in obstructed terrain. The attention demand of responding to a metronome, therefore, may confound studies.

The studies conducted by Thelen et al., (1997), Wojcik et al. (1999; 2001) and Pavol et al. (1999) required the use of a safety-harness device in order to protect participants from injury. A question remains, however (as previously discussed), as to what influence harness-support devices have upon the recovery response.

A further limitation of the studies conducted by Thelen et al. (1997) and Wojcik et al. (1999; 2001) involved the requirement to regain balance within a single step. This may have forced participants, in particular the older adults, to use a non-instinctive recovery strategy. Such a constraint may have confounded the studies since older adults may instinctively prefer to regain balance over a number of steps as opposed to a single step.

Past studies have shown that factors such as age, gender, trunk lean, gait speed, response time and lower extremity strength can affect a person's ability to regain balance after the onset of an unexpected perturbation. The majority of studies focusing upon age differences, however, have adopted methods that lack a degree of ecological validity. For instance, the studies conducted by Thelen et al. (1997) and Wojcik et al. (1999; 2001) focused upon recovery from unexpected release from a forward leaning position. In contrast, Pavol et al.

(2001) used a more realistic perturbation device, but employed a harness-support device.

Further comparisons of the ability of the young and elderly to regain balance after the onset of a known or unexpected perturbation are needed. A paucity of literature focusing upon age-related differences exists. Preferably, this research should be conducted without harness-support devices since such devices may confound outcomes. In addition, studies should focus on the affect of gait speed and the associated increase in trunk lean. Both of these factors most likely reduce the time to recover from a loss of balance.

The studies by Thelen et al. (1997) and Wojcik et al. (1999; 2001) also suggest the elderly may have difficulty in suddenly accepting (with the recovery limb) weight forces greater than body weight; that is, the elderly experience difficulty, or may even refuse, to rapidly load (eccentrically) the lower limb musculature. This was evidenced in the forward lean studies where it was suggested that the elderly may have improved their success rate if allowed to take more than one step.

In summary, this project aimed to advance work in the field of obstructed gait by: 1) employing an "everyday" task that required rapid weight acceptance (e.g., descending a step whilst walking fast); 2) improving ecological validity by not employing a harness-support device; and, 3) ensuring the integrity of the gait response by not employing the use of an attention division device such as a metronome to dictate gait speed.

2.3.3 Accommodation strategies

Accommodation strategies have been defined to include the gait adjustments made to accommodate terrain that cannot/need not be avoided and has to be stepped upon (Patla, 1991). The terrain stepped upon may be different in geometry (stairs or sloped surface) or surface properties (such as compliance or friction) and may or may not be hazardous. Examples of terrain routinely accommodated include stairs (multiple level changes), sloped terrains, footpath kerbs and door thresholds (single level change), surfaces with different compliance and frictional characteristics such as carpet, a narrow or winding path, or a path of stepping stones.

To date, staircase studies have primarily involved stairways consisting of 3 to 7 steps with riser heights and tread depths of about 18 cm and 28 cm respectively (e.g., Andriacchi, Andersson, Fermier, Stern & Galante, 1980; McFadyen & Winter, 1988; Livingston, Stevenson & Olney, 1991; Simoneau et al., 1991; Krebs et al., 1992; McFadyen & Carnahan, 1997; Cromwell & Wellmon, 2001; Christina & Cavanagh, 2002; Riener, Rabuffetti & Frigo, 2002). Single stair or step studies have predominantly used platforms with riser heights ($\approx$ 12 to 15 cm) representative of a kerb or door threshold (e.g., Crosbie, 1996; Lythgo & Begg, 1999a; 1999b; 1999c; Sims & Brauer, 2000; Begg & Sparrow, 2000; McFadyen & Prince, 2002), and studies involving sloped terrain have used ramps and treadmills of varying grade (e.g., Redfern & DiPasquale, 1997; Leroux, Fung & Barbeau, 2002).

It has been consistently reported that stair climbing involves greater muscle activity, joint forces and ranges of motion compared to level walking (e.g., Joseph & Watson, 1967; Flynn, 1977; Costigan, Deluzio & Wyss, 2002; Lamoureux, Sparrow, Murphy & Newton, 2002; Startzell et al., 2002). Studies also support the view that stair or ramp descent, compared to ascent or level walking, imposes greater physical demands upon a person. Walking down stairs, for example, has been reported to involve significantly greater vertical ground reaction forces, larger ($p < .05$) stance limb joint flexion moments and reduced ($p < .05$) single limb support periods (Andriacchi et al., 1980; Livingston et al., 1991; Christina & Cavanagh, 2002; Riener et al., 2002). Redfern and DiPasquale (1997) have similarly found downhill walking (ramp descent) to involve greater vertical ground reaction forces and reduced single limb support periods ($p < .05$) compared to level walking.

The previous findings show that weight must be controlled over a shortened single limb support period and greater ground impact must be attenuated when descending a stair. Such demands may heighten the risk of a fall or stumble in populations with reduced lower limb strength or musculoskeletal control limitations. It is important to note that stair descent is primarily achieved through eccentric contractions of the lower limb musculature, whereas stair ascent mainly involves the pulling and pushing of the body through concentric contractions of this same musculature (McFadyen & Winter, 1988; McFadyen & Carnahan, 1997).

2.3.3.1 Foot-clearance

Only a few studies involving stairs and platforms have reported measures of foot clearance. Riener et al. (2002) reported toe clearance for a group of young adults to be about 7 cm in stair ascent. In stair descent, Simoneau et al. (1991) reported foot clearance (sole of foot) for a group of elderly adults to be about 2.6 cm. Begg and Sparrow (2000) similarly found foot clearances ($\approx$ 2 cm) to be lower when descending a platform (height: 15 cm) compared to platform ascent ($\approx$ 10 cm). They also found older adults, compared to young adults, exhibit greater lead heel ($p < .05$) and trail toe-step-clearances when descending a platform. In ascent, however, the elderly exhibited lower lead heel ($p < .05$) and trail toe-step-clearances. In a recent study involving a platform ascent task (length: 366 cm; width: 122 cm; height: 11.75 cm), McFadyen and Prince (2002) found an age-related reduction ($p < .05$) in lead toe-step-clearance (elderly $\approx$ 6 cm, young adults $\approx$ 7.5 cm) but no significant age difference was found in trail toe-step-clearance (elderly $\approx$ 2 cm, young adults $\approx$ 3 cm).

These findings suggest that the risk of foot contact is greater in stair or platform descent. Lead-limb toe contact in ascent, however, poses a greater threat to dynamic stability since forward progression of the foot would be fully arrested. In stair descent, however, the forward progression of the foot may not be fully arrested but slowed as the foot drags along or "brushes" the top surface of the step. The increased danger of foot contact in ascent is probably recognized by the elderly since they were found to clear a platform step by a greater margin.

Interestingly, Simoneau et al. (1991) found elderly adults increased foot clearance and placed the trail foot further back on the step ($p < .05$) of a staircase when the field of vision was artificially blurred. This finding strongly supports the need to screen subjects for visual deficits that may cause them to adopt a more cautious crossing strategy or make a perceptual error. As such, this project adopted a test of visual acuity and visual contrast sensitivity (refer to method) in order to screen for visual deficits.

2.3.3.2 Foot orientation

Ankle joint motion (dorsi-plantar flexion) and foot orientation (with respect to the horizontal) are important for safe negotiation of terrain containing stairs or platforms. Toe or heel clearance of a stair can be adjusted by altering the orientation of the foot, and impact with the ground in stair descent can be better attenuated by a forefoot landing (Riener et al., 2002). Ankle joint motions reported for staircase ascent include 14° to 27° of dorsiflexion and 23° to 30° of plantar flexion (Livingston et al., 1991). Andriacchi et al. (1980) has reported the foot to land in a neutral orientation (0°), whereas Riener et al. (2002) reported foot orientation to be about -4° upon landing. Ankle joint motions reported for staircase descent include 20° to 35° of dorsiflexion and 20° to 30° of plantar flexion (Livingston et al., 1991). Andriacchi et al. (1980) has reported the foot to be placed in about 20° plantar flexion upon landing, whereas Riener et al. (2002) reported foot orientation to be about -14° to -21° upon landing.

In platform ascent, Lythgo and Begg (1999a) found adults (6 elderly, 6 young) orientated the foot (relative to the horizontal) to provide a heel landing (elderly = 11.7°, young = 19.5°, $p < .05$). Over the edge of the platform the elderly orientated the foot upwards (2.1°) with respect to the horizontal, whereas the young orientated it downwards (-1.9°). When descending a platform, a significant difference ($p < .001$) in foot orientation was found upon landing. The elderly orientated the foot so as to provide a forefoot landing (-7.4°), whereas the young orientated the foot to provide a heel landing (10.5°). Over the edge of the platform both groups positioned the foot in a downward orientation (≈ -13°). The ensemble average patterns for the lead foot orientation throughout the crossing step are shown in figures 2.3.3.2.1 and 2.3.3.2.2 for both step conditions. Little difference in the pattern of foot orientation is evident in the ascent task. Large differences, however, are shown in the descent task. The elderly never orient the foot upwards in this condition; the position of the toe is always held below the heel.

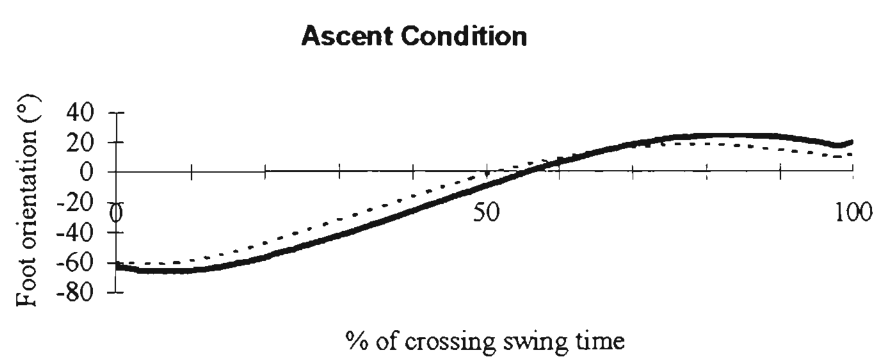


Figure 2.3.3.2.1 Ensemble average pattern of the lead foot orientation (taken from Lythgo and Begg, 1999a) in the accommodation step (ascent condition) from toe-off to foot landing (_ _ elderly, ___ young).

Descent Condition

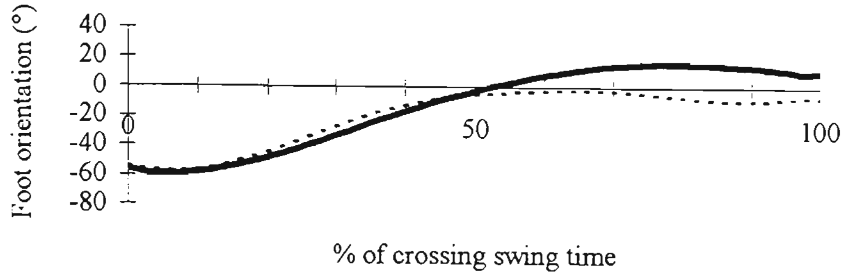


Figure 2.3.3.2.2 Ensemble average pattern of the lead foot orientation (taken from Lythgo and Begg, 1999a) in the accommodation step (descent condition) from toe-off to foot landing (_ _ elderly, ___ young).

These findings show the elderly to be more cautious when negotiating a platform. In ascent, for example, they were found to adopt an upward orientation of the foot which lessens the chance of unwanted toe contact. In descent they adopted a forefoot landing strategy in order to better attenuate weight upon landing.

2.3.3.3 Foot placement

In an early investigation involving stairs of varying riser and tread dimensions, Fitch, Templer and Corcoran (1974) found fewer missteps to occur on stairs with 10 to 18 cm riser heights and 27 to 36 cm tread depths. Missteps were reported to result in unwanted foot contact with the stair or partial placement of the foot on the stair tread. More missteps were reported to occur in stair descent than ascent and were found to increase with walking pace for both stair conditions. These findings must be deliberated with some caution since the study used a mechanical stairway that operated as a treadmill. Despite this limitation, however, the study suggests that missteps on stairs may lead to a stumble or trip-induced fall.

Recently, investigators have begun to focus on the step adjustments made to approach and accommodate raised surfaces such as a kerb (Crosbie, 1996) or platforms representative of a kerb or door threshold (eg., Lythgo & Begg, 1999a 1999b; 1999c; McFadyen & Prince, 2002). Some studies found young adults adjust their step pattern at least 2 to 3 steps prior to the raised surface (Crosbie, 1996; Lythgo & Begg, 1999b). Other studies involving young and elderly adults have found differences in measures of foot placement (Lythgo & Begg, 1999c; Begg & Sparrow, 2000; McFadyen & Prince, 2002). As examples these studies found: (1) that when descending a platform, both old and young adults place the toe of the trail foot near the step edge or about 7 cm from it, whereas in ascent it is placed further from the edge ($\approx$ 22 cm); (2) elderly adults, compared to young adults, exhibit shorter crossing step lengths ($p < .05$); and, (3) in ascent, elderly adult females land the heel of the lead foot (in the crossing step) close to the edge of a step (young $\approx$ 16 cm, elderly $\approx$ 6 cm, $p < .05$), whereas adult males land it further from the edge (young $\approx$ 30 cm, elderly $\approx$ 22 cm, $p < .05$). The later outcome may have been due to the lower platform height (11.75 cm) used in male study (McFadyen & Prince, 2002). The female study used a 15 cm high platform (Begg & Sparrow, 2000).

Two important findings can be drawn from the previous work. Firstly, adults place the trail foot close to the edge of a step when descending a kerb or platform (refer to figure 2.3.3.3.1). Secondly, elderly adults place the lead foot (in the crossing step) close to the edge in ascent. These foot placement strategies are probably dangerous since there is less margin for a mistake; that is, close foot placement coupled with an ill-timed distraction or perceptual motor error may result in a misstep (Konczak, Meeuwsen and Cress, 1992). A misstep is undesirable as it has been linked to unwanted foot contact and a loss of dynamic balance (Fitch et al. 1974). To date, no study has comprehensively examined foot placement in obstructed gait. As such, this project is unique since it is the first investigation to fully examine this issue across age.

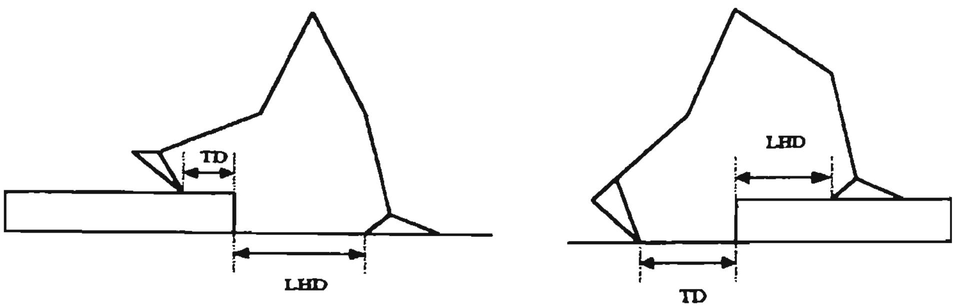


Figure 2.3.3.3.1 Diagrammatic representation of the trail and lead foot placement in a crossing step. Left panel: descent condition. Right panel: ascent condition. *LHD*: lead-heel-edge distance; *TD*: trail-toe-edge distance.

Another unique aspect of this project is the adoption of a method in order to examine how gait is regulated in stair ascent and descent conditions. This method is drawn from investigations of the long jump event in athletics (e.g., Lee, Lishman & Thomson, 1982; Hay, 1988; Berg, Wade & Greer, 1994; Berg & Greer, 1995; Scott, Li & Davids, 1997; Galloway & Connor, 1999; Montagne, Cornus, Glize, Quaine & Laurent, 2000). Essentially, these investigations found athletes exerted visual control about 4 to 5 steps from the take-off board. This was ascertained by measuring the variability of footfall position (toe-to-board distance) across a number of trials. Figure 2.3.3.3.2 illustrates the footfall variability found in a number of these studies. It shows the mean variability of the toe-to-board distance to increase methodically up to the 4th or 5th step from the board after which a systematic reduction takes place. This point was defined as the "visual switch point" or the point where gait is regulated by the visual system.

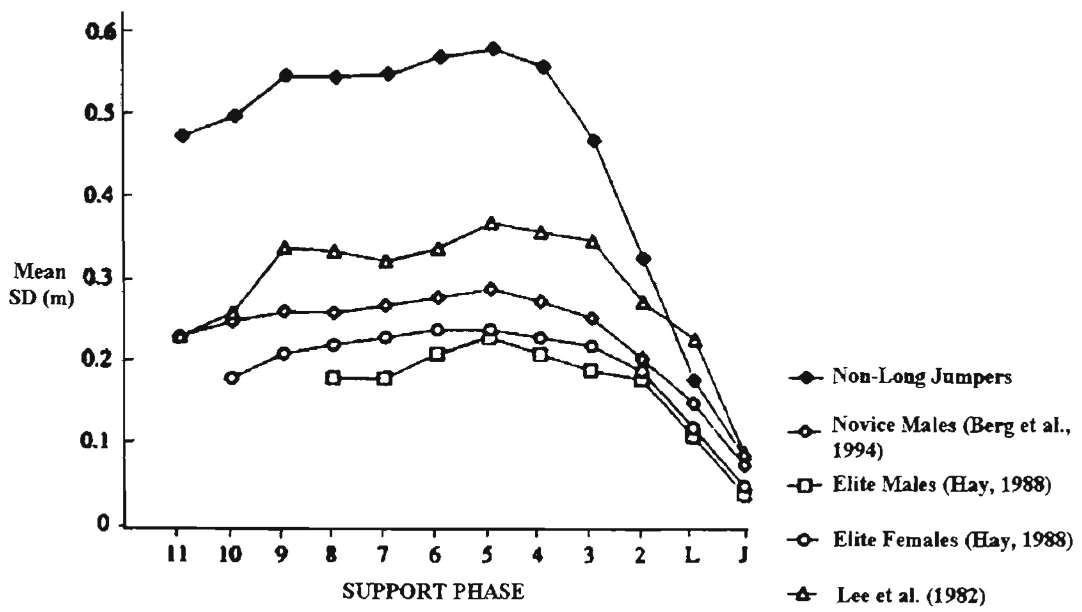


Figure 2.3.3.3.2 Mean standard deviation of toe-board distance in the run-up for non-long jumpers, novices and elite long jumpers. Data adapted from Lee et al, (1982), Hay (1988) and Berg et al. (1994). L = last; J = jump (taken from Scott et al., 1997, p. 602).

Importantly, the method employed in the long jump studies is profitably used in this project. It provided the instrument to ascertain whether any age differences exist in the approach to a stair or step. The ability to spread step length adjustments, for example, over a greater number of steps may be advantageous when avoiding or accommodating an obstacle or surface (Chen et al., 1991). Such an approach strategy may reduce the likelihood of actions such as missteps which have been directly linked to falls in uneven terrain (e.g., Pauls, 1985).

It is difficult to ascertain the accuracy of the footfall measures collected in the long jump studies. It seems reasonable, based on reported camera setups, to suggest that measurement errors may have been in the order of 1 to 5 cm (e.g. Lee et al., 1982; Hay, 1988; Berg et al., 1994; 1995). It is important, therefore, to quantify measurement error since it can have a large affect upon measures of small magnitude (e.g., foot-obstacle clearance). As such, this project adopted several procedures recommended by Bartlett (1992) so as to minimise the effects of perspective, parallax and digitising error. This involved locating the camera as far from the plane of motion as possible and the adoption of a multiple camera setup in order to maximise the size of the performer on the projected image in each stage of the accommodation task (approach and crossing phases). An instrument reliability study was also conducted in order to quantify measurement error.

2.3.3.4 Head and trunk motion

Head and trunk motion increases in obstructed gait. Studies have reported large excursions (in the sagittal plane) of the head and trunk in stair climbing (particularly in stair descent) compared to free-speed walking (e.g., Krebs et al., 1992; Cromwell & Wellmon, 2001). Head excursions and forward tilts of at least 2 to 3 times the magnitude of level walking have been reported with stair descent eliciting the largest responses (excursions ≈ 27°, forward tilt ≈ 24°). Investigators suggest (Cromwell & Wellmon, 2001) that populations with deficits in the sensory systems (visual and vestibular) used to stabilize the head or maintain balance are at great risk of falling on stairs since they have a reduced capacity to attenuate the large head movement required to complete the task safely. Any large or rapid movements of the head may result in a loss of balance or degrade important visual information required to prevent a misstep (Grossman et al., 1988; Patla, 1997).

Forward tilt (Krebs et al., 1992; Cromwell & Wellmon, 2001) of the trunk has been reported to be larger ($p < .01$) during stair ascent ($\approx 12°$) than descent ($\approx 6°$) and free-speed gait ($\approx 2°$). Krebs et al. proposed that adults assume a more inclined posture, roughly parallel to the slope of stairs, during stair climbing in order to project the whole body centre of mass forward. In stair descent however, trunk flexion is restricted in order to maintain stability by shifting the trunk's mass away from the declension of the stairs.

Leroux et al. (2002) similarly found trunk forward tilt to increase with the grade (-10%, -5%, 0%, 5%, 10%) of a treadmill but not in the same systematic order reported by Krebs et al. (1992). Trunk forward tilt was found to be about 12° for the 10% slope, approximately 7° for level walking, and about 3° for a slope of -10%.

Reasons for the differing order of trunk forward tilt found across the stair and treadmill tasks may lie in the methods. For instance, Krebs et al. (1992) used a metronome to control walking speed (80 bpm), whereas Leroux et al. (2002) used a self-selected walking speed. Leroux et al. also used a safety-harness device and required subjects to walk with their elbows at 90°. In addition, Krebs et al. involved elderly adults, whereas Leroux et al. involved adults ranging from

25 to 52 yrs. All of these factors might contribute to the differing result. Perhaps, however, the use of a treadmill is the main reason for the observed difference. Stolze, Kuhtz-Buschbeck, Mondwurf, Boczek-Funcke, Deuschl and Illert (1997) have shown significant changes in gait measures such as decreased stride length and stance time, and increased step frequency, when walking on a treadmill compared to overground walking.

The studies of head and trunk motion show that stair climbing poses a great risk to dynamic stability. The increased magnitude of head and trunk forward tilt observed in stair climbing may place the body's centre of mass outside the base of support. Any foot contact at this time would be dangerous since the body is inherently unstable. In addition, hip flexion is reduced by the forward lean of the trunk. Any restriction of this motion reduces foot clearance and the length of the crossing step (McFadyen & Carnahan, 1997). Reductions in these parameters may lead to missteps resulting in a stumble or trip-induced fall.

2.3.3.5 Dynamic stability

To date, only a few measures of dynamic stability have been found to significantly differ across age. A study conducted by Stemmons Mercer, Sahrmann, Diggles-Buckles, Abrams, and Norton (1997) suggests that the elderly require more time to control movement in an accommodation task.

Older adults were found to exhibit longer reaction times ($p < .002$), compared to young adults, to respond to a visual stimulus and step onto a wooden step (height: 20 cm). This suggested to the investigators that the elderly required a longer time to control destabilisation; that is, a longer time period was needed to control displacement of the centre of mass over the changing base of support. Alternatively, it was proposed that the older adults may use lower forces, acting over a longer interval, to generate the momentum necessary to complete such a task.

The finding by Stemmons Mercer et al. (1997) suggests the elderly may experience more difficulty in stair climbing tasks. In particular, it supports the notion that hurrying may further challenge their ability to maintain balance when climbing stairs or steps. Recent work by Sims and Brauer (2000) involving young adults partly supports this notion. They found greater medio-lateral excursions of the centre of pressure of the trail foot when completing a rapid step up task (15 cm high step) compared to a rapid step forward task. This demonstrates the need to control destabilisation in the medio-lateral plane when performing a rapid stepping task. The elderly may experience more difficulty in controlling such destabilisation.

A platform investigation by Lythgo and Begg (1999c) found both young and elderly adults to hold their trunk marker (approximate location of the whole body centre of mass) inside their base of support (posterior to the trail foot toe) at the moment the lead toe crossed the step in both ascent and descent conditions (refer to figure 2.3.3.5.1). Unfortunately, no significant age differences were found in this measure. The investigation, however, did report age differences in the foot landing velocities. The lead foot of the elderly landed with a backward horizontal velocity, whereas the young landed with a forward horizontal velocity (elderly = -0.056 $m \cdot s^{-1}$, young = 0.018 $m \cdot s^{-1}$, $p < .005$). This represents the implementation of a safety strategy by the elderly since the negative velocity reduces the chance of a slip.

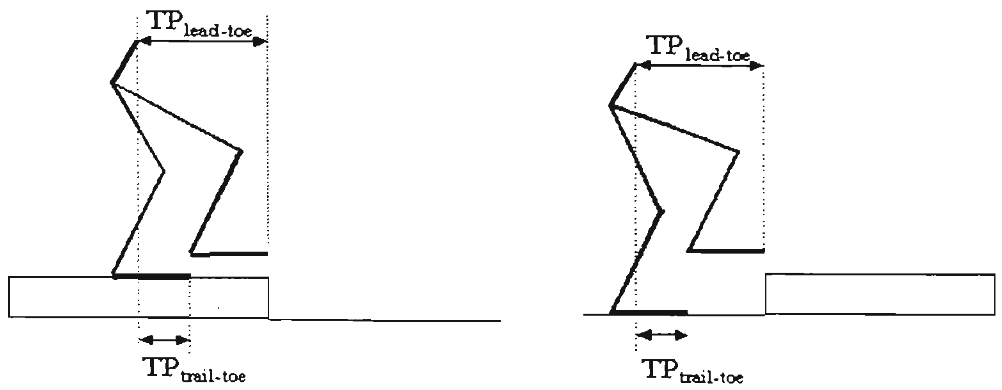


Figure 2.3.3.5.1 Trunk marker position relative to the lead ($TP_{lead\text{-}toe}$) and trail toe ($TP_{trail\text{-}toe}$) at the moment the lead toe crosses the step edge.

Interestingly, Christina and Cavanagh (2002) have suggested that a slip is more likely to occur on the first step (or transition step) of a staircase. Significantly greater braking forces and reduced first vertical *GRF* peaks ($p < .0001$) were exhibited by adults on this step compared to the 4th step (staircase consisted of 7 steps). Additionally, the older adults involved in this study were found to exhibit greater caution than the young adults. They exhibited a more cautious use of available friction ($p < .05$) or a reduced required coefficient of friction upon footstrike.

2.3.3.6 Summary

Accommodation studies have reported age-related differences in a number of gait measures. Many of the gait parameters, however, were not found to significantly differ across age. This is probably due to the low participant numbers involved. As an example, the investigation by Lythgo and Begg (1999c) only involved 6 young and 6 elderly adults. This study failed to find significant age-related differences in the majority of outcome measures (e.g., dynamic stability, foot placement and foot orientation). A power analysis, however, showed that participant numbers of 30 or more would have obtained such differences. As such, this project involved large participant numbers in order to provide sufficient power to ascertain whether age-related gait differences exist.

Further investigation of stair climbing tasks is needed in order to better understand the causes of a trip or stumble on sites containing kerbs or door thresholds. Unlike some of the previous studies (e.g., Stemmons Mercer et al., 1997; Sims & Brauer, 2000), this project adopted a more realistic task where subjects approached (from distance) and accommodated a platform representing a kerb or door threshold. Additionally, foot placement was not constrained in this project, whereas investigations such as Stemmons Mercer et al. constrained the placement of both the trail and lead limbs. The adoption of these constraints most likely resulted in atypical foot trajectories and orientations.

In summary, this project aimed to better understand the biomechanical mechanisms or reasons for the high rate of falling behaviour exhibited by the elderly adult female population in terrain containing surface height changes. To date, few studies of obstructed gait have reported significant age differences. Step tasks (in particular a descent task), however, perturb the gait of elderly females more than young adult females since they fall more often in terrain containing surface height changes. It is important to thoroughly examine gait characteristics in terrain containing surface height changes. Such information is important in helping the community understand why the elderly fall. Furthermore, it assists professionals to: (1) better monitor age-related changes in gait; (2) assess a person's propensity to fall; (3) understand circumstances surrounding falls; and, (4) provide, where necessary, appropriate intervention.

Finally, this study aimed to improve and extend the methods of previous work by: (1) ascertaining the experimental setup needed to minimize error associated with 2D planar analyses; (2) involving large participant numbers in order to provide sufficient power to identify age differences in outcome measures (e.g., dynamic stability); (3) adopting a new method so as to record the footfall positions, and step adjustments made, in the approach and accommodation phases. This method was used to identify the point where visual control of gait was initiated; (4) comprehensively examining the trajectory and orientation of the foot throughout the crossing step; (5) adopting a more realistic accommodation task; that is, surface height changes representative of a kerb or door threshold; (6) examining the effect of faster walking speed upon outcome measures; and, (7) measuring head and trunk motion throughout the crossing step in order to ascertain the challenge to dynamic stability.

CHAPTER 3 OBJECTIVES OF INVESTIGATION

3.1 General aims

(1) To examine the effect of age upon the human adaptive gait strategies employed by healthy adult females to approach (over distance) and accommodate (ascend and descend) at varying speed (comfortable and fast) surface height changes representative of a typical kerb or door threshold encountered in "everyday" life.

(2) To identify age-related differences in the spatio-temporal characteristics of the gait adjustments employed by healthy adult females to accommodate surface height changes at varying speed.

(3) To gain further insight into the risk factors (ageing, walking speed, step ascent and descent) that have been directly linked to a high rate of falling behaviour exhibited by elderly adult females when accommodating surfaces representative of a typical kerb or door threshold encountered in "everyday" life.

3.2 Specific aims

Stage 1

(1) To determine the experimental setup (camera field of view and location) required to accurately measure the sagittal plane spatio-temporal characteristics of the gait adjustments employed by healthy adult females to approach and accommodate (ascend and descend) surface height changes at varying speed.

(2) To determine the multiple camera setup required to accurately record the sagittal plane spatio-temporal characteristics of the gait adjustments made by healthy adult females in the approach or transport phase of an accommodation task.

Stage 2

(3) To examine the effect of age (young or old), walking speed (fast or normal) and stepping task (ascent and descent) upon the approach and crossing strategies employed by healthy adult females to accommodate surface height changes. The measures to be examined include: (i) dynamic stability; (ii) footfall patterns (placement and variability); (iii) foot trajectory and orientation; and, (iv) crossing and landing speeds.

(4) To determine whether a visual "switch" point exists that signals a change from a transport (stereotyped) phase to a zeroing-in or homing phase in the approach to a surface height change. This will be identified as the point at

which a marked and systematic reduction in the variability of toe-to-step-edge distance occurs.

3.2.1 Hypotheses

Aim 3: Null Hypotheses

The reader is referred to table 5.4.1.1 (Methods Chapter) for a comprehensive description of the outcome measures (biomechanical) collected in this investigation. These include measures of step length, step time, foot placement and orientation, foot-step-clearance, support time and dynamic stability.

- No significant effects of age upon the outcome measures.
- No significant effects of walking speed upon the outcome measures.
- No significant effects of surface height condition (ascent or descent) upon the outcome measures.

Aim 4: Null Hypothesis

- No visual "switch" point exists that signals a change from a transport phase to a zeroing-in phase.

CHAPTER 4 INSTRUMENT RELIABILITY

4.1 Methods

An instrument reliability study was conducted in order to quantify the measurement error contained in 2D spatial data commonly collected in gait research (e.g., footfall position, foot-obstacle-clearance or foot orientation). Error is produced by factors such as lens or image distortion, perspective error, parallax error and digitization error (Bartlett, 1992). As such, this study examined the measurement error associated with filming and digitization processes. This was achieved by employing a variety of camera setups (location and field of view) and marker sets (stationary and moving) and involved three experiments:

- Experiment 1 - varying camera location (camera field of view = 3 m) for a set of stationary markers positioned at varying depth.
- Experiment 2 - varying field of view (location = 10 m) for a set of stationary markers positioned within the same 2D measurement plane.
- Experiment 3 – varying field of view (location = 10 m) for a set of moving markers positioned within the same 2D measurement plane.

Generally, the term "field of view" refers to the whole view of an image captured on film. For convenience and ease of explanation, this term is used to describe both the view and width of an image. Additionally, camera location describes the perpendicular distance of the camera lens from the 2D measurement plane.

In this project, three measures of measurement error (absolute magnitude) were found:

- mean error ($\bar{x}$);
- mean maximum error ($\bar{x}_{max}$);
- maximum error (Max_{error}) or the largest error.

These measures were found by comparing known distances or angles between markers (e.g., placed on a wall) to those derived from filming and digitization processes. Three different marker images (3 frames) were digitized to produce three sets of data for each condition investigated (e.g., camera location or field of view). These data sets were then used to extract the measurement errors listed above. Mean error is the average error found across the three marker images. Mean maximum error is the average maximum error found across the images and maximum error is the largest error found across the images. Absolute error values were derived for each measure.

The same equipment and setup procedures were employed across experiments. These included: (1) film recording equipment; (2) passive reflective markers; (3) floodlights; (4) camera alignment (levelling); (5) camera lens height; (6) camera zooming-in and focus procedures; and, (7) data collection and analysis procedures.

The maximum camera location (perpendicular distance from the 2D measurement plane) investigated in this project was 10 m. This was the maximum distance, within the laboratory setting, that the camera could be positioned from the 2D measurement plane for the second stage of this project. A camera height of

0.85 m (height of optical axis of lens from the ground) was used since it represents about half the average height of the target population (Australian Bureau of Statistics, 1995b) involved in the second stage of this project.

The following equipment was used:

- Panasonic Colour CCTV 50 Hz camera (model no. WV-CL830/G).
- Computar camera lens (model no. H6Z0812, 8-45 mm, 1:1.2).
- Panasonic VCR (model no. AG4700).
- 38 cm Panasonic Colour TV Video Monitor (BT-M1420).
- 3M reflective tape – high gain sheeting (make: 7610WS).
- Manfrotto adjustable tripod.
- ARLEC HL18 (250/500 watt) floodlight with adjustable stand.
- Peak Motus Motion Measurement System – 2000 version.
- Metal calibration rod (2.55 m in length).

4.1.1 Experiment 1 - camera location

This experiment involved two phases:

- measurement error in data representative of footfalls in gait.
- measurement error in data representative of foot-obstacle-clearances.

Typical foot placement along a straight-walkway or path does not occur along its centre-line (refer to figure 4.1.1.1). People either straddle the centre-line or place the feet to one side of it. Both of these actions contribute to the magnitude of the depth/perspective error contained in non-planar 2D spatial coordinate data extracted from markers placed on body segments such as the feet (Bartlett, 1992); that is, any placement of the feet away from the centre-line, where a 2D calibration rod would be positioned, results in perspective error. As such, the aim of this part of Experiment 1 was to determine the magnitude of the depth/perspective error contained in footfall data. Camera locations of 5 to 10 m (1 m increments) were selected in order to ascertain perspective error across locations typically used in gait research (e.g., Prince et al., 1994; Redfern & DiPasquale, 1997; Sparrow, Shinkfield & Summers, 1998; Begg & Sparrow, 2000; Cutlip, Mancinelli, Huber & DiPasquale, 2000). This was necessary in order to identify the best camera location for the remaining phases of this investigation.

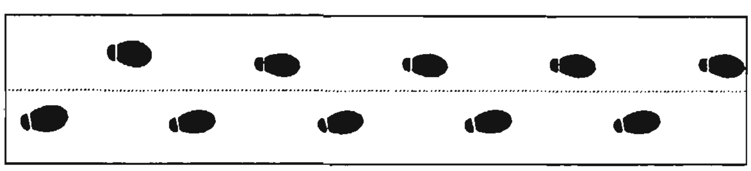


Figure 4.1.1.1 Schematic representation of footfalls along a walkway. The feet are shown to straddle the centre-line of the walkway.

For each camera location, 7 passive reflective markers (2 cm square) mounted on the front of 2 cm cubic blocks were positioned 50 cm apart (refer to figure 4.1.1.2) and at varying depths (5, 10 and 15 cm) so as to represent footfalls along a walkway. Depths of 5 to 15 cm were chosen since walking base or stride width usually falls in the range of 5 to 10 cm (Whittle, 1991; Smidt, 1990). Cubic blocks, as opposed to spherical markers, were used since they could be easily moved and re-positioned perpendicular to the camera. Four of the markers were placed against the wall of the laboratory (Victoria University Biomechanics

Laboratory) with the remaining three placed forward of the wall (depth condition). A camera field of view (*FOV*) of 3 m was employed since this has been commonly used in gait research (e.g., Simoneau et al., 1991; Prince et al., 1994; Redfern & DiPasquale, 1997; Begg & Sparrow, 2000).

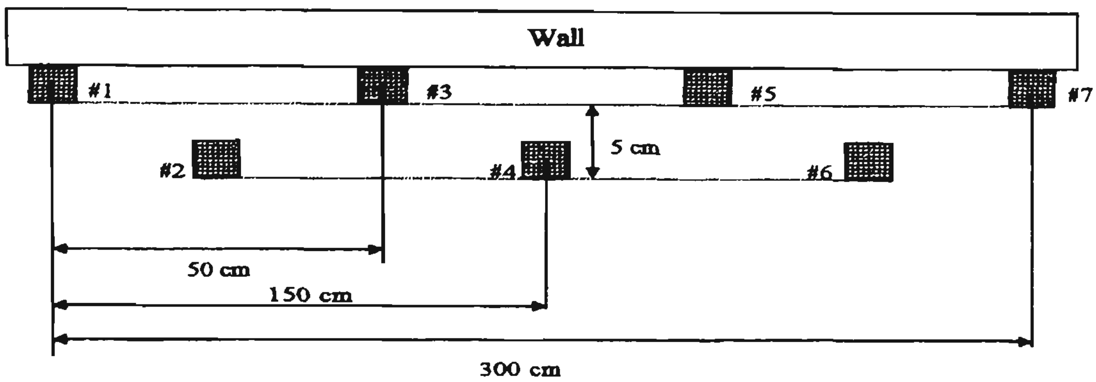


Figure 4.1.1.2 Schematic representation of ground-level markers mounted on the front of 2 cm cubic blocks representing footfalls (superior view). Adjacent markers are shown as being a depth of 5 cm from each other and a horizontal distance of 50 cm from each other. Markers are shown against the wall and forward of the wall. Note that the diagram is not drawn to scale.

A calibration rod (2.55 m in length) was filmed for each camera location. It was placed at the base of the wall and in the middle of the field of view. The rod length was chosen in order to minimize system error (Peak Motus Motion Measurement System Manual) or reduce scaling error to no more than 0.2%. Scaling error was calculated by the method described by Bartlett (1992). In fact, a scaling error of 0.2% falls well below the threshold level of 0.5% recommended by Dainty, Gagnon, Lagasse, Norman, Robertson and Sprigings (1987) and Bartlett (1992). In addition, the thickness of the rod (2 cm) ensured that the markers placed on its ends were in the same 2D measurement plane as the markers positioned against the wall (refer to figure 4.1.1.2).

A floodlight located directly behind and slightly above the camera was used to illuminate the filming area so that the markers appeared as bright spots on the television monitor. The spatial positions of the markers were recorded at a sampling rate of 50 Hz (shutter rate of 1/500 s). A shutter rate of 1/500 s was chosen since it was used in the final phase of this project.

The Motus Motion Measurement System (Peak Performance Technologies Inc., USA) was used to determine the 2D spatial coordinate positions (x, y) of the markers for the three images collected in each condition (manual digitization using the ¼ pixel option). These data were then used to calculate the horizontal distance between adjacent markers (e.g., #1 and #2 in figure 4.1.1.2). These distances were compared to the known distances in order to ascertain measurement error (absolute magnitude).

In the second stage of this investigation, the effect of perspective error on vertical distance variables (e.g., foot-obstacle-clearance) was examined. It was considered important to examine this issue since the foot in "real life" activity may not pass directly above the centre-line of a walkway.

Two markers were placed at known vertical distances (5, 8 and 11 cm) and depths (5, 10 and 15 cm) from each other (refer to figure 4.1.1.3). The vertical distances represent typical foot clearances reported in the literature (e.g., Simoneau et al., 1991; Begg & Sparrow, 2000). This was achieved by using an adjustable stand that was placed against the wall of the laboratory. The camera location was 10 m (height: 0.85 m) and field of view was 3 m. The same calibration, camera and data extraction procedures adopted in the first phase of this experiment were adopted. The extracted 2D spatial coordinate data were used to calculate the vertical distance between the markers. These distances were then compared to the known distances (i.e., 5, 8, 11 cm) in order to ascertain measurement error (absolute magnitude).

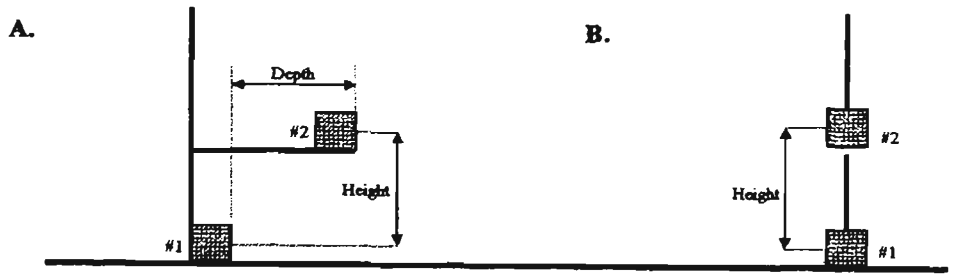


Figure 4.1.1.3 Schematic representation of the experimental setup used to examine the effect of perspective error on vertical marker positions. Reflective tape was attached to the front of two plastic cubes (2 x 2 x 2 cm) that were placed on a stand. The stand allowed marker #2 to be positioned at depths of 5, 10 and 15 cm from #1, and at heights of 5, 8 and 11 cm above #1. Marker #1 was fixed to the base of the stand. **A**. Side view of setup. **B.** Front view of setup.

4.1.2 Experiment 2 - camera field of view

This experiment examined the effect of camera field of view upon measurement error. The camera location and height were fixed at 10 m and 0.85 m respectively. Twenty-five passive reflective markers (circular markers: 2 cm diameter) were placed at known locations on a wall (refer to figure 4.1.2.1) of the laboratory to form a 2D measurement plane. The markers were placed so as to represent the position of various anatomical landmarks on a person (height: 170 cm) moving across a 2D measurement plane; marker #1 (refer to figure 4.1.2.1) represented the apex of the head, #2 the ear, #3 the hip, #4 the knee, and #5 the ankle or toe.

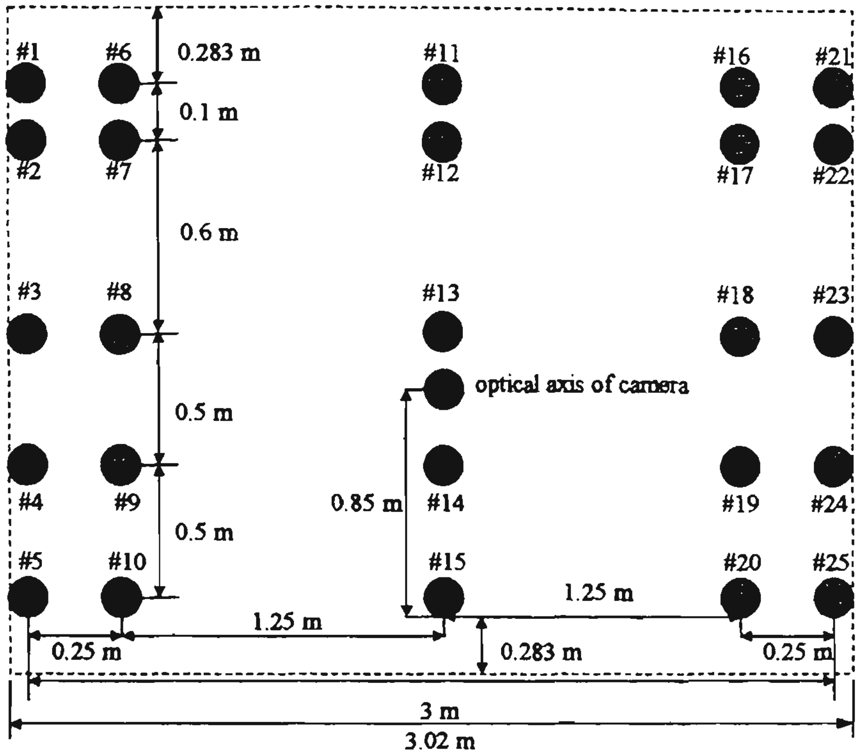


Figure 4.1.2.1 Schematic representation of fixed marker location (#1- #25) on the wall of the laboratory (frontal view). The horizontal locations of the markers were dependent upon the field of view. In this diagram the *FOV* is 3.02 m and the distance separating markers #5 and #25 is 3 m. Note that the diagram is not drawn to scale.

The optical axis of the camera lens was positioned perpendicular to the plane of the wall (2D measurement plane). The levelling of the camera in the sagittal and transverse planes was achieved with the aid of a "bullseye" spirit level. Once the camera had been levelled, the *FOV* (displayed on the TV monitor) was zoomed-in until the four outer markers (#1, #5, #21 and #25) were observed to be at the boundaries of the image (as shown in figure 4.1.2.1). If the markers on one side (e.g., #1 and #5) were found to be located further inward (on the TV monitor) than the markers on the opposite side (e.g., #21 and #25), the camera was rotated about its anteroposterior axis until the markers were observed to be simultaneously positioned at the horizontal boundaries of the TV image. Similarly, the camera was rotated about its longitudinal axis (figure 4.1.2.2) in order to ensure that markers #1 and #5 (or #21 and #25) were simultaneously positioned on the same boundary of the image. Once the camera was levelled, it was focused with the aid of a Snellen visual acuity chart that was positioned in the centre of the 2D measurement plane.

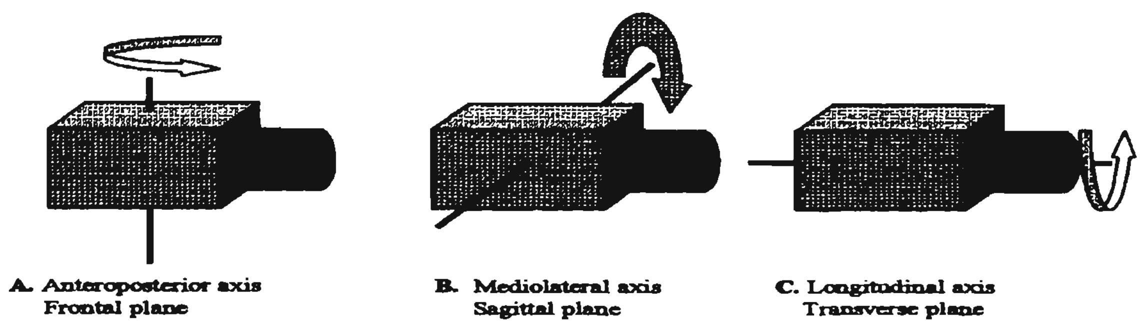


Figure 4.1.2.2 Camera planes of motion and axes of rotation. **A**. Camera rotated in frontal plane about an anteroposterior (*AP*) axis (side view of camera). **B**. Camera rotated in sagittal plane about mediolateral (*ML*) axis (side view of camera). **C.** Camera rotated in transverse plane about longitudinal axis (side view of camera).

The horizontal distance between markers #10 and #20 was used to derive a scale factor (cm/pixel) since these markers:

- were located on the same level (ground level) and in the region where the majority of data were to be collected in the second stage of this investigation (e.g., footfall position, foot-obstacle-clearance, foot angle).
- filled a large portion of the field of view (Bartlett, 1992);
- were located at least 25 cm inside the horizontal and vertical boundaries of the *FOV*;
- the distance between these markers provided a scaling error of no more than 0.2 %.

For comparison purposes, the horizontal distance between markers #8 and #18 (near the centre of the *FOV*) was also used to derive a scale factor (cm/pixel) to examine measurement accuracy.

A floodlight located directly behind and slightly above the camera was used to illuminate the filming area so that markers appeared as bright spots on the TV monitor. The spatial positions of the markers were film recorded for *FOVs* of 2.5 to 4.5 m (0.5 m increments) at a sampling rate of 50 Hz (shutter rate of 1/500 s). The Motus Motion Measurement System (Peak Performance Technologies Inc., USA) was used to determine the 2D spatial coordinate positions (x, y) of the markers from three images for each *FOV* (manual digitization using the ¼ pixel option).

The difference (absolute magnitude) between the horizontal 2D spatial coordinate data of selected markers (refer to table 4.1.2.1) and the known horizontal distances between these markers were calculated. Similarly, the difference (absolute magnitude) between the vertical 2D spatial coordinate data of selected markers (refer to table 4.1.2.2) and the known vertical distances between these markers were calculated. These difference values were used to determine measurement error.

Table 4.1.2.1 The horizontal segment distances calculated in Experiment 1.

Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
H1-H6	H2-H7	H3-H8	H4-H9	H5-H10
H1-H11	H2-H12	H3-H13	H4-H14	H5-H15
H1-H16	H2-H17	H3-H18	H4-H19	H5-H20
H1-H21	H2-H22	H3-H23	H4-H24	H5-H25
H6-H11	H7-H12	H8-H13	H9-H14	H10-H15
H6-H16	H7-H17	H8-H18	H9-H19	H10-H20
H6-H21	H7-H22	H8-H23	H9-H24	H10-H25
H11-H16	H12-H17	H13-H18	H14-H19	H15-H20
H11-H21	H12-H22	H13-H23	H14-H24	H15-H25
H16-H21	H17-H22	H18-H23	H19-H24	H20-H25

Table 4.1.2.2 The vertical segment distances calculated in Experiment 1.

Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
V1-V2	V6-V7	V11-V12	V16-V17	V21-V22
V1-V3	V6-V8	V11-V13	V16-V18	V21-V23
V1-V4	V6-V9	V11-V14	V16-V19	V21-V24
V1-V5	V6-V10	V11-V15	V16-V20	V21-V25
V2-V3	V7-V8	V12-V13	V17-V18	V22-V23
V2-V4	V7-V9	V12-V14	V17-V19	V22-V24
V2-V5	V7-V10	V12-V15	V17-V20	V22-V25
V3-V4	V8-V9	V13-V14	V18-V19	V23-V24
V3-V5	V8-V10	V13-V15	V18-V20	V23-V25
V4-V5	V9-V10	V14-V15	V19-V20	V24-V25

2D coordinate data (x, y), for example, were used to calculate the horizontal distance (segment H1-H11 in table 4.1.2.1) between markers #1 and #11 (refer to figure 4.1.2.1). Similarly, 2D coordinate data (x, y) were used to calculate the vertical distance (segment V1-V2 in table 4.1.2.2) between markers #1 and #2. These segment distances were then compared to the known distances to determine measurement error.

Figures 4.1.2.3 and 4.1.2.4 illustrate the horizontal and vertical areas of the *FOV* examined in this experiment. Figure 4.1.2.3, for example, shows a zone 1 (horizontal orientation) which incorporates markers #1, #6, #11, #16 and #21. Within this zone, ten horizontal segment distances (refer to table 4.1.2.1) were calculated and compared to the known horizontal distances. Similarly, figure

4.1.2.4 shows a zone 1 (vertical orientation) which incorporates markers #1 to #5. Within this zone, ten vertical segment distances (refer to table 4.1.2.2) were calculated and compared to the known vertical distances. Ten segment distances (refer to equation 4.1.2.1; Bluman, 1992) were compared (in each zone) since this was the maximum number of segment distances that could be calculated (ten combinations).

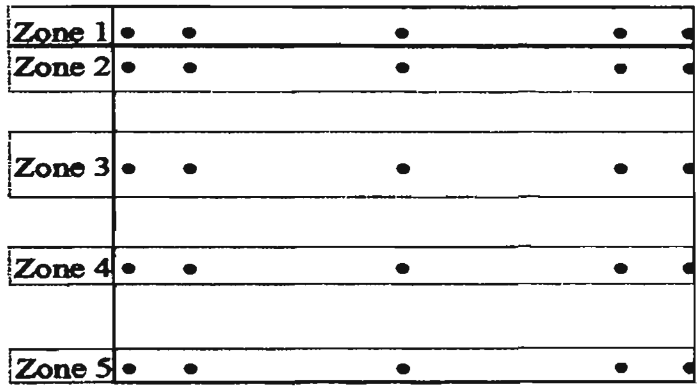


Figure 4.1.2.3 Schematic representation of "zones" for horizontal segment data.

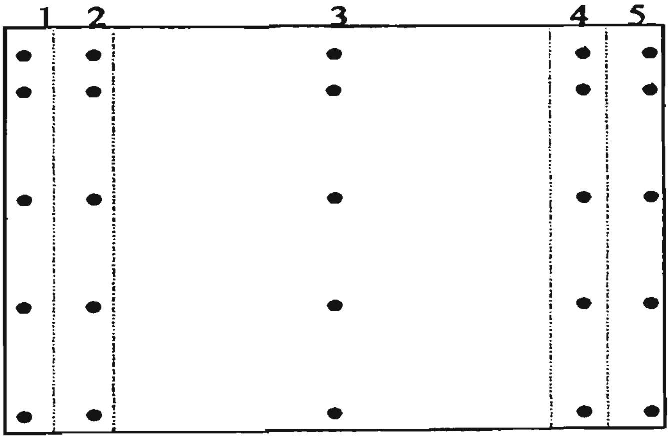


Figure 4.1.2.4 Schematic representation of "zones" for vertical segment data.

The number of combinations of "r" objects (in this case $r = 2$) selected from "n" (in this case $n = 5$) objects is as follows:

$$_{n}C_{r} = n!/(n-r)!r! \qquad \text{Equation 4.1.2.1}$$

$$\text{e.g.} \quad _{5}C_{2} = 5!/(5-2)!2! = 10$$

Angular data were calculated across *FOV* conditions. The angles selected were considered to best represent angular data (e.g., foot, head, trunk) collected in the second stage of this project. This involved calculating the orientation of the vertical line joining two adjacent markers (refer to figure 4.1.2.5). The orientation of the vertical line joining markers #6 and #7 (i.e. *A5*), for example, was calculated by equation 4.1.2.2 (equation 4.1.2.3 is the generic form of this equation). This measure was then compared to the "true orientation" (i.e., 90°) to determine error.

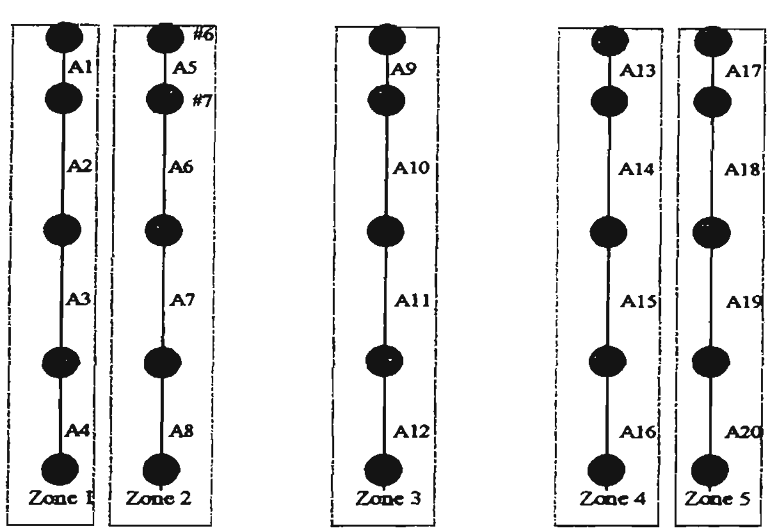


Figure 4.1.2.5 Schematic representation of fixed marker location (#1 - #25) on the wall of the laboratory (frontal view). Angles were calculated (as shown by symbols *A1* to *A20*) using the 2D spatial coordinate data of two markers. Angle *A5*, for example, was calculated by using the 2D spatial coordinate data of markers 6 and 7.

$$A5 = \tan^{-1}\frac{y_6 - y_7}{|x_6 - x_7|} - 90°$$ Equation 4.1.2.2

$$A_i = \tan^{-1}\frac{y_n - y_{n+1}}{|x_n - x_{n+1}|} - 90°$$ Equation 4.1.2.3

4.1.3 Experiment 3 - marker motion

Since human motion is dynamic, an experimental setup using a set of moving markers was employed to examine aspects of measurement accuracy. The camera location and height were fixed at 10 m and 0.85 m respectively. Five passive reflective markers (2 cm spherical markers) were attached at known distances along a weighted pendulum suspended from the ceiling of the laboratory (2 cm from the wall). The pendulum markers (refer to table 4.1.3.1) were positioned 1.53 m (#1), 1.43 m (#2), 1.15 m (#3) and 0.745 m (#4) from a bottom marker (#5). The markers were positioned so as to represent landmarks (e.g., head, knee etc.) on a person. The bottom marker hung approximately 2 cm from the floor when the pendulum was stationary. Initially the markers were placed along the pendulum at known distances. Once the markers were positioned, true locations of the markers along the pendulum were determined. This was necessary since the weight attached to the bottom of the pendulum caused a slight stretching of the pendulum cable when it hung free.

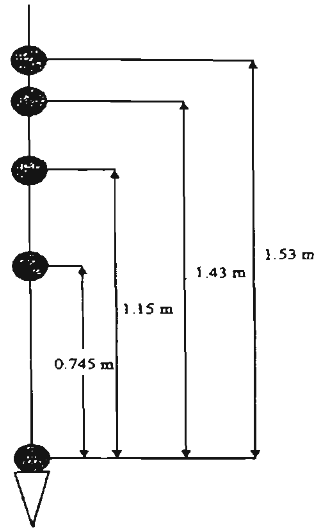


Figure 4.1.3.1 Marker location on pendulum. A weight was attached to the bottom of the pendulum.

Table 4.1.3.1 Segment distance values calculated in Experiment 3.

Segment	Actual Distance (m)
#1 – #2	0.100
#2 – #3	0.280
#3 – #4	0.405
#4 – #5	0.745

The 2D spatial positions of the pendulum markers were recorded for *FOVs* of 2.5 to 4.5 m (0.5 m increments) whilst the pendulum swung from one side to the other. The pendulum was released from the same height ($\approx$ 1 m above its resting point) for each *FOV*. This produced a maximum horizontal velocity at the base of the swing that fell in the range of 4-5 $m \cdot s^{-1}$ for the bottom marker (#5). This is representative of maximum toe velocities found in gait (Winter, 1991; McFadyen & Prince, 2002). Marker locations were measured in the following phases: (1) in the initial phase of the swing immediately after release; (2) when the pendulum attained a position of approximately 45° to the vertical; and, (3) when the pendulum achieved a vertical position (maximum horizontal velocity).

A calibration rod was placed in each *FOV* and filmed. The length of the rod was always 0.5 m shorter than the *FOV* and it was positioned in the centre of the *FOV* at the base of the wall. These procedures ensured scaling error was no more than 0.2%.

Table 4.1.3.1 lists the segment distances along the pendulum examined in this experiment. The Motus Motion Measurement System (Peak Performance Technologies Inc., USA) was used to determine the 2D spatial coordinate positions (x, y) of the markers from three images for each *FOV* (manual digitization using the ¼ pixel option). The extracted 2D spatial coordinate data were used to calculate distances between the markers. These distances were then compared to the known distances in order to ascertain measurement error (absolute magnitude).

4.2 Results

4.2.1 Experiment 1 - camera location

Tables 4.2.1.1 to 4.2.1.3 list the results of the first phase of this experiment. Specifically, the effect of perspective error (caused by movement outside the 2D calibrated measurement plane) was examined for various camera locations (5 to 10 m) from a 2D measurement plane. This plane contained stationary markers representing footfalls in gait. The camera field of view and height were 3 m and 0.85 m respectively.

Table 4.2.1.1 Measurement error ($\bar{x}$, Max_{error}) found for footfall data (5 cm depth condition) across camera locations.

Camera location	5 m	6 m	7 m	8 m	9 m	10 m
$\bar{x}$ (cm)	1.19	0.7	0.67	0.36	0.41	0.40
SD (cm)	0.54	0.44	0.22	0.24	0.24	0.16
Max_{error} (cm)	1.91	1.22	0.97	0.73	0.62	0.58

Table 4.2.1.2 Measurement error ($\bar{x}$, Max_{error}) found for footfall data (10 cm depth condition) across camera locations.

Camera location	5 m	6 m	7 m	8 m	9 m	10 m
$\bar{x}$ (cm)	1.76	1.33	0.76	0.68	0.63	0.65
SD (cm)	0.99	0.95	0.41	0.27	0.35	0.33
Max_{error} (cm)	2.78	2.15	1.21	1.02	1.05	0.9

Table 4.2.1.3 Measurement error ($\bar{x}$, Max_{error}) found for footfall data (15 cm depth condition) across camera locations.

Camera location	5 m	6 m	7 m	8 m	9 m	10 m
$\bar{x}$ (cm)	2.49	1.68	1.07	1.11	1.14	0.85
SD (cm)	1.53	1.23	0.76	0.56	0.58	0.36
Max_{error} (cm)	3.92	2.71	1.9	1.88	1.92	1.24

The results show large and systematic reductions (refer to figures 4.2.1.1 and 4.2.1.2) in measurement error (mean and maximum) as the camera location increased from 5 to 7 m. Compared to the 5 m location, camera locations of 7 m or more reduced measurement error by about half. Measurement error appears to stabilize by about the 7 to 8 m camera location with relatively smaller reductions found as the camera location increased to 10 m. At the 10 m location, the mean and maximum errors were found to fall below 0.86 cm and 1.25 cm respectively. The 5 cm depth condition exhibited the least error (less than 0.6 cm for both error measures).

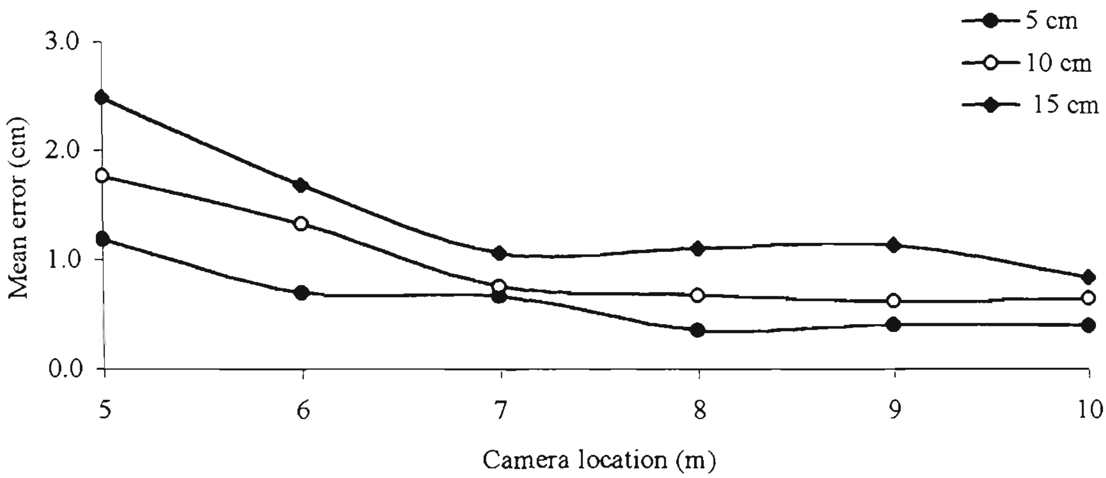


Figure 4.2.1.1 Plots of mean errors ($\bar{x}$) found for footfall markers across depth conditions and camera locations.

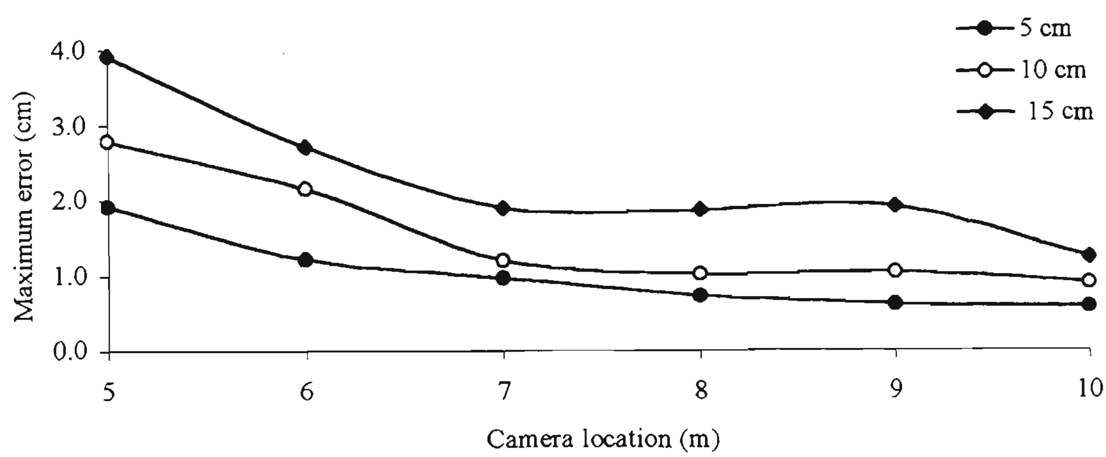


Figure 4.2.1.2 Plots of maximum errors (Max_{error}) found for footfall markers across depth conditions and camera locations.

The results of the second phase of this experiment are listed in table 4.2.1.3. Specifically, the effect of perspective error on the vertical distance between two stationary markers was examined in order to ascertain the likely error in data such as foot-obstacle-clearances. The camera location, field of view and height were 10 m, 3 m and 0.85 m respectively.

Table 4.2.1.3 Measurement error ($\bar{x}$ and Max_{error}) found for vertical separations (5, 8, 11 cm) across depths of 5 to 15 cm.

Vert. separation	**5cm**			**8 cm**			**11 cm**		
Depth	**5 cm**	**10 cm**	**15 cm**	**5 cm**	**10 cm**	**15 cm**	**5 cm**	**10 cm**	**15 cm**
$\bar{x}$ (cm)	0.14	0.28	0.82	0.15	0.32	0.70	0.17	0.24	0.44
SD (cm)	0.06	0.12	0.10	0.10	0.21	0.06	0.27	0.31	0.15
Max_{error} (cm)	0.21	0.41	0.93	0.26	0.56	0.77	0.40	0.51	0.60

The results show marked and systematic increases in measurement error (mean and maximum) as the depth of separation increased. When the markers, for example, were vertically separated by a distance of 11 cm, the maximum errors increased from 0.40 to 0.60 cm with increasing depth (refer to table 4.2.1.3). Overall, the maximum errors fell below a magnitude of 1 cm across all depths, and below 0.57 cm for the 5 and 10 cm depths. Figure 4.2.1.3 is a plot of the average measurement error (mean and maximum) across depth conditions; that is, the errors (mean and maximum) obtained for each vertical separation condition (5, 8 and 11 cm) were averaged to produce a mean value for each depth (5, 10 and 15 cm). This figure shows systematic increases in measurement error with increasing depth.

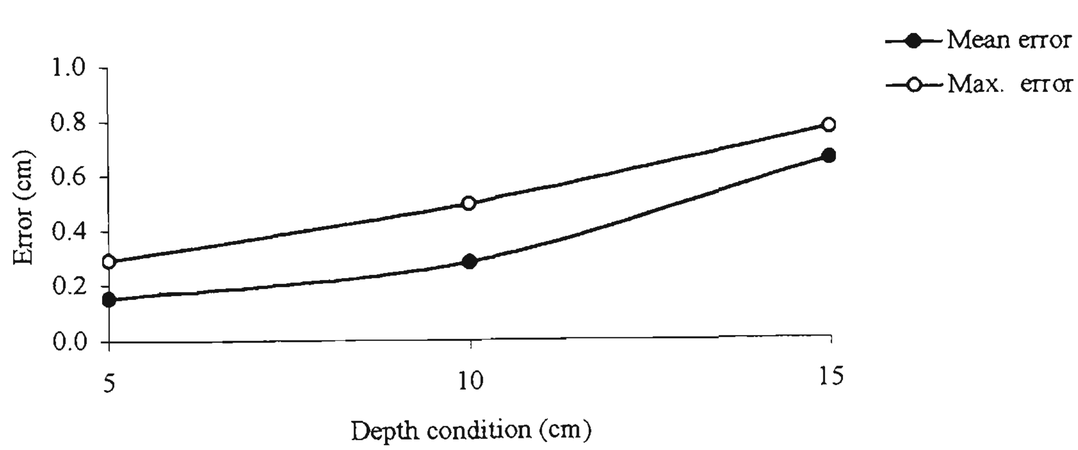


Figure 4.2.1.3 Plots of average measurement error found for markers located 5, 8 and 11 cm apart (vertical separation) across each depth (5, 10, 15 cm). Note that the errors (mean and maximum) found for each vertical separation have been averaged to produce a mean value for each depth.

4.2.2 Experiment 2 - camera field of view

4.2.2.1 Horizontal and vertical segment data

Tables 4.2.2.1.1 and 4.2.2.1.2 list the measurement accuracy results obtained by using a scale factor derived from markers #10 and #20 (refer to figure 4.1.2.1), and from markers #8 and #18. The tables show little difference in mean measurement accuracy (≤ 0.11 cm) with the largest difference found in the maximum error (Max_{error}) of the horizontal data (0.47 cm). In general, the scale factor derived from markers #10 and #20 produced the least error in the data extracted in this experiment.

Table 4.2.2.1.1 Measurement error ($\bar{x}$, $\bar{x}_{max}$, Max_{error}) found for vertical segment data across *SF* conditions and across all *FOV* conditions. *SF*: scale factor.

SF	#10 and #20	#8 and #18	Difference
$\bar{x}$ (cm)	0.46	0.47	0.01
SD (cm)	0.33	0.35	-0.02
$\bar{x}_{max}$ (cm)	0.61	0.62	-0.01
SD (cm)	0.37	0.39	-0.02
Max_{error} (cm)	1.56	1.71	-0.14

Table 4.2.2.1.2 Measurement error ($\bar{x}$, $\bar{x}_{max}$, Max_{error}) found for horizontal segment data across *SF* conditions and across all *FOV* conditions. *SF*: scale factor.

SF	#10 and #20	#8 and #18	Difference
$\bar{x}$ (cm)	0.59	0.69	-0.10
SD (cm)	0.37	0.46	-0.09
$\bar{x}_{max}$ (cm)	0.69	0.80	-0.11
SD (cm)	0.40	0.48	-0.08
Max_{error} (cm)	1.65	2.12	-0.47

Tables 4.2.2.1.3 and 4.2.2.1.4 list the results for each camera *FOV*. Specifically, measurement error was examined for varying fields of view of a 2D measurement plane. This plane contained stationary markers (refer to figure 4.1.2.1)

representing anatomical landmarks on a person moving along a 2D measurement plane. The camera location and height were 10 m and 0.85 m respectively.

Table 4.2.2.1.3 Measurement error ($\bar{x}$, $\bar{x}_{max}$, Max_{error}) found for vertical segment data across *FOV* conditions. *SF*: scale factor.

FOV (m)	4.5 m	4.0 m	3.5 m	3.0 m	2.5 m
SF (cm·pixel^{-1})	0.64	0.57	0.50	0.42	0.39
$\bar{x}$ (cm)	0.39	0.46	0.55	0.45	0.47
SD (cm)	0.22	0.28	0.39	0.37	0.38
$\bar{x}_{max}$ (cm)	0.60	0.62	0.67	0.57	0.61
SD (cm)	0.31	0.32	0.43	0.39	0.40
Max_{error} (cm)	1.48	1.29	1.91	1.53	1.60

Table 4.2.2.1.4 Measurement error ($\bar{x}$, $\bar{x}_{max}$, Max_{error}) found for horizontal segment data across *FOV* conditions. *SF*: scale factor.

FOV (m)	4.5 m	4.0 m	3.5 m	3.0 m	2.5 m
SF (cm·pixel^{-1})	0.64	0.57	0.50	0.42	0.39
$\bar{x}$ (cm)	0.55	0.59	0.65	0.62	0.55
SD (cm)	0.37	0.37	0.38	0.39	0.36
$\bar{x}_{max}$ (cm)	0.67	0.69	0.72	0.73	0.63
SD (cm)	0.41	0.39	0.40	0.44	0.37
Max_{error} (cm)	1.66	1.61	1.58	1.70	1.70

Overall, the mean errors ($\bar{x}$, $\bar{x}_{max}$) were found to be less than 0.66 cm. No systematic reduction in the magnitude of the measurement error was found across *FOV* conditions (refer to figure 4.2.2.1.1). In fact, only small differences were found across *FOV* conditions. The vertical values were found to differ by no more than 1.6 mm, and the horizontal values by no more than 1 mm.

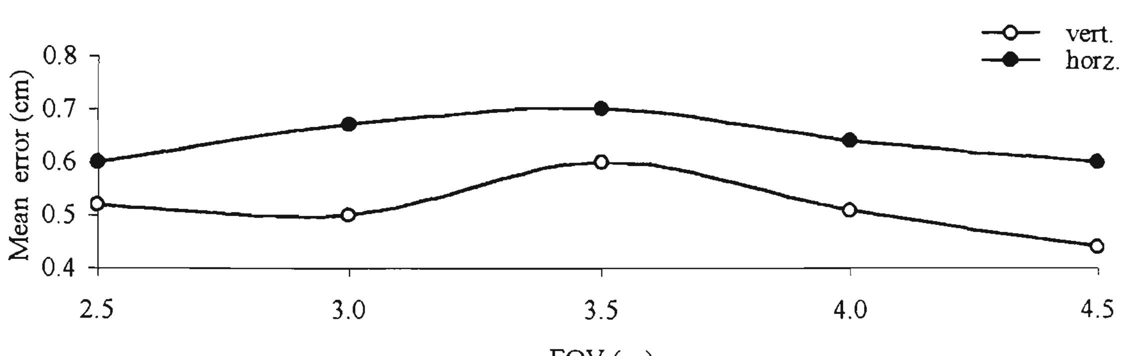


Figure 4.2.2.1.1 Plot of mean errors found for the horizontal and vertical segment data across *FOV* conditions.

As expected, the mean maximum errors ($\bar{x}_{max}$) were found to be greater ($\approx$ 1.2 mm) than the mean errors (refer to tables 4.2.2.1.3 and 4.2.2.1.4). A plot (figure 4.2.2.1.2) of the mean maximum errors shows no systematic reduction across *FOV* conditions. For both error values ($\bar{x}$, $\bar{x}_{max}$) the horizontal segment data displayed greater error ($\approx$ 1 mm) than the vertical segment data.

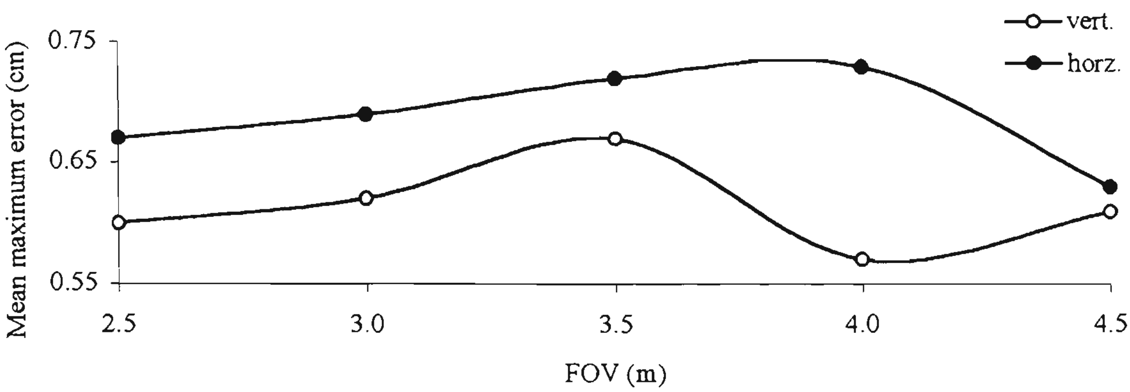


Figure 4.2.2.1.2 Plot of mean maximum errors ($\bar{x}_{max}$) found for the horizontal and vertical segment data across *FOV* conditions.

Maximum errors (Max_{error}) were found for the vertical and horizontal segment data (tables 4.2.2.1.3 and 4.2.2.1.4). These values represent the largest measurement errors found in the *FOV* conditions and ranged from 1.29 to 1.91 cm. Again, no systematic.reduction was found across *FOV* conditions.

Table 4.2.2.1.5 lists the measurement errors ($\bar{x}$, $\bar{x}_{max}$, Max_{error}) found when the outer horizontal markers (zones 1 and 5) were not included in error calculations; these markers were located at the horizontal boundaries of the *FOV* (refer to figure 4.2.2.1.3). As evident in figure 4.2.2.1.4, the removal of these markers produced a trend of increasing mean error ($\bar{x}$, $\bar{x}_{max}$) with increasing *FOV*. In addition, the plot shows the *FOV* of 2.5 m to be associated with the least mean error.

Table 4.2.2.1.5 Measurement errors ($\bar{x}$, $\bar{x}_{max}$) found for the horizontal segment data when markers near the boundaries of the image were excluded.

FOV (m)	**4.5 m**	**4.0 m**	**3.5 m**	**3.0 m**	**2.5 m**
$\bar{x}$ (cm)	0.63	0.62	0.67	0.54	0.49
SD (cm)	0.31	0.30	0.37	0.34	0.34
$\bar{x}_{max}$ (cm)	0.76	0.74	0.74	0.67	0.57
SD (cm)	0.34	0.33	0.35	0.39	0.35
Max_{error} (cm)	1.44	1.18	1.22	1.38	1.29

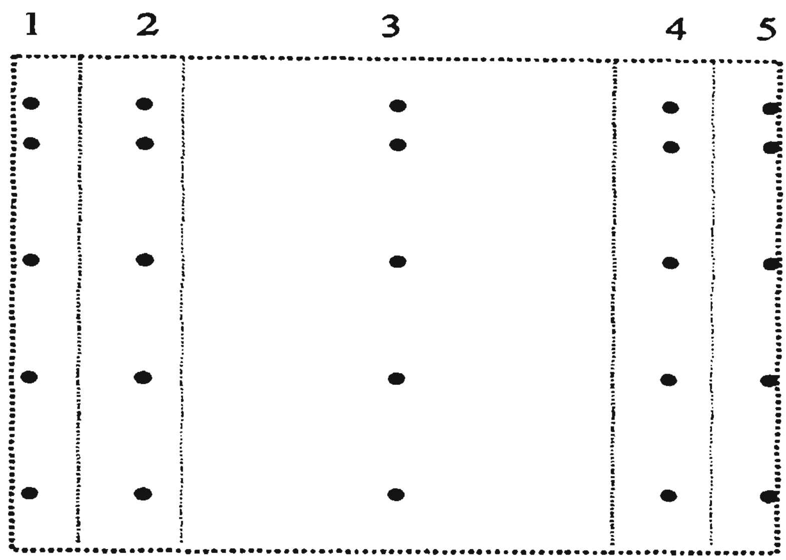


Figure 4.2.2.1.3 Schematic representation of "zones" for marker locations within a camera *FOV*.

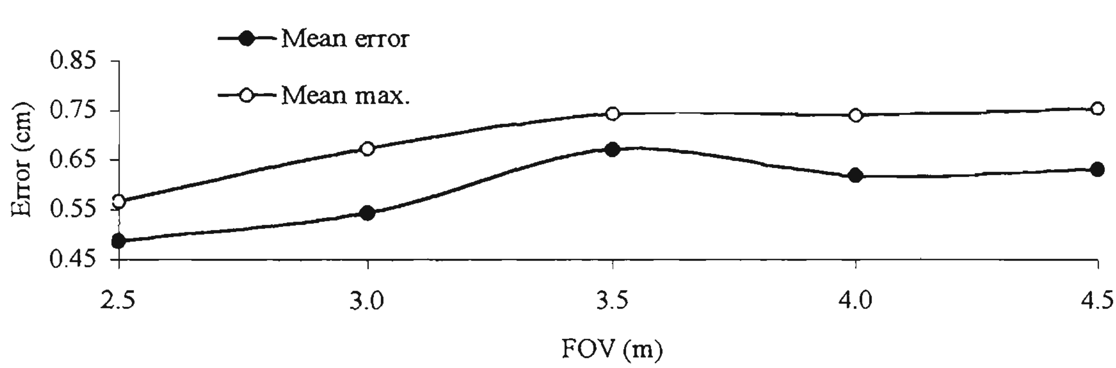


Figure 4.2.2.1.4 Plot of measurement error values ($\bar{x}$ and $\bar{x}_{max}$) found for the horizontal segment data (excluding outer markers) across *FOV* conditions.

The results of excluding the vertical segment data derived from the outer markers located in zones 1 and 5 (figure 4.2.2.1.3) are listed in table 4.2.2.1.6. A plot of these data (figure 4.2.2.1.4) reveals a trend of increasing mean maximum error ($\bar{x}_{max}$) with increasing *FOV*. No such pattern however is evident in the mean or maximum error data ($\bar{x}$, Max_{error}). In fact, the maximum errors show little difference from the original data set (table 4.2.2.1.1).

Table 4.2.2.1.6 Measurement error ($\bar{x}$, $\bar{x}_{max}$) found for the vertical segment data when the data from markers at the edge of the *FOV* were removed.

FOV (m)	**4.5 m**	**4.0 m**	**3.5 m**	**3.0 m**	**2.5 m**
$\bar{x}$ (cm)	0.41	0.45	0.58	0.41	0.43
SD (cm)	0.23	0.27	0.43	0.32	0.33
$\bar{x}_{max}$ (cm)	0.64	0.62	0.70	0.55	0.58
SD (cm)	0.32	0.33	0.47	0.34	0.37
Max_{error} (cm)	1.48	1.29	1.91	1.27	1.60

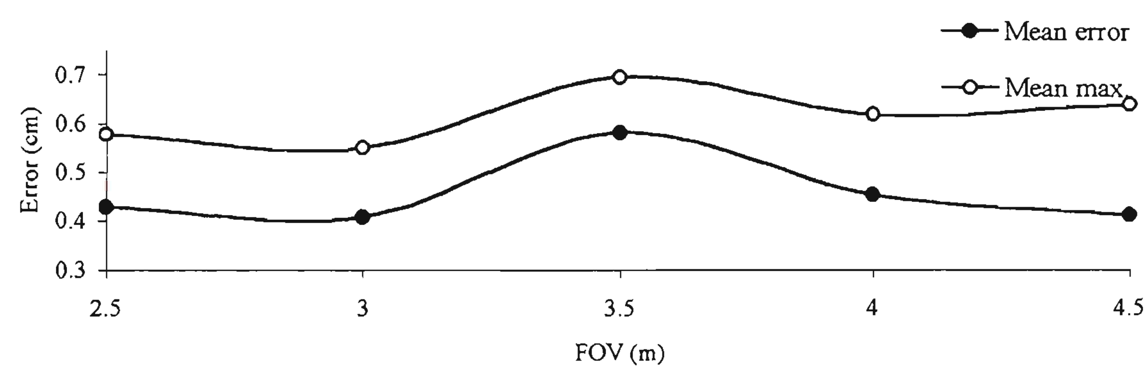


Figure 4.2.2.1.5 Plot of mean errors ($\bar{x}$ and $\bar{x}_{max}$) found for the vertical segment data (excluding outer horizontal markers) across *FOV* conditions.

4.2.2.2 Angular data

Table 4.2.2.2.1 lists the measurement error (mean and maximum) found for the angular data. The tables show the mean errors to range from 0.71° to 0.87°, the mean maximum errors to range from 0.90° to 1.07°, and the maximum errors to range from 1.61° to 2.38°. Figure 4.2.2.2.1 is a plot of the mean errors ($\bar{x}$, $\bar{x}_{max}$) and shows a trend of increasing error with increasing *FOV*.

Table 4.2.2.2.1 Measurement errors ($\bar{x}$, $\bar{x}_{max}$, Max_{error}) found for the angular data across *FOV* conditions.

FOV (m)	**4.5 m**	**4.0 m**	**3.5 m**	**3.0 m**	**2.5 m**
$\bar{x}$ (°)	0.87	0.75	0.75	0.71	0.74
SD (°)	0.34	0.29	0.44	0.38	0.36
$\bar{x}_{max}$ (°)	1.07	0.94	0.92	0.91	0.90
SD (°)	0.46	0.42	0.45	0.48	0.40
Max_{error} (°)	1.88	2.38	2.17	1.89	1.61

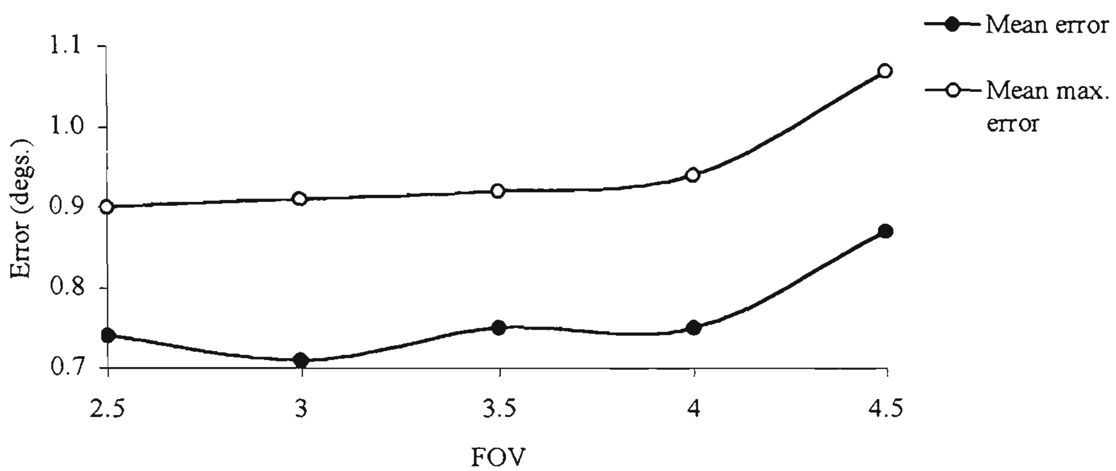


Figure 4.2.2.2.1 Plot of mean errors ($\bar{x}$ and $\bar{x}_{max}$) found in the angular data across *FOV* conditions.

Further inspection of the angular data revealed camera misalignment to be a possible source of systematic error. Table 4.2.2.2.2 shows the mean values of the angles found across *FOV* conditions to range from 89.19 to 89.34°. This suggests that either the camera may have been on a slight angle, or rotated (counter-clockwise as viewed from the rear) in the transverse plane about its longitudinal axis. Put simply, the left side of the camera was lower than the right side (refer to figure 4.2.2.2.2). This may have resulted from the experimental setup or may have been caused by the *CCD* not being "squarely" mounted inside the camera.

Table 4.2.2.2.2 Mean angle values found across *FOV* conditions. Angle values should be 90°.

FOV (m)	**4.5 m**	**4.0 m**	**3.5 m**	**3.0 m**	**2.5 m**
$\bar{x}$ (°)	89.19	89.31	89.25	89.34	89.29
SD (cm)	0.56	0.49	0.48	0.53	0.49

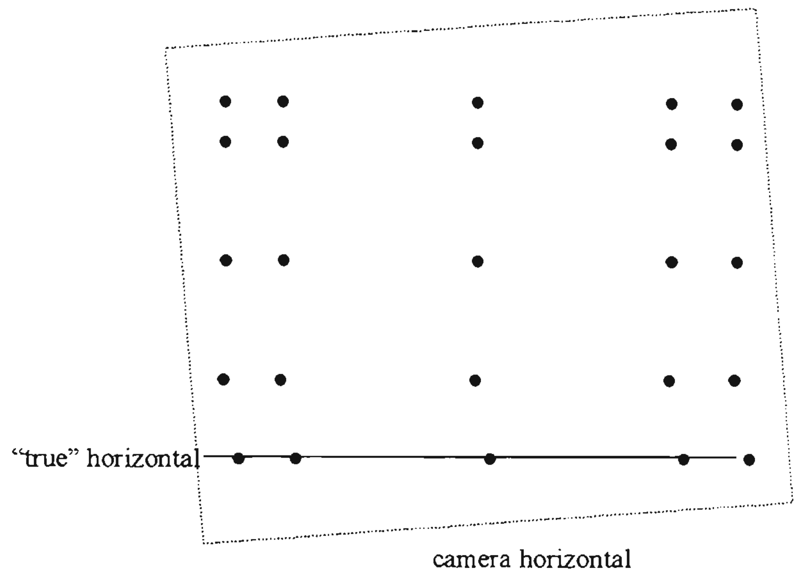


Figure 4.2.2.2.2 Schematic representation of a camera *FOV* where the left side of the camera is lower than the right side; that is, the camera is not in a neutral position (level) in its transverse plane about its longitudinal axis. Such a position produces an error in the angular data, since it is not calculated relative to a "true horizontal" but to a camera horizontal.

The angular data were re-calculated relative to a "true horizontal" (refer to table 4.2.2.2.3). The "true horizontal" was calculated from the horizontal segment joining markers #10 and #20. This segment was selected since a similar horizontal segment would be used to calculate the "true horizontal" in the second stage of this investigation.

Table 4.2.2.2.3 Adjusted (relative to earth-based horizontal axis) measurement errors ($\bar{x}$, $\bar{x}_{max}$, Max_{error}) found across *FOV* conditions.

FOV (m)	**4.5 m**	**4.0 m**	**3.5 m**	**3.0 m**	**2.5 m**
$\bar{x}$ (°)	0.61	0.48	0.45	0.45	0.60
SD (°)	0.36	0.26	0.32	0.26	0.38
$\bar{x}_{max}$ (°)	0.80	0.67	0.56	0.62	0.73
SD (°)	0.53	0.42	0.37	0.36	0.46
Max_{error} (°)	2.18	2.01	1.74	1.48	1.48

After correcting the angular data, the mean errors ($\bar{x}$) were found to range from 0.45° to 0.61°, the mean maximum errors from 0.56° to 0.80°, and the maximum errors from 1.48° to 2.18°. Overall, the error values reduced as a result of the correction. Only the Max_{erorr} values were found to systematically increase across *FOV* conditions (figure 4.2.2.2.3). In general, the angles near the boundaries of the *FOV*, especially the top boundary were associated with the greatest errors. Of the five Max_{erorr} values found, three were associated with angle *A13* (2.01°, 1.74° and 1.48°), and two with angle *A9* (2.18°, 1.48°).

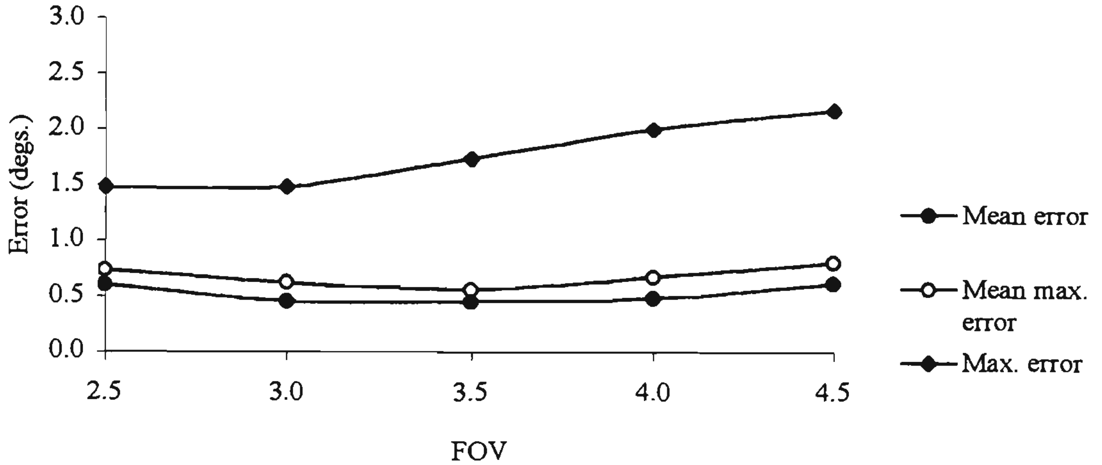


Figure 4.2.2.2.3 Plot of measurement errors (adjusted) found in the angular data across the *FOV* conditions.

Tables 4.2.2.2.4 and 4.2.2.2.5 list the maximum errors (Max_{error}) found after adjusting the horizontal and vertical segment data for the incline values found across *FOV* conditions. Comparisons with tables 4.2.2.1.1 and 4.2.2.1.2 show differences of no more than 0.01 cm for both the horizontal and vertical segment data. This indicates that the camera levelling was not a major source of measurement error in these linear data.

Table 4.2.2.2.4 Measurement errors ($\bar{x}_{max}$, Max_{error}) found, with correction for incline, for the vertical segment data across *FOV* conditions.

FOV (m)	4.5 m	4.0 m	3.5 m	3.0 m	2.5 m
$\bar{x}_{max}$ (cm)	0.60	0.62	0.67	0.57	0.61
SD (cm)	0.31	0.32	0.43	0.39	0.40
Max_{error} (cm)	1.48	1.28	1.91	1.54	1.59

Table 4.2.2.2.5 Measurement errors ($\bar{x}_{max}$, Max_{error}) found, with correction for incline, for the horizontal segment data across *FOV* conditions

FOV (m)	4.5 m	4.0 m	3.5 m	3.0 m	2.5 m
$\bar{x}_{max}$ (cm)	0.67	0.69	0.72	0.73	0.64
SD (cm)	0.41	0.39	0.40	0.44	0.38
Max_{error} (cm)	1.66	1.61	1.58	1.71	1.71

4.2.3 Experiment 3 - marker motion

The results of Experiment 3 are listed in table 4.2.3.1. For the 2.5 and 3 m *FOV* conditions, errors (mean and maximum) fell below 0.77 cm. A large Max_{error} value (1.91 cm) was found for the 4.5 *FOV* condition which differs by more than 0.76 cm from the other *FOV* conditions. In general, the error across the *FOV* conditions shows some increases with increasing *FOV* (refer to figure 4.2.3.1).

Table 4.2.3.1 Measurement error values ($\bar{x}$, $\bar{x}_{max}$, Max_{error}) found for pendulum marker distances across *FOV* conditions.

FOV (m)	4.5 m	4.0 m	3.5 m	3.0 m	2.5 m
$\bar{x}$ (cm)	0.57	0.23	0.25	0.23	0.29
SD (cm)	0.30	0.16	0.13	0.08	0.15
$\bar{x}_{max}$ (cm)	1.12	0.36	0.43	0.34	0.45
SD (cm)	0.64	0.18	0.14	0.11	0.24
Max_{error} (cm)	1.91	0.54	0.60	0.42	0.76

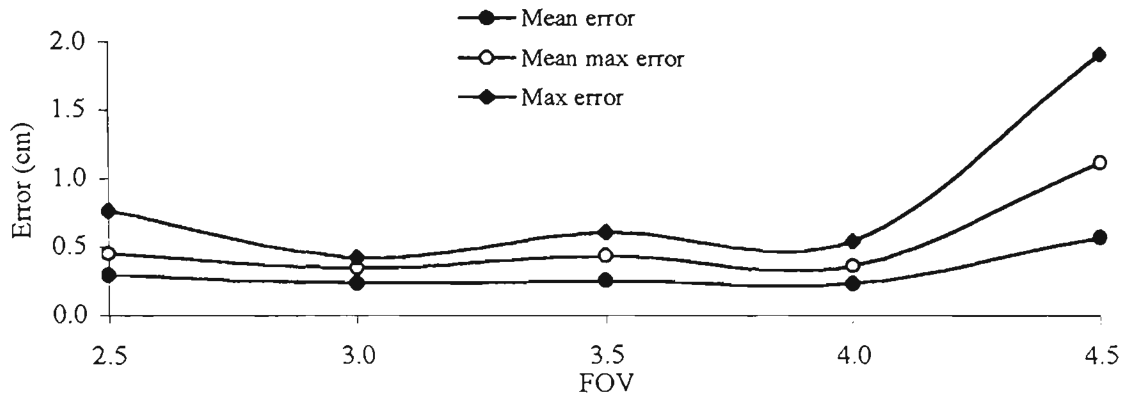


Figure 4.2.3.1 Plot of measurement error values ($\bar{x}$, $\bar{x}_{max}$, Max_{error}) found for the segment lengths on the pendulum.

4.3 Discussion

Experiment 1 examined the error, across varying camera locations, contained in data representing footfalls and foot-obstacle-clearances in gait. The results show the 10 m camera location to be associated with the least error. The magnitude of error found for this location was about a third of that found for the 5 m location. For the 10 m location, mean error in the data representing footfalls and foot-obstacle-clearances were found to range from 0.14 to 0.85 cm. The largest depth condition (15 cm separation) was associated with the largest error. If these data are ignored, measurement error (mean) drops below 0.66 cm for the footfall data and 0.33 cm for the foot-obstacle-clearance data. It is reasonable to exclude this data since typical walking bases have been reported to range from 5 to 10 cm (Whittle, 1991). Put simply, it is highly unlikely that the feet would be separated by more than 10 cm or placed more than 10 cm from the centre-line of a walkway (refer to figure 4.3.1).

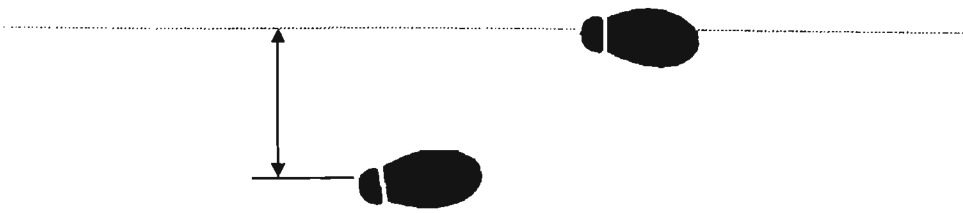


Figure 4.3.1 Schematic representation of a footfall pattern along a walkway (one step). The segmented line represents the centre-line of the walkway. The walking base is depicted by the double-headed arrow.

The previous findings are important to the field of gait research. It is clear that camera location has a significant affect on the accuracy of 2D spatial data. Unfortunately, the majority of gait studies do not report the location of the camera. It is impossible, therefore, to ascertain the likely measurement error contained in the data. In addition, previous studies used camera locations of 5 or 6 m (e.g., Prince et al., 1994; Redfern & DiPasquale, 1997; Cutlip et al., 2000). Large errors ($\approx$ 2 to 4 cm), therefore, may be contained in the data reported by these studies. In fact, Cutlip et al. (2000) evaluated the accuracy of an instrumented walkway by comparing its 2D spatial data (e.g., step length) to the same data extracted from a camera located 5 m from the 2D measurement plane. A camera location of 7 m or more should have been employed to test the accuracy of the instrumented walkway.

Experiment 2 examined measurement error, across varying camera fields of view (*FOV*), contained in data representing anatomical landmarks on a person. These landmarks (stationary) were placed in the same 2D measurement plane on a wall. No systematic changes in measurement error were found across the *FOVs*. Overall, the mean error fell below 0.66 cm and differed by no more than 1.6 mm across the *FOVs*. Mean maximum error fell below 0.74 cm and differed by no more than 1.0 mm across the *FOVs*. Maximum error fell below 1.91 cm across *FOVs*.

These findings are similar to those reported by Ehara, Fujimoto, Miyazaki, Tanaka and Yammoto (1995) who used the PEAK Motion Measurement System to determine the accuracy of 3D spatial data (*FOV* $\approx$ 2.4 to 3.0 m). The data was captured from a rod (900 cm long) carried by person who moved along a walkway. This study reported mean error in marker position to be 0.53 cm and maximum error to be 1.41 cm.

The mean errors ($\bar{x}$, $\bar{x}_{max}$) contained in the angular data (relative to earth-based horizontal axis) fell below 0.62° and 0.81° respectively. These values are similar to those reported by Scholz and Millford (1993) who found mean error to range from 0 to 0.8° for a 3D accuracy study involving angular data extracted from a pendulum by the PEAK Motion Measurement System. In this study, high maximum errors were found across the *FOVs*. These ranged from 1.48 to 2.18° with the 2.5 and 3 m *FOVs* associated with the least error of 1.48°.

In Experiment 3 (dynamic condition), the largest errors were found for the 4.5 m *FOV*. ($\bar{x}$ = 0.57 cm, $\bar{x}_{max}$ = 1.12 cm, Max_{error} = 1.91 cm). The errors found for the other *FOVs* were about half these error values; 0.31 cm, 0.58 cm and 1.14 cm respectively. No systematic changes in error were found across the *FOVs*.

The results show that camera location must be maximized, or at least 7 to 8 m, in order to reduce measurement error (perspective and parallax) in gait research. In addition, the results suggest that 2.5 to 3 m *FOVs* are most likely associated with the least error contained in spatial data (in particular angular data) collected for gait. The results of the *FOV* work, however, are somewhat inconclusive. It is suggested that the practice of fixing the vertical separation of the markers across *FOV* conditions in this study may have confounded the results; that is, as the camera *FOV* increased, the vertical separation of the markers remained the same. As can be seen in figure 4.3.2, such a practice causes the markers in the larger *FOV* conditions to be positioned relatively closer to the optical axis of the camera. Such a practice probably reduces measurement error in the larger *FOV* conditions since the markers are moved away from areas traditionally associated with image distortion (lens distortion). This is supported by the fact that the vertical segment data consistently displayed less error ($\approx$ 0.1 cm) than the horizontal segment data.

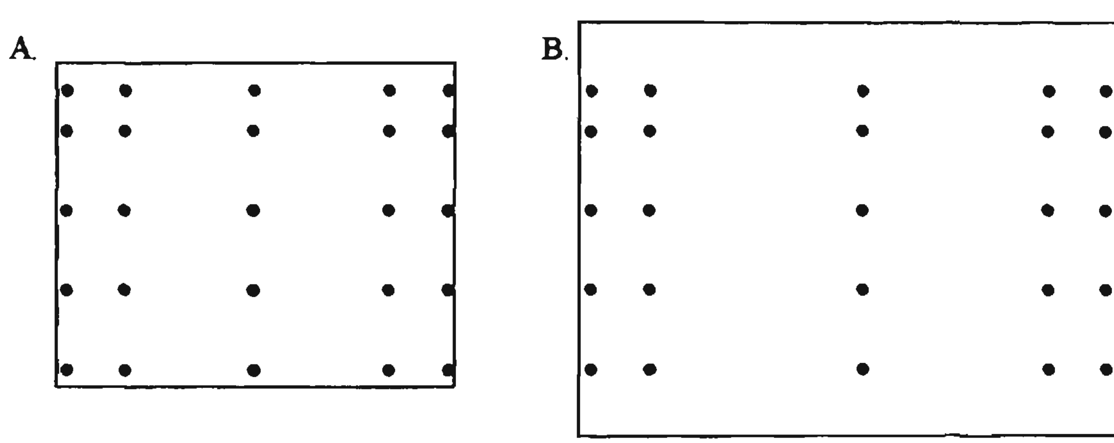


Figure 4.3.2 Schematic representation of two camera *FOVs* used in this investigation. As can be seen the larger *FOV* (part B.) causes the markers to be located closer to the middle horizontal line or optical axis of the camera.

A better method would have been to place markers at the same relative vertical distances across *FOV* conditions. The aim of this investigation, however, was to determine the magnitude of measurement error for markers located on a person as they moved across a camera *FOV*. Typical placement of markers in the second stage of this project were to be on sites such as the toe and head.

Camera levelling was not found to be a major source of measurement error (refer to table 4.2.2.2.3). In Experiment 2, for example, it was found that the camera was rotated counter-clockwise (on average ≈ 0.25°) about its longitudinal axis and in its transverse plane. The data was mathematically adjusted to correct for the lean of the camera. As a result, segment length data were found to differ by no more than 0.1 mm from the original data set and angular data by no more than 0.25°. Digitisation error, perspective error and image distortion near the boundary of the *FOV*, therefore, most likely constitute the majority of measurement error.

On the basis of the error findings reported above, it was concluded that the experimental setup listed below was likely to produce the least amount of error in 2D spatial data commonly collected in gait research. Table 4.3.1 lists the error likely to be contained in such data.

- A camera location of 10 m;
- A *FOV* of 2.5 to 3 m;
- A *FOV* overlap of at least 20 cm (refer to figure 4.3.2).

Table 4.3.1 Error likely to be contained in spatial data collected for a camera location, *FOV* and height of 10 m, 3 m and 0.85 m respectively.

	Error	
Parameter	$\bar{x}$	SD
Footfall position (cm)	0.53	0.25
Foot-obstacle-clearance (cm)	0.22	0.18
Horz. segment lengths (cm)	0.59	0.38
Vert. segment lengths (cm)	0.46	0.38

Angular data (°)	0.5	0.32

A *FOV* overlap of about 20 cm allows markers to be digitized away from the horizontal edges of the image (refer to figure 4.3.3). In addition, a 3 m *FOV* ensures that the highest and lowest markers (toe and head) placed on a person are well inside the *FOV*.

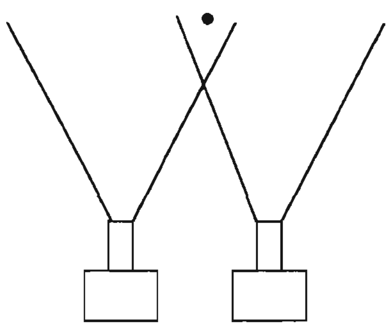


Figure 4.3.3 Schematic representation of a marker located in the overlap region of two cameras (superior view).

CHAPTER 5 METHODS

5.1 Accommodation of surface height change

5.1.1 Participants

Ninety six healthy adult female volunteers participated in this study. The elderly participants were at least 55 years of age (n = 48). The young participants were no more than 31 years of age (n = 48). The young adult females were primarily recruited from the Australian Catholic University (ACU) community at Christ Campus, Melbourne. The elderly female adults were recruited from a variety of clubs (lawn bowling, health and fitness) and Catholic organisations (ACU and Catholic parishes) located in Melbourne. A summary of the general participant details is presented in table 5.1.1.1. The study population was limited to females due to: (1) the greater prevalence of falling behaviour exhibited by elderly females compared to elderly males (please refer to section 2.1.1); (2) the time constraints of this project; and, (3) gender differences previously reported in basic measures of gait (e.g., Öberg et al., 1993; 1994; Whittle, 1991).

Table 5.1.1.1 Details of participants.

Factor	Young	Range	Elderly	Range
Age (yrs.)	20.0 ± 2.4	18 - 31	67.4 ± 5.4	55 - 77
Stature (cm)	167.5 ± 6.8	151 - 180	161.4 ± 5.7	150 - 174
Mass (kg)	60.9 ± 7.8	47 - 80	65.4 ± 13.1	41 - 110

A power analysis performed on data previously reported by Lythgo and Begg (1999a; 1999c) revealed that a sample size of 30 was needed in order to detect significant differences between elderly and young adult females when performing an accommodation task. It was on this basis that a sample size greater than 30 was sought.

5.1.2 Screening items

The fundamental aim of this project was to investigate the effect of age upon the performance of an "everyday" walking task that has been directly linked to falls in the elderly adult population. It has been previously reported that factors such as inactivity, the presence of disease or the use of specific medications (e.g., benzodiazepines) affect balance (Hill, 1997). Consequently, it was important to employ a screening methodology that excluded participants who suffered from medical conditions or exhibited behaviours that may affect the validity of this study. As a result, the screening items recommended by Hill (1997) were adopted for this project.

Participants voluntarily completed a questionnaire (appendix A) and a series of screening tests. Testing occurred in the order listed, with questionnaires and tests requiring minimal physical exertion interspersed between tests requiring greater physical exertion; screening took about 45 minutes. Fifty-four elderly adult females were screened for this investigation, six were excluded since they failed to pass all the screening measures.

5.1.2.1 List of prescribed medications

All prescribed medications being taken were recorded (as recommended by Hill, 1997). Participants were excluded if they had taken any hypnotics or sedatives within 24 hours of testing.

5.1.2.2 Self-reported medical, activity level, and falling history

Specific surgical procedures, as well as any major events requiring medical intervention in the past or present were recorded (Hill, 1997). These included severe heart or breathing disorders, musculo-skeletal dysfunction, neuromuscular dysfunction, traumatic injuries or surgeries, arthritis, persistent vertigo, light-headedness or pain in the major joints of the body (lower back, hips, legs, knee, ankles or feet) whilst walking. Participants were excluded if any of these were considered to have a significant impact upon balance and/or mobility. The participant's ability to ascend and descend stairs independently without upper extremity support was recorded. Participants unable to perform these tasks were excluded.

Activity level was recorded on the following scale: (1) inactive (no exercise), (2) slightly active (exercise 1 - 2 times per week), (3) active (exercise 3 - 4 times per week), and (4) very active (exercise 5 - 7 times per week). Participants were instructed that exercise periods were to be at least 20 to 30 minutes or more. Participants were excluded if they rated their activity level as inactive.

Each participant's falling history was recorded. If a participant had experienced two or more falls in the previous twelve months they were excluded from the study (Hill, 1997).

5.1.2.3 Cognition

The Abbreviated Mental Test Score (Hodkinson, 1972) was administered as a measure of cognitive status. This is a 10 item questionnaire (Table 5.1.2.3.1) that provides a gross screen of various aspects of cognition. A score of seven or below is considered a sign of moderate cognitive impairment, and was an exclusion criterion.

Table 5.1.2.3.1 The Abbreviated Mental Score Test (AMTS, Hodkinson, 1972).

Item	Score
1. Age	1 point
2. Time (to the nearest hour)	1 point
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	1 point if fully correct
4. Year	1 point
5. Name of Hospital/Institution/Home	1 point
6. Recognition of two persons (doctor, nurse)	1 point if fully correct
7. Date of birth	1 point
8. Years of First World War	1 point
9. Name of present Monarch (Prime Minister used)	1 point
10. Count backwards 20-1	1 point if fully correct
Maximum	10 points

5.1.2.4 Vibration sense.

Vibration sense was assessed in a supine position with eyes closed (Hill, 1997). A 128 Hz tuning fork was placed on the lateral malleolus of each leg one at a time, and on the tibial tuberosity of each leg, one at a time. On each occasion, the participant was asked to state whether they could feel the vibration. If they could sense the vibration, the participant was asked to state when the vibration ceased. The tester stopped the vibration at a random time over 5 seconds. Participants were excluded if they could not perceive the vibration, or if they could not accurately report when the stimulus was stopped (manually) by the tester.

5.1.2.5 Lower limb joint proprioception.

Proprioception was tested with the participant lying supine (Hill, 1997). The great toe of one foot was held on each side by the examiner, separated slightly from the other toes to minimise other sensory cues. The task was explained, and the toe movement up and down was demonstrated on the participant to ensure comprehension of the test. Confounding movements of the great toe were used, between which the great toe was held at full flexion or full extension, and the participant would describe the position as “up” or “down”. Five trials were used to test each great toe with the participant’s eyes closed. If any responses were incorrect, the participant was excluded.

5.1.2.6 Vestibular stepping test

The Vestibular stepping test employed by Peitersen (1967) was used in this project. The participant stood with the feet comfortably apart on an area of floor marked as shown in figure 5.1.2.6.1. The participant was instructed to close their eyes and to march on the spot for 50 steps. The assessor counted the steps. The final position of the feet was noted after the 50 steps. Participants were excluded from the study if they turned more than 45 degrees.

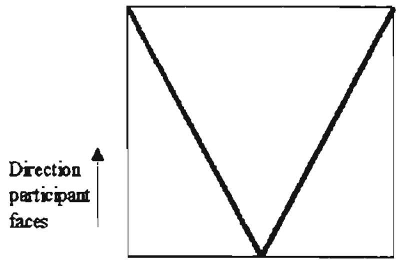


Figure 5.1.2.6.1 Position and marked-out floor for Vestibular Stepping Test.

5.1.2.7 Romberg test

The Romberg test employed by Black, Wall, Rockette and Kitch (1982) was used in this project. Participants were asked to stand with their feet together, then to close their eyes and balance for thirty seconds. If a participant lost balance and stepped, opened their eyes during testing, or needed manual steadying during the test, they were excluded from the study.

5.1.2.8 Visual acuity

A Snellen chart was used to measure visual acuity from a distance of 6 metres in a room brightly lit with both artificial and natural lighting (Lord, Clark & Webster, 1991). Corrected vision using glasses or contact lenses was assessed. The score from the lowest complete line read accurately was recorded. Participants with a logMAR score higher than 0.4 or Snellen denominator higher than 15 were excluded from the study.

5.1.2.9 Visual contrast sensitivity

Contrast sensitivity was assessed using the Melbourne Edge Test (Verbaken & Johnston, 1986). Participants were tested in a brightly lit room with artificial lighting above and natural lighting behind them. The Melbourne Edge Test consists of a series of 24 circles, divided into halves of contrasting shades, with the angle of division between the two contrasting halves varying randomly between horizontal, vertical, 45° to the left, and 45° to the right. The degree of contrast reduces as the participant progresses through the chart, to a point where they are unable to perceive any contrast. The last numbered circle in which the contrast is accurately identified is the contrast sensitivity score. A maximum score of 24 can be achieved if all 24 circles of reducing contrast are successfully identified. A cut-off score of 16 has been described as representing poor contrast sensitivity (Lord et al., 1991). Participants scoring 16 or less were excluded.

5.2 Tasks

Basic anthropometric measures such as height, mass, and leg length were recorded prior to testing using standard equipment and procedures recommended by Vaughan, Davis, and O'Connor (1992). In each task participants wore their "everyday" shoes or shoes they found comfortable for walking (participants were not allowed to wear shoes with heels greater than 2.5 cm): the majority of participants wore athletic-type shoes. Participants also wore dark coloured (firm fitting) clothing such as tights, leggings, bike shorts and firm fitting tops. The clothing did not restrict movement and presented the best conditions for the placement of passive reflective markers on important landmarks of the body. Clothing was supplied for those participants whose dress was inappropriate.

In the accommodation tasks, a 2 (walking velocity) × 2 (step condition) experimental design was employed. The walking velocities were comfortable and fast, and the step condition was a step-off or on (descent or ascent). This investigation adopted a fast walking velocity range of 115 to 125% of comfortable velocity. Waters and Yakura (1989) reported fast walking speed (*FWS*) to be about: (1) 25% more than comfortable walking speed (*CWS*) in adult females aged 20 to 59 years; and (2) 20% more than *CWS* for elderly adults aged 60 to 80 years of age. Similarly, in a study of 84 males, Cunningham, Rechnitzer, Pearce and Donner, (1982) reported *FWS* to be about 20 to 23% more than *CWS*. Karst et al. (1999) also reported a 24% increase in *FWS* when a group of elderly women (65 to 79 yrs.) were instructed to walk "as fast as you comfortably can". Lastly, Smidt (1990) has defined *FWS* to be about 25% more than *CWS*.

Walking velocity was manipulated because previous studies have shown that a reduction in available response time may be associated with falls in the elderly (e.g., Chen et al., 1994b; Cao et al., 1997). The surface height conditions were selected because activities such as climbing a step or kerb have been directly linked to trip-induced falls (e.g., Lilley et al., 1995).

5.2.1 Task 1: comfortable walking velocity (CWV)

Initially, participants familiarised themselves with the environment by walking along a 22 m level walkway positioned in the middle of a hall at the Australian Catholic University (Melbourne, Australia). Once familiar with the environment and task, the participants completed 6 walking trials at a comfortable velocity. Two photoelectric timing gates (Performance Technologies, Victoria University, Australia) located near the centre of the walkway, and placed six metres apart (height: 1.4 m), recorded the participant's time over the six metres. These data were then used to calculate an average walking velocity in order to monitor velocity in Task 2 of this investigation.

5.2.2 Task 2: accommodation of surface height change

5.2.2.1 Walkway design

The walkway consisted of a platform fixed to a 22 m level walkway. Brackets screwed into the floor and placed at the sides and ends of the platforms prevented it from moving or sliding: it consisted of a series of segments (3 m long $\times$ 1 m wide $\times$ 0.15 m high, $\approx$ 50 kg mass) constructed of marine board (thickness: 2 cm) that had been painted with slip resistant paint (colour: footpath grey). The platform was representative of a typical kerb or door threshold encountered in "everyday" activity (Ramsey, 2000). The floor of the hall (ground level) consisted of floor boards with frictional qualities similar to the platform.

Figures 5.2.2.1.1 and 5.2.2.1.2 illustrate the walkways used in the raised surface conditions. In a typical test session, participants ($n \approx 4$) completed the descent task followed by the ascent task. Upon completion of the descent task, the walkway was dismantled and configured for the ascent task. The change of set-up took approximately 30 minutes.

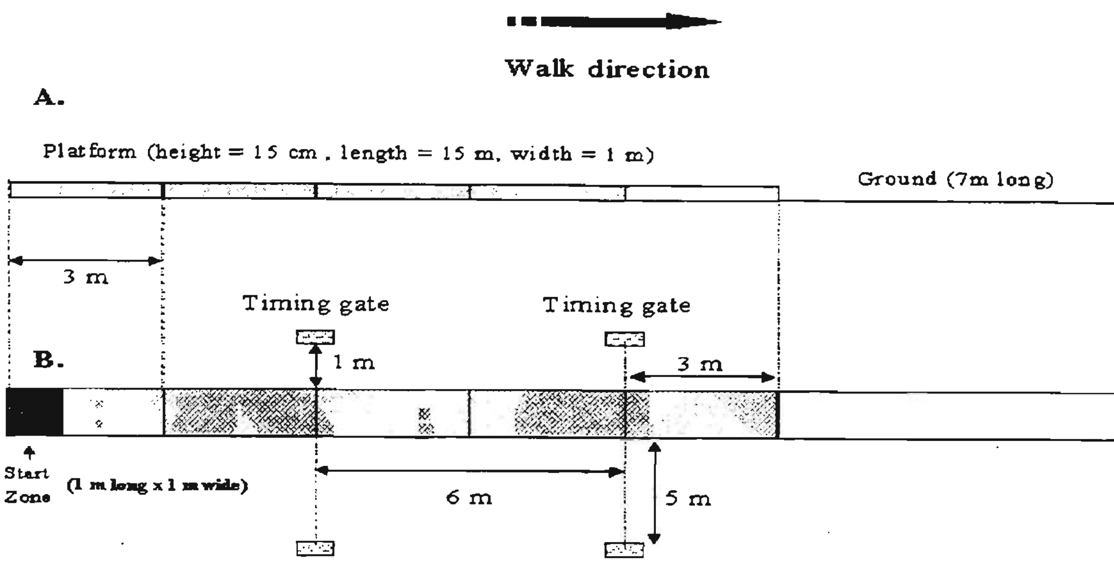


Figure 5.2.2.1.1 Schematic representation of walkway set-up used in the descent task. **A**. Side-on view of the walkway. **B**. Superior view of walkway. Note that the start zone was 1 m long × 1 m wide.

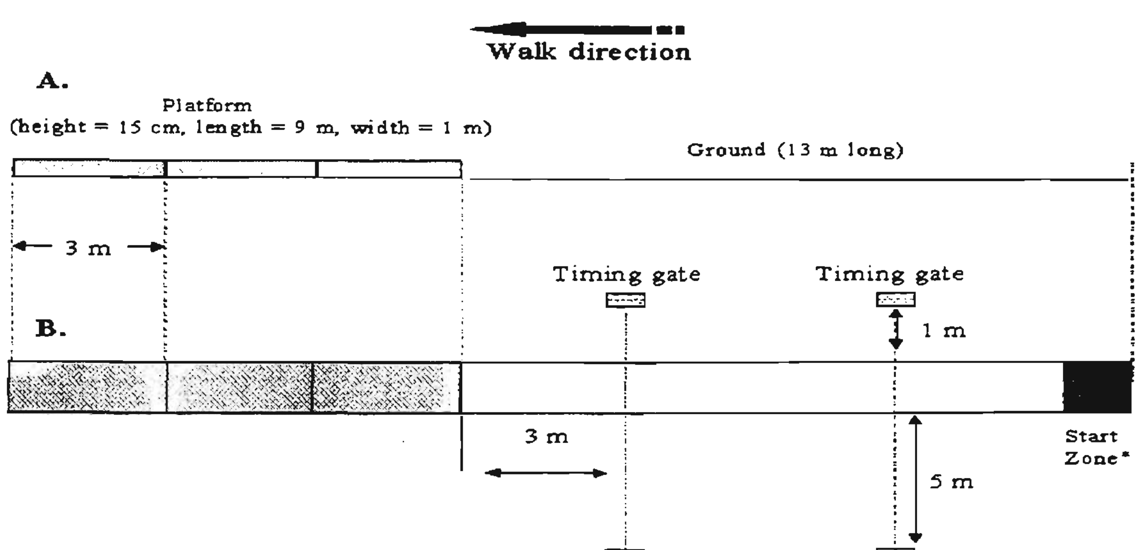


Figure 5.2.2.1.2 Schematic representation of walkway set-up used in the ascent task. **A**. Side-on view of the walkway. **B**. Superior view of walkway. Note that the start zone was 1 m long × 1 m wide.

5.2.2.2 Multi-camera video-tape recording system

A multi-camera video-tape recording system with genlock and time-code (synchronised) was used to film the participant's gait along the walkway. This system consisted of the following equipment:

- 4 × Panasonic Colour CCTV 50 Hz genlock camera (model no. WV-CL830/G).
- 4 × Computar camera lens (model no. H6Z0812, 8-45 mm, 1:1.2).
- 4 × Panasonic VCRs (model no. AG4700).
- A 38 cm Panasonic Colour TV Video Monitor (BT-M1420).
- 4 × Manfrotto adjustable tripods.
- 4 × ARLEC HL18 (250 watts) floodlight with adjustable stand.
- CINDE 4VP video distribution amplifier.
- 4 × Panasonic time date generators (WJ – 810).
- Vision switcher (4 outputs).

Table 5.2.2.2.1 lists the camera settings. Camera #1 was the "master" camera, and cameras #2, #3 and #4 were "slave' cameras. Figures 5.2.2.2.1 and 5.2.2.2.2 illustrate the location of the cameras and walkway configurations (descent and ascent tasks) employed in this investigation. The cameras (front of lens) were located 10 m from the centre of the walkway. This was the maximum distance within the laboratory setting that the camera could be located from the 2D measurement plane. The camera heights were 0.85 m (ground level to lens centre). This height represented about half the average height of the participants filmed in this study. Figure 5.2.2.2.3 is a schematic representation of the multi-camera video-tape recording system used in this investigation.

Table 5.2.2.2.1 Camera menu and settings.

Item	Setting
Camera	ON
ALC/ELC	ELC
SHUTTER	1/500
AGC	OFF
SENS UP	OFF
SYNC	INT (Camera 1)
EXT (VBS)	Camera 2,3,4
WHITE BALANCE	AWC
MOTION DET	OFF
LENS DRIVE	DC

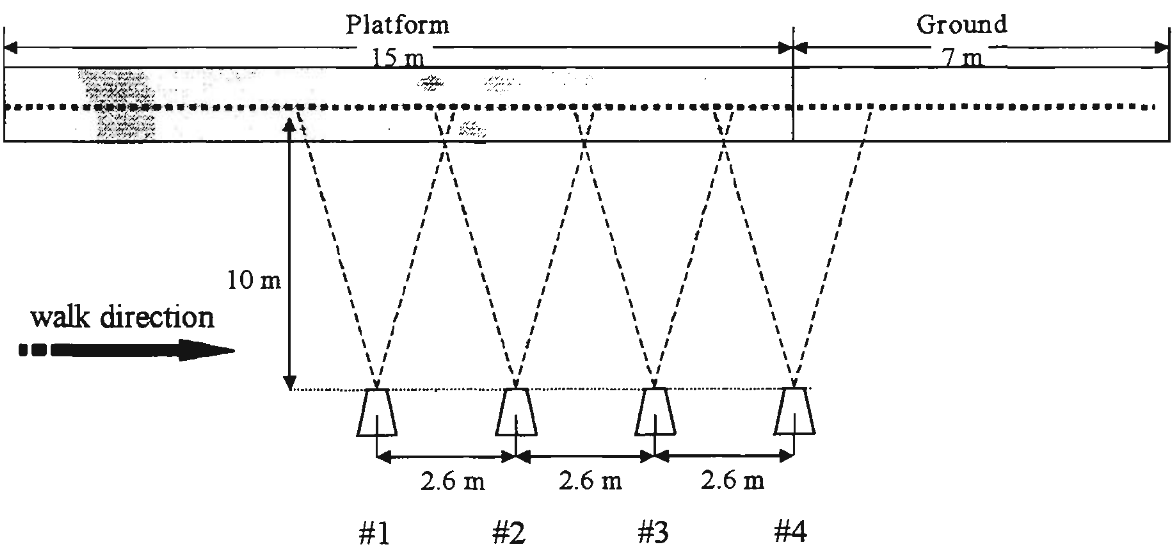


Figure 5.2.2.2.1 Schematic representation of camera location (10 m from centre of walkway) for the descent task (superior view). Camera #4 was positioned in-line with the step edge. Each camera *FOV* was 2.8 m. Floodlights were positioned directly behind and above each camera.

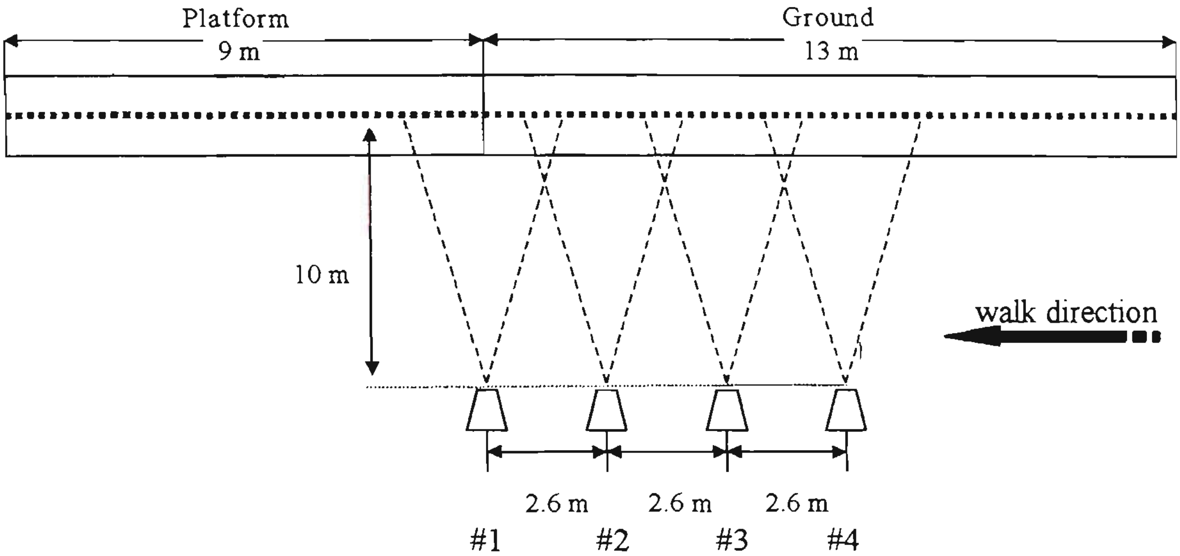


Figure 5.2.2.2.2 Schematic representation of camera location (10 m from centre of walkway) for the ascent task (superior view). Camera #1 was positioned in-line with the step edge. Each camera *FOV* was 2.8 m. Floodlights were positioned directly behind and above each camera.

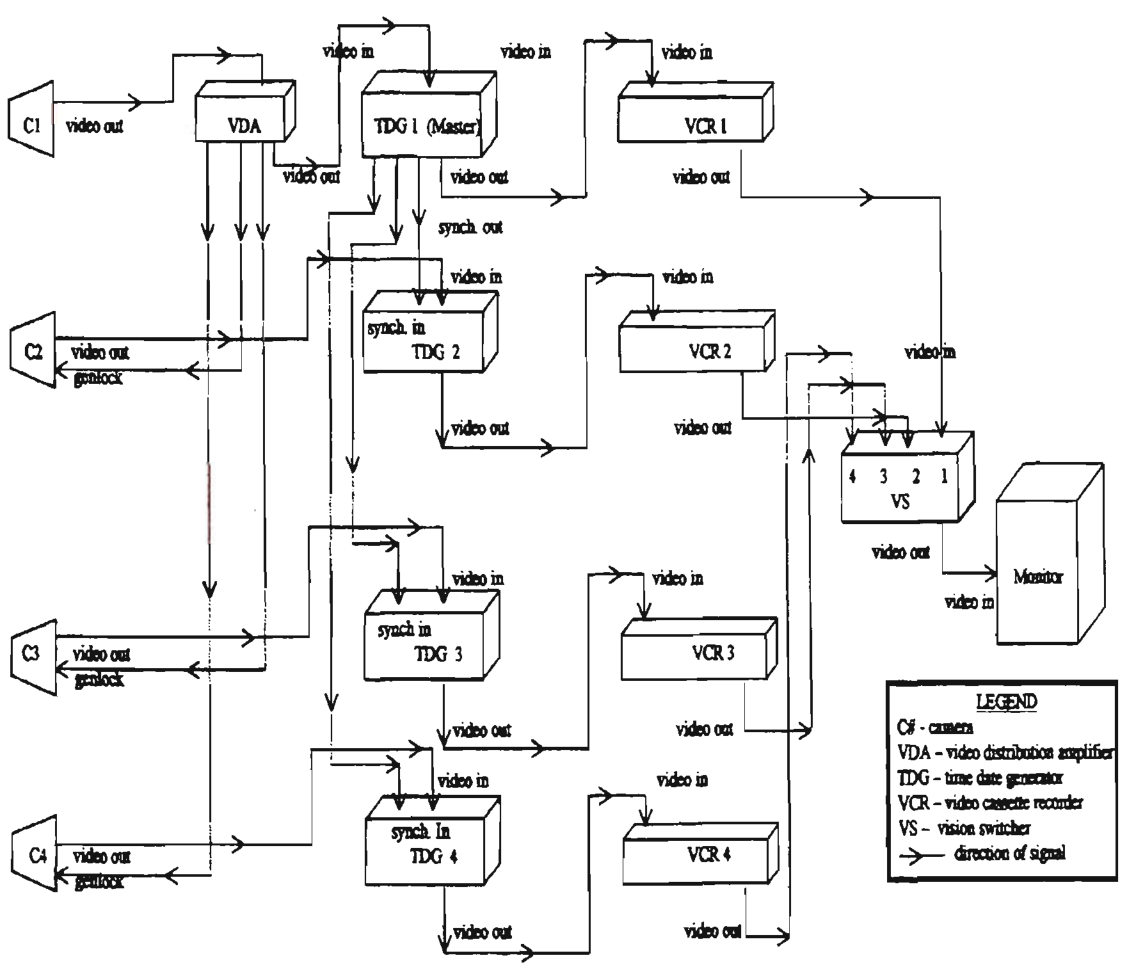


Figure 5.2.2.2.3 Schematic representation of the multi-camera video-tape recording system used in this investigation.

5.2.2.3 Calibration of 2D measurement plane

Prior to each surface height condition, markers were positioned along the mid-line of the walkway (refer to Figures 5.2.2.3.1 and 5.2.2.3.2) and filmed. The markers were located at known distances from the step edge along the walkway. These markers were used: (1) to check the alignment of the cameras in the frontal, sagittal and transverse planes; (2) to calculate foot placement and clearance relative to the step edge; (3) to calculate the orientation of the earth-based horizontal axis. Outer markers in each *FOV* (e.g. *#2* and *#4* in figure 5.2.2.3.1) were used to compute the level or incline of each section of the walkway. This value was then used to adjust the angular data extracted (refer to section 5.4.2); and; (4) to provide at least a 0.2 m *FOV* overlap.

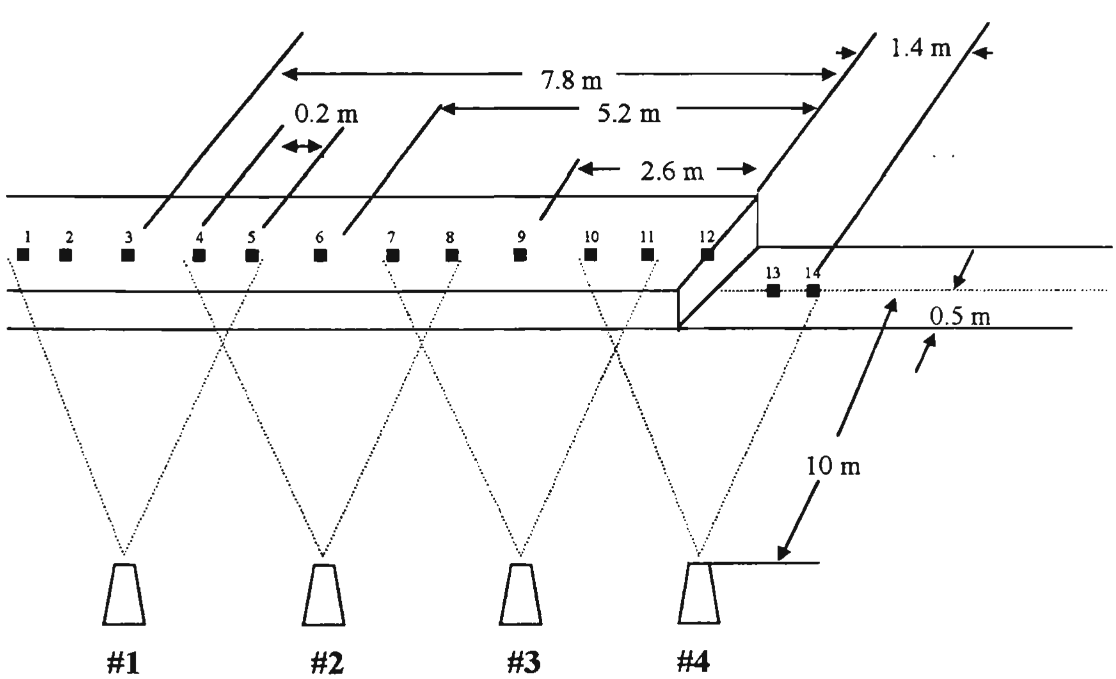


Figure 5.2.2.3.1 Marker location for the descent task. The markers consisted of block cubes (2 cm long × 2 cm wide × 2 cm high) covered with passive reflective tape and were placed along the mid-line of the walkway. Cameras were positioned directly in-line with, and perpendicular to (10 m from the base of the marker) markers #3, #6, #9 and #12. In total, 14 markers were positioned along the mid-line of the walkway. Marker #12 was positioned half-on and off the edge of the step. Cameras were positioned 2.6 m apart (horizontal distance).

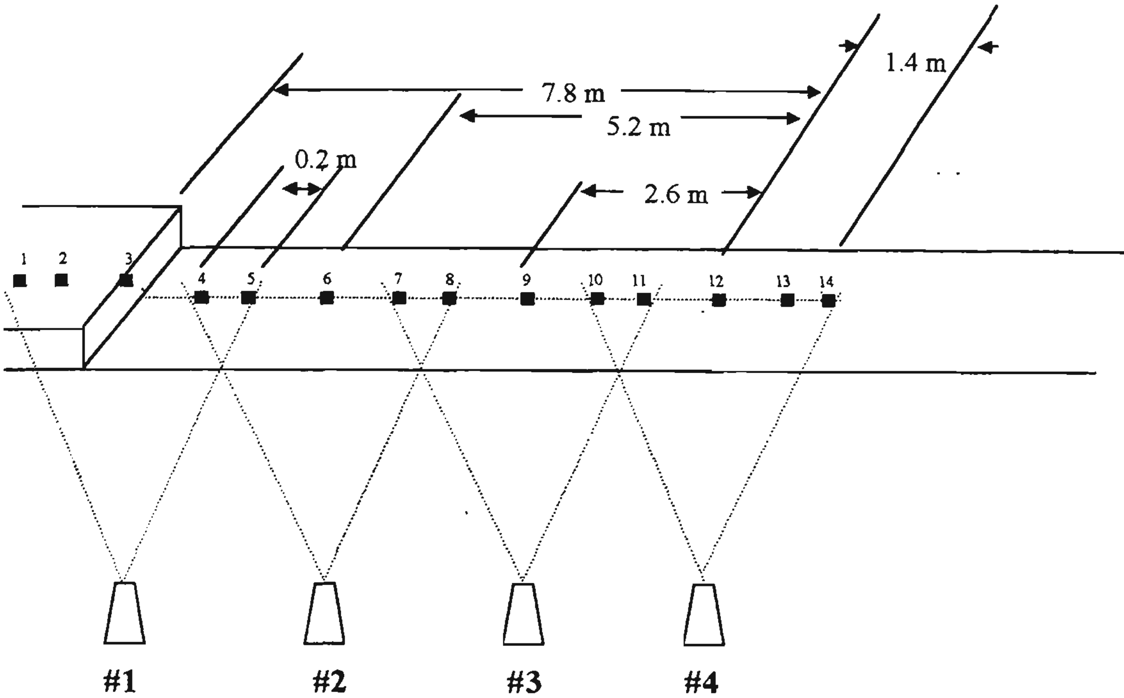


Figure 5.2.2.3.2 Marker location in the ascent task. The markers consisted of square blocks (2 cm long x 2 cm wide x 2 cm square) covered with passive reflective tape and were placed along the mid-line of the walkway. Cameras were positioned directly in-line with, and perpendicular to (10 m from the base of the marker) markers #3, #6, #9 and #12. In total, 14 markers were positioned along the midline of the walkway. Marker #3 was positioned half-on and off the edge of the step. Cameras were positioned 2.6 m apart (horizontal distance).

Once the cameras were levelled, they were zoomed-in to the horizontal boundaries of the outer markers (e.g. camera #1 outer markers were #1 and #5) providing a *FOV* greater than 2.8 m but no more than 3.0 m. This also provided a minimum 0.2 m *FOV* overlap for cameras adjacent to each other. Camera focus was adjusted with the aid of a board-mounted Snellen visual acuity chart placed along the mid-line of the walkway. Lastly, a calibration rod (2.55 m) was placed along the mid-line of the walkway for each camera *FOV*. The calibration rod was filmed in order to provide a scale factor for each *FOV*.

5.2.2.4 Participant protocol

Participants completed a test session that consisted of (1) informed consent, (2) screening tests, (3) anthropometric measures, (4) attachment of passive reflective markers, (5) comfortable walking velocity trials (task 1), (6) descent task, and (7) ascent task. Ethics approval was gained from the respective Offices of Research at Victoria University and the Australian Catholic University (No. HRETH.FHD.039/99). If a participant failed a screening test, they were excluded from the investigation.

Typically, groups of 3 to 5 participants took part in a test session (≈ 3-4 hours). In total, twenty five test sessions were conducted. Since the sessions were labour intensive, the aid of several research assistants was procured. The assistants conducted the less demanding screening tests (basic measurements) and assisted with the walkway change-over; that is, from the descent task to the ascent task. The assistants were trained prior to the test sessions.

At the completion of the screening tests, passive reflective markers (dimensions: 2 cm square) were placed on the sites and body landmarks listed below (refer to figures 5.2.2.4.1 and 5.2.2.4.2). The sites of attachment on the lower limbs were the anatomical landmarks recommended by Vaughan et al. (1992) for gait analysis.

- Toe region - the end (anterior aspect) of the distal phalanx of the 1st metatarsal (big toe) was palpated on each shod foot. Marker centres were then placed on the lateral and medial sides of the participants' shoes directly below this anatomical landmark.

- Heel region - the posterior aspect of the calcaneus (heel) was palpated on each shod foot. Marker centres were placed on the medial and lateral sides of the participants' shoes directly below this anatomical landmark.
- Ankle region - lateral and medial malleoli of the right and left limbs.
- Knee region - lateral and medial femoral condyles of the right and left limbs.
- Hip region - right and left greater trochanters.
- Shoulder region - right and left glenohumeral joints.
- Sites representative of the position of the whole body centre of mass. Markers were placed on the left and right sides of the trunk (directly above the greater trochanter) at 57% of body height (Broer, 1966; Rasch & Burke, 1978; Hay & Reid, 1988; Adrian & Cooper, 1995). Single points on the trunk (sacrum, hip or pelvis) have been used to examine the motion of the centre of mass during level walking and obstacle avoidance tasks (e.g., Cotes & Meade, 1960; Patla & Rietdyk, 1993; Kerrigan, Viramontes, Corcoran & LaRaia, 1995; Duff-Raffaele, Kerrigan, Corcoran & Saini, 1996; Thirunarayan, Kerrigan, Rabuffetti, Croce & Saini, 1996; Saini, Kerrigan, Thirunarayan & Duff-Raffaele, 1998; Cao et al., 1997; 1998a; 1998b). Thirunarayan et al. found a single point on the sacrum located near the median sacral crest ($\approx$ 57% of standing height) provided reliable information about the vertical motion of the centre of mass during level walking. The sacrum, however, was not used in this

investigation since it is a poor representation of the horizontal position of the body's centre of mass.

- Two markers were attached to the ends of rigid plastic rod (length: 30 cm, diameter: 0.5 cm) that was mounted on a light-weight head brace worn by the participants. The head brace was positioned on the head so that the rod was parallel to a line formed by the canthus of the eye and the meatus of the ear (Pozzo, Berthoz & Lefort, 1989). This line approximates the plane of the horizontal semi-circular canals (the Frankfurt plane: F-P). The head brace did not impair vision.

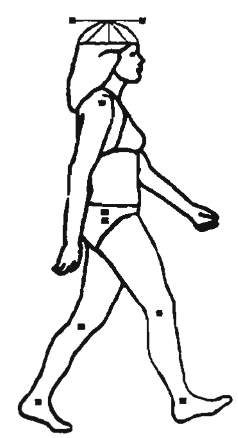


Figure 5.2.2.4.1 Schematic representation of marker placement on head brace and various anatomical landmarks on the body.

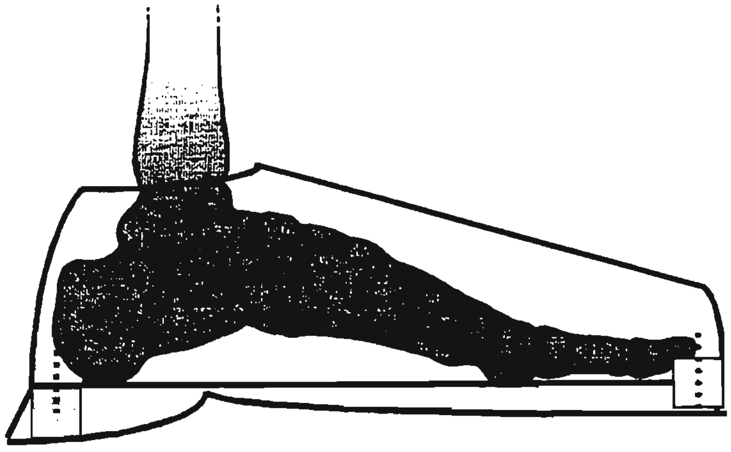


Figure 5.2.2.4.2 Schematic representation of marker placement (lateral aspect) on the participant's shoes. The centre of the markers were placed vertically below anatomical landmarks on the foot.

Prior to the descent task, participants were taken straight to (but not along the walkway incorporating the platform) the platform step and allowed to step-on and off the platform. This allowed them to become familiar with the frictional and compliant qualities of the platform and ground. Once familiar with the surfaces, they were taken from the step, along the platform to a starting zone (1 m long × 1 m wide) 14 m from the step. At this point, participants were given the following instructions: (1) always begin walking from within the "start zone" (refer to figures 5.2.2.1.1 and 5.2.2.1.2); (2) a controller will inform you of the velocity with which you are to walk. This velocity will be fast "as if hurrying to cross a road or make an appointment" (Karst et al., 1999) or comfortable "the velocity you typically walk along a path". All participants were instructed to walk at comfortable velocity on the first trial and fast velocity on the second trial. For subsequent trials the velocity condition alternated from comfortable to fast walking velocity; (3) walk to the end of the walkway; and, (4) a total of six walking trials will be performed; 3 fast and 3 comfortable.

A controlled or pre-set walking velocity and cadence set by a metronome were not used because it was believed that such a constraint would cause participants to approach and accommodate the raised walkway in an atypical manner. The major emphasis of this study was to identify the typical gait adjustments made in these environments. It was accepted that large variability in walking velocity and cadence would occur within each age group as a result of using self-selected walking velocities. It was believed, however, that the implementation of controlled velocities would produce less valuable data by imposing undesirable constraints upon the participants' walking patterns.

Upon completion of the descent task, the walkway was configured for the ascent task; this took about 30 minutes. Participants were given the same instructions as those used for the descent task.

In each surface height condition, the approach velocity (transport phase) was monitored by two photoelectric timing gates (placed 6.0 m apart). The second or last gate was located 3.0 m from the step of the raised walkway (figures 5.2.2.1.1 and 5.2.2.1.2). It was thought that such a distance was necessary to ensure the participants' safety in the fast walking condition; that is, to allow participants to adjust their velocity, if desired, from this point on.

5.3 Data collection

5.3.1 Trial selection

Investigators (Thomson, 1983; Maki et al., 1994; McIlroy & Maki, 1995; Patla et al., 1996) have proposed that the first response to a perturbation (e.g., a novel travel path) is fundamentally different from subsequent responses. In fact, studies of balance recovery have shown that predictability of a perturbation brings about anticipatory movements that improve functional stability (Maki et al., 1994; McIlroy & Maki, 1995). McIlroy and Maki, for example, reported different stepping responses to a perturbation in the third and fourth trials compared to the first and second trials. In the initial trials, participants took multiple steps to regain balance, whereas by the third and fourth trials participants took a single step to recover. As such, the authors recommended that adequate levels of unpredictability should be maintained during balance assessment tasks so as to evoke the compensatory behaviour that is characteristic of responses occurring in the unpredictable circumstances of "everyday" activity.

A few studies of obstructed gait have examined the effect of practice on obstacle avoidance tasks. In a study involving the random presentation of a solid obstacle of varying height, for example, Chen et al. (1991) found the majority of subjects (60%) decreased foot-obstacle-clearance ($p < .04$) after the first trial to a value that was stable in the following trials. In studies involving the random presentation of a virtual obstacle (light-band) across three blocks of trials, Chen et al. (1994a; 1996) found the mean rate of success (i.e. not stepping on the light-band) improved from the first block to the last. In these studies, eight obstacle conditions were presented twice in each block. In addition, this study found walking speed (unobstructed) to increase over the test session in 77% of subjects. Finally, a study conducted by Hreljac (1993) reported a practice effect when stepping over an obstacle in a block of 30 repeat trials. Movement time and the movement smoothness of a marker located on the 5^{th} metatarsal of the lead foot were found to significantly reduce ($p < .05$) after the first trial (refer to figure 5.3.1.1).

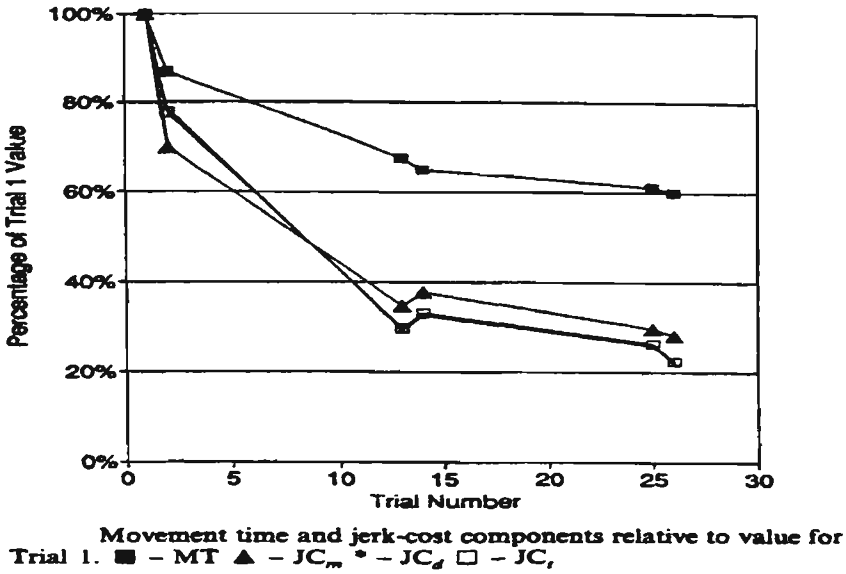


Figure 5.3.1.1 Changes in movement time (MT) and measures of lead foot movement smoothness (JC - jerk cost: JC_m – magnitudinal jerk cost, JC_d – directional jerk cost, JC_t – total jerk cost) for trials 1, 2, 13, 14, 25 and 26. Smoothness measures were extracted from the movement of a marker located on the 5th metatarsal of the lead foot (taken from Hreljac, 1993, p. 377).

The previous findings, coupled with the suggestions of other investigators (e.g., Patla et al., 1996), support the notion that clinical or experimental assessment of dynamic stability is most likely confounded by adaptive changes that occur during repeated or blocked testing. This is a major concern since many studies have involved repeat trials (5 to 15 trials) presented in either blocked (e.g., McFadyen & Winter, 1988; Livingston et al., 1991; Patla et al., 1996; Riener et al., 2002; McFadyen & Prince, 2002) or randomised conditions (e.g., Chen et al., 1991; 1996; Patla et al., 1991; Patla & Rietdyk, 1993; Patla & Prentice, 1995; Liu et al., 1996; Sparrow et al., 1996; Patla & Vickers, 1997; Stemmons Mercer et al., 1997; Lythgo & Begg, 1999a; Sims & Brauer, 2000). These studies have sought to attain a high level of statistical power by employing "multiple" trial methodologies. Although this increases mathematical power, such methodologies actually reduce the real power of a comparison study since subsequent responses are inherently different to the first response. Put simply, repeat trials (extraneous variable) exert a confounding influence on independent variables such as age or obstacle condition (e.g., height). This contaminates the independent variables in such a way that separate effects on outcome measures (e.g., foot-obstacle-clearance) are obscured (Portney & Watkins, 2000).

A number of studies of obstructed gait have employed single trial methodologies where only the first response to a task has been analysed (Crosbie, 1996; Patla et al., 1996; Chou et al., 1997; Chou & Draganich, 1997; Pavol et al., 1999; 2001). These investigators support the notion that the first response is unique since repeat trials reduce novelty (e.g., Patla et al., 1996). Other studies have analysed 2 to 3 repeat trials to gain mean values for comparison (e.g., Simoneau et al., 1991; Krebs et al., 1992; McFadyen et al., 1993; Austin et al., 1999; Chou & Draganich, 1998a; 1998b; 2001).

In this project, preliminary work examined the issue of task novelty. Six participants' footfall patterns (comfortable-velocity descent condition) were examined near the platform step for 12 repeat trials. Another participant's footfall pattern was examined for the entire length of the platform for 12 repeat trials (comfortable-velocity descent task).

Based on the preliminary work and previous literature, this study sought to improve ecological validity and statistical power by (1) focusing upon the first response to a novel travel path, and (2) involving large participant numbers. As such, only the first two trials (comfortable and fast walking velocity) in each step condition (descent and ascent) were fully analysed in this investigation. A total of six trials were collected for each step condition; that is 3 at comfortable walking velocity and 3 at fast walking velocity. Trial presentation for each step condition is shown in table 5.3.1.1.

Table 5.3.1.1 Order of trial presentation; CWV: comfortable, FWV: fast.

Trial	1	2	3	4	5	6
Velocity	CWV	FWV	CWV	FWV	CWV	FWV

The first comfortable and fast walking velocity trials were focused upon (trials 1 and 2) since these best represent a novel travel path presentation. The remaining trials (2 trials per step-velocity condition) were used to examine the step adjustments (step length, step time, toe-to-step-edge displacement) made in the approach and accommodation phases. It was believed that valuable information about targeting could be extracted from these trials.

5.3.2 Digitisation procedures

The Peak Motus Motion Measurement System (version 2000) was used for the digital conversion (digitising) of the location of the passive reflective markers. The video-tape recorded film of each participant's motion was captured in digital format by the Motus system. The digitisation process involved manual digitisation (1/4 pixel function used for toe and heel clearance markers) of markers.

Manual digitisation was performed since it produced a data file format that allowed computer software programs (written by the author) to accurately identify key events such as foot contact with the ground (crossing step). The identification of these events was central to the process of data extraction for this investigation. Previous pilot work had shown that key events could be missed or misreported (≈ 20% failure rate) when data files produced by automatic digitisation were processed by the programs. This failure was due to factors such as the orientation of the foot upon landing and marker distortion caused by deformation of the shoe during stance (e.g., Startzell & Cavanagh, 1999). In the crossing step, for example, some participants chose to land on the forefoot, some on the heel, and others grounded the entire foot. This meant that no single parameter (e.g., toe velocity) could be used to identify foot contact across participants. In addition, markers placed on the toe or heel of some participants' shoes were deformed or compressed at toe-off and foot landing.

The manual digitization process was labour intensive since it took about 8 hours of continuous work to extract the data for each participant. In reality, it took about a day and a half to extract each participant's data.

The digitisation procedure for the film recorded by cameras #1, #2, #3 and #4 (refer to figures 5.2.2.3.1 and 5.2.2.3.2) involved the digitisation of the toe markers (right and left foot) at foot flat (mid-stance). This information was required to examine footfall patterns.

The digitisation procedure for the film recorded by cameras #3 and #4 involved the digitisation of additional markers:

- The markers attached to the head brace were digitised from the 4^{th}-last heel contact from the step to lead limb mid-stance past the step (refer to Figure 5.3.2.1). This interval was chosen since previous investigations have found that gait is seldom adjusted more than two to three step durations ahead of an obstacle (Chen et al., 1994b; Crosbie, 1996).

- The lead foot markers were digitised from toe-off to foot landing (crossing stride).

- The trail foot markers were digitised from toe-off to the event of lead limb mid-stance past the step (trail limb crossing). The trail foot was not digitised to foot landing since the majority of the participants' trail limb stride length caused the foot to move out of the camera *FOV*.

- The hip, trunk marker (nominal centre of mass marker) and shoulder markers were digitised from trail limb heel contact before the step to lead limb mid-stance past the step (Figure 5.3.2.1).

- The knee and ankle markers were digitised from lead foot toe-off to lead limb mid-stance past the step (crossing stride).

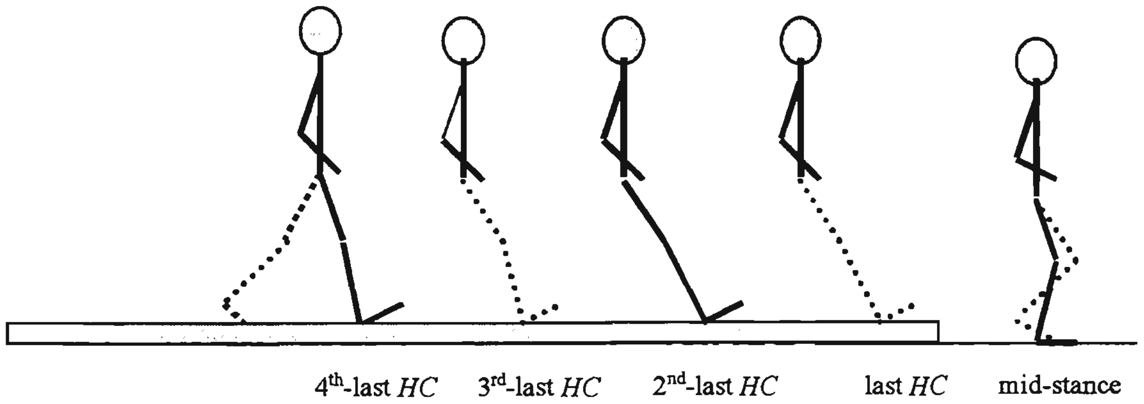


Figure 5.3.2.1 This diagram illustrates the interval over which the markers were digitised for the video-tape film recorded by cameras #3 and #4. *HC*: heel contact.

- Mid-markers #3, #6, #9 and #12 (refer to figures 5.2.2.3.1 and 5.2.2.3.2) which were located on the ground and in the middle of each camera *FOV* were digitised in order to obtain toe-to-step-edge displacements for each footfall. The 2D spatial coordinate data of marker #12 in the descent condition and marker #3 in the ascent condition were used to calculate foot clearance variables. The bottom (centre) of these markers was digitised in order to provide the 2D position of the step edge. The 2D spatial coordinate data of all the mid-markers was placed in data files that were used by the computer software programs to calculate variables of interest.

5.3.3 Two-dimensional spatial coordinate data

Previous pilot work showed that the computer software programs written by the author could not reliably identify key events such as toe-off and foot landing. Attempts to identify events such as foot landing based upon estimations of foot velocity (vertical and horizontal) were not reliable. Factors such as foot orientation at landing, slippage of the foot, deformation of shoe markers and measurement error confounded these attempts. On this basis, data sets such as that shown in table 5.3.3.1 were produced in order to gain reliable information. The table only lists the first 5 points digitised. It shows ("highlighted and underlined") key events such as lead foot toe-off (frame 9) and landing (frame 31), and the position of the lead toe at foot flat before (frame 1) and after the step (frame 43). The adoption of this data file structure allowed the computer software programs to reliably identify key events. Note that key events were not actually highlighted or underlined in the data files.

A raw pixel data file was produced from the digitisation of the film. This data was filtered by a 4th order Butterworth digital filter with a cut-off frequency (optimal filtering option was selected) ranging between 4 to 6 Hz (Bartlett, 1992). This produced a filtered raw pixel data file which contained "zeros" in the cells (or fields) where points were not digitised (table 5.3.3.1). The filtered raw pixel data files were then used to produce 2D spatial coordinate data files.

Table 5.3.3.1 Example of first 15 columns of a data file (2D spatial coordinate data) generated from the digitisation of film recorded by camera #1. The cells containing "zeros" indicate that the point was not digitised. Note that the first two rows were inserted to identify points for the reader.

Frame	Hip			Rheel			Rtoe			Lheel			Ltoe		
	x	y	r	x	y	r	x	y	r	x	y	r	x	y	r
1	0	0	0	0	0	0	0.598	0.311	0.674	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0.85	1.142	1.424	0	0	0	0	0	0	0	0	0	0	0	0
6	0.895	1.14	1.449	0	0	0	0	0	0	0	0	0	0	0	0
7	0.94	1.136	1.474	0	0	0	0	0	0	0	0	0	0	0	0
8	0.985	1.13	1.499	0	0	0	0	0	0	0	0	0	0	0	0
9	1.029	1.124	1.524	0.543	0.512	0.746	0.614	0.28	0.675	0	0	0	0	0	0
10	1.071	1.12	1.55	0.606	0.534	0.808	0.66	0.299	0.725	0	0	0	0	0	0
11	1.111	1.121	1.578	0.67	0.548	0.865	0.72	0.313	0.786	0	0	0	0	0	0
12	1.148	1.125	1.608	0.736	0.55	0.919	0.8	0.322	0.863	0	0	0	0	0	0
13	1.186	1.132	1.64	0.806	0.54	0.97	0.897	0.325	0.954	0	0	0	0	0	0
14	1.223	1.142	1.673	0.879	0.522	1.023	1.003	0.326	1.055	0	0	0	0	0	0
15	1.26	1.152	1.707	0.957	0.498	1.079	1.112	0.325	1.159	0	0	0	1.488	0.323	1.523
16	1.297	1.161	1.741	1.041	0.471	1.142	1.221	0.323	1.263	0	0	0	0	0	0
17	1.333	1.17	1.774	1.129	0.441	1.212	1.328	0.321	1.366	0	0	0	0	0	0
18	1.37	1.177	1.806	1.221	0.41	1.288	1.432	0.319	1.468	0	0	0	0	0	0
19	1.408	1.182	1.838	1.317	0.378	1.37	1.536	0.318	1.569	0	0	0	0	0	0
20	1.449	1.183	1.87	1.414	0.347	1.456	1.64	0.319	1.67	0	0	0	0	0	0
21	1.492	1.178	1.901	1.512	0.317	1.545	1.741	0.322	1.771	0	0	0	0	0	0
22	1.535	1.17	1.93	1.609	0.291	1.635	1.839	0.327	1.868	0	0	0	0	0	0
23	1.579	1.158	1.958	1.704	0.268	1.725	1.93	0.333	1.959	0	0	0	0	0	0
24	1.622	1.142	1.984	1.796	0.248	1.813	2.014	0.34	2.043	0	0	0	0	0	0
25	1.665	1.125	2.01	1.882	0.231	1.896	2.09	0.345	2.119	0	0	0	0	0	0
26	1.71	1.106	2.036	1.959	0.216	1.971	2.157	0.347	2.185	0	0	0	0	0	0
27	1.756	1.086	2.065	2.024	0.2	2.034	2.213	0.343	2.24	0	0	0	0	0	0
28	1.803	1.067	2.095	2.075	0.184	2.083	2.259	0.333	2.283	0	0	0	0	0	0
29	1.851	1.049	2.127	2.11	0.166	2.116	2.294	0.314	2.316	0	0	0	0	0	0
30	1.898	1.032	2.161	2.131	0.15	2.137	2.322	0.287	2.34	0	0	0	0	0	0
31	1.945	1.017	2.195	2.146	0.134	2.15	2.346	0.256	2.36	0	0	0	0	0	0
32	1.988	1.004	2.228	0	0	0	0	0	0	0	0	0	0	0	0
33	2.028	0.994	2.259	0	0	0	0	0	0	0	0	0	0	0	0
34	2.063	0.987	2.287	0	0	0	0	0	0	1.449	0.52	1.539	1.488	0.307	1.519
35	2.094	0.981	2.312	0	0	0	0	0	0	1.516	0.521	1.603	1.558	0.306	1.588
36	2.123	0.977	2.337	0	0	0	0	0	0	1.586	0.516	1.668	1.632	0.301	1.66
37	2.151	0.975	2.362	0	0	0	0	0	0	1.659	0.501	1.733	1.716	0.289	1.74
38	2.182	0.976	2.39	0	0	0	0	0	0	1.736	0.474	1.799	1.81	0.271	1.83
39	2.213	0.979	2.42	0	0	0	0	0	0	1.816	0.435	1.867	1.917	0.248	1.932
40	2.246	0.984	2.452	0	0	0	0	0	0	1.902	0.389	1.941	2.032	0.224	2.044
41	2.279	0.992	2.486	0	0	0	0	0	0	1.995	0.339	2.023	2.154	0.203	2.164
42	2.313	1.003	2.521	0	0	0	0	0	0	2.096	0.289	2.116	2.28	0.191	2.288
43	2.346	1.016	2.557	0	0	0	2.394	0.15	2.398	2.205	0.245	2.219	2.408	0.188	2.415

5.4 Data analysis

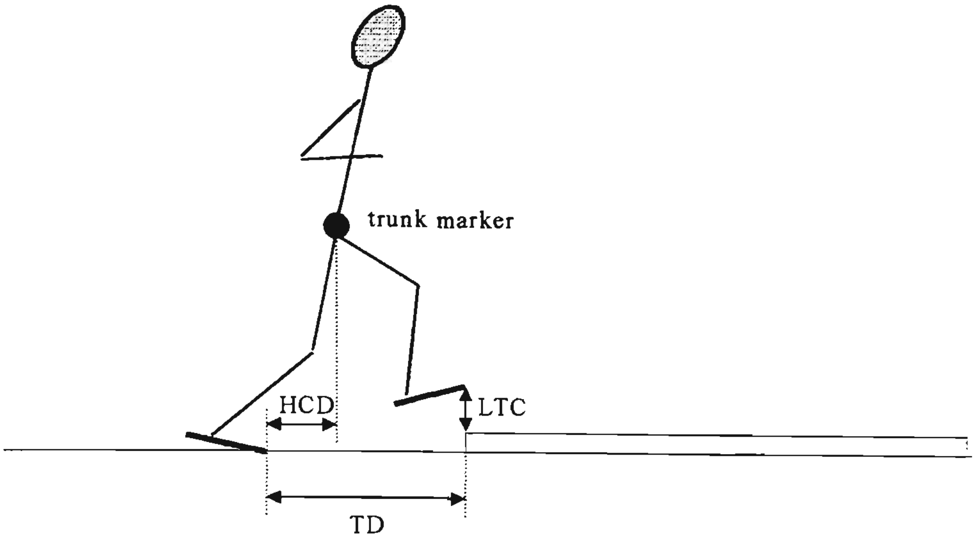
5.4.1 Linear spatio-temporal parameters

The linear spatio-temporal variables (refer to table 5.4.1.1 and figure 5.4.1.1) extracted by computer software programs written by the author are listed in table 5.4.1.1.

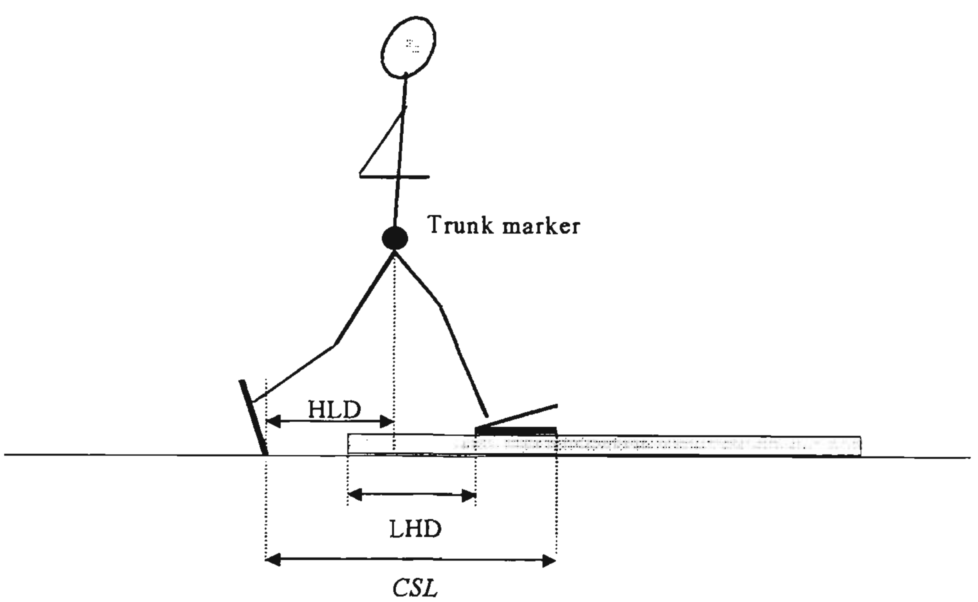
Table 5.4.1.1 Alphabetical list of dependent variables collected in the surface height conditions (descent and ascent): ✔ collected, ✘ not collected.

Variable	Description	Descent	Ascent
ART (ms)	Available response time	✔	✔
ASL (cm)	Approach step lengths (ipsilateral heel contact to contralateral heel contact).	✔	✔
AST (s)	Approach step times (ipsilateral heel contact to contralateral heel contact).	✔	✔
CSL (cm)	Crossing step length (determined from lead and trail toe position).	✔	✔
CST (s)	Lead limb crossing swing time (toe-off to foot landing).	✔	✔
DFST (s)	Double foot support time (trail limb crossing stride).	✔	✔
HA (°)	Head pitch angle (approach and crossing phases).	✔	✔
HCD (cm)	Horizontal displacement of trunk marker from the trail toe as the lead toe crosses the step. .	✔	✔
HCV ($m \cdot s^{-1}$)	Horizontal crossing velocity of trunk marker (lead foot step crossing).	✔	✔
HLD (cm)	Horizontal displacement of trunk marker from the trail toe as the lead foot lands.	✔	✔
HLV ($m \cdot s^{-1}$)	Horizontal landing velocity (after crossing) of trunk marker.	✔	✘
LCA (°)	Lead foot angle at step crossing.	✔	✔
LFM (%)	Lead foot focal movement trajectory (crossing step).	✔	✔
LHC (cm)	Lead heel-step-clearance (vertical).	✔	✔
LHD (cm)	Lead heel horizontal displacement from step (after crossing).	✔	✔
LLA (°)	Lead foot landing angle (crossing step).	✔	✔
LLV ($m \cdot s^{-1}$)	Lead foot horizontal landing velocity (lead limb crossing step)	✔	✔
LTC (cm)	Lead toe-step-clearance (vertical).	✔	✔
TCA (cm)	Trail foot angle at step crossing.	✔	✔
TD (cm)	Trail toe horizontal displacement from step (single limb support phase before crossing).	✔	✔
TSED (cm)	Toe-to-step-edge displacement (horizontal).	✔	✔
THC (cm)	Trail heel-step-clearance (vertical).	✔	✔
TRKCA (°)	Trunk orientation (relative to horizontal) at lead foot crossing.	✔	✔
TTC (cm)	Trail toe-step-clearance (vertical)	✔	✔
VLV ($m \cdot s^{-1}$)	Vertical landing velocity of trunk marker (lead foot landing).	✔	✘

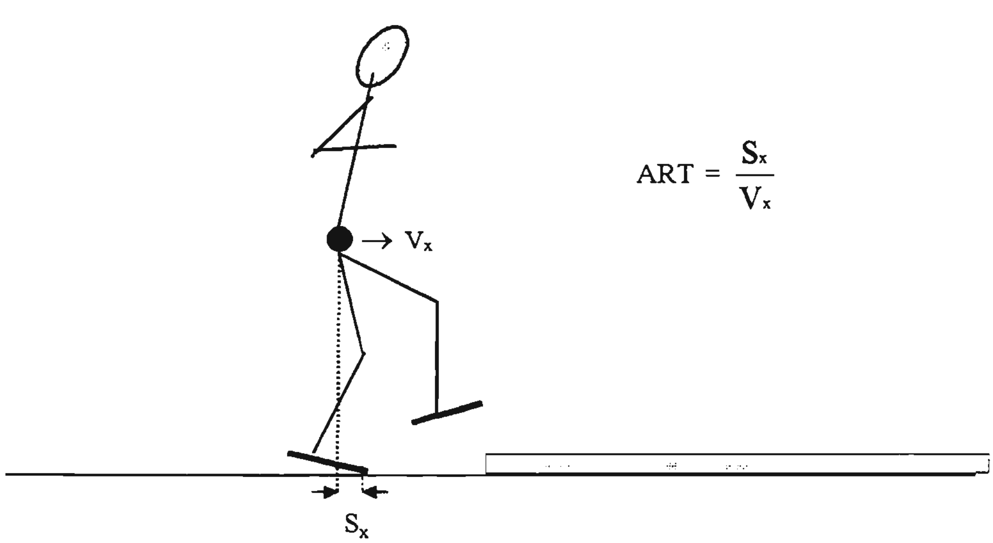
A.



B.



C.



$$ART = \frac{S_x}{V_x}$$

Figure 5.4.1.1 Diagrams showing some of the dependent variables collected in this investigation: lead-toe-clearance (*LTC*), trail toe displacement from step (*TD*), trunk marker displacement (horizontal) from trail toe at lead foot crossing and landing (*HCD*, *HLD*), lead heel displacement (horizontal) from step (*LHD*), and crossing step length (*CSL*).

Available response time (*ART*) was calculated (when the lead foot crosses the step) by using the information shown in figure 5.4.1.1 (panel C). It is an estimate of the amount of time until a person's trunk marker moves outside the base of support (trail foot toe). Essentially, it is a measure of the time available to regain balance should the foot contact the step.

The decision to include/exclude dependent variables (*DVs*) for this investigation was based upon the following criteria: (1) the importance assigned to them by previous investigations of obstructed gait (e.g. Chen et al., 1991; McFadyen et al., 1993; Patla & Rietdyk, 1993; Chen et al., 1994a, 1994b; Eng et al., 1994; Patla et al., 1996; Austin et al., 1999); (2) the outcomes of pilot work conducted by the author (Lythgo & Begg, 1999a; 1999b; 1999c); and, (3) the need to meet a minimum participant:variable ratio (≈ 3:1) in order to optimise statistical power and satisfy basic requirements for the use of multivariate statistical techniques (e.g. *MANOVA*).

All clearance data (*LTC*, *LHC*, *TTC*, *THC*) were calculated by using equations 5.4.1.1 to 5.4.1.3 (refer to figure 5.4.1.2). The following 2D spatial coordinate data were used to calculate these data: (1) 2D position of the marker (toe or heel) in the field before the step (x_1, y_1); (2) 2D position of the marker (toe or heel) in the field past the step (x_2, y_2); and, (3) 2D position of the step edge (x_{SE}, y_{SE}). These equations were used since the toe or heel marker was not captured (x_{SE}, y) directly above the step edge due to the 50 Hz sampling rate of the cameras. A linear interpolation method, therefore, was used to estimate vertical clearance.

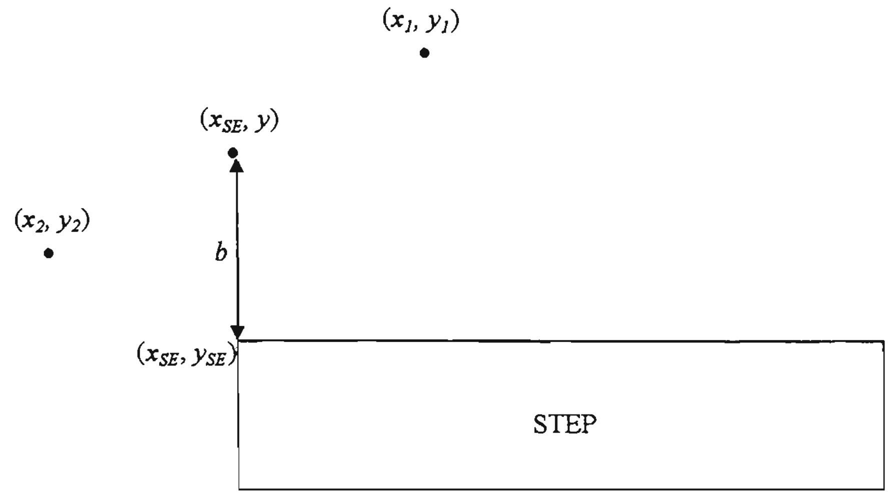


Figure 5.4.1.2 Schematic representation of toe marker positions: (1) before the step edge (x_1, y_1); (2) past the step edge (x_2, y_2); and, (3) above the step edge (x_{SE}, y).

Calculation of clearance data (b):

Since,
$$\frac{y_2 - y_1}{x_2 - x_1} = \frac{y - y_1}{x_{SE} - x_1}$$

$$y - y_1 = \frac{(y_2 - y_1)}{(x_2 - x_1)} \cdot (x_{SE} - x_1)$$

$$\therefore \quad y = \left\{ \frac{(y_2 - y_1)}{(x_2 - x_1)} \cdot (x_{SE} - x_1) \right\} + y_1$$

Equation 5.4.1.1

Now,
$$b = y - y_{SE}$$

Substituting y from equation 5.4.1.1,

$$b = \left\{ \frac{(y_2 - y_1)}{(x_2 - x_1)} \cdot (x_{SE} - x_1) \right\} + y_1 - y_{SE}$$

Equation 5.4.1.2

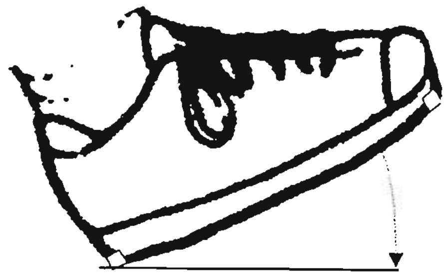
Once clearance data were extracted by the computer programs, they were corrected in order to provide a more accurate measure of step edge clearance.

The programs calculated the vertical separation (b) of the centre-of-the-marker (digitised) from the step edge (refer to figure 5.4.1.3). Such a calculation overestimates toe or heel clearance by a 1 cm or more. A more accurate measure of clearance is the vertical displacement of a point on the base-of-the-marker (in alignment with the sole of the foot) when it is positioned vertically above the step edge. All clearance data, therefore, were adjusted by using equation 5.4.1.3. This equation estimates clearance of the base-of-the-marker by accounting for the orientation (in the sagittal plane) of the foot at the time of crossing.

$$\text{clearance} = b - a \qquad \text{Equation 5.4.1.3}$$

where $a = 1/\cos\theta$ for $-45° \le \theta \le 45°$.
$a = 1/\cos(90 + \theta)$ for $-135° < \theta < -45°$.
b: vertical clearance of the centre-of-the-marker (digitised) from the step edge.
NB: θ (foot angle) never exceeded 45° at the time of crossing.

A.



B.

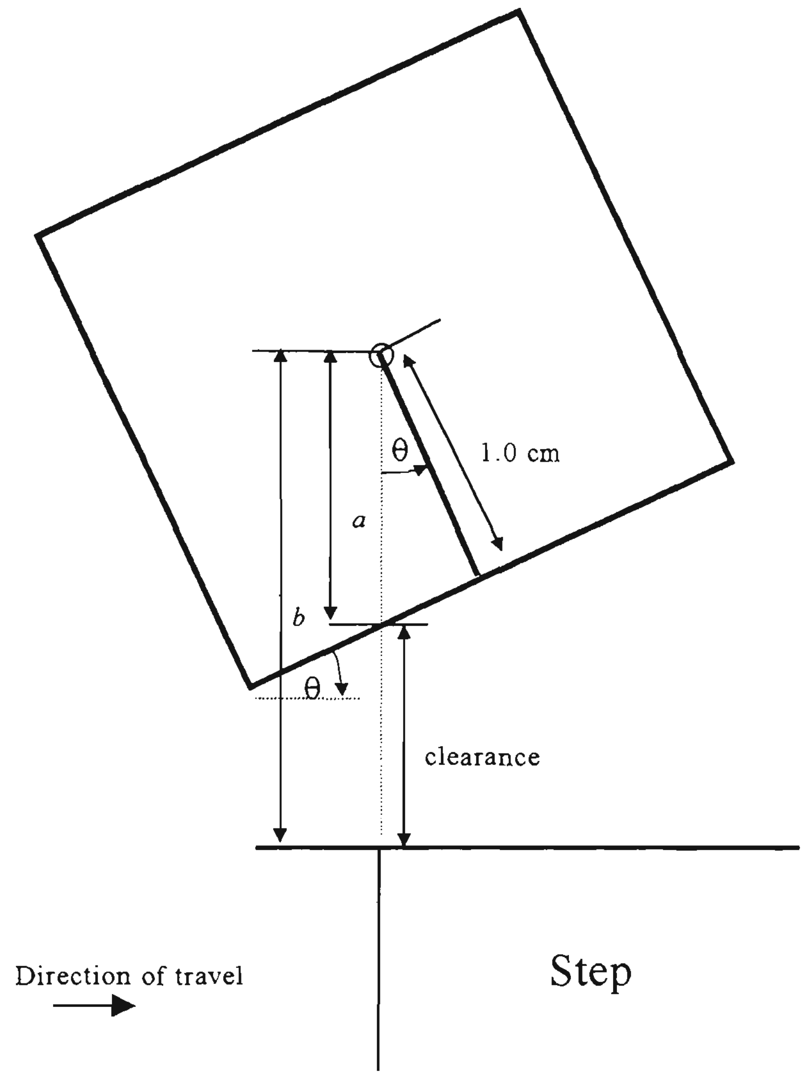


Figure 5.4.1.3 **A**. Diagram illustrating the position of the toe marker on the foot. **B.** Diagram illustrating a foot marker (2 cm × 2 cm) positioned above the step edge in the ascent condition ($\theta > 0°$): clearance data is also shown. θ: foot angle; *b*: centre-of-marker vertical clearance of the step edge; *a*: vertical displacement from the centre-of-marker to the point on the base-of-the-marker which is vertically above the step edge; clearance: vertical clearance reported in this investigation.

The conventions adopted for foot placement (relative to the step) are shown in figure 5.4.1.4. These data were calculated relative to the step edge. In the descent condition, for example, toe placement (trail foot) before the step is assigned a negative magnitude, whereas toe placement past it is assigned a positive magnitude. In the ascent condition, heel placement (lead foot) past the step is assigned a positive magnitude, whereas heel placement before the step is assigned a negative magnitude.

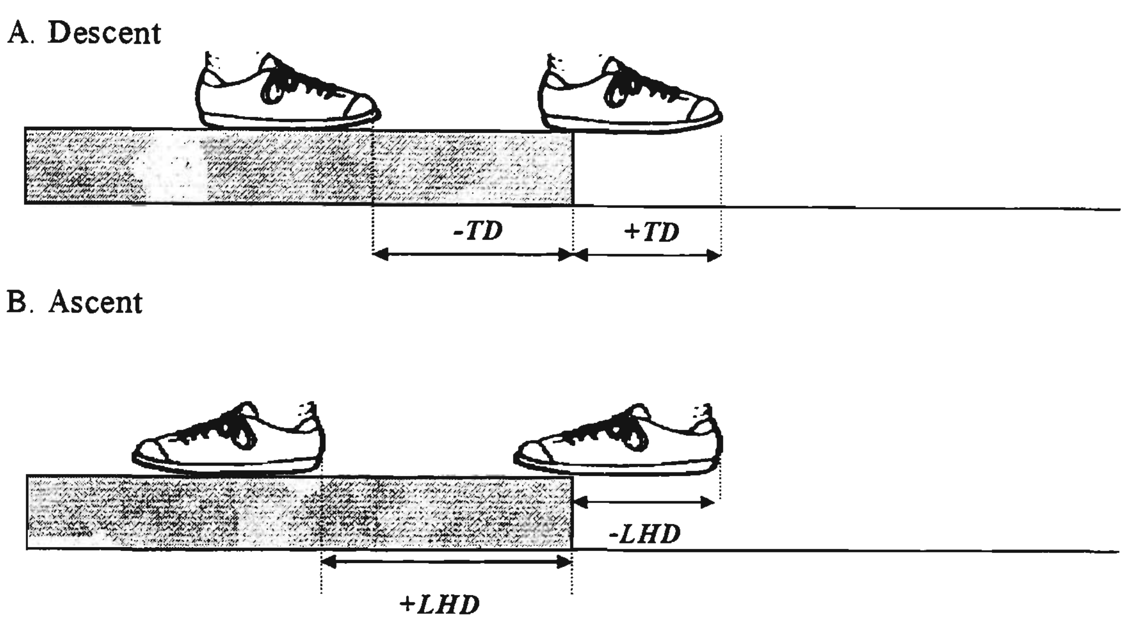


Figure 5.4.1.4 **A**. Convention adopted for the *TD* footfall data in the descent condition. **B**. Convention adopted for the *LHD* footfall data in the ascent condition.

The convention adopted for the trunk marker position relative to the trail or support toe is shown in figure 5.4.1.5. These variables were assigned a negative magnitude when the trunk marker was positioned behind the trail foot toe; when positioned in front they were assigned a positive magnitude.

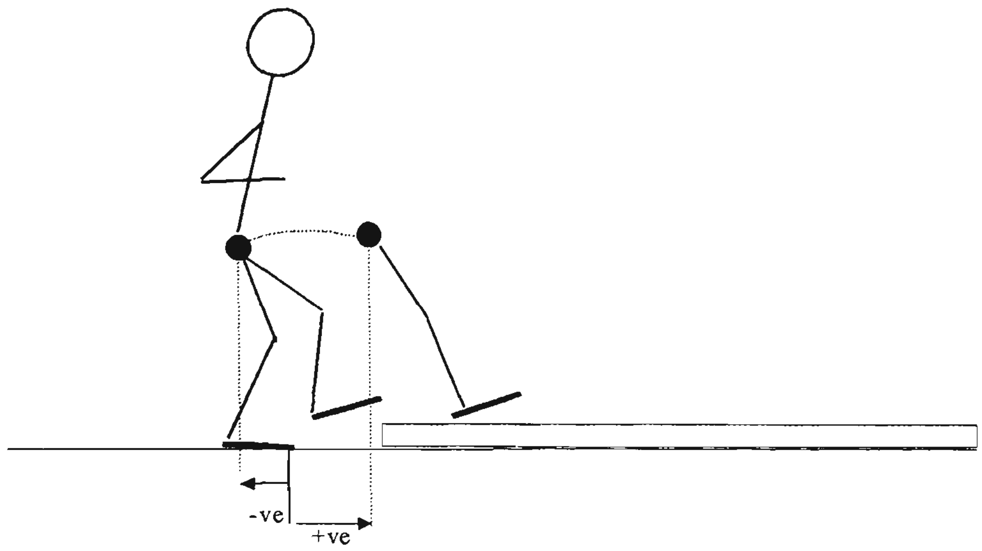


Figure 5.4.1.5 Convention adopted for the *HCD* and *HLD* data. The diagram shows the relative displacement (from the trail toe) of the trunk marker at lead toe crossing and lead foot landing.

The method adopted by Stemmons Mercer et al. (1997) was employed to examine the smoothness of the focal movement trajectory of the lead foot (*LFM*). This involved calculating the displacement of the foot marker from its position above the step edge to its point of landing. If a participant landed on the forefoot, for example, the displacement along a straight line from the toe position above the step to the toe position at landing was computed (figure 5.4.1.6). If the heel landed first, the displacement along a straight line from the heel position above the step to the heel position at landing was computed. The actual distance travelled by the foot marker (toe or heel) was then calculated. A displacement-distance ratio was calculated in order to ascertain the smoothness of the focal movement trajectory. A large ratio value indicates that the trajectory is relatively straight or linear.

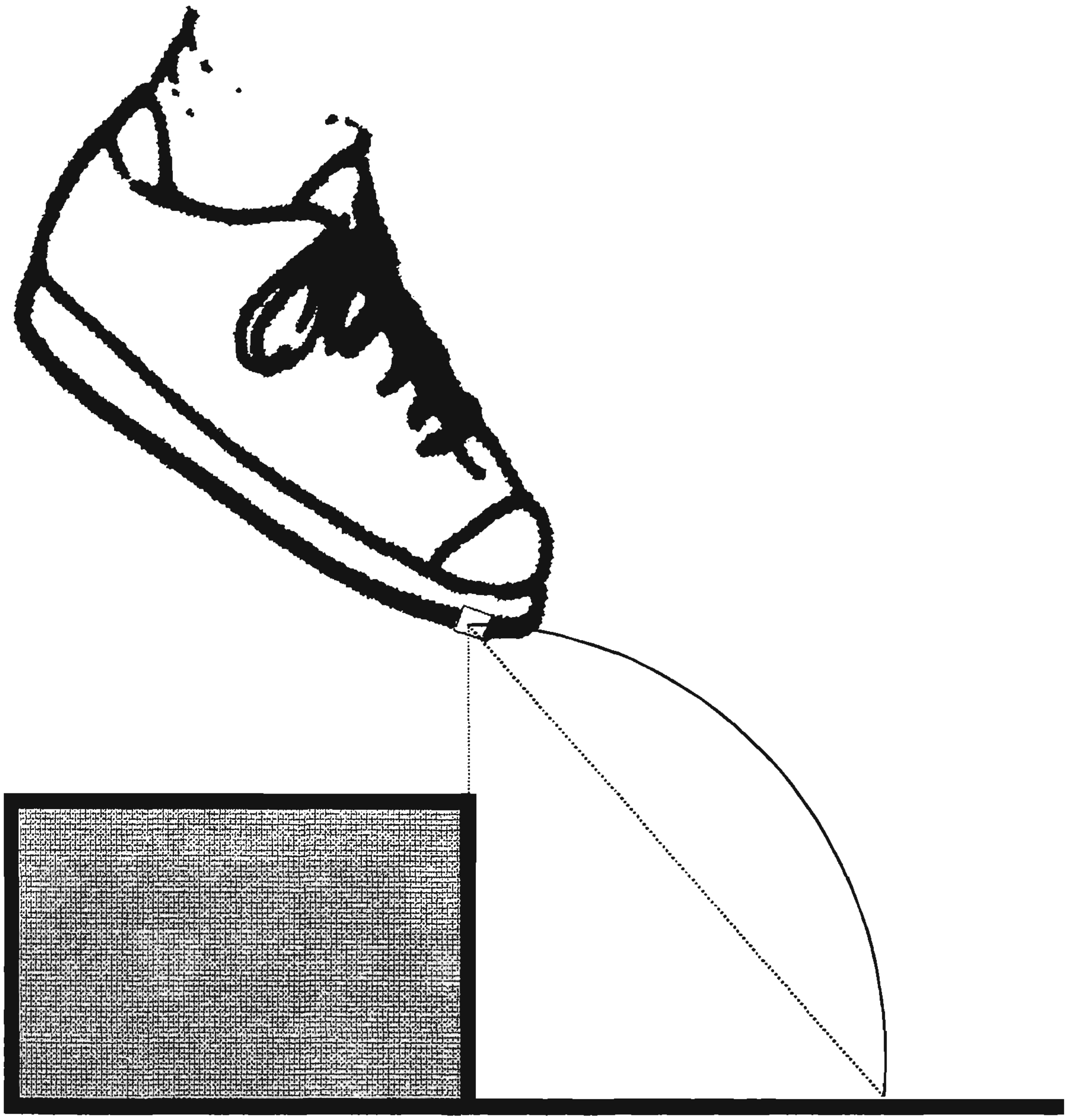


Figure 5.4.1.6 Schematic representation of the trajectory of a toe marker (_____) relative to straight line motion (........) for the descent task. The focal movement trajectory of the lead foot (*LFM*) was determined by calculating the displacement and distance along these two paths. The straight line displacement was then divided by the trajectory path distance to produce a displacement-distance ratio.

Normalised (to crossing swing time) data were generated for the lead toe marker trajectory in the crossing stride for each participant (Winter, 1991). This was achieved by: (1) determining crossing stride time (*CST*); (2) setting the *CST* to 100%; and, (3) dividing the *CST* into equal intervals of 2% to generate 50 normalised data points. These data sets were then used to generate ensemble average patterns for each group of participants.

The horizontal velocity of the trunk marker (*HCV*) as the lead foot crossed the step edge was estimated by first identifying the field (f_i) in which the lead foot was closest to the step edge. Its horizontal displacement in the fields before (f_{i-1}) and after (f_{i+1}) were then used to calculate velocity (refer to equation 5.4.1.4). The horizontal and vertical landing velocities of this marker (*HLV*, *VLV*) were only extracted for the descent condition. Once again, the field in which the foot landed was identified (f_i). The displacement of the trunk marker in this field (f_i) and two fields beforehand (f_{i-2}) were then used to calculate velocity (refer to equation 5.4.1.5). The reason for only calculating these velocities in the descent condition lies in the fact that greater load carriage or weight acceptance occurs in a descent task compared to an ascent task (e.g., Andriacchi et al., 1988; Livingston et al., 1991; Riener et al., 2002). This may be linked to falls during descent activities.

$$\dot{x} = \frac{x_{i+1} - x_{i-1}}{2\Delta t}$$

Equation 5.4.1.4

$$\dot{x} = \frac{x_i - x_{i-2}}{2\Delta t}$$

Equation 5.4.1.5

where $\dot{x}$ is velocity, x is displacement, i is the field number (50 Hz camera) and Δt is 0.02 s (Bartlett, 1997).

The lead foot horizontal landing velocity (*LLV*) was calculated for each step condition. This required the identification of the lead foot landing field (f_i) and the point of first contact with the ground (i.e. toe or heel). Once these events were identified, the horizontal displacement of the foot marker (toe or heel) in the landing field (f_i) and two fields beforehand (f_{i-2}) were used to calculate velocity (refer to equation 5.4.1.5).

Toe-to-step-edge displacement data were calculated from the 2D spatial coordinate data files and mid-marker position data files (refer to section 5.2.2.3). A computer software program written by the author extracted this data. Essentially, the program subtracted the horizontal position of the toe marker (x_{toe} coordinate value), in each camera field of view, from the mid-marker horizontal position to gain a toe-to-step-edge displacement (*TSED*). This process was achieved by using equation 5.4.1.6.

$$\mathrm{TSED} = x_{\text{mid-marker}} - x_{\text{toe}} + \text{known mid-marker displacement from step edge}$$

Equation 5.4.1.6

If the digitised 2D horizontal position, for example, of a toe marker (descent condition) in the *FOV* of camera #1 was found to be 0.80 m, and the digitised 2D horizontal position of mid-marker #3 (refer to figure 5.2.2.3.1) was found to be 1.45 m (its true or known displacement from the step edge is 7.8 m), the *TSED* would equal to 8.45 m (refer to figure 5.4.1.7); that is,

$$TSED = 1.45 - 0.80 + 7.80 = 8.45 \text{ m}$$

Equation 5.4.1.7

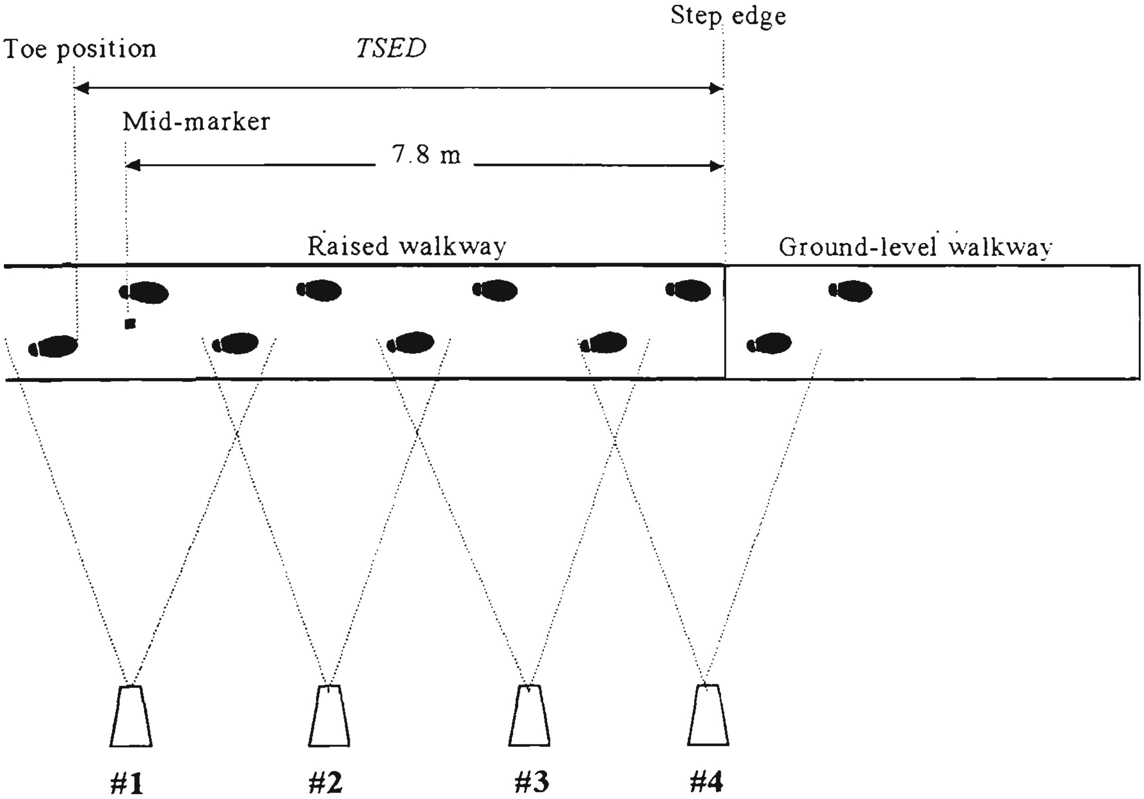


Figure 5.4.1.7 Schematic representation of foot placement relative to the mid-marker (# 3) located in the *FOV* of camera #1. *TSED* was calculated relative to the step edge.

Note, approach step times were manually determined by visual inspection of the time-code layed onto the video-tapes.

Step velocities were estimated for the approach and crossing phases (refer to equation 5.4.1.8). The quotient of step length (SL) and step time (ST) was used to estimate velocity (Whittle, 1991; McFadyen & Prince, 2002).

$$\text{Step velocity } (\text{m}\cdot\text{s}^{-1}) = \frac{\text{SL}}{\text{ST}}$$

Equation 5.4.1.8

5.4.2 Angular spatio-temporal parameters

Body segment orientations were extracted by computer software programs written by the author. These included: (1) head pitch angle or orientation (relative to earth-based horizontal axis) in the approach and crossing phases (refer to figure 5.4.2.1); (2) trunk angle or orientation (relative to earth-based horizontal axis) at lead foot step crossing (refer to figure 5.4.2.2); and, (3) lead and trail foot angular trajectories (relative to earth-based horizontal axis) in the crossing stride (refer to figure 5.4.2.3).

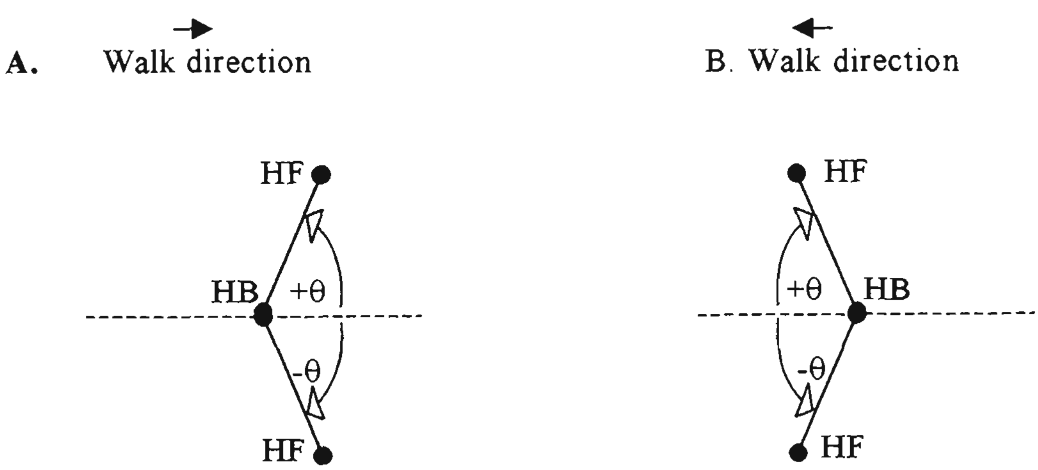


Figure 5.4.2.1 **A**. Angular convention adopted for the head orientation in the descent condition. **B**. Angular convention adopted for the head orientation in the ascent condition. In both conditions a horizontal head orientation (relative to earth-based horizontal axis ------) represented an angular magnitude of 0°. *HF*: marker at the front of the head. *HB*: marker at the back of the head.

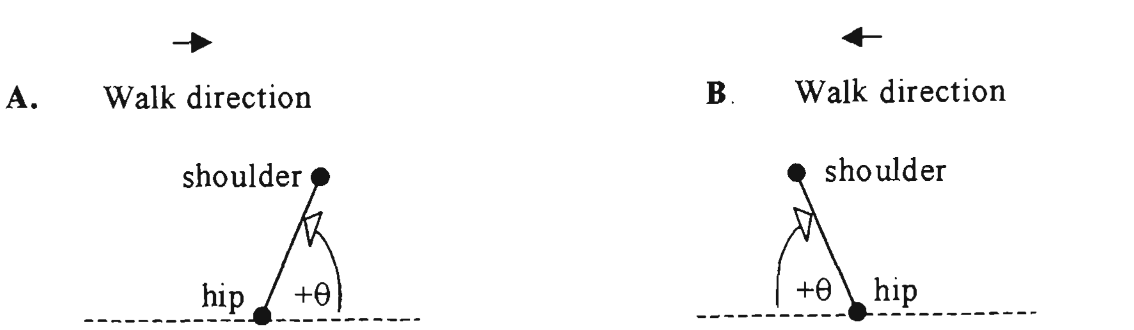


Figure 5.4.2.2 **A**. Angular convention adopted for the trunk orientation in the descent condition. **B**. Angular convention adopted for the trunk orientation in the ascent condition.

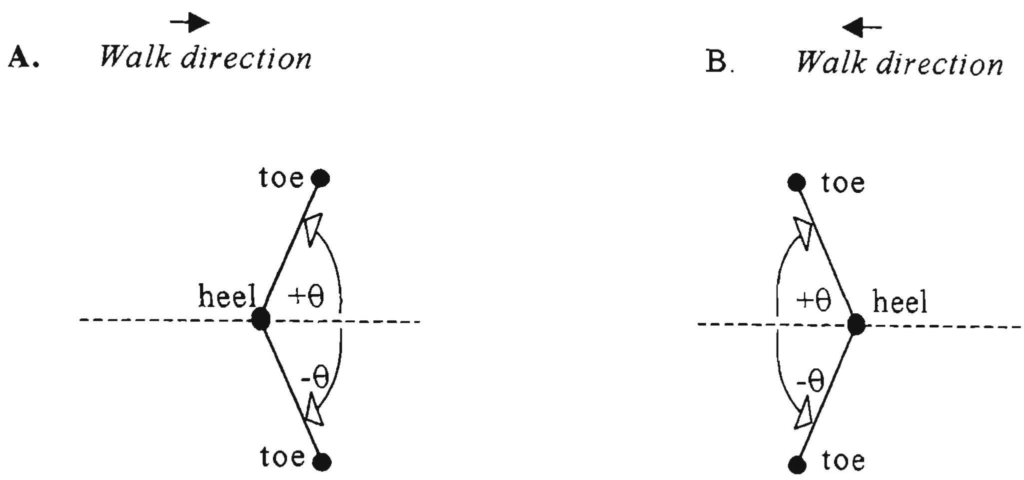


Figure 5.4.2.5 **A.** Angular convention adopted for the foot orientation in the descent condition. **B.** Angular convention adopted for the foot orientation in the ascent condition. In both conditions a horizontal foot orientation (relative to earth-based horizontal axis ------) represented an angular magnitude of 0°.

Angular displacement data were calculated relative to an earth-based horizontal axis. Equations 5.4.2.1 to 5.4.2.3 were used to calculate the angular displacement (radians) of the foot, head and trunk segments. The 2D spatial coordinate data of markers (refer to section 5.2.2.3) positioned along the walkway in each camera *FOV* were used to calculate the orientation of the earth-based horizontal axis or true gradient (equation 5.4.2.4). In the descent condition: (1) markers #2 and #4 were used for data extracted from camera #1; (2) markers #5 and #7 were used for data extracted from camera #2; (3) markers #8 and #10 were used for data extracted from camera # 3; and (4) markers #11 and #12 were used for data extracted from camera #4. All angular displacement data (degrees) were calculated relative to an earth-based horizontal axes by using equation 5.4.2.5 (Gieck & Gieck, 1990).

$$\text{foot\_gradient} = \frac{y_{toe} - y_{heel}}{x_{toe} - x_{heel}} \qquad \text{Equation 5.4.2.1}$$

$$\text{head\_gradient} = \frac{y_{HF} - y_{HB}}{x_{HF} - x_{HB}} \qquad \text{Equation 5.4.2.2}$$

$$\text{trunk\_gradient} = \frac{y_{shoulder} - y_{hip}}{x_{shoulder} - x_{hip}} \qquad \text{Equation 5.4.2.3}$$

$$\text{true\_gradient} = \frac{y_{right\_marker} - y_{left\_marker}}{x_{right\_marker} - x_{left\_marker}} \qquad \text{Equation 5.4.2.4}$$

$$\text{segment\_angle} = \tan^{-1}\left[\frac{m_2 - m_1}{1 + m_2 \cdot m_1}\right] \cdot 57.29 \qquad \text{Equation 5.4.2.5}$$

where m_2 is the segment gradient (e.g., foot_gradient) and m_1 is the gradient of the earth-based horizontal axis (i.e. true_gradient).

Normalised (to crossing swing time) data were generated for the lead foot angle in the crossing stride (toe-off to foot landing) for each participant (Winter, 1991). This was achieved by: (1) estimating crossing swing time (*CST*); (2) setting *CST* to 100%; and, (3) dividing the *CST* into equal intervals of 2% to generate 50 normalised data points. These data sets were then used to generate ensemble average patterns for each group of participants.

Head angle data from the last two *FOVs* were calculated from the raw coordinate pixel data. The head angle data from these *FOVs* were joined and filtered (smoothed) by using a 4th order Butterworth digital filter with a cut-off frequency of 6 Hz (Winter, 1991; Bartlett, 1992). This process smoothed the point at which the head angle data were merged or joined from the different datafiles. Head angle data was normalised by subtracting it from the value found at midstance in the 9th-last step of the approach. This value was chosen for the following reasons: (1) the participants were in a transport phase and not a targeting phase; (2) minimum angular displacement has been observed to occur in midstance (Pozzo et al., 1990); and, (3) it allowed the head angular data to be ensemble averaged across each group for comparison purposes.

5.4.3 Stepping Strategies

Stepping strategies were identified by adopting the method used by Chen et al. (1994b). The strategies were classified as: (1) a long step strategy (*LSS*); (2) a mixture of short and long steps; (3); short step strategy (*SSS*); and, (4) a normal step strategy. Deliberate step length adjustments were identified by comparing the pre-crossing and accommodation step lengths (3rd-last to final step) to the step length distribution found for the 9th-last to 4th-last step lengths (transport phase). This distribution was considered to approximate a $\pm$ 2.57 *SD* (where $n = 6$, $df = 5$, $\alpha = 0.05$) normally distributed range of step lengths; the value of 2.57 is obtained from the t distribution. Step lengths lying outside of the 2.57 $\pm$ *SD* bounds were considered to have resulted from deliberate adjustment of the stepping pattern. The stepping pattern, for example, shown in figure 5.4.3.1 would be classified as a short step strategy (*SSS*) since short steps were made in 2nd-last, penultimate and final step. The 1st seven step lengths lie within the 2.57 $\pm$ *SD* bounds, whereas the last 3 step lengths lie outside these bounds. The stepping pattern shown in figure 5.4.3.2 would be classified as a long step crossing strategy (*LSS*) since the last step falls outside the 2.57 $\pm$ *SD* bounds. A stepping strategy was classified as "mixed" if participants used a combination of short and long steps (e.g., *LS* or *SSL* etc.).

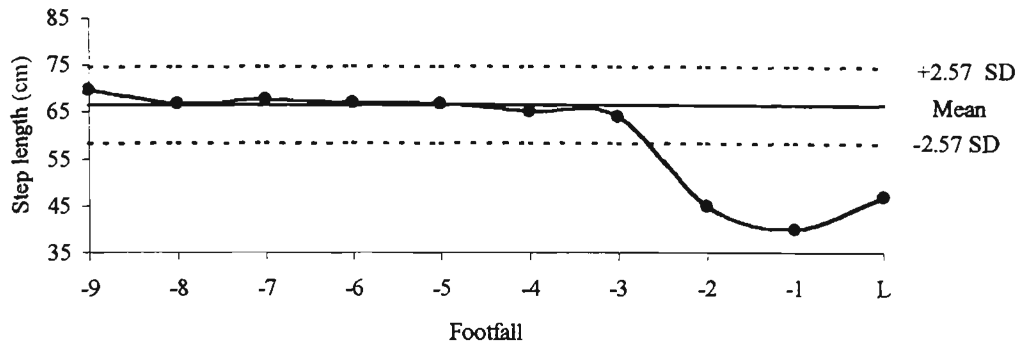


Figure 5.4.3.1 Sample step length control chart. Mean ± 2.57 SD values are shown.

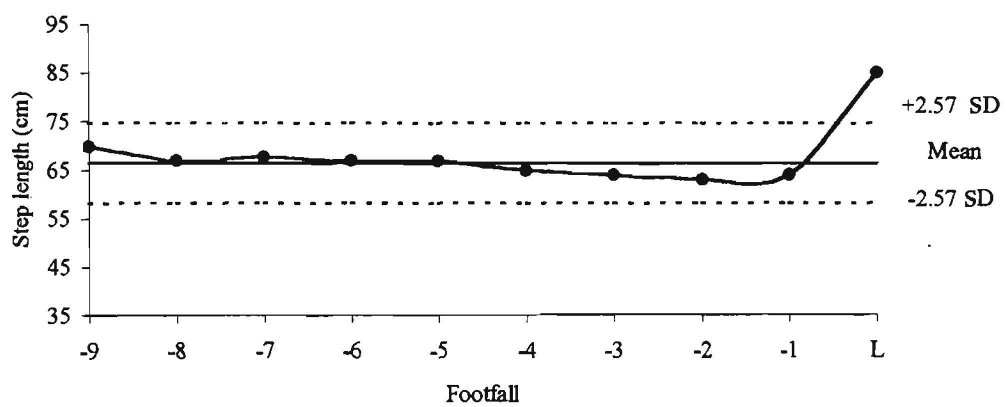


Figure 5.4.3.2 Sample step length control chart. Mean ± 2.57 SD values are shown.

Mean percentage step length adjustments were calculated by the method adopted by Berg et al. (1994). The percentage step length adjustments were calculated by using equation 5.4.3.1.

$$\left[\frac{SL_{i+1} - SL_i}{SL_i}\right] \cdot 100\% \qquad \text{Equation 5.4.3.1}$$

In the crossing step, lead limb preference or selection was examined by frequency counts; that is, limb selection (right or left) was identified and recorded for the six trials conducted.

5.4.4 Computer software listing

In total, 8 computer software programs (refer to appendices B, C, D, E), written by the author, were used to extract the spatio-temporal data collected in this project. Microsoft C language (Version 2.0, 1994) was used to write the programs. Each program used the spatial coordinate data files produced by the digitisation process to extract the data of interest. Only the programs used to extract data from the descent condition are listed in the appendices. The programs used to extract the data in the ascent condition required only minor modifications of these programs to account for the movement of the participants in the opposite direction; hence, it would be redundant to include these programs.

5.5 Statistical analysis

All statistics were calculated by SPSS (version 10.0).

5.5.1 Descriptive statistics

Descriptive statistics, including measures of normality, were calculated for each age group and condition (surface height condition and walking velocity).

Assumptions of normality and homogeneity of variance were not met for some of the data sets collected in this study. Attempts were made to normalise these sets by conducting transformations recommended by Afifi and Clark (1990), and Hair, Anderson, Tatham and Black (2000). The transformations, however, failed to satisfactorily normalise the majority of these data sets. Data sets analysed in this investigation, therefore, were not transformed.

Ensemble average plots of the following variables were generated for each age group and step-velocity condition (1st trial only): (1) lead foot orientation in the crossing stride (normalised to crossing stride time); (2) lead-foot-toe-marker vertical trajectory (normalised to crossing stride time); and, (3) head orientation (normalised from the 4th-last heel contact to foot landing past step). These plots were visually examined for aging effects.

The following graphs were generated for each age group and condition: (1) mean step length and time patterns (from the 9th-last to crossing step); (2) mean percentage step length adjustment (from the 9^{th}-last to crossing step); and, (3) footfall (*TSED*) variability (10^{th}-last to final footfall).

Toe-to-step-edge displacement (*TSED*) was calculated for each participant's footfalls in the 3 comfortable and 3 fast walking velocity trials. Footfall variability values were derived from these data. These data were then used to calculate mean values of footfall variability for each age group and step-velocity condition. It was assumed that the location at which visual control began was at the beginning of a marked and systematic reduction in the mean value of footfall variability (Lee et al., 1982; Hay, 1988; Berg et al., 1994; Berg & Greer, 1995; Scott et al., 1997; Galloway & Connor, 1999; Montagne et al., 2000). These plots were visually examined to identify any aging or velocity effects.

Step lengths were calculated for each participant's footfalls in the 3 comfortable and 3 fast walking velocity trials. Mean step length values were then derived for each age group and step-velocity condition. These plots were visually examined to identify any aging or velocity effects.

Frequency counts of stepping strategies were made. These strategies included long, mixed, short and normal stepping strategies. Participants adopting a normal stepping strategy were considered to take it "in their stride"; that is, they accommodated the step without significant step length adjustments.

Frequency counts of lead limb selection were also made by observing which limb was used across the six trials.

5.5.2 Data reduction techniques

Factor analyses were conducted in an attempt to reduce the data extracted in this investigation. These analyses, however, were found to be inappropriate for the following reasons (Hair et al., 1998); (1) inadequate measures of sampling accuracy (*MSA*) for the outcome variables; and, (2) the repeated measures (velocity) samples and between measures (age) samples were not found to be homogenous with respect to an underlying factor structure; that is, different factor structures were identified across groups.

5.5.3 Inferential statistics

5.5.3.1 Age and velocity effects (main and interaction)

A three-stage approach (listed below) was used to examine the main effects of age and velocity. Interaction (velocity $\times$ age) was also examined. In order to ensure the power of the multivariate analyses and protect against violations of basic assumptions, a subject-to-dependent-variable ratio of 3:1 or greater was sought (Vincent, 1995).

<u>Stage 1</u>

- In the descent condition, a two-way between-within MANOVA (refer to figure 5.5.3.1.1) was conducted in order to identify effects of age and velocity on all dependent variables except for the *TCA*, *THC* and *TTC* variables.

- In the ascent condition, a two-way between-within MANOVA (refer to figure 5.5.3.1.1) was conducted in order to identify main effects of age and velocity on all dependent variables except for the *LFM* and *LHC* variables.

Stage 2

- In the descent condition, a one-way between subjects MANOVA was conducted in order to examine the main effects of age on the *TCA*, *THC* and *TTC* variables.

- In the ascent condition, a one-way between subjects MANOVA was conducted in order to examine the main effects of age on the *LFM* and *LHC* variables.

Stage 3

- In the descent condition, a one-way repeated measures MANOVA was conducted in order to examine the main effects of velocity on the *TCA*, *THC* and *TTC* variables.

- In the ascent condition, a one-way repeated measures MANOVA was conducted in order to examine the main effects of velocity on the *LFM* and *LHC* variables.

		VELOCITY	
		CWV	FWV
	Elderly		
AGE			
	Young		

Figure 5.5.3.1.1 Two-way between-within design employed for each step condition (descent and ascent). Age: between factor (2 levels), velocity: within factor (2 levels). CWV: comfortable walking velocity. FWV: fast walking velocity.

A three-stage approach was used because numerous missing values were found in several of the data sets. In the descent condition, for example, many of the participants placed their trail foot so that it straddled the step (i.e. the foot was partially supported); hence, no pertinent trail foot crossing angles (*TCA*), or trail or heel toe clearances (*THC*, *TTC*) could be extracted for these participants. In the ascent condition, many of the participants placed their lead foot so that it straddled the step. Once again, no pertinent *LFM* or *LHC* data could be extracted for these participants. These variables were removed from the first stage because SPSS removes all of a participant's dependent variables if a single dependent variable value is missing. Missing values, therefore, or incomplete data sets reduce the power of the analysis by reducing cell size and unbalancing the design. In addition, violations of normality and homogeneity were found amongst these data sets. It was considered important, therefore, to protect against such violations (Coakes & Steed, 2001) by maintaining cell size (i.e. $n = 48$) and equality ($n_1 = n_2 = n_3 = n_4$). Removal of incomplete data sets due to missing values ensured cell sizes were maximised ($n = 48$) and equalised in the first stage of the analysis.

Since multiple MANOVAs were conducted, the alpha level was modified (Bonferroni adjustment) in order to protect against an increased chance of a making a Type I error.

Bartlett's test of sphericity was conducted in order to identify whether correlations existed amongst the dependent variables. The existence of significant correlations validates the use of MANOVA over simple ANOVA.

5.5.3.2 Main effects of surface height condition

Repeated measures MANOVAs were used to examine the effect of surface height condition. Since multiple MANOVAs were conducted, the alpha level was modified (Bonferroni adjustment) in order to protect against an increased chance of making a Type I error.

5.5.3.3 Group membership

Discriminant analyses were conducted in order to: (1) reinforce differences already found by the MANOVA analyses; (2) determine which of the outcome variables, or combination of, accounted for most of the differences in the average score profiles of the two age groups; and, (3) establish the accuracy of participant classification according to age on the basis of their scores on the set of outcome variables.

A cluster analysis was conducted in order to confirm the existence of two types of foot landing strategies (forefoot and heel landing) found in the descent condition.

5.5.3.4 Chi-square

Chi-square analyses were conducted in order to compare the frequency of the stepping strategies adopted by the young and old groups (e.g., *SSS* or *LSS*).

5.5.3.5 Probability of foot contact

The probability of foot contact with the step was calculated by the following method:

1. Foot contact represents a foot clearance of 0 cm or less.

2. $\text{z score} = \dfrac{x - \bar{x}}{SD}$

3. If the mean foot clearance of a group is 2.7 cm (SD = 1.5 cm), then a foot clearance of 0 cm is equivalent to a z score of -1.8. The area under a normal distribution curve (assuming normality) to the left of this score is 0.0359. This represents a 3.59% chance of foot contact; that is, a foot clearance of 0 cm or less.

CHAPTER 6 RESULTS

6.1 Participant screening

A total of 102 female adults (elderly and young) were screened for this investigation. Six elderly adults failed to pass the screening tests and were excluded from the study. Reasons for exclusion were: (1) musculo-skeletal impairment (n = 3); (2) failure on the vestibular stepping test (n = 2); and, (3) failure on the Romberg test (n =1). Fourty-eight elderly adult females (EA) and 48 young adult females (YA) completed the step tasks in stage 2 of this investigation.

Table 6.1.1 lists the anthropometric and screening test data collected in this project. The data shows poorer performances on the visual acuity and contrast sensitivity tests for the elderly (EA) compared to the young adults (YA). An independent t-test comparison revealed significant differences in these measures ($p < .001$). Self-reported activity levels and leg length (right-side) were similar across the age groups. Since multiple t-testing was conducted, a Bonferroni correction was used to protect against a Type I error; that is, in order for a t-test value to be considered significant, the *p-value* had to fall below .0125 (= 0.05/4) to be significant at an α level of .05.

Table 6.1.1 Descriptive statistics for the elderly participants. Actual *p-values* have been reported. For significance *p*-values must fall below .0125 (Bonferroni correction).

Screening item	Elderly (n = 48)	Young (n = 48)	$p <$
Visual acuity	7.0 (1.9)	5.3 (1.1)	.001
Contrast sensitivity	20.7 (1.9)	23.1 (1.3)	.001
Activity level	3 (0.6)	3.2 (0.6)	ns
Leg length (cm)	87.1 (4.8)	89.2 (5.4)	ns

6.2 Walking velocity in unobstructed condition

The comfortable walking velocities adopted by the participants in the unobstructed condition (no surface height change) are reported in table 6.2.1. A significant age-related reduction was found ($p < .014$).

Table 6.2.1 Walking velocities in unobstructed condition.

Young ($m \cdot s^{-1}$)	Elderly ($m \cdot s^{-1}$)	p
1.49 (0.15)	1.40 (0.17)	.013

6.3 Walking velocity in surface height conditions

Tables 6.3.1 and 6.3.2 list the walking velocities (comfortable and fast) found in the surface height conditions (ascent and descent). Both groups (young and elderly) were found to increase walking velocity ($p < .001$) in the surface height conditions (table 6.3.1). Overall, the participants walked significantly faster (≈18 to 27%) in the fast walking velocity trials (FWV) compared to the comfortable walking velocity trials (CWV). The young participants (descent task), for example, were found to walk significantly faster (1.93 $m \cdot s^{-1}$) than in the comfortable velocity condition (1.52 $m \cdot s^{-1}$). Since multiple t-testing (dependent) was conducted, a Bonferroni correction was used to protect against a Type I error. As a result, the *p-value* had to fall below .0125 (= .05/4) to be significant at an α level of .05.

Table 6.3.1 Comparison of walking velocities (within age groups) for each surface height condition.

Group	Task	Comfortable ($m \cdot s^{-1}$)	Fast ($m \cdot s^{-1}$)	$p <$
Young	Descent	1.52 (0.16)	1.93 (0.18)	.001
Elderly	Descent	1.43 (0.18)	1.68 (0.19)	.001
Young	Ascent	1.55 (0.18)	1.96 (0.22)	.001
Elderly	Ascent	1.46 (0.18)	1.73 (0.25)	.001

Velocity differences within age groups by dependent t-test .To be significantly different (.05) the *p-value* had to fall below .0125 (Bonferroni correction).

Table 6.3.2 Comparison of walking velocities (across age groups) for each surface height condition.

Task	Young	Elderly	$p <$
Descent: CWV ($m \cdot s^{-1}$)	1.52 (0.16)	1.43 (0.18)	.01
Descent: FWV ($m \cdot s^{-1}$)	1.93 (0.18)	1.68 (0.19)	.001
Ascent: CWV ($m \cdot s^{-1}$)	1.55 (0.18)	1.46 (0.18)	.008
Ascent: FWV ($m \cdot s^{-1}$)	1.96 (0.22)	1.73 (0.25)	.001

Velocity differences across age groups by independent t-test. To be significantly different (.05) the *p-value* had to fall below .0125 (Bonferroni correction).

The young adults were found to walk significantly faster ($p < .01$) in the approach to the step (table 6.3.2). Velocity differences ranged from six to 13% with the largest increase found in the fast conditions.

6.4 Lead limb preference (all trials)

Tables 6.4.1 and 6.4.2 list the lead limb frequencies, or limb preference, exhibited by the participants for the 6 trials; that is, the frequency with which the same limb (left or right leg) was selected as the lead limb. Table 6.4.1, for example, shows that in the descent task: (1) 11 of the participants (*YA* = 6, *EA* = 5) used the same lead limb (ratio 6:0) for the trials; (2) 29 of the participants (*YA* = 15, *EA* = 14) used the same limb in 5 of the 6 trials (ratio 5:1); (3) 35 of the participants (*YA* = 17, *EA* = 18) used the same limb in 4 of the trials (4:2); and, (4) 21 of the participants (*YA* = 10, *EA* = 11) used the same lead limb in 3 of the trials (3:3); that is, the left and right limb were equally selected as the lead limb. A chi-square frequency analysis revealed no age or step condition differences in the frequency of lead limb selection.

In both surface height conditions, the majority of participants exhibited a limb preference (≈ 78%); that is, one limb was used more often as the lead limb. Interestingly, a small number of participants (≈ 10%) exhibited a limb dominance for all trials; the same limb was used. Correlation analyses revealed no relationship between lead limb preference across step conditions (descent and ascent); that is, different lead limbs were used across step conditions.

Table 6.4.1 Lead limb frequencies for the 6 descent trials. Ratios indicate the number of trials in which the same lead limb was used. The ratio 6:0, for example, indicates that the same lead limb was used for all 6 trials.

Descent	**YA (*f*)**	**EA (*f*)**
6 : 0	6	5
5 : 1	15	14
4 : 2	17	18
3 : 3	10	11

Table 6.4.2 Lead limb frequencies for the 6 ascent trials.

Ascent	**YA (*f*)**	**EA (*f*)**
6 : 0	6	3
5 : 1	11	11
4 : 2	21	22
3 : 3	10	12

Tables 6.4.3 and 6.4.4 list the lead limb frequencies, or limb preference, exhibited by the participants for each velocity and step condition. Table 6.4.3 shows that in the descent task about 40% of the participants used the same lead limb (ratio 3:0) in the comfortable and fast velocity conditions. In the comfortable velocity condition, 13 used the left limb (3:0 left) for each trial, whereas 25 used the right limb (0:3 right) for each trial. The number on the left side of the ratio indicates the frequency of left limb use, whereas the number on

the right side indicates the frequency of right limb use. A 2:1 ratio, for example, indicates the left limb was used twice, the right limb once.

Table 6.4.3 Lead limb frequencies for the 3 descent trials in each velocity condition. Ratios indicate the number of trials in which the same lead limb was used. The ratio 3:0, for example, indicates that the left limb was the lead limb for all trials.

Descent	**CWV**		**FWV**	
Limb	**YA (*f*)**	**EA (*f*)**	**YA (*f*)**	**EA (*f*)**
3:0 left	6	7	8	14
2:1	14	14	12	16
1:2	12	18	15	6
0:3 right	16	9	13	12

Table 6.4.4 Lead limb frequencies for the 3 ascent trials in each velocity condition.

Ascent	**CWV**		**FWV**	
Limb	**YA (*f*)**	**EA (*f*)**	**YA (*f*)**	**EA (*f*)**
3:0 left	9	7	10	12
2:1	13	21	13	6
1:2	21	12	11	18
0:3 right	5	8	14	12

In the ascent task, between 29% and 50% of the participants used the same lead limb (ratio 3:0). In the comfortable velocity condition, for example, 16 participants used the left limb (3:0 left) for each trial, whereas 13 used the right limb (0:3 right) for each trial.

Correlation analyses revealed no relationship between limb preference across step conditions; that is, different lead limbs were used in the step conditions (ascent and descent).

6.5 Descent task

6.5.1 Descriptive Statistics (1st trial)

The outcome variables (with labels and descriptors) collected in this phase of the investigation are listed (alphabetically) in table 6.5.1.1.

Table 6.5.1.1 Outcome variables (listed alphabetically) collected in this phase of the investigation.

Variable	Description
ART (ms)	Available response time.
ASL (cm)	Approach step lengths (ipsilateral heel contact to contralateral heel contact).
AST (s)	Approach step times (ipsilateral heel contact to contralateral heel contact).
CSL (cm)	Crossing step length (determined from lead and trail toe position).
CST (s)	Lead limb crossing swing time (toe-off to foot land).
DFST (s)	Double foot support time (trail limb crossing stride).
HA (°)	Head pitch angle (approach and crossing phases).
HCD (cm)	Horizontal displacement of trunk marker from the trail toe when the lead toe crosses the step.
HCV ($m \cdot s^{-1}$)	Horizontal velocity of trunk marker when the lead toe crosses the step.
HLD (cm)	Horizontal displacement of trunk marker from the trail toe as the lead foot lands.
HLV ($m \cdot s^{-1}$)	Horizontal velocity (after crossing) of trunk marker when the lead foot lands.
LCA (°)	Lead foot angle (orientation) at step crossing.
LFM (%)	Lead foot focal movement trajectory (crossing step).
LHC (cm)	Lead heel-step-clearance (vertical).
LHD (cm)	Lead heel horizontal displacement from step (after crossing).
LLA (°)	Lead foot landing angle (orientation) in crossing step.
LLV ($m \cdot s^{-1}$)	Lead foot horizontal landing velocity (crossing step).
LTC (cm)	Lead toe-step-clearance (vertical).
TCA (cm)	Trail foot angle (orientation) at step crossing.
TD (cm)	Trail toe horizontal displacement from step (single limb support phase before crossing).
TSED (cm)	Toe-to-step-edge displacement (horizontal).
THC (cm)	Trail heel-step-clearance (vertical).
TRKCA (°)	Trunk orientation (relative to horizontal) at lead foot crossing.
TTC (cm)	Trail toe-step-clearance (vertical).
VLV ($m \cdot s^{-1}$)	Vertical velocity of trunk marker when the lead foot lands.

Non-normal data sets were identified by the Shapiro-Wilks test of normality. Attempts were made to normalise these data sets by (1) removing outliers, and/or (2) by performing data transformations (Afifi & Clark, 1990). These attempts failed to produce a satisfactory outcome for two reasons: (1) the majority of the non-normal data could not be normalised; and, (2) some data sets (e.g. elderly - *CST*) could be normalised by a specific transformation (e.g., logarithmic) but the application of this transformation to the equivalent data set from the other age group (e.g. young - *CST*), needed for comparison purposes, led to non-normality.

In this investigation, outliers were retained on the basis that there was no demonstrable proof that they were truly aberrant or unrepresentative of any observations in the population (Hair et al., 1998).

Descriptive statistics are listed in tables 6.5.1.2 to 6.5.1.5. Note that the number of cases (n) for some variables is less than 48. The reason being that some participants placed their trail foot so that it straddled the step (foot partially supported), therefore, no pertinent trail foot crossing angles (*TCA*) or foot clearances (*TTC, THC*) could be extracted for these participants. Table 6.5.1.2, for example, only shows 39 cases for these variables because 9 participants placed the trail foot on the step edge.

The tables show that 10 of the 84 data sets exhibit significant levels of skewness and/or kurtosis ($p < .05$); that is, the measures fall outside the 95% confidence interval bounded by $\pm$ 1.96 (Vincent, 1995). The Shapiro-Wilks normality test results show that 31 of the data sets may be classified as non-normal.

Table 6.5.1.2 Descriptive statistics for the 1st trial of the elderly group in the descent task (comfortable walking velocity). Tests of normality: Shapiro-Wilks (SW).

Elderly	Mean	SD	Min.	Max.	Skew.	Kurt.	SW Sig.	n
ART (ms)	107	70	-2	340	-1.080	1.829	.011	48
CSL (cm)	59.5	11.3	40.1	93.5	0.781	1.119	.137	48
CST (s)	0.48	0.09	0.38	0.86	2.162	6.624	.01	48
DFST (s)	0.09	0.04	0	0.22	1.018	3.743	.01	48
HCD (cm)	-10.4	4.7	-19.3	0.3	0.349	-0.499	.436	48
HCV ($m \cdot s^{-1}$)	1.12	0.31	0.44	1.87	0.346	0.083	.766	48
HLD (cm)	25.1	9.9	8.1	51.0	0.535	0.604	.078	48
HLV ($m \cdot s^{-1}$)	1.51	0.31	0.86	2.28	0.235	0.005	.822	48
LCA (°)	-22.3	7.5	-36.5	-3.7	0.115	-0.338	.706	48
LFM (%)	92.1	5.0	77.5	99.7	-0.835	0.747	.019	48
LHC (cm)	3.4	1.9	0	9.2	0.769	1.094	.125	48
LHD (cm)	29.1	13.3	7.9	71.1	1.139	1.896	.01	48
LLA (°)	-14.3	7.3	-23.1	27.5	4.129	23.68	.01	48
LLV ($m \cdot s^{-1}$)	0.12	0.43	-0.93	1.31	0.59	1.043	.249	48
LTC (cm)	2.7	1.5	0.2	6.0	0.166	-0.564	.359	48
TCA (°)	-62.9	8.0	-82.4	-41.6	0.406	0.636	.629	39
TD (cm)	-8.3	8.1	-30.0	3.0	-0.816	0.305	.01	48
THC (cm)	18.3	3.5	12.5	25	0.107	-1.056	.174	39
TRKCA (°)	88.1	5.0	71.5	97.0	-0.895	1.517	.111	48
TTC (cm)	1.3	1.3	0.2	4.6	1.206	0.806	.01	39
VLV ($m \cdot s^{-1}$)	-0.55	0.11	-0.74	-0.33	-0.043	-0.978	.138	48

Table 6.5.1.3 Descriptive statistics for the 1st trial of the young group in the descent task (comfortable walking velocity). Test of normality: Shapiro-Wilks (SW).

Young	Mean	SD	Min.	Max.	Skew.	Kurt.	SW Sig.	n
ART (ms)	64	47	-21	183	-0.396	0.357	.495	48
CSL (cm)	76.1	12.1	46.1	105	0.072	0.182	.973	48
CST (s)	0.47	0.04	0.38	0.56	0.241	-0.427	.251	48
DFST (s)	0.08	0.03	0.02	0.12	-0.215	-0.563	.01	48
HCD (cm)	-7.7	4.8	-16.6	4.0	0.394	-0.202	.45	48
HCV ($m \cdot s^{-1}$)	1.38	0.31	0.75	2.09	0.353	-0.306	.479	48
HLD (cm)	34.4	9.3	16	52.9	-0.067	-0.617	.391	48
HLV ($m \cdot s^{-1}$)	1.86	0.29	1.21	2.55	-0.099	0.042	.833	48
LCA (°)	-25.2	10.4	-40.2	-2.9	0.386	-0.822	.036	48
LFM (%)	94.1	4.4	81.6	99.6	-1.094	0.494	.01	48
LHC (cm)	4.3	2.4	0.4	9.7	0.351	-0.761	.143	48
LHD (cm)	44.2	15.1	12.9	76.5	0.052	-0.371	.77	48
LLA (°)	0.3	20.6	-23	35.3	0.695	-1.379	.01	48
LLV ($m \cdot s^{-1}$)	0.42	0.42	-0.36	1.44	0.374	-0.086	.537	48
LTC (cm)	2.6	1.5	0.2	6.5	0.543	0.277	.436	48
TCA (°)	-76.2	9.3	-93.1	-55.4	0.263	-0.484	.915	29
TD (cm)	-7.9	13.3	-43.7	8.2	-1.066	0.257	.01	48
THC (cm)	23.2	2.8	15.2	27.9	-0.721	1.034	.472	29
TRKCA (°)	91.4	3.6	84.3	98.2	-0.084	-0.783	.495	48
TTC (cm)	1.9	1.5	0.1	5.3	0.591	0.223	.242	29
VLV ($m \cdot s^{-1}$)	-0.73	0.12	-1.04	-0.51	-0.256	-0.489	.513	48

Table 6.5.1.4 Descriptive statistics for the 1st trial of the elderly group in the descent task (fast walking velocity). Tests of normality: Shapiro-Wilks (SW).

Elderly	Mean	SD	Min.	Max.	Skew.	Kurt.	SW Sig.	n
ART (ms)	60	43	-82	182	0.104	2.370	.447	48
CSL (cm)	66.3	11.8	41.9	97	0.572	0.445	.337	48
CST (s)	0.44	0.04	0.34	0.6	1.125	3.103	.01	48
DFST (s)	0.06	0.03	0	0.14	0.057	0.473	.03	48
HCD (cm)	-7.5	5.4	-17.4	17.3	1.842	8.402	.01	48
HCV ($m \cdot s^{-1}$)	1.38	0.29	0.96	2.14	0.979	0.582	.01	48
HLD (cm)	31.1	10.2	12.1	62.3	0.872	1.21	.076	48
HLV ($m \cdot s^{-1}$)	1.85	0.31	1.35	2.6	0.377	-0.491	.286	48
LCA (°)	-25.0	8.1	-43.4	-5.6	-0.058	-0.138	.746	48
LFM (%)	93.0	3.6	84.1	99.5	-0.224	-0.395	.404	48
LHC (cm)	4.4	2.0	0.9	9	0.073	-0.565	.205	48
LHD (cm)	34.7	12.1	18.0	73.2	0.948	0.878	.016	48
LLA (°)	-13.2	8.9	-25.3	27.1	3.371	13.319	.01	48
LLV ($m \cdot s^{-1}$)	0.2	0.43	-0.43	1.58	0.998	1.118	.012	48
LTC (cm)	3.1	1.8	0.2	8.4	0.528	0.376	.582	48
TCA (°)	-68.9	9.8	-93	-39.1	0.514	1.368	.448	41
TD (cm)	-9.3	8.2	-36.5	2.8	-1.171	2.08	.01	48
THC (cm)	21.1	3.2	12.6	29.3	-0.078	0.424	.951	41
TRKCA (°)	86.8	5.8	68.2	100.1	-0.677	1.615	.333	48
TTC (cm)	1.7	1.4	0.2	6.5	1.133	2.123	.01	41
VLV ($m \cdot s^{-1}$)	-0.62	0.12	-0.89	-0.34	-0.077	-0.289	.923	48

Table 6.5.1.5 Descriptive statistics for the 1st trial of the young group in the descent task (fast walking velocity). Tests of normality: Shapiro-Wilks (SW).

Young	Mean	SD	Min.	Max.	Skew.	Kurt.	SW Sig.	n
ART (ms)	33	30	-35	113	-0.396	0.357	.666	48
CSL (cm)	87.5	11.0	51.3	105.5	-0.755	1.126	.122	48
CST (s)	0.43	0.03	0.36	0.52	0.304	1.064	.011	48
DFST (s)	0.05	0.02	0	0.10	0.44	-0.51	.01	48
HCD (cm)	-5.5	4.8	-14.4	7.5	0.29	0.226	.608	48
HCV ($m \cdot s^{-1}$)	1.80	0.32	1.14	2.33	-0.493	-0.612	.031	48
HLD (cm)	44.1	7.5	22.6	59.7	-0.552	0.446	.379	48
HLV ($m \cdot s^{-1}$)	2.31	0.29	1.39	2.89	-0.604	0.817	.504	48
LCA (°)	-28.2	9.4	-50.6	-4.5	0.491	0.612	.436	48
LFM (%)	96.1	3.1	86.8	99.6	-1.314	1.277	.01	48
LHC (cm)	5.0	2.7	0.1	11.7	0.268	-0.096	.783	48
LHD (cm)	56.2	14.8	21.0	80.3	-0.63	-0.442	.024	48
LLA (°)	3.2	21.2	-22.9	34.4	0.305	-1.753	.01	48
LLV ($m \cdot s^{-1}$)	0.66	0.50	-0.26	1.74	0.17	-0.381	.45	48
LTC (cm)	2.4	1.4	0.2	5.8	0.276	-0.059	.768	48
TCA (°)	-80.9	8.8	-95.1	-62.5	0.47	-0.822	.339	29
TD (cm)	-7.1	11.1	-41.3	7.3	-1.218	0.904	.01	48
THC (cm)	24.7	2.2	17.0	27.3	-1.69	3.735	.01	29
TRKCA (°)	89.5	3.6	80.4	96.3	-0.072	-0.331	.585	48
TTC (cm)	2.1	1.4	0.2	6.2	0.999	1.741	.191	29
VLV ($m \cdot s^{-1}$)	-0.79	0.15	-1.02	-0.52	0.199	-1.032	.024	48

Figures 6.5.1.1 to 6.5.1.4 are plots of the descriptive statistics listed in tables 6.5.1.2 to 6.5.1.5. The plots are organised so that variables are grouped in the following categories: (1) foot placement measures; (2) measures of dynamic stability upon landing; (3) measures of dynamic stability at the time of crossing; (4) measures of foot-step-clearance; and, (5) measures of foot orientation at crossing. Significant age differences ($p < .05$) are indicated by an asterisk positioned between age-group bars. Significant velocity differences ($p < .05$) are indicated by an asterisk above the bars of an age-group.

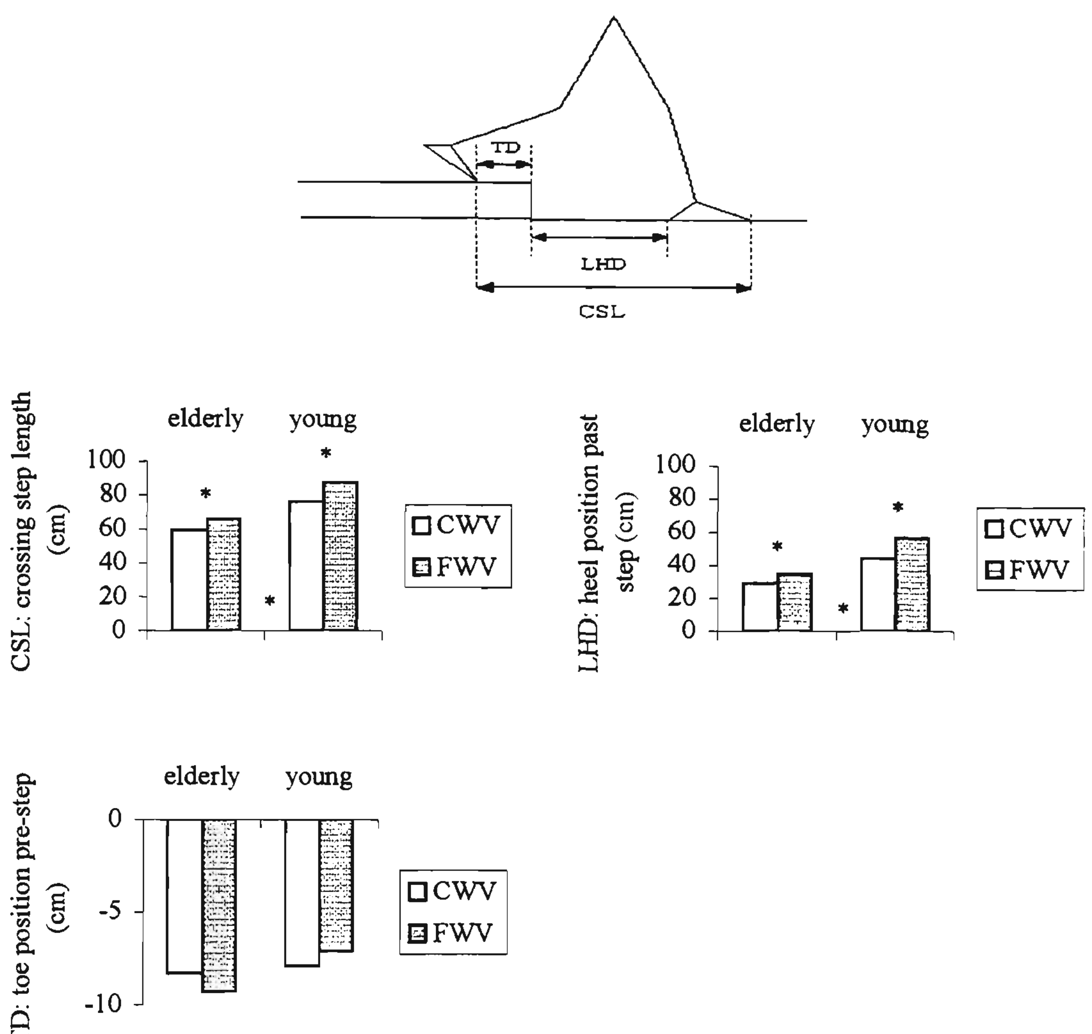


Figure 6.5.1.1 Measures of foot placement (*LHD, TD*) and crossing step length (*CSL*) found across age, step and velocity conditions. CWV: comfortable walking velocity; FWV: fast walking velocity. Significant age differences ($p < .05$) are indicated by an asterisk (*) positioned between age-group bars. Significant velocity differences ($p < .05$) are indicated by an asterisk (*) above the bars of an age-group.

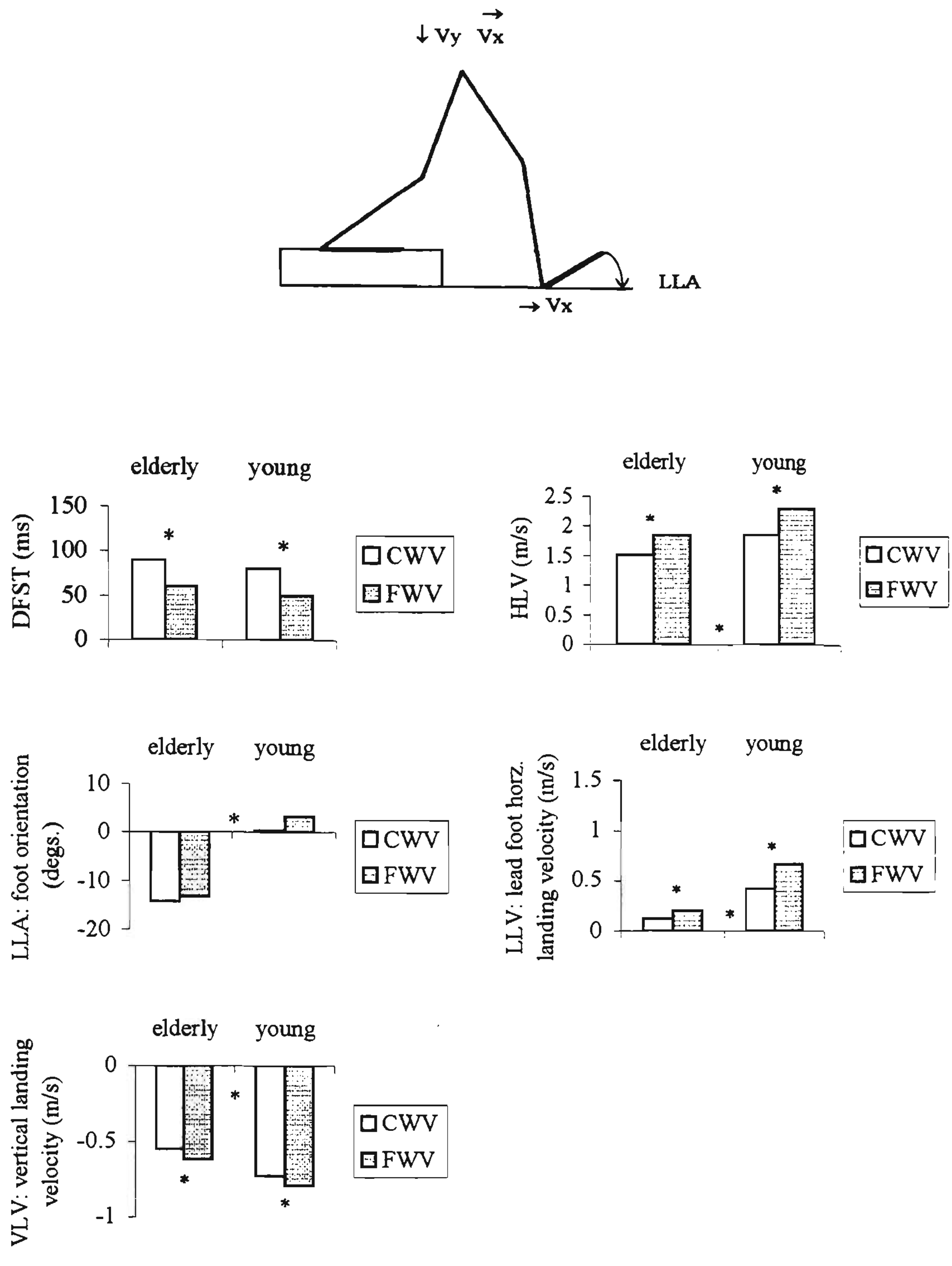


Figure 6.5.1.2 Measures of dynamic stability upon landing (*DFST*, *HLV*, *LLA*, *LLV*, *VLV*) found across age, step and velocity conditions. CWV: comfortable walking velocity. FWV: fast walking velocity. Significant age differences ($p < .05$) are indicated by an asterisk (*) positioned between age-group bars. Significant velocity differences ($p < .05$) are indicated by an asterisk (*) above the bars of an age-group.

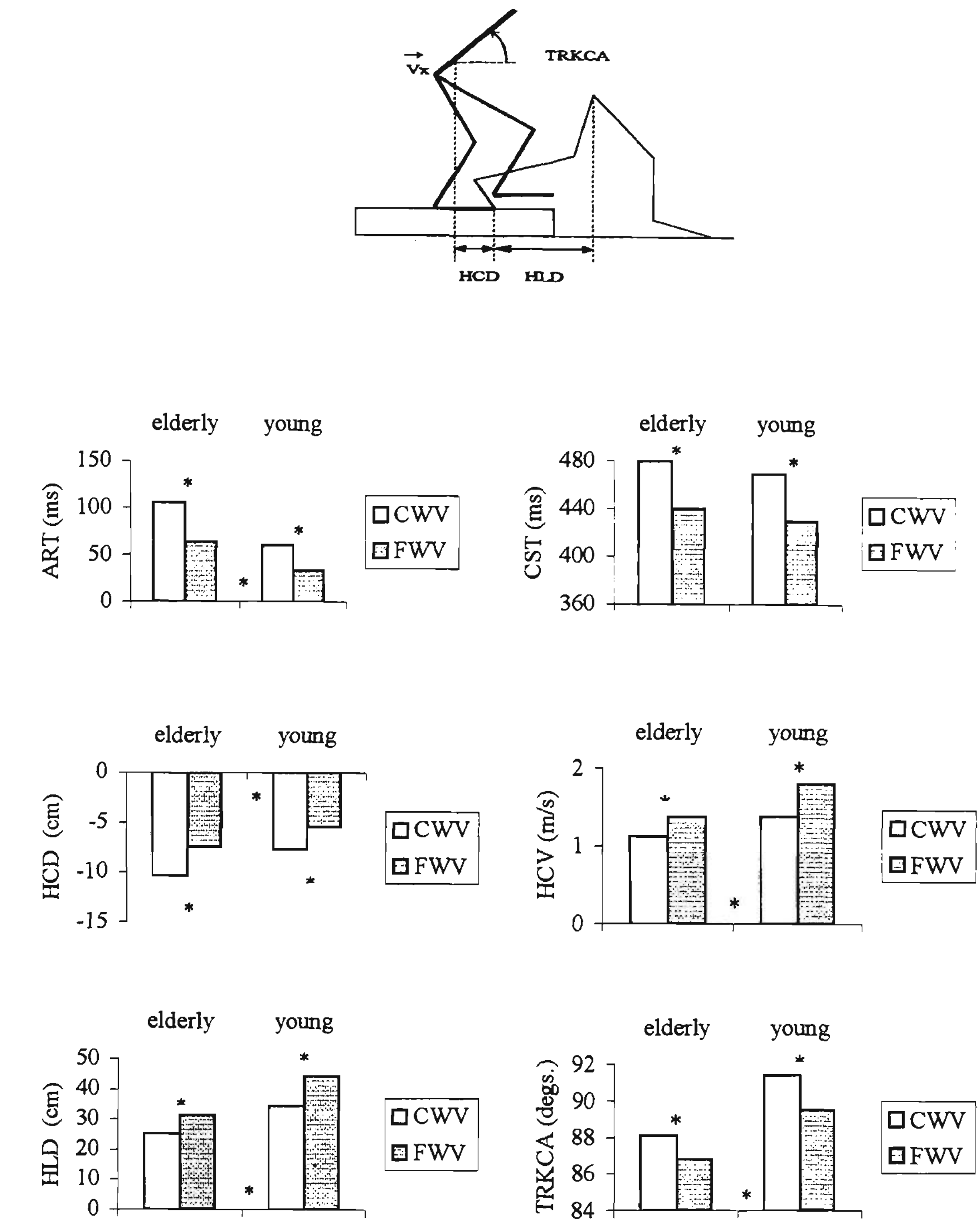


Figure 6.5.1.3 Measures of dynamic stability at crossing (*ART*, *CST*, *HCD*, *HLD*, *TRKCA*) found across age, step and velocity conditions. CWV: comfortable walking velocity. FWV: fast walking velocity. Significant age differences ($p < .05$) are indicated by an asterisk (*) positioned between age-group bars. Significant velocity differences ($p < .05$) are indicated by an asterisk (*) above the bars of an age-group.

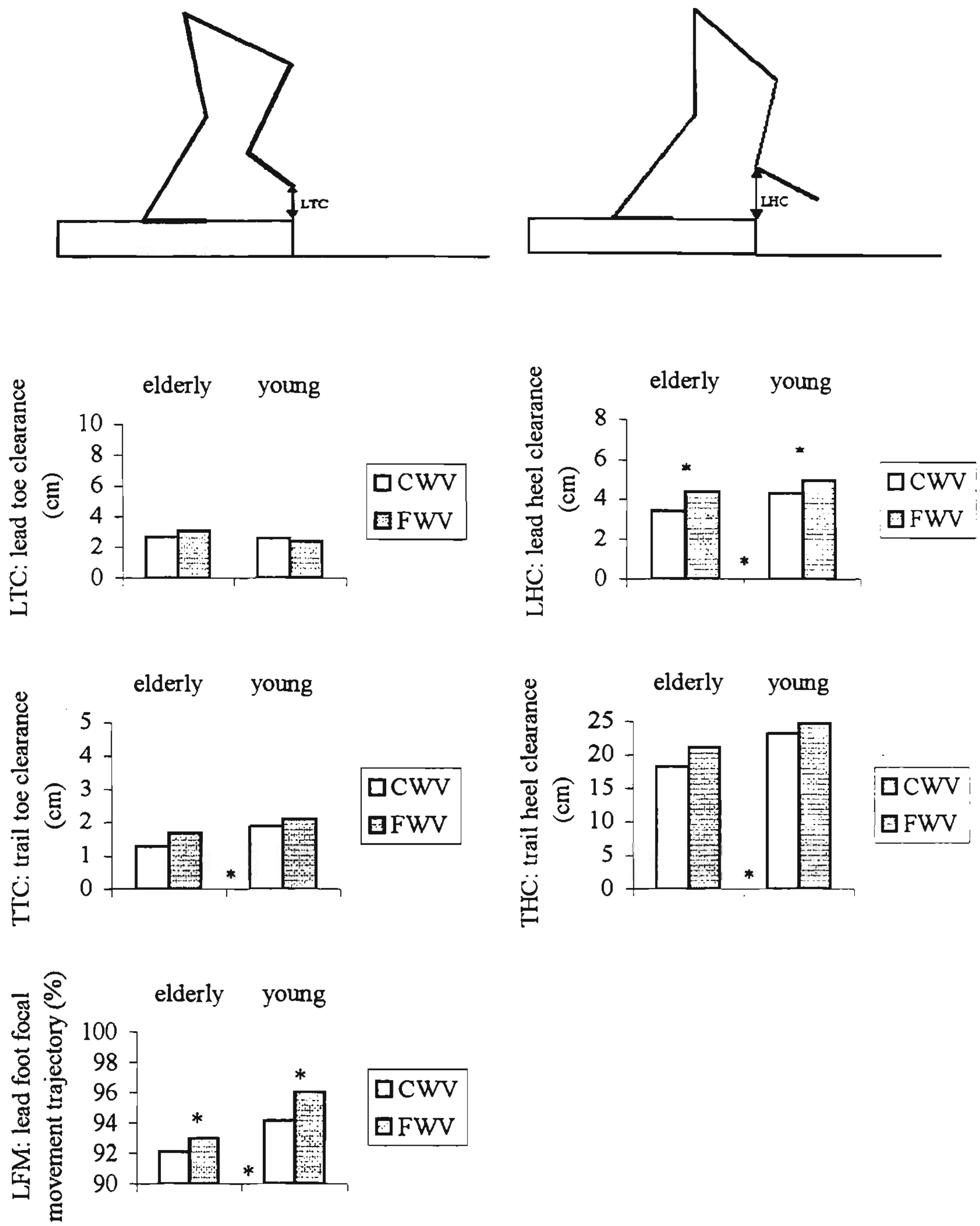


Figure 6.5.1.4 Measures of foot clearance (*LTC*, *LHC*, *TTC*, *THC*) and lead foot focal movement trajectory (*LFM*) across age, step and velocity conditions. CWV: comfortable walking velocity. FWV: fast walking velocity. Significant age differences ($p < .05$) are indicated by an asterisk (*) positioned between age-group bars. Significant velocity differences ($p < .05$) are indicated by an asterisk (*) above the bars of an age-group. N.B. The *TTC* variable was only significantly different across age for the CWV condition and the *THC* variable was only significantly different across age for the FWV condition.

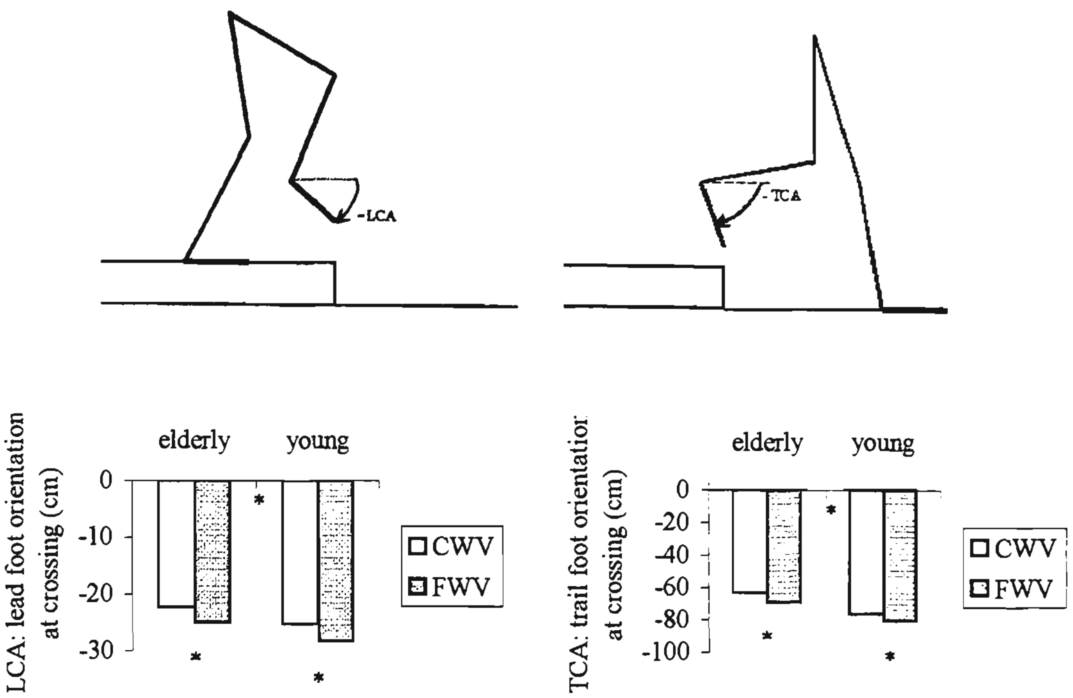


Figure 6.5.1.5 Measures of foot orientation at crossing (*LCA*, *TCA*) found across age, step and velocity conditions. CWV: comfortable walking velocity. FWV: fast walking velocity. Significant age differences ($p < .05$) are indicated by an asterisk (*) positioned between age-group bars. Significant velocity differences ($p < .05$) are indicated by an asterisk (*) above the bars of an age-group.

6.5.2 Inferential statistics (1st trial)

6.5.2.1 Age effects

The size (n) of the MANOVA cells was generally greater than 30 and of equal magnitude (i.e. $n_1 = n_2 = n_3 = n_4$). Since these criteria were met, any violations of normality and homogeneity of variance (refer to table 6.5.2.1.1) were regarded as being of little concern (Coakes & Steed, 2000).

Table 6.5.2.1.1 Levene's test of equality of error variances (between age groups) in the descent task (comfortable and fast walking velocity).

CWV	Sig.	FWV	Sig.
ART (ms)	.102	*ART* (ms)	.096
CSL (cm)	.619	*CSL* (cm)	.811
CST (s)	.004	*CST* (s)	.113
DFST (s)	.478	*DFST* (s)	.691
HCD (cm)	.924	*HCD* (cm)	.958
HCV ($m \cdot s^{-1}$)	.806	*HCV* ($m \cdot s^{-1}$)	.298
HLD (cm)	.928	*HLD* (cm)	.099
HLV ($m \cdot s^{-1}$)	.626	*HLV* ($m \cdot s^{-1}$)	.553
LCA (°)	.014	*LCA* (°)	.497
LFM (%)	.466	*LFM* (%)	.198
LHC (cm)	.024	*LHC* (cm)	.049
LHD (cm)	.263	*LHD* (cm)	.074
LLA (°)	.001	*LLA* (°)	.001
LLV ($m \cdot s^{-1}$)	.948	*LLV* ($m \cdot s^{-1}$)	.299
LTC (cm)	.645	*LTC* (cm)	.158
TCA (°)	.289	*TCA* (°)	.030
TD (cm)	.002	*TD* (cm)	.029
THC (cm)	.086	*THC* (cm)	.179
TRKCA (°)	.135	*TRKCA* (°)	.025
TTC (cm)	.509	*TTC* (cm)	.676
VLV ($m \cdot s^{-1}$)	.690	*VLV* ($m \cdot s^{-1}$)	.102

A three-stage approach was used to analyse the data. The reader is referred to section 5.5.3.1 for a more detailed discussion of this approach. The first stage examined the effects of age and velocity on the outcome variables that had 48 cases (n). The second stage examined the effect of age on the variables that contained missing cases, and the third stage examined the effect of velocity upon these variables.

The first stage of this analysis revealed a significant main effect of age ($F(18, 77) = 7.133$, $p < .001$). The Box M's test for homogeneity of variance-covariance matrices was found to be significant ($p < .001$). This was most probably due to the presence of the non-normal data sets: the test is highly sensitive to such data sets. The violation of this assumption was considered to have minimal impact since the cell sizes were greater than 30 and equal (Hair et al., 1998; Coakes & Steed, 2000).

In the second stage of this analysis, main age effects were found for the variables with missing cases (*LTC*, *LHC*, *LCA*) in both the comfortable ($F(3, 64) = 16.164$, $p < .001$) and fast walking velocity ($F(3, 66) = 11.078$, $p < .001$) conditions. The Box's M test for homogeneity of variance-covariance matrices (CWV: $p = .296$; FWV: $p = .509$) indicated that this assumption was not violated.

Bartlett's test of sphericity did reveal the presence of significant correlations among at least some of the dependent variables ($p < .001$) for each stage. This provides support for the use of MANOVA over simple ANOVA. Note that Mauchly's test of sphericity could not be conducted since there were only two levels on the repeated measures factor (Vincent, 1995).

Tables 6.5.2.1.2 and 6.5.2.1.3 list the main effects of age for each outcome variable. Main effects of age are illustrated in figures 6.5.1.1 to 6.5.1.5 presented in the previous section. The following variables did not differ across age:

- lead toe-step-clearance (*LTC*);
- trail toe pre-step distance (*TD*);
- double foot support time (*DFST*);
- lead limb crossing swing time (*CST*);
- trail toe-step-clearance (*TTC*) in the FWV condition.
- trail heel-step-clearance (*THC*) in the CWV condition.

All other variables were found to significantly differ ($p < .05$) across age.

Table 6.5.2.1.2 Main effects of age on variables analysed in the first stage.

Combined Variable	Sig.	Observed Power
ART	.001	.972
CSL	.001	1.001
CST	.393	0.136
DFST	.099	0.378
HCD	.011	0.725
HCV	.001	1.000
HLD	.001	1.000
HLV	.001	1.000
LCA	.043	0.527
LFM	.001	0.973
LHC	.044	0.525
LHD	.001	1.000
LLA	.001	1.000
LLV	.001	0.999
LTC	.187	0.260
TD	.451	0.116
TRKCA	.001	.929
VLV	.001	1.000

Table 6.5.2.1.3 Main effects of age on variables analysed in the second stage.

Variable	Velocity	Sig.	Observed Power
TTC	CWV	.003	0.869
THC	CWV	.069	0.444
TCA	CWV	.001	1.000
TTC	FWV	.173	0.274
THC	FWV	.001	0.999
TCA	FWV	.001	0.999

In the comfortable walking velocity condition, the elderly exhibited significant reductions ($p < .05$) compared to the young in the following variables:

- crossing step length (*CSL*: EA = 59.5 cm, YA = 76.1 cm);
- horizontal displacement of the trunk marker relative to the toe of the trail limb at the instant the lead toe crossed the step edge (*HCD*: EA = -10.4 cm, YA = -7.7 cm), and when the lead foot landed (*HLD*: EA = 25.1 cm, YA = 34.4 cm);

- horizontal crossing velocity (*HCV*: EA = 1.12 $m{\cdot}s^{-1}$, YA = 1.38 $m{\cdot}s^{-1}$);
- horizontal (*HLV*: EA = 1.51 $m{\cdot}s^{-1}$, YA = 1.86 $m{\cdot}s^{-1}$) and vertical landing velocities (*VLV*: EA = -0.55 $m{\cdot}s^{-1}$, YA = -0.73 $m{\cdot}s^{-1}$);
- focal movement trajectory of the lead foot (*LFM*: EA = 92.1%, YA = 94.1%);
- lead heel-step-clearance (*LHC*: EA = 3.4 cm, YA = 4.3 cm);
- lead heel placement past the step (*LHD*: EA = 29.1 cm, YA = 44.2 cm);
- lead foot horizontal landing velocity (*LLV*: EA = 0.12 $m{\cdot}s^{-1}$, YA = 0.42 $m{\cdot}s^{-1}$);
- trunk crossing angle (*TRKCA*: EA = 88.1°, YA = 91.4°);
- trail toe-step-clearance (*TTC*: EA = 1.3 cm, YA = 1.9 cm).

A significant increase in available response time was found with age (*ART*: EA = 107 ms, YA = 64 ms, $p < .001$).

In the fast walking velocity condition, the elderly exhibited significant reductions ($p < .05$) compared to the young in the following variables:

- crossing step length (*CSL*: EA = 66.3 cm, YA = 87.5 cm);
- focal movement trajectory of the lead foot (*LFM*: EA = 93.0%, YA = 96.1%);

- lead heel placement past the step (*LHD*: EA = 34.7 cm, YA = 56.2 cm);
- trunk displacement relative to the toe of the trail limb at the instant the lead foot toe crossed the step edge (*HCD*: EA = -7.5 cm, YA = -5.5 cm), and when the lead foot landed (*HLD*: EA = 31.1 cm, YA = 44.1 cm);
- horizontal crossing velocity (*HCV*: EA = 1.38 $m \cdot s^{-1}$, YA = 1.80 $m \cdot s^{-1}$);
- horizontal (*HLV*: EA = 1.85 $m \cdot s^{-1}$, YA = 2.31 $m \cdot s^{-1}$) and vertical landing velocities (*VLV*: EA = -0.62 $m \cdot s^{-1}$, YA = -0.79 $m \cdot s^{-1}$);
- lead foot horizontal landing velocity (*LLV*: EA = 0.20 $m \cdot s^{-1}$, YA = 0.66 $m \cdot s^{-1}$);
- lead heel-step-clearance (*LHC*: EA = 4.4 cm, YA = 5.0 cm);
- trunk crossing angle (*TRKCA*: EA = 86.8°, YA = 89.5°);
- trail heel-step-clearance (*THC*: EA = 21.1 cm, YA = 24.7 cm).

A significant increase in available response time was found with age (*ART*: EA = 60 ms, YA = 33 ms, $p < .001$).

Further inspection of the raw data revealed other differences in the toe and heel clearance data across age. Tables 6.5.2.1.4 and 6.5.2.1.5 list the descriptive statistics (and frequency count) of the foot clearance data found to be less than or equal to a value of 1.0 cm. A chi-square goodness of fit test revealed significant differences ($p < .005$) across age for each velocity condition. The most notable difference was found in the trail toe clearance data. Thirty five percent of the elderly, compared to 13.5% of the young, had values less than or equivalent to 1.0 cm. In the comfortable walking velocity condition contact ($n_{contact}$) was made (i.e. the heel was grounded) with the edge on one occasion. No contact was made in the fast walking velocity condition.

Table 6.5.2.1.4 Descriptive statistics (and frequency count) of the foot clearance data found to be less than or equal to a value of 1.0 cm in the comfortable walking velocity condition.

YA	Mean	SD	Min.	Max	$n \leq 1$	$n_{contact}$	EA	Mean	SD	Min.	Max	$n \leq 1$	$n_{contact}$
LTC	0.5	0.3	0.2	0.9	6	0	*LTC*	0.3	0.3	0.2	0.9	7	0
LHC	-	-	0.4	0.8	2	0	*LHC*	0.6	0.3	0	0.9	6	1
TTC	0.3	0.4	0.1	0.8	8	0	*TTC*	0.3	0.2	0.2	0.8	20	0
THC	-	-	-	-	0	0	*THC*	-	-	-	-	0	0

Table 6.5.2.1.5 Descriptive statistics (and frequency count) of the foot clearance data found to be less than or equal to a value of 1.0 cm in the fast walking velocity condition.

YA	Mean	SD	Min.	Max	$n \leq 1$	$n_{contact}$	EA	Mean	SD	Min.	Max	$n \leq 1$	$n_{contact}$
LTC	0.4	0.3	0.2	0.8	6	0	*LTC*	0.5	0.3	0.2	0.8	5	0
LHC	-	-	0.1	0.2	2	0	*LHC*	-	-	-	0.9	1	0
TTC	0.5	0.3	0.2	0.8	5	0	*TTC*	0.3	0.3	0.2	0.9	14	0
THC	-	-	-	-	0	0	*THC*	-	-	-	-	0	0

No age effect was found for the placement of the trail toe (TD_{CWV}: EA = -8.3 cm, YA = -7.9 cm; TD_{FWV}: EA = -9.3 cm, YA = -7.1 cm) near the step edge. The young, however, were found to have significantly greater variability ($p < .05$) in this measure (SD_{CWV}: EA = 8.1 cm, YA = 13.3 cm; SD_{FWV}: EA = 8.2 cm, YA = 11.1 cm). Further analysis of the raw data showed that significantly fewer ($\chi^2 = 26.7$, $p < .005$) of the elderly participants placed their trail foot on the step edge in both velocity conditions (CWV: n_{EA} = 16.6%, n_{YA} = 29.1%; FWV: n_{EA} = 14.6%, n_{YA} = 37.5%). Further analysis of these participants' data showed the young placed their trail toe at greater distances past the edge (CWV: EA = 1.5 cm, YA = 3.3 cm; FWV: EA = 1.1 cm, YA = 1.9 cm).

The lead foot angular data (*LCA*, *LLA*) were found to differ significantly ($p < .05$) across age in both velocity conditions. The data shows both groups crossed the step edge with a downward foot orientation (CWV: EA = -22.3°, YA = -25.2°; FWV: EA = -25.0°, YA = -28.2°). Upon landing, the majority of the elderly (n_{CWV} = 98%, n_{FWV} = 96%) used a forefoot landing strategy (CWV: EA = -14.3°, YA = 0.3°; FWV: EA = -13.2°, YA = 3.2°) whereas the young used either a forefoot or heel landing strategy (forefoot strategy: n_{CWV} = 67%, n_{FWV} = 58%).

The lead foot focal movement trajectory data (*LFM*) shows that the elderly exhibited less linearity in the trajectory of the foot after the lead foot crossed the step and landed. Further inspection of the data revealed that twice as many of the elderly (27%) compared to the young (13.5%) had *LFM* values less than 90%. In fact, two of the elderly participants had *LFM* values of 79.4% and 77.5%. None of the young participants exhibited a value less than 80%.

The trail foot angular data (*TCA*) shows that both groups crossed the step edge with the foot in a downward orientation. This measure was significantly different ($p < .05$) across age (CWV: EA = -62.9°, YA = -76.2°; FWV: EA = -68.9°, YA = -80.9°). In both velocity conditions, the young exhibited greater downward orientation of the foot compared to the elderly.

6.5.2.2 Velocity effects

The MANOVA analyses revealed significant main effects of velocity in both the 1st and 2nd stages (1st stage: $F(18, 77) = 16.851$, $p < .001$; 2nd stage:

F(3, 53) = 15.971, $p < .001$). Main effects of velocity are illustrated in figures 6.5.1.1 to 6.5.1.5 in section 6.5.1. The results of the univariate comparisons are listed in table 6.5.2.2.1. This table shows significant differences ($p < .05$) on 17 of the 21 variables. Lead toe-step-clearance (*LTC*), trail toe pre-step distance (*TD*), lead foot landing angle (*LLA*) and trail toe-step-clearance (*TTC*) measures were not found to significantly differ. Trail-toe-clearance (*TTC*), however, did increase across velocity for both age groups.

Table 6.5.2.2.1 Main effects of velocity on all outcome variables.

Variable	Sig.	Observed Power
ART (ms)	.001	1.000
CSL (cm)	.001	1.000
CST (s)	.001	1.000
DFST (s)	.001	1.000
HCD (cm)	.001	1.000
HCV ($m \cdot s^{-1}$)	.001	1.000
HLD (cm)	.001	1.000
HLV ($m \cdot s^{-1}$)	.001	1.000
LCA (°)	.010	.736
LFM (%)	.007	.775
LHC (cm)	.001	.943
LHD (cm)	.001	1.000
LLA (°)	.208	.241
LLV ($m \cdot s^{-1}$)	.002	.898
LTC (cm)	.542	.093
TCA (°)	.001*	.999
TD (cm)	.914	.051
THC (cm)	.001*	1.000
TRKCA (°)	.001	.985
TTC (cm)	.227*	.225
VLV ($m \cdot s^{-1}$)	.001	.998

*reduced sample size due to missing cases (*n:* YA = 21, EA = 36).

Significant reductions ($p < .05$) were found in available response time (*ART*) double foot support time (*DFST*), crossing swing time (*CST*), trail foot crossing angle (*TCA*), trunk orientation at crossing (*TRKCA*) and *HCD* across velocity for both groups. For the elderly, significant increases were found in the following variables:

- crossing step length (*CSL*: CWV = 59.5 cm, FWV = 66.3 cm);
- focal movement trajectory of the lead foot (*LFM*: CWV = 92.1%, FWV = 93.0%);
- lead foot heel placement past the step (*LHD*: CWV = 29.1 cm, FWV = 34.7 cm);
- lead heel-step-clearance (*LHC*: CWV = 3.4 cm, FWV = 4.4 cm);
- horizontal crossing velocity (*HCV*: CWV = 1.12 $m \cdot s^{-1}$, FWV = 1.38 $m \cdot s^{-1}$);
- horizontal displacement of the trunk marker relative to the toe of the trail limb when the lead foot landed (*HLD*: CWV = 25.1 cm, FWV = 31.1 cm);
- horizontal (*HLV*: CWV = 1.51 $m \cdot s^{-1}$, FWV = 1.85 $m \cdot s^{-1}$) and vertical landing velocities (*VLV*: CWV = -0.55 $m \cdot s^{-1}$, FWV = -0.62 $m \cdot s^{-1}$);
- lead foot horizontal landing velocity (*LLV*: CWV = 0.12 $m \cdot s^{-1}$, FWV = 0.20 $m \cdot s^{-1}$);
- trail heel-step-clearance (*THC*: CWV = 18.0 cm, FWV = 20.6 cm).

Significant increases were found across velocity for the young in the following variables:

- crossing step length (*CSL*: CWV = 44.2 cm, FWV = 56.2 cm);

- focal movement trajectory of the lead foot (*LFM*: CWV = 94.1%, FWV = 96.1%);

- lead heel-step-clearance (*LHC*: CWV = 4.3 cm, FWV = 5.0 cm);

- lead foot heel placement past the step (*LHD*: CWV = 44.2 cm, FWV = 56.2 cm);

- horizontal crossing velocity (*HCV*: CWV = 1.38 $m \cdot s^{-1}$, FWV = 1.80 $m \cdot s^{-1}$);

- horizontal displacement of the trunk marker relative to the toe of the trail limb when the lead foot landed (*HLD*: CWV = 34.4 cm, FWV = 44.1 cm);

- horizontal (*HLV*: CWV = 1.86 $m \cdot s^{-1}$, FWV = 2.31 $m \cdot s^{-1}$) and vertical landing velocities (*VLV*: CWV = -0.73$m \cdot s^{-1}$, FWV = -0.79 $m \cdot s^{-1}$);

- lead foot horizontal landing velocity (*LLV*: CWV = 0.42 $m \cdot s^{-1}$, FWV = 0.66 $m \cdot s^{-1}$);

- trail heel-step-clearance (*THC*: CWV = 23.3 cm, FWV = 25.2 cm).

6.5.2.3 Velocity-age interaction

Significant interaction effects ($p < .05$) were found in the following variables:

- crossing step length (*CSL*)

- horizontal displacement of the trunk marker from the trail toe as the lead foot landed (*HLD*).

- horizontal velocity of trunk marker at landing (*HLV*) and crossing (*HCV*).

6.5.2.4 Group membership

Discriminant (stepwise) analyses with cross-validation procedures were conducted in order to determine which of the dependent variables accounted the most for the differences in the average score profiles of the two groups. In the comfortable walking velocity condition the analysis identified the *CSL* and *VLV* variables as the most useful in discriminating ($p < .001$) the groups. In the fast walking velocity condition the analysis identified the *CSL*, *VLV* and *LTC* variables as the most useful in discriminating ($p < .001$) the groups. In the comfortable walking velocity condition (refer to table 6.5.2.4.1) 81.3% of the elderly and 85.4% of the young were correctly classified. In the fast walking velocity condition (refer to table 6.5.2.4.2) 83.3% of the elderly and 85.4% of the young were correctly classified.

Table 6.5.2.4.1 Accuracy of predicted group membership (CWV) using a stepwise discriminant analysis.

Classification Results					
			Predicted Group Membership		
		AGE	**YA**	**EA**	**Total**
Original	**Count**	YA	41	7	48
		EA	9	39	48
	%	YA	85.4	14.6	100
		EA	18.8	81.3	100
Cross-validated	**Count**	YA	40	8	48
		EA	9	39	48
	%	YA	83.3	16.7	100
		EA	18.8	81.3	100

Table 6.5.2.4.2 Accuracy of predicted group membership (FWV) using a stepwise discriminant analysis.

Classification Results					
			Predicted Group Membership		
		AGE	YA	EA	Total
Original	**Count**	YA	41	7	48
		EA	8	40	48
	%	YA	85.4	14.6	100
		EA	16.7	83.3	100
Cross-validated	**Count**	YA	40	8	48
		EA	8.0	40.0	48
	%	YA	83.3	16.7	100
		EA	16.7	83.3	100

Tables 6.5.2.4.3 and 6.5.2.4.4 profile the correctly classified and misclassified observations in the two-group discriminant analysis. It demonstrates that some of the misclassified observations significantly differ ($p < .05$) from their age group. Furthermore, it shows these misclassified observations to be closer to the other age group data. The misclassified young *CSL* data (CWV condition), for example, have a mean value of 61.5 cm ($n = 7$) that is much closer to the elderly group value of 56.6 cm ($n = 40$).

Table 6.5.2.4.3 Profiling of correctly classified and misclassified observations in the two-group discriminant analysis for the YA group in both velocity conditions.

Velocity	Young	Correctly Classified	Misclassified	Difference	t-test Sig.
CWV		(n = 41)	(n = 7)		
	CSL	78.6	61.5	17.1	.05
	VLV	-0.75	-0.59	-0.16	.05
FWV		(n = 38)	(n = 10)		
	CSL	90.4	70.5	19.9	.05
	VLV	-0.81	-0.69	0.12	ns
	LTC	2.3	3.2	-0.9	ns

Table 6.5.2.4.4 Profiling of correctly classified and misclassified observations in the two-group discriminant analysis for the elderly group in both velocity conditions.

Velocity	Elderly	Correctly Classified	Misclassified	Difference	t-test Sig.
CWV		(n = 40)	(n = 8)		
	CSL	56.6	74.2	-17.5	.05
	VLV	-0.52	-0.68	0.16	.05
FWV		(n = 41)	(n = 7)		
	CSL	62.5	85.3	-21	.05
	VLV	-0.61	-0.65	0.04	ns
	LTC	3.2	2.4	0.8	ns

6.5.2.5. Variable association (correlation)

Correlation analyses were conducted in order to examine the relationship between variables. The results are listed in appendices F and G and will be referred to throughout other sections of this thesis.

6.5.3 Ensemble average patterns (1st trial)

6.5.3.1 Lead foot orientation

Figures 6.5.3.1.1 and 6.5.3.1.2 are the ensemble average plots of the orientation of the lead foot (with respect to an earth-based horizontal axis) in the crossing stride (toe-off to foot land) for participants who landed on the forefoot. Figures 6.5.3.1.3 and 6.5.3.1.4 are the plots for participants who landed on the heel. On each plot the approximate position of the mean percentage value of the time at which the lead toe crossed the step edge is shown by a dashed line. For each velocity condition, and across both age groups, this value ranged from 38.1% to 45.5%. The reader is referred to Appendix H for each age group and velocity condition ensemble average plot.

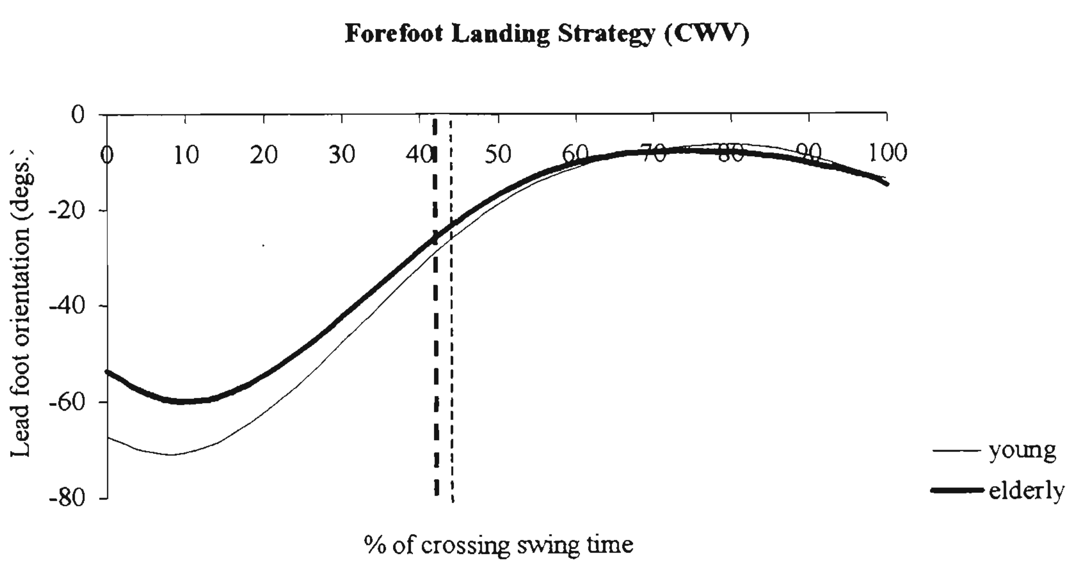


Figure 6.5.3.1.1 Ensemble average plot of the lead foot orientation for participants who adopted a forefoot landing strategy (EA = 47; YA = 32) in the comfortable velocity condition. Mean percent cross time (approximate position shown by dashed lines) of the step edge by the lead toe (EA = 42.0%, YA = 43.5%).

Forefoot Landing Strategy (FWV)

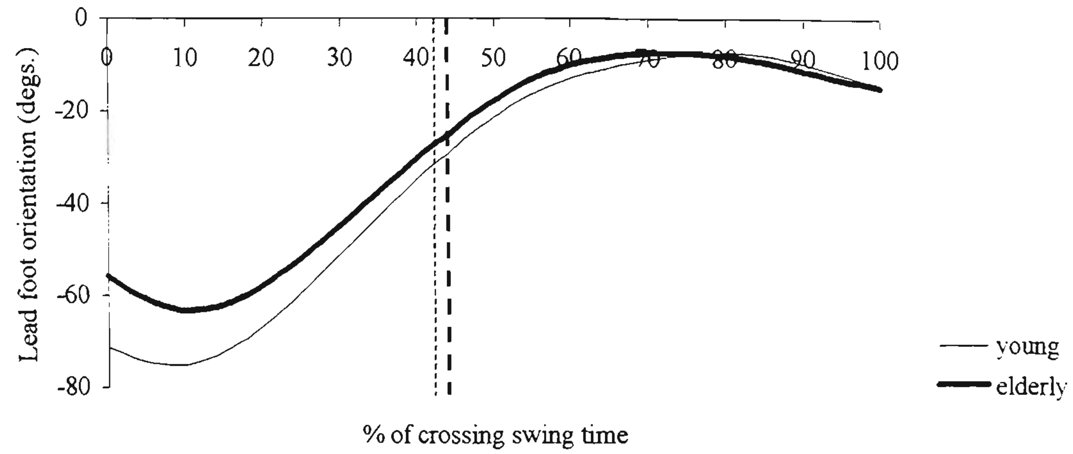


Figure 6.5.3.1.2 Ensemble average plot of the lead foot orientation for participants who adopted a forefoot landing strategy (EA = 46; YA = 27) in the fast velocity condition. Mean percent cross time (approximate position shown by dashed lines) of the step edge by the lead toe (EA = 43.7%, YA = 43.2%).

Heel Landing Strategy (CWV)

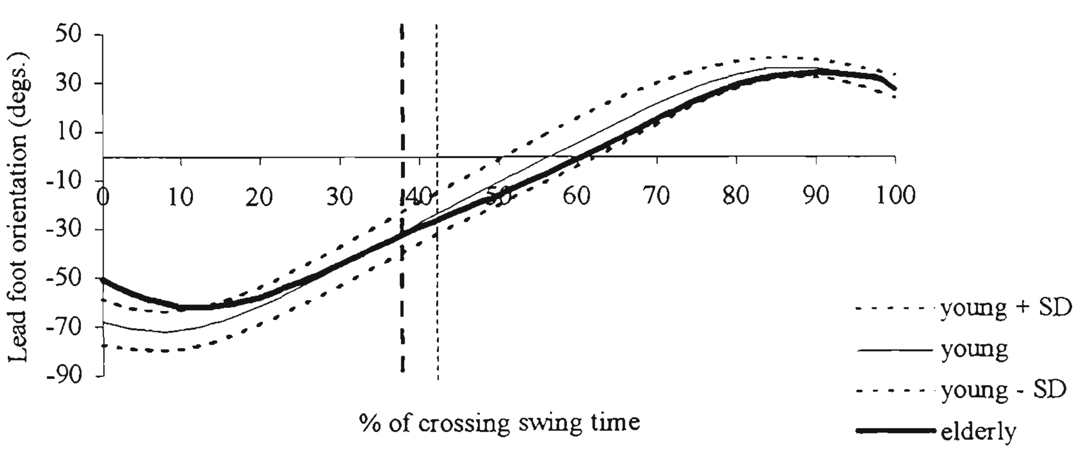


Figure 6.5.3.1.3 Ensemble average plot for the participants who adopted a heel landing strategy (EA = 1; YA = 16) in the comfortable velocity condition. Mean percent cross time (approximate position shown by dashed lines) of the step edge by the lead foot toe (EA = 38.1%, YA = 42.2%).

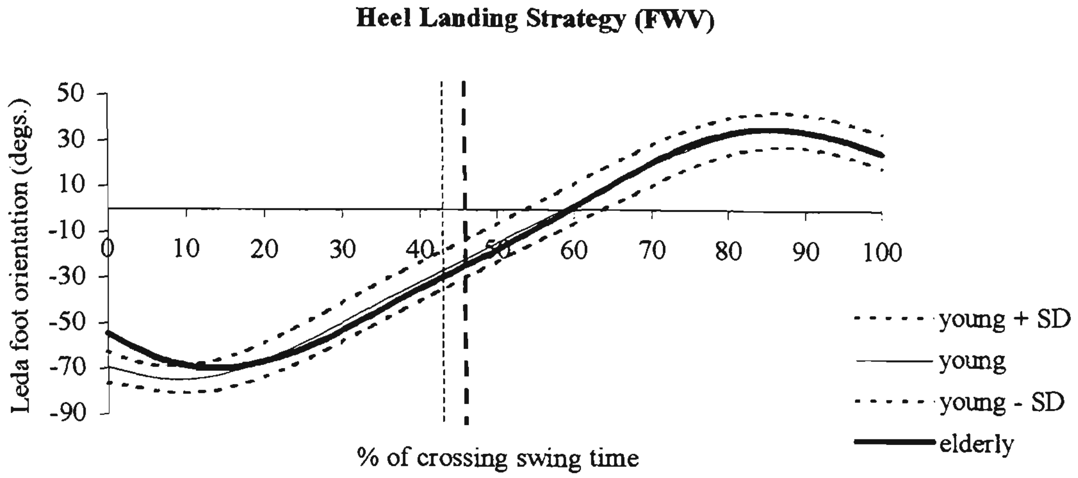


Figure 6.5.3.1.4. Ensemble average plot for the participants who adopted a heel landing strategy (EA = 2; YA = 21) in the fast velocity condition. Mean percent cross time (approximate position shown by dashed lines) of the step edge by the lead foot toe (EA = 45.5%, YA= 42.9%).

Across walking velocity conditions, 97% of the elderly and 62% of the young adopted a forefoot landing strategy. The remaining participants adopted a heel landing strategy. Throughout the crossing step, participants who landed on the forefoot maintained a downward orientation of the foot (toe-down). In addition, these participants took the foot through a smaller range of motion (≈ 50° to 60°) compared to those who landed on the heel (≈ 100°).

An independent t-test comparison of foot orientation (across walking velocity conditions) at take–off showed the elderly (-54.8°, SD = 8.6°) to exhibit significantly less downward orientation of the foot (p < .001) compared to the young (-69.0°, SD = 8.6°).

6.5.3.1.1 Group membership

Cluster analyses confirmed the existence of the two types of foot orientations upon landing. The results of these analyses are listed in table 6.5.3.1.1.1. One of the young participants who landed on the heel (*LLA* = 2.6°) in the fast velocity condition was clustered with the group of forefoot strikers.

Table 6.5.3.1.1.1 Cluster analysis results for the *LLA* variable across both velocity conditions.

Comfortable walking velocity		
Cluster	Final cluster centres (*LLA*)	*n*
Forefoot	-14.7°	79
Heel	28.4°	17
Fast walking velocity		
Cluster	Final cluster centres (*LLA*)	*n*
Forefoot	-14.5°	74
Heel	26.9°	22

MANOVA analyses were conducted to determine whether the characteristics of the group of young forefoot landers differed from the group of elderly forefoot landers for each velocity condition. These analyses revealed significant differences (refer to table 6.5.3.1.1.2) in 11 of the variables for the comfortable walking velocity condition ($F(18, 60) = 3.790$, $p < .001$), and 11 of the variables in the fast velocity condition ($F(16, 54) = 3.050$, $p < .001$). This indicates that even though the same foot landing strategy was adopted, the age groups still differ significantly on the majority of variables.

Table 6.5.3.1.1.2 Between-subjects effects for the YA and EA comparison (MANOVA) of forefoot strikers' data.

Combined Variable	CWV Sig.	Observed power	FWV Sig.	Observed power
LTC	.361	0.148	.021	0.641
LHC	.002	0.887	.010	0.737
CSL	.001	0.999	.001	1.000
LHD	.001	0.936	.001	0.999
TD	.911	0.051	653	0.073
LCA	.057	0.479	.022	0.637
LLA	.127	0.331	.800	.057
LFM	.422	0.125	.037	0.553
HCD	.010	0.740	.121	0.341
HLD	.001	0.958	.001	1.000
HCS	.001	0.926	.001	0.998
LLV	.030	0.589	.002	0.890
HLV	.001	0.994	.001	1.000
VLV	.001	1.000	.001	0.973
DFST	.898	0.052	.055	0.486
CST	.354	0.151	.582	0.085
ART	.002	0.880	.014	.703
TRKCA	.001	0.916	.065	.455

A comparison (MANOVA) of foot clearance and placement data (*LTC*, *LHC*, *LHD*, *TD*) was conducted in order to ascertain whether differences existed between the group classified as forefoot landers and the group classified as heel landers. Significant differences were found in each velocity condition (CWV: $F(4, 91) = 42.556$, $p < .001$; FWV: $F(4, 91) = 29.850$, $p < .001$). In the comfortable velocity condition, the *LTC* and *LHD* data were found to significantly differ ($p < .05$), whereas in the fast velocity condition only the *LHD* data ($p < .001$) was found to significantly differ (refer to table 6.5.3.1.1.3).

Table 6.5.3.1.1.3 Between-subjects effects (grouped by landing strategy: forefoot or heel) for the comparison (MANOVA) of foot clearance and placement variables.

	Forefoot		**Heel**			
CWV	**Mean**	**SD**	**Mean**	**SD**	**Sig.**	**Observed Power**
LTC (cm)	2.5	1.4	3.4	1.7	.025	0.619
LHC (cm)	3.8	2.1	3.9	2.7	.926	0.051
LHD (cm)	32.2	13.1	57.5	12.1	.001	1.000
TD (cm)	-8.6	10.6	-5.8	12.3	.352	0.153
FWV	**Mean**	**SD**	**Mean**	**SD**	**Sig.**	**Observed Power**
LTC (cm)	2.7	1.6	3.1	1.7	.238	0.217
LHC (cm)	4.7	2.4	4.7	2.6	.932	0.051
LHD (cm)	39.9	14.7	64.3	10.8	.001	1.000
TD (cm)	-8.8	9.2	-6.2	11.3	.277	0.191

The analysis indicates that the adoption of a forefoot landing strategy significantly reduces lead toe-step-clearance (forefoot landing: *LTC* = 2.5 cm; heel landing: *LTC* = 3.4 cm). Forefoot landers also placed the heel significantly closer to the step edge upon landing. In the comfortable and fast velocity conditions, the forefoot strikers placed the heel 25.3 cm and 24.4 cm closer to the step edge respectively.

6.5.3.2 Lead foot vertical trajectory

Figures 6.5.3.2.1 to 6.5.3.2.2 are the ensemble average plots of the vertical displacement of the centre of the lead toe marker for participants who landed on the forefoot. Figures 6.5.3.2.3 and 6.5.3.2.4 are the plots of the participants who landed on the heel. The displacement of the marker was calculated relative to the step height (15 cm) for the crossing step (toe-off to foot land). On each plot the approximate position of the mean percentage value of the time at which the lead toe crossed the step edge is shown by a dashed line. For each velocity condition, and across both age groups, this value ranged from 38.1% to 45.5%. The reader is referred to Appendix I for each age group and velocity condition ensemble average plot.

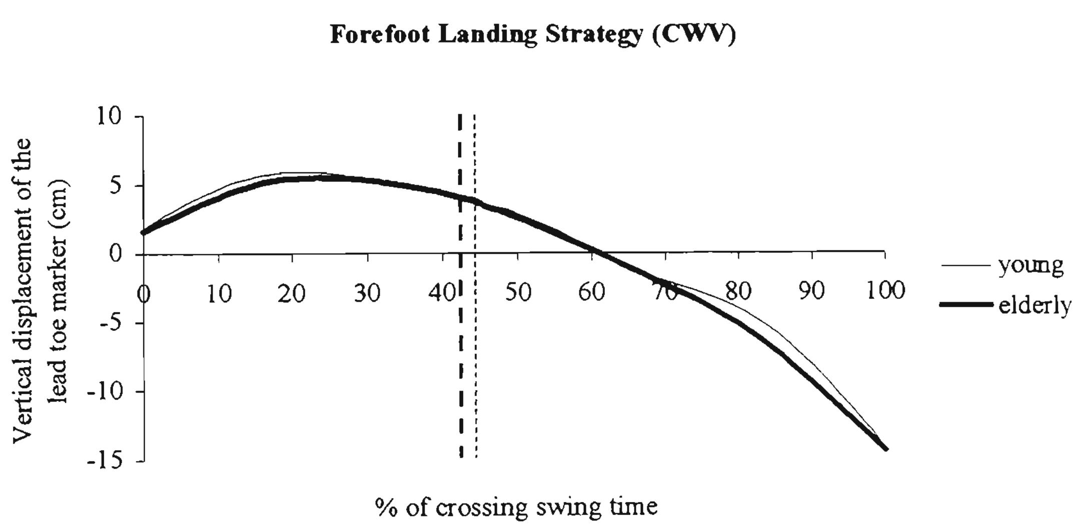


Figure 6.5.3.2.1 Ensemble average plot of the vertical displacement of the lead toe marker (relative to step height) for the participants who adopted a forefoot landing strategy (EA = 47, YA = 32) in the comfortable velocity condition. Mean percent cross time (approximate position shown by dashed lines) of the step edge by the lead toe (EA = 42.0%, YA = 43.5%).

Forefoot Landing Strategy (FWV)

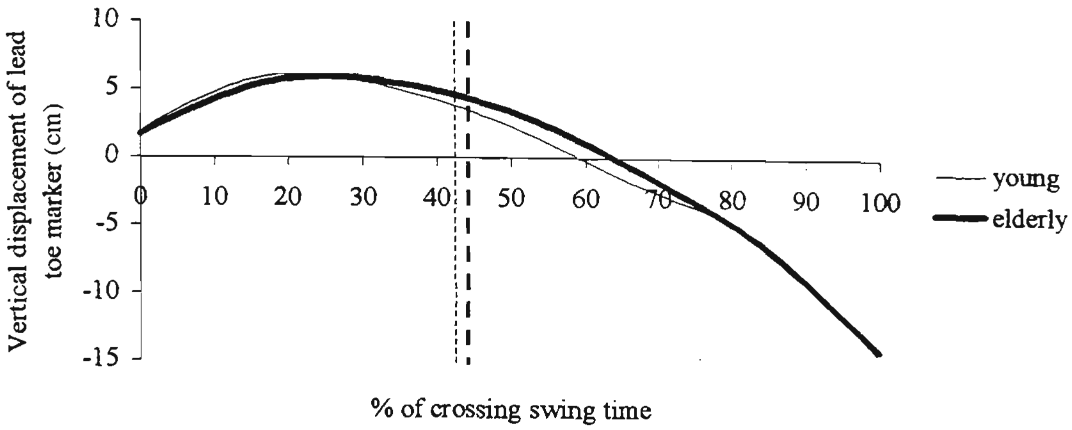


Figure 6.5.3.2.2 Ensemble average plot of the vertical displacement of the lead toe marker (relative to step height) for the participants who adopted a forefoot landing strategy (EA = 46, YA = 27) in the fast velocity condition. Mean percent cross time (approximate position shown by dashed lines) of the step edge by the lead toe (EA = 43.7%, YA = 43.2%).

Heel Landing Strategy (CWV)

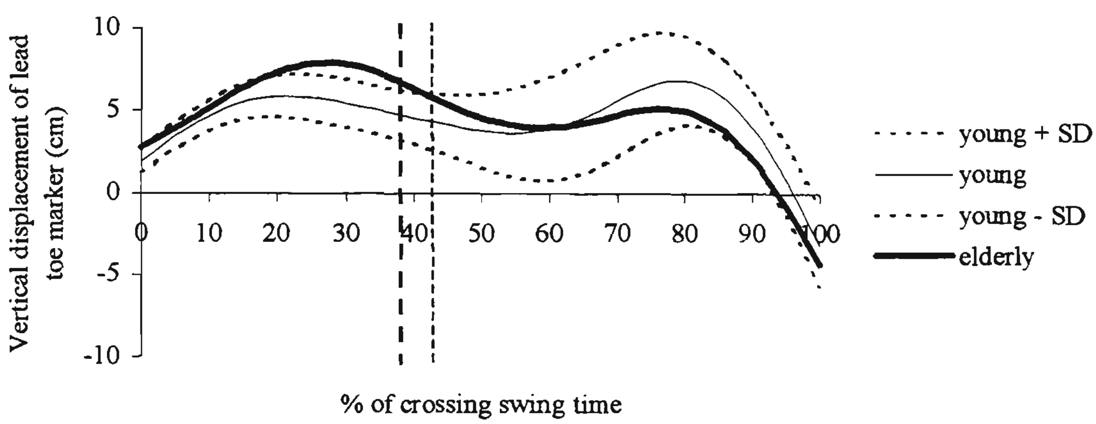


Figure 6.5.3.2.3 Ensemble average plot of the vertical displacement of the lead toe marker (relative to step height) for the participants who adopted a heel landing strategy (EA= 1, YA = 16) in the comfortable velocity condition. Mean percent cross time of the step edge (approximate position shown by dashed lines) by the lead toe (EA = 38.1%, YA = 42.2%).

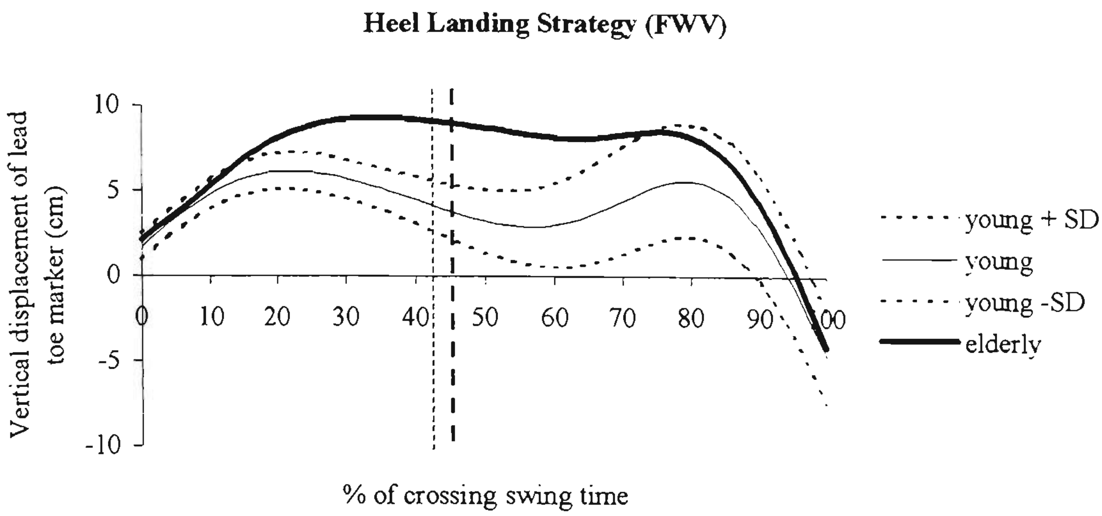


Figure 6.5.3.2.4 Ensemble average plot of the vertical displacement of the lead toe marker (relative to step height) for the participants who adopted a heel landing strategy (EA = 2, YA = 21) in the fast velocity condition. Mean percent cross time (approximate position shown by dashed lines) of the step edge by the lead toe (EA = 45.5%, YA = 42.9%).

Across walking velocity conditions, 97% of the elderly and 62% of the *YG* adopted a forefoot landing strategy; the remaining participants adopted a heel landing strategy. After the clearance of the step edge these participants lowered the toe to the ground with a "spearing" like action. The remaining participants adopted a heel landing strategy where the toe was elevated (relative to the step) after edge clearance and then lowered to the ground.

6.5.3.3 Head pitch

Figures 6.5.3.3.1 to 6.5.3.3.5 are the ensemble average plots of the head pitch variable for each age group. Figure 6.5.3.3.5 is a group comparison plot. Head pitch was recorded from the 3rd-last footfall until midstance past the step (refer to figure 5.3.2.1). Head pitch was normalised to the value found at midstance in the 9th-last step of approach. A positive magnitude indicates the head is rotated upwards, whereas a negative magnitude indicates the head is rotated downwards. On each plot the events of heel contact (*HC*), foot landing past step (*FL*), lead toe-step-clearance (*LTC*), lead toe-off (*LTO*), and trail toe-off (*TTO*) are shown.

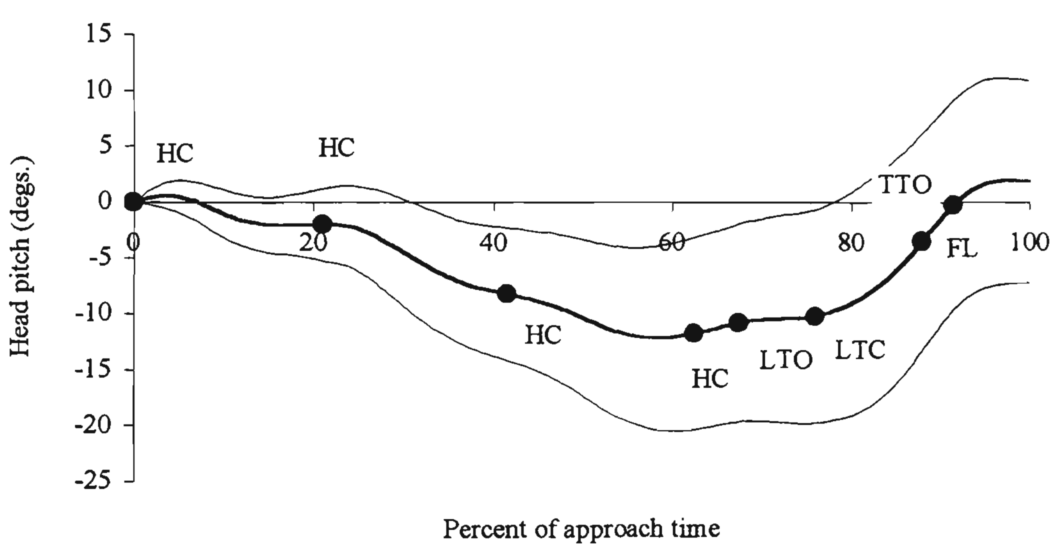


Figure 6.5.3.3.1 Elderly ensemble average plot of head pitch in the comfortable velocity condition. The events of heel contact (*HC*; occurring at 0, 21, 42 & 63%), foot landing past step (*FL*; 88%), lead toe-step-clearance(*LTC*; 76%), lead toe-off (*LTO*; 67%), and trail toe-off (*TTO*; 91%) are shown.

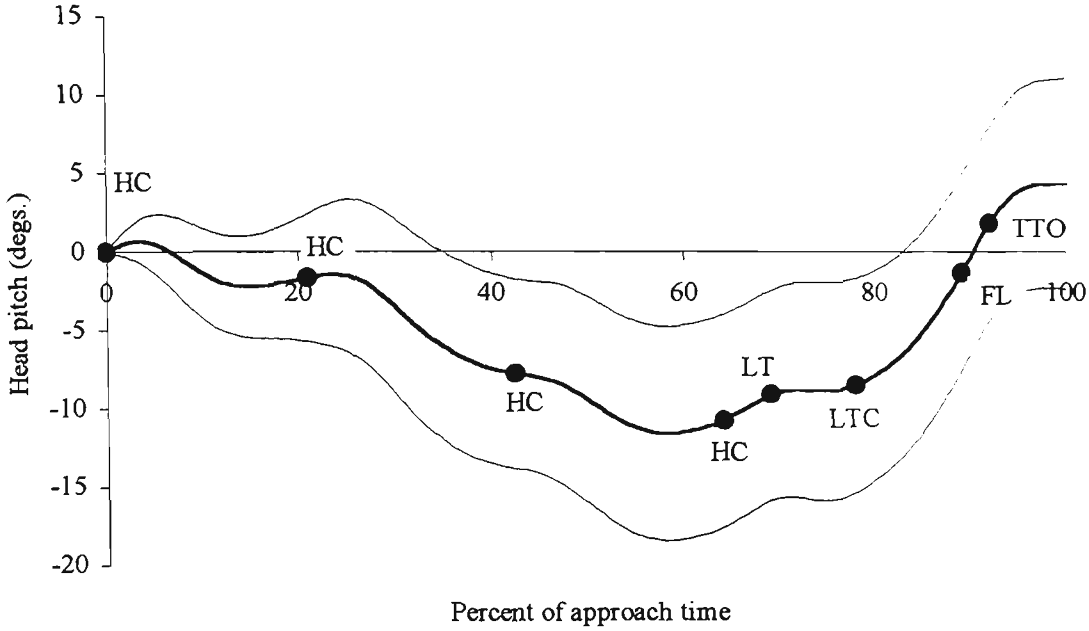


Figure 6.5.3.3.2 Elderly ensemble average plot of head pitch in the fast velocity condition. The events of heel contact (*HC*; occurring at 0, 21, 43 & 64%), foot landing past step (*FL*; 89%), lead toe-step-clearance (*LTC*; 78%), lead toe-off (*LTO*; 69%), and trail toe-off (*TTO*; 92%) are shown.

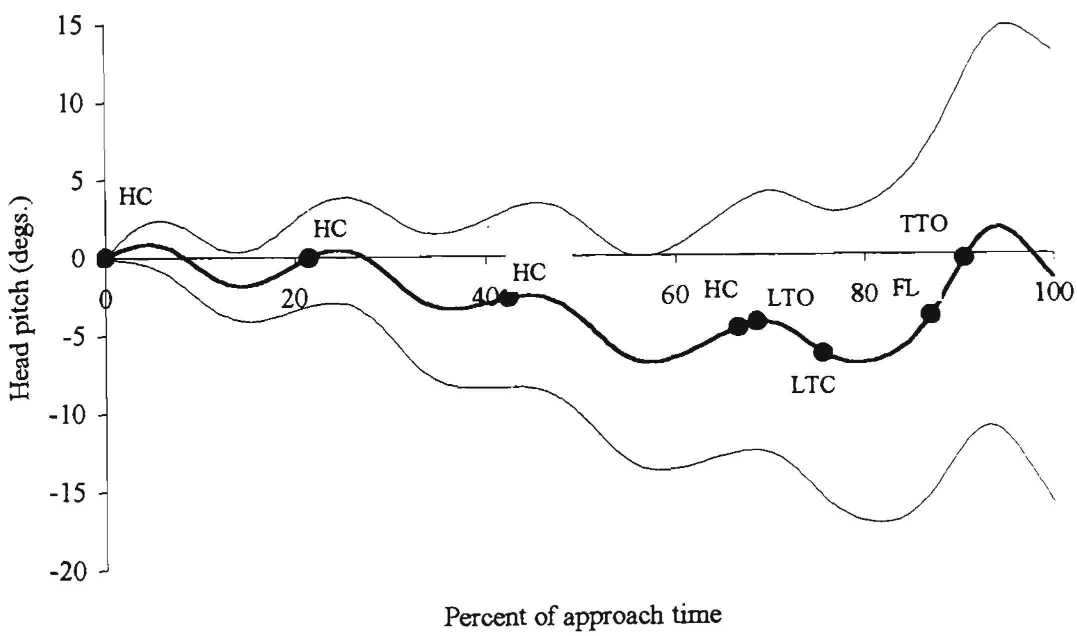


Figure 6.5.3.3.3 Young ensemble average plot of head pitch in the comfortable velocity condition. The events of heel contact (*HC*; occurring at 0, 21, 43 & 66%), foot landing past step (*FL*; 87%), lead toe-step-clearance (*LTC*; 76%), lead toe-off (*LTO*; 67%), and trail toe-off (*TTO*; 90%) are shown.

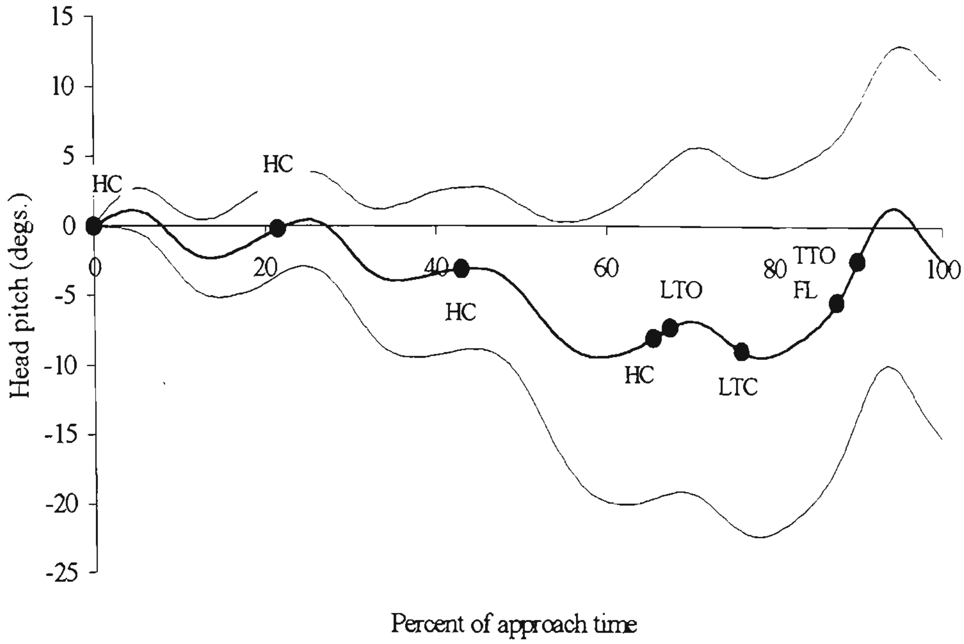


Figure 6.5.3.3.4 Young ensemble average plot of head pitch in the fast velocity condition. The events of heel contact (*HC*; occurring at 0, 22, 43 & 66%), foot landing past step (*FL*; 88%), lead toe-step-clearance (*LTC*; 76%), lead toe-off (*LTO*; 68%), and trail toe-off (*TTO*; 90%) are shown.

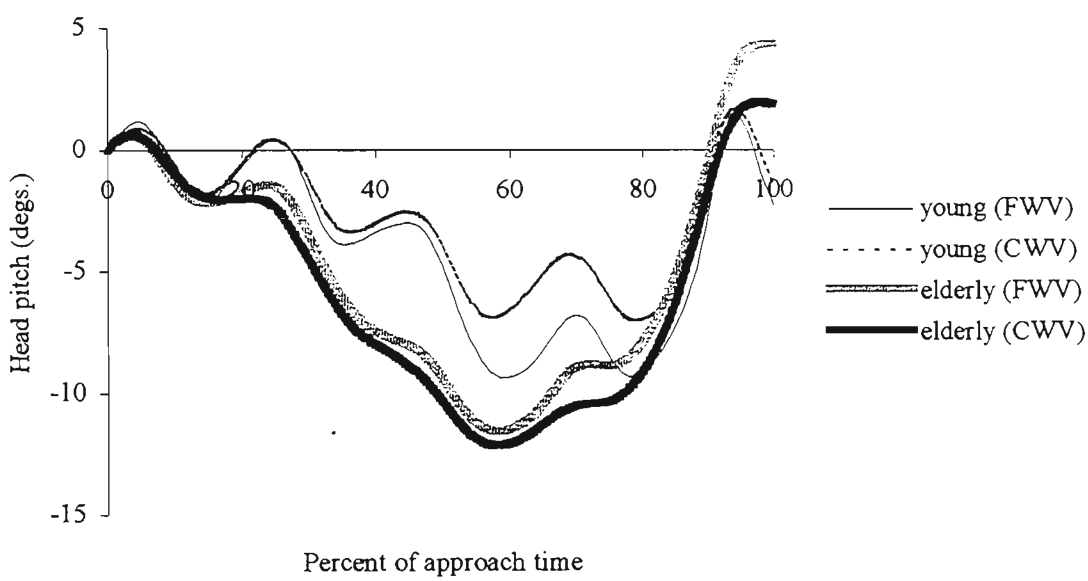


Figure 6.5.3.3.5 Ensemble average plots of head pitch for both groups across velocity.

The plots show the elderly implement a marked and systematic reduction in head pitch (rotate the head downwards) earlier than the young (EA ≈ 5%, YA ≈ 25%). The elderly also show greater head pitch reductions than the young. The maximum head pitch angle (EA ≈ -12°, YA ≈ -7 to -9°) was found to occur just prior to the last heel contact ($\approx 60\%$) before the step edge. After this event, the elderly show a marked and systematic increase in head pitch, whereas the young exhibit this phase later ($\approx 80\%$). Overall the elderly were found to exhibit greater head rotation throughout the approach and accommodation phases.

6.5.4 Footfall adjustments

6.5.4.1 Trial selection

A pilot study was conducted in order to examine whether the initial footfall pattern (1st trial) or patterns (e.g., 1st, 2nd or 3rd trials) exhibited in an accommodation task were different from subsequent responses (e.g., 4th, 5th trial). Seven healthy adult females (≈ 20 yrs.) completed 12 comfortable velocity walking trials for the descent task described in section 5.2.2.1. Six of the participants' footfall patterns (randomly selected trials) were examined in the interval bounded by the third-last footfall and the last footfall (crossing step). The 7th participant's footfall patterns were examined for the entire length of the walkway or from the 11th-last footfall to the last footfall (all 12 trials).

Figure 6.5.4.1.1 is a plot of footfall variability found for the 6 participants across trials #1, #6 and #11. Trials # 6 and # 11 were randomly selected for comparison with trial #1. The plots show marked reductions in variability from the 3rd and 2nd-last footfalls. Additionally, the plots show the footfall variability of trial #1 to be greater than trials #6 and #11. A repeated measures ANOVA with post-hoc testing found the variability of trial #1 to be greater ($p < .006$) than trials #6 and #11, whereas no difference was found between trials #6 and #11.

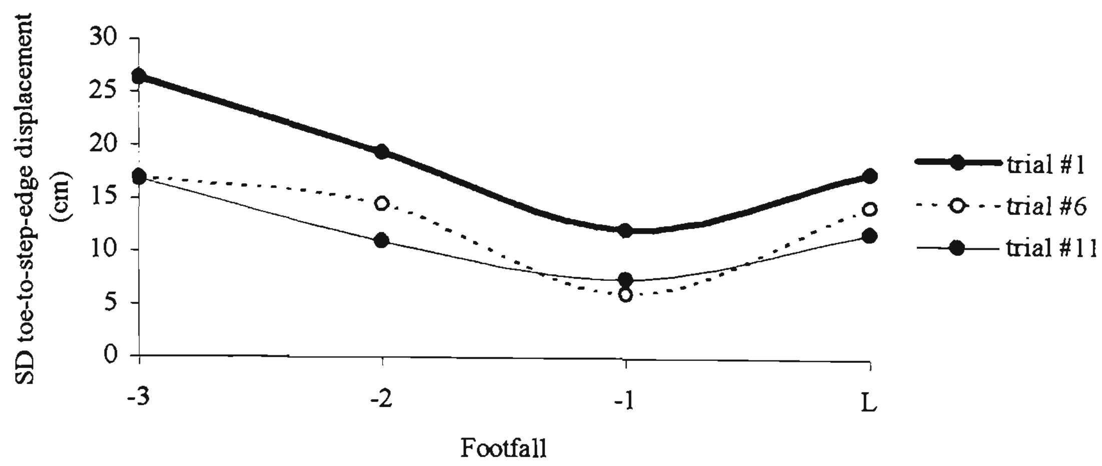


Figure 6.5.4.1.1 Plot of footfall variability for the 1st, 6th and 11th trials. Last footfall (L).

Figure 6.5.4.1.2 is a plot of footfall variability found for all 12 trials of the 7th participant. The plot shows reductions from the 8th-last footfall with a marked reduction occurring at the penultimate footfall (footfall = -1).

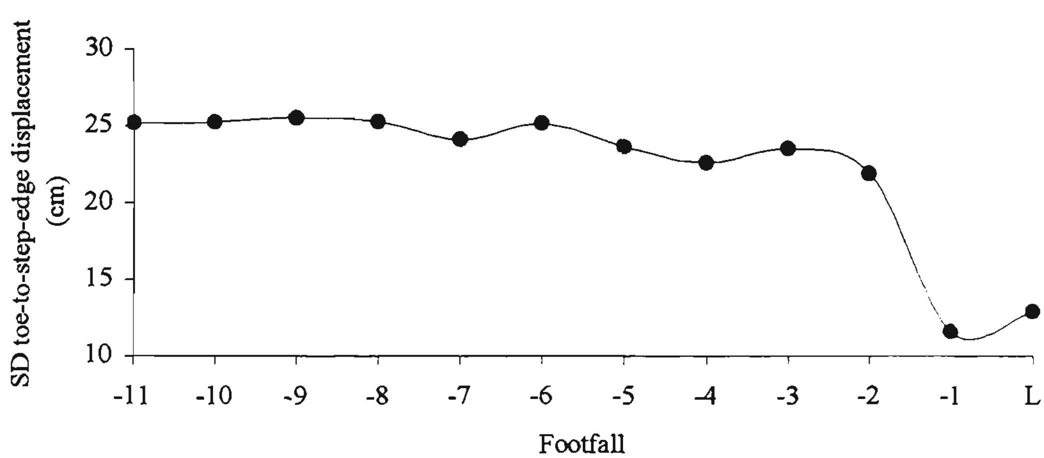


Figure 6.5.4.1.2 Plot of footfall variability for the 7th participant (12 trials). Last footfall (L).

Figure 6.5.4.1.3 is a plot of the footfall variability found in the following blocks of trials for the 7th participant; (1) the first 3 trials; (2) the first 6 trials; (3) the first 9 trials; and, (4) all 12 trials. The shape of the curves or plots is similar across the four conditions, however, the variability of the data in the first block of 3 trials is significantly greater than the other blocks of trials.

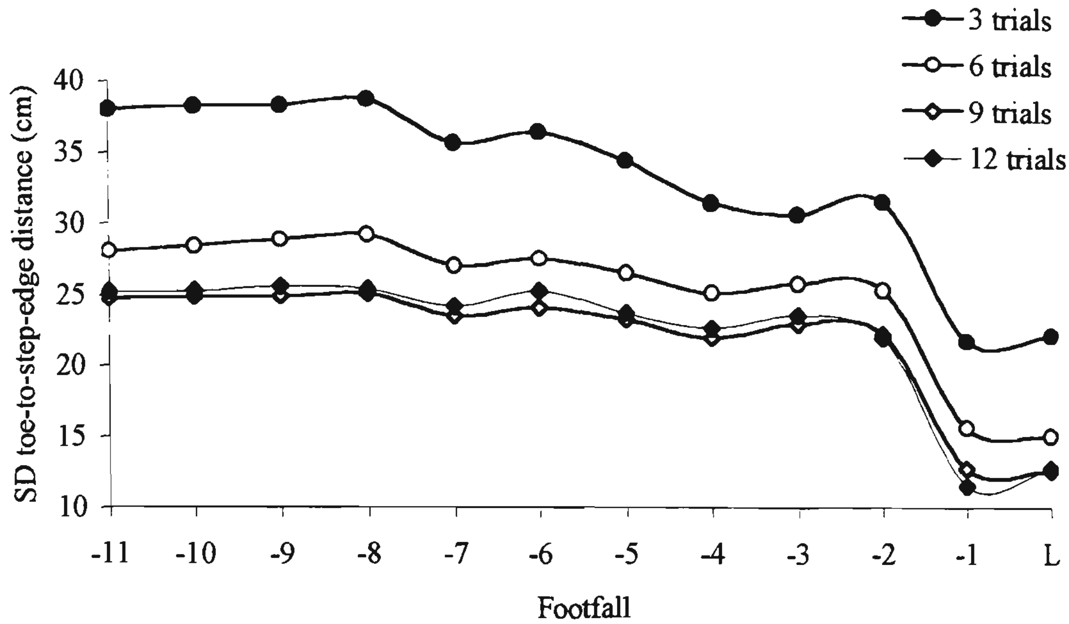


Figure 6.5.4.1.3 Plot of footfall variability for the 7^{th} participant in the following blocks of trials; (1) the first 3 trials; (2) the first 6 trials; (3) the first 9 trials; and, (4) all 12 trials. Last footfall (L).

Figure 6.5.4.1.4 is a plot of the footfall variability for the following blocks of trials for the 7^{th} participant; (1) trials #1-3; (2) trials #4-6; (3) trials #7-9; and, (4) trials #10-12. It is evident that the shape of the curve for the 1^{st} block of trials (trials #1-3) is fundamentally different from the other curves in the interval bounded by the 11^{th}-last footfall to the 3^{rd}-last footfall. Interestingly, the first three curves exhibit the same pattern in the last 3 footfalls, whereas the fourth curve (trials #10-12) differs markedly from the other curves in the last footfall (L).

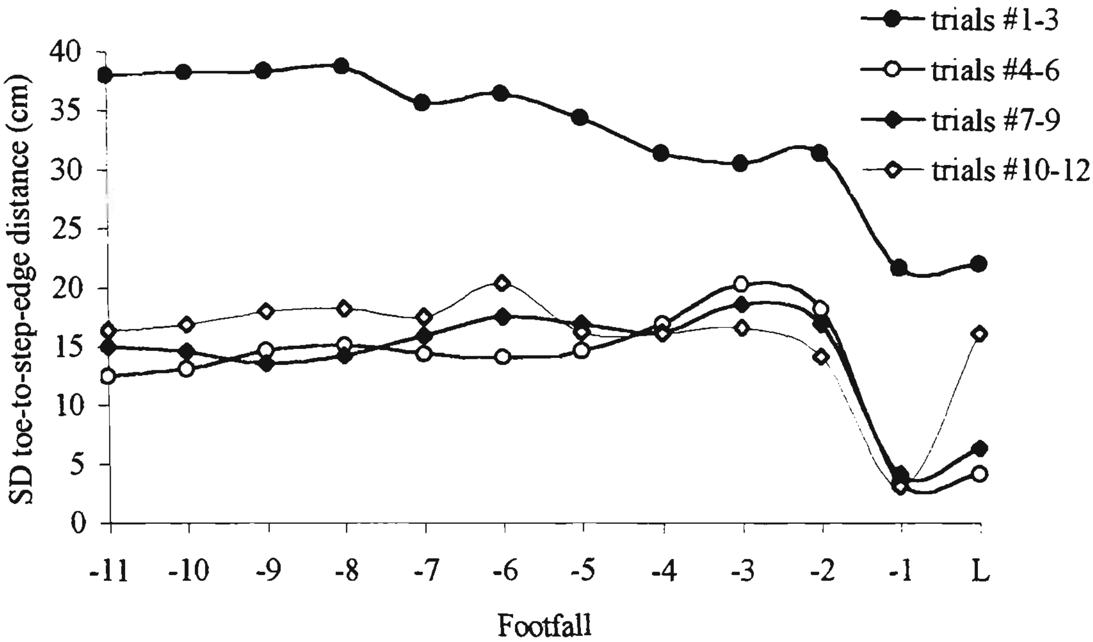


Figure 6.5.4.1.4 Plot of footfall variability for the following blocks of trials for the 7th participant; (1) trials #1-3; (2) trials #4-6; (3) trials #7-9; and, (4) trials #10-12. Last footfall (L).

A repeated measures ANOVA with post-hoc testing found the variability of trials #1-3 to be greater ($p < .001$) than trials #4-6, #7-9 and #10-12, whereas no difference was found between the other sets of trials.

6.5.4.2 Footfall variability (all trials)

Toe-to-step-edge displacement (*TSED*) was calculated for each participant's footfalls in the 3 comfortable and 3 fast walking velocity trials. Footfall variability values were derived from these data. These data were then used to derive mean values of footfall variability for each age. Ensemble average plots of footfall variability across age and velocity conditions are shown in figure 6.5.4.2.1. The reader is referred to Appendix J for each age group plot.

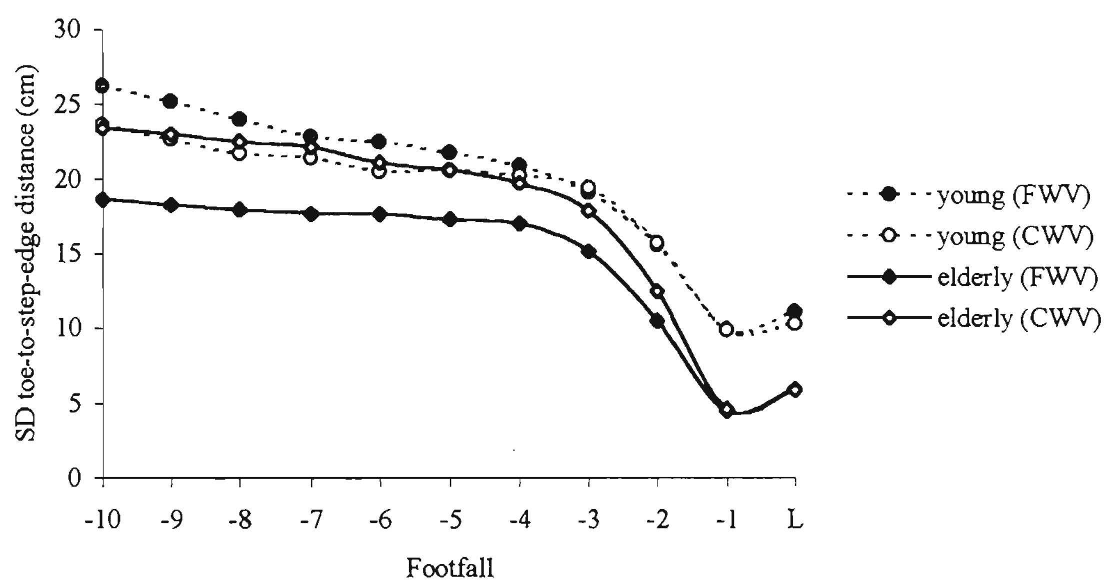


Figure 6.5.4.2.1 Mean plots of footfall variability for each age group and velocity condition. CWV: comfortable walking velocity, FWV: fast walking velocity. Last foofall (L).

The plots show small systematic reductions from the 10^{th} to 3^{rd}-last footfall (0.3 to 1.8 cm reductions). Larger reductions (4 to 8 cm) occur from the 3^{rd}-last to penultimate footfall followed by a small increase ($\approx$ 1 cm) in the final footfall. The figure also shows the elderly exhibit less footfall variability than the young in the following intervals: (1) 3^{rd}-last-to-penultimate-footfall (CWV) ; and, (2) across all footfalls (FWV).

The elderly also show less variability in the fast velocity condition (FWV) compared to the comfortable velocity condition (CWV) in the interval bounded by the 10th to 3rd-last footfalls.

One-way (factor: age) MANOVAs were conducted in order to statistically validate some of the above observations. The analyses revealed significant age differences ($p < .05$) in mean footfall variability in the following phases:

- the 2nd-last to final footfall for the comfortable velocity condition;
- all footfalls, except for the 7th-last to 4th-last, in the fast velocity condition.

Inspection of the individual plots of footfall variability revealed the existence of three distinct patterns (refer to figures 6.5.4.2.2 to 6.5.4.2.4). In the comfortable walking velocity condition, 54% of the participants exhibited an ascending-descending pattern, whereas 45% exhibited a descending trend from the 10th-last footfall. Interestingly, one elderly participant displayed very low variability throughout the approach but exhibited similar variability (compared to others) on the final footfall.

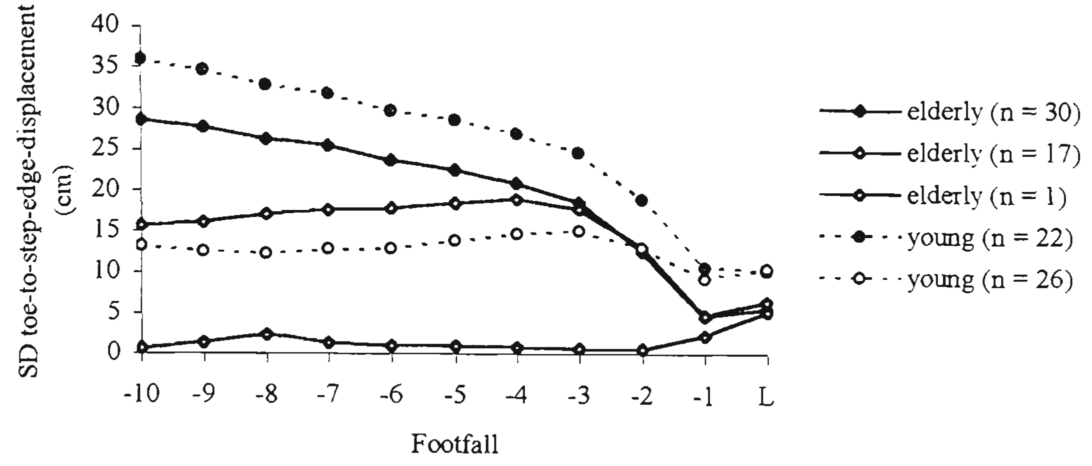


Figure 6.5.4.2.2 Plots of footfall variability showing three distinct patterns (comfortable walking velocity).

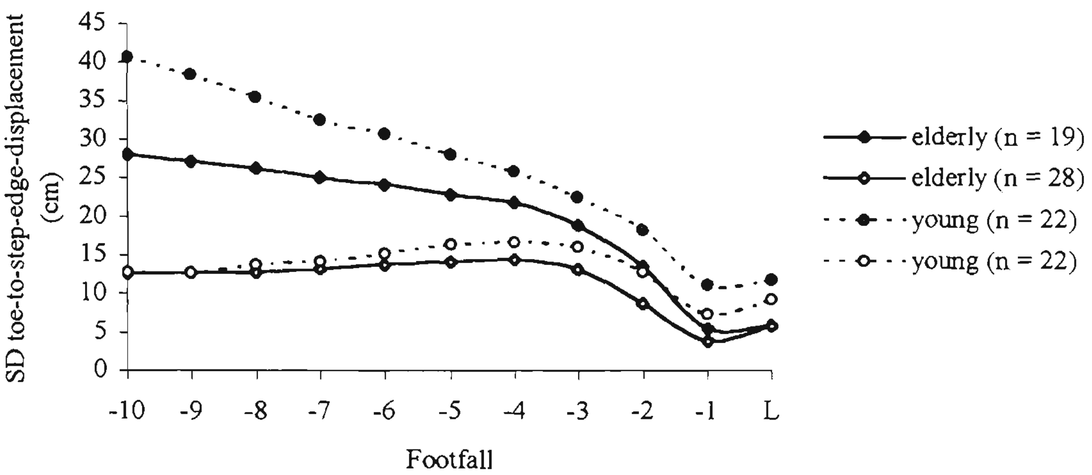


Figure 6.5.4.2.3 Plots of footfall variability showing two distinct patterns (fast walking velocity).

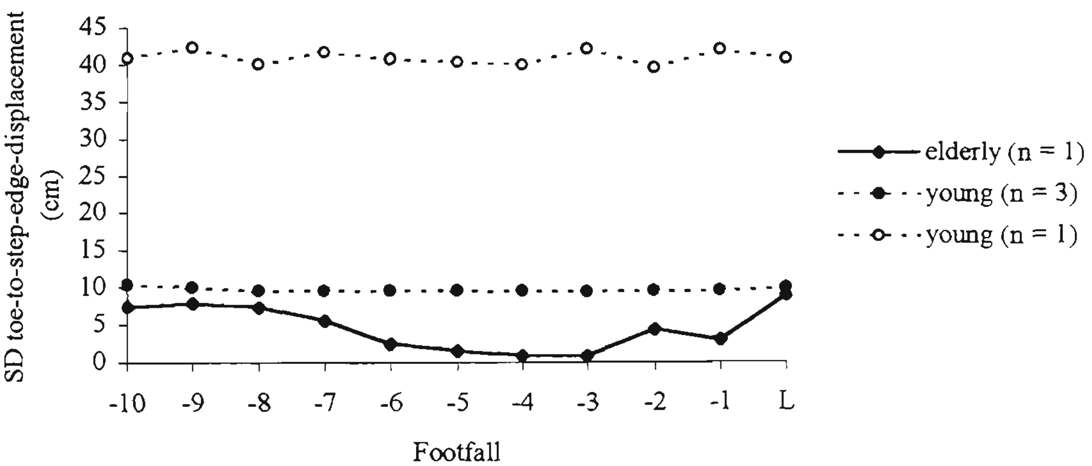


Figure 6.5.4.2.4 Plots of footfall variability displaying minimal variation (fast walking velocity).

Inspection of the individual plots of the footfall variability in the fast velocity condition revealed three distinct patterns (refer to figures 6.5.4.2.3 and 6.5.4.2.4). Fifty-two percent of the participants exhibited an ascending-descending pattern described, whereas 43% exhibited a descending trend from the 10th-last footfall. Four participants displayed very low variability throughout the approach but exhibited similar variability on the final footfall. One young participant exhibited high variability throughout the approach and crossing phases.

Three patterns of footfall variability are exhibited by the participants. The majority of participants were found to start with high variability followed by a gradual reduction up to the penultimate footfall (early adjustment). Others showed a gradual increase followed by a marked reduction from the 3rd or 2nd-last footfall (late adjustment). Finally, a small number of participants showed little change in variability but generally exhibited similar variability on the final footfall. Overall, the elderly were found to exhibit less variability.

6.5.4.3 Foot placement (1st trial)

On average, the young and elderly placed the toe of the trail limb (*TD*) approximately 8 cm from the step edge in the descent task (refer to figure 6.5.4.3.1). Interestingly, the young adults placed the trail foot on the step edge (i.e., the foot was partly supported by the step) in about 33% of trials, whereas this figure fell to 16% for the elderly. Further analysis of these trials revealed the elderly placed the trail foot so that about 95% (SD = 4.4%) of it (foot length) was supported by the step, whereas the young adults exhibited a value of 87% (SD = 9.8%).

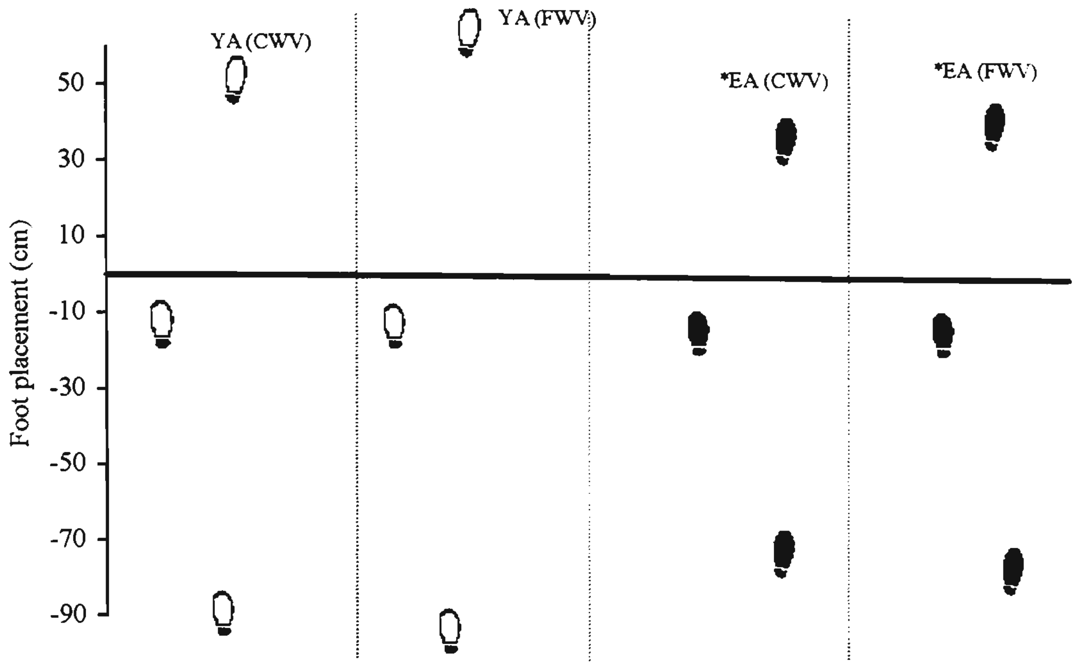


Figure 6.5.4.3.1 Plan view of lead and trail foot placement in the crossing stride for the descent task. CWV: comfortable walking velocity; FWV: fast walking velocity. An asterisk (*) indicates a significant age effect ($p < .05$).

In the crossing step, the elderly placed the heel of the lead limb (*LHD*) closer to the step edge (EA ≈ 32 cm, YA ≈ 50 cm, $p < .001$). In fact, a misstep by an elderly participant led to the lead heel being grounded on the step. This caused the participant to stumble but not fall.

The elderly exhibited less variability in the placement of the trail foot (*TD*) before the step (EA: SD ≈ 8 cm; YA: SD ≈ 12 cm, $p < .029$). A significant age difference was not found in the variability of lead heel placement (*LHD*).

Foot placement data (time and displacement) were normalised across age by expressing it as a percentage of lead limb crossing swing time (lead limb toe-off to foot landing) and as a percentage of crossing stride length (operationally defined as pre-step toe-off to post-step heel position). Significant age and velocity differences ($p < .05$) were found in the normalised stride length data (refer to table 6.5.4.3.1 and 6.5.4.3.2). No differences, however, were found in the normalised crossing time data. The bottom panel of figure 6.5.4.3.2 shows the elderly positioned their lead foot relatively farther away from the step (EA $\approx$ 69%, YA $\approx$ 63%). As such, this only allowed the elderly about 31% of stride length, compared to 37% for the young adults, in which to position the lead foot after crossing the step.

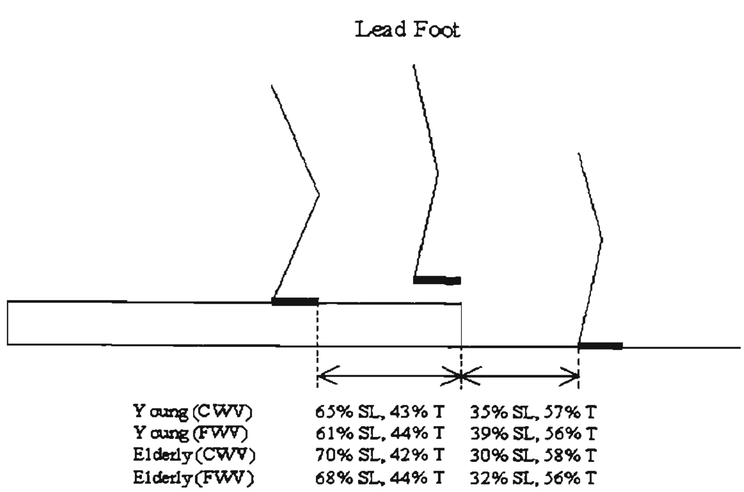


Figure 6.5.4.3.2 Lead foot pre-step and post-step crossing percentage distances and times for the descent task. SL: stride length; T: time.

Table 6.5.4.3.1 Crossing time (expressed as a percentage of lead limb swing time).

	Elderly				Young			
Velocity	**Mean (%)**	**SD (%)**	**Min (%)**	**Max (%)**	**Mean (%)**	**SD (%)**	**Min (%)**	**Max (%)**
CWV	41.9	5.5	31.8	56.5	43.1	5.7	30.4	59.3
FWV	43.9	5.5	33.3	56.5	43.1	5.6	31.6	57.1

Table 6.5.4.3.2 Step crossing (expressed as a percentage of lead limb stride length).

	Elderly				Young			
Velocity	**Mean (%)**	**SD (%)**	**Min (%)**	**Max (%)**	**Mean (%)**	**SD (%)**	**Min (%)**	**Max (%)**
CWV	69.9	11.3	42.8	91	64.7	11.2	41.9	89.7
FWV	67.9	9.0	43.0	86.3	61.3	9.4	45.1	81.1

6.5.4.4 Step length (all trials)

Step length values were calculated for each participant's footfalls in the 3 comfortable and 3 fast walking velocity trials. Mean step length values were derived from these data for each age group and velocity condition. The plots of these mean values are shown in figure 6.5.4.4.1. The reader is referred to Appendix K for each age group and velocity condition ensemble average plot.

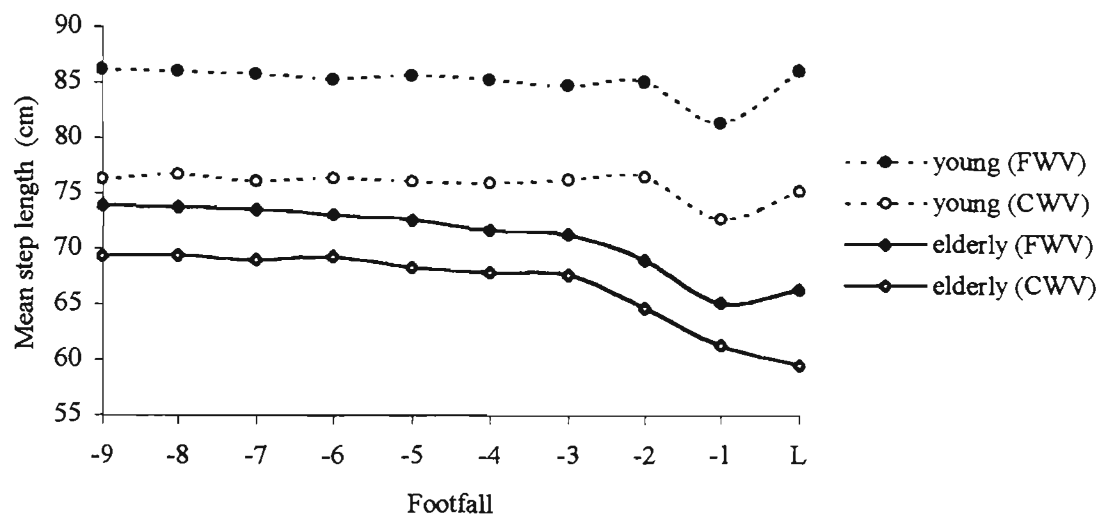


Figure 6.5.4.4.1 Mean step length plots (all trials).

In the comfortable walking velocity condition, the elderly plot shows a marked and systematic reduction in step length from the 2^{nd}-last-footfall (mean ≈ 2.3 cm). In the fast velocity condition, the elderly show a reduction from the 2^{nd}-last to penultimate footfall followed by an increase in the last footfall (L). The young plots only show marked reductions from the penultimate footfall for the comfortable (mean of 3.8 cm) and fast velocity conditions (mean of 3.7 cm). The elderly also appear to make small reductions (≈ 1.0 cm) from the 6^{th}

to the 3rd-last footfall in the comfortable velocity condition. This trend is not evident in the young plots.

6.5.4.5 Step length (1st trial)

Step length values were calculated for each participant's footfalls in the 1st trial of each velocity condition. Mean step length values were derived from these data for each age group and velocity condition. The plots of these mean values are shown in figure 6.5.4.5.1. The reader is referred to Appendix L for each age group plot.

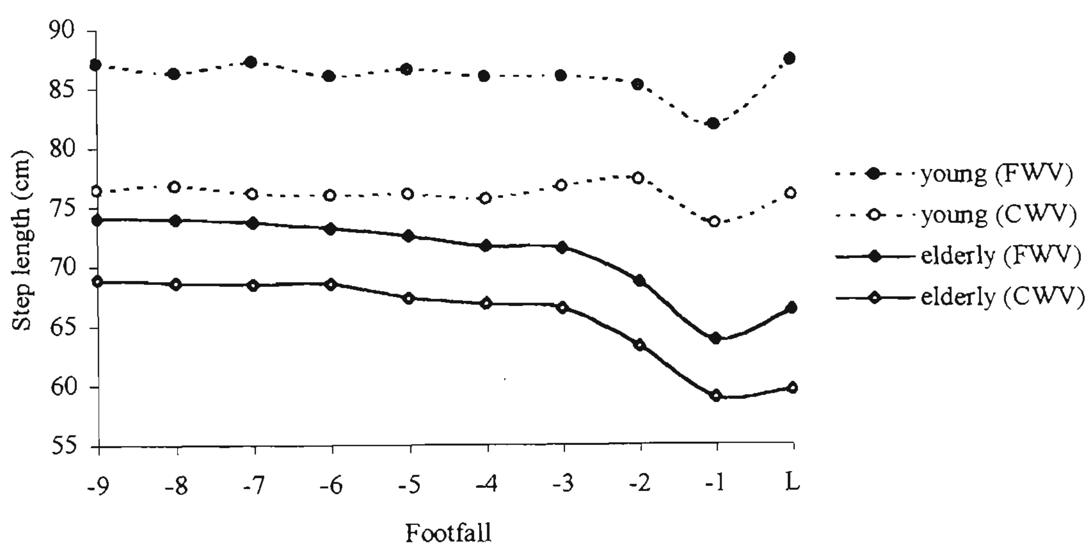


Figure 6.5.4.5.1 Mean step length plots (1st trial).

The elderly plots show marked and systematic step length reductions from the 3rd-last to penultimate footfall. The young plots only show a marked reductions in the penultimate footfall for both velocity conditions. Each group increased step length in the last footfall (L).

Figures 6.5.4.5.2 to 6.5.4.5.3 are comparison plots of the mean percentage step length adjustment (absolute value) made by each age group in the 1st trial. In both velocity conditions each group exhibit marked and systematic step length adjustments from the 3rd-last footfall. The elderly also exhibit greater adjustments (refer to figures 6.5.4.5.4 and 6.5.4.5.5) in the penultimate and final footfall compared to the young; in the comfortable velocity condition, the elderly made adjustments about twice the magnitude of the young.

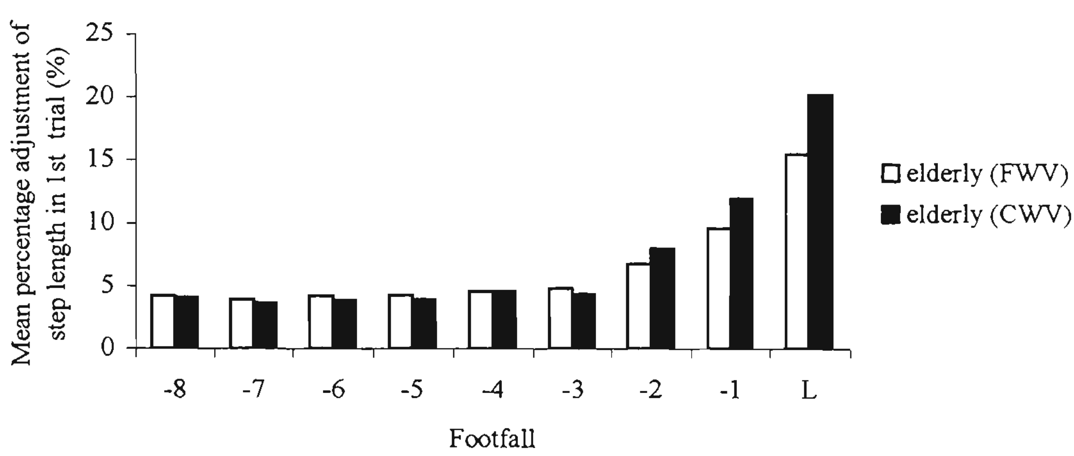


Figure 6.5.4.5.2 Mean percentage step length adjustment (absolute) made by the elderly in the 1st trial (velocity comparison).

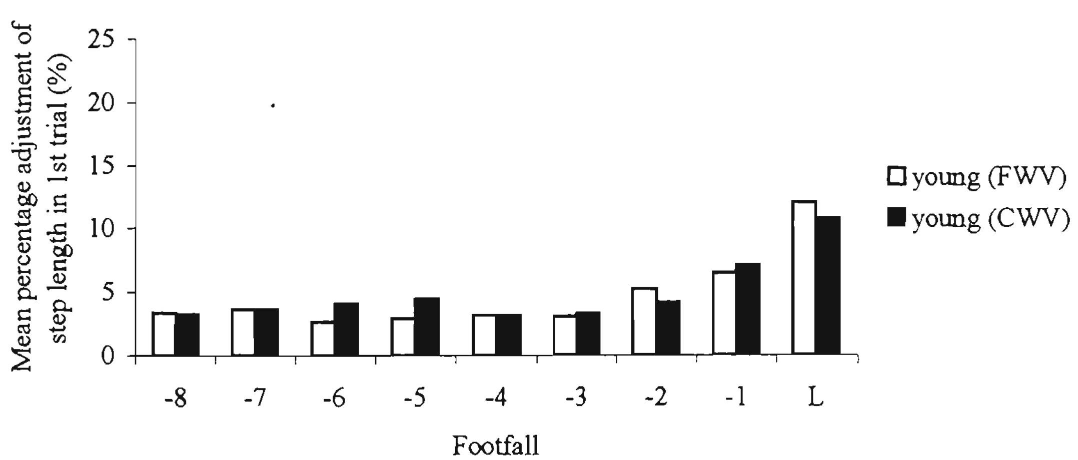


Figure 6.5.4.5.3 Mean percentage step length adjustment (absolute) made by the young in the 1st trial (velocity comparison).

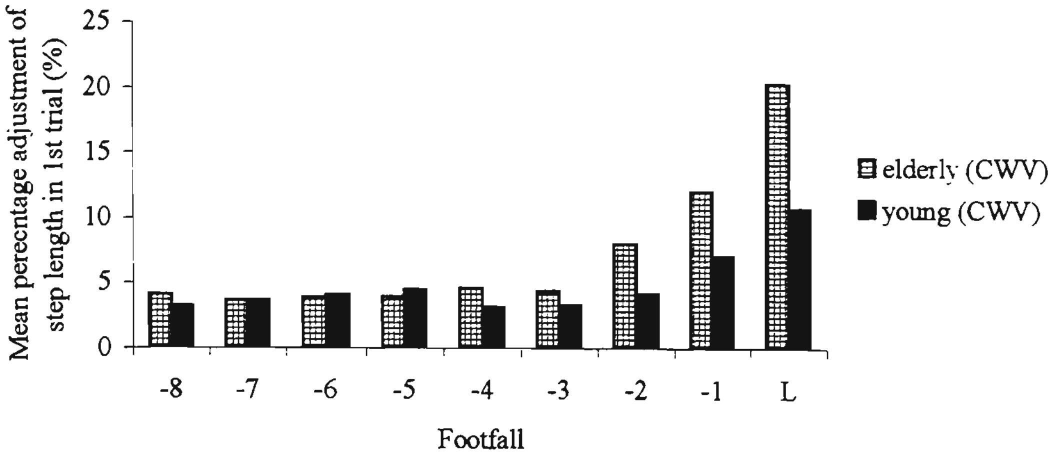


Figure 6.5.4.5.4 Age comparison plot of mean percentage step length adjustment (absolute) made by the elderly and young in the 1st trial (CWV).

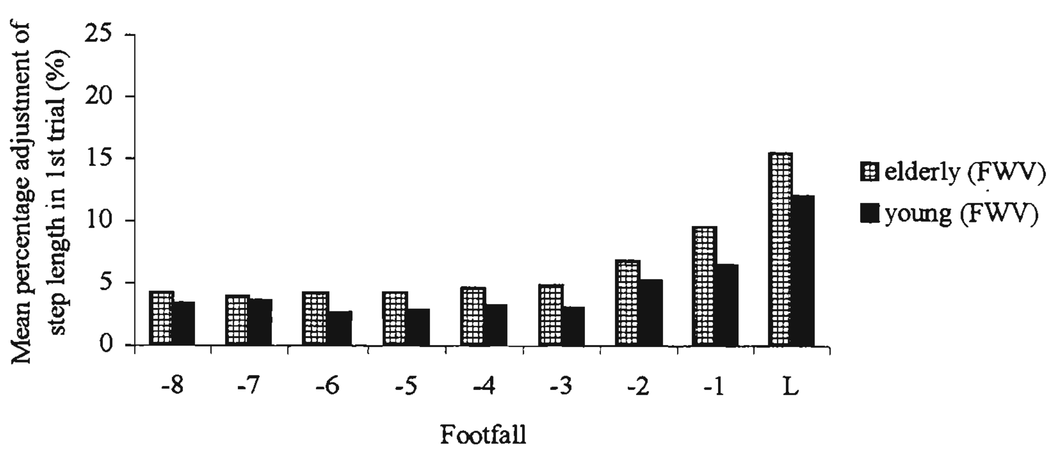


Figure 6.5.4.5.5 Age comparison plot of mean percentage step length adjustment (absolute) made by the elderly and young in the 1st trial (FWV).

6.5.4.6 Stepping strategies (1st trial)

Table 6.5.4.6.1 lists the stepping strategies employed by each group in the first trial (refer to section 5.4.3). A chi-square analysis revealed a significant age difference in the frequency of the stepping strategies adopted ($p < .001$). The strategies employed were: (1) a long step strategy (*LSS*); (2) a mixture of short and long steps; (3); short step strategy (*SSS*); and, (4) a normal step strategy. In the comfortable velocity condition, 5 elderly adults and 11 of young adults "took it in their stride" (normal step strategy), whereas in the fast velocity condition 15 of the elderly and 13 of the young "took it in their stride"; that is, these participants did not make significant step adjustments in approaching and accommodating the step.

Table 6.5.4.6.1 Frequency count of step strategies adopted.

	CWV	CWV	FWV	FWV
Step Strategy	**Elderly**	**Young**	**Elderly**	**Young**
Long	2	17	4	11
Mixed	5	3	0	11
Short	36	17	29	13
Normal	5	11	15	13
Total	48	48	48	48

In 67% of the trials the elderly adopted a short step strategy compared to 31% for the young. The young also employed a long step strategy more often (29.2%) than the elderly (6.3%).

6.5.4.7 Step time and velocity (1st trial)

Plots of the mean step times are shown in figure 6.5.4.7.1. The reader is referred to Appendix M for each age group plot. Each plot in figure 6.5.4.7.1 exhibits the same pattern; there is a marked step time increase in the final footfall (L). The elderly exhibit lower step times ($p < .001$) than the young in the comfortable velocity condition, whereas in the fast velocity condition the step times are similar.

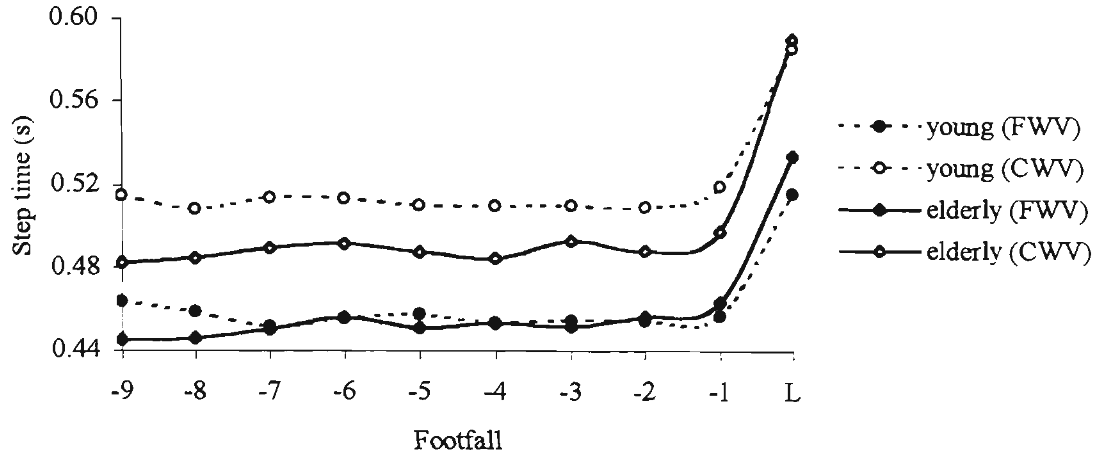


Figure 6.5.4.7.1 Plots of mean step time (1st trial).

Plots of mean step velocity for the 1st trial (expressed as $\frac{SL}{ST}$) are shown in figure 6.5.4.7.2. In both velocity conditions the young exhibit significantly greater velocity throughout the approach and crossing phases. The elderly show marked and systematic reductions in step velocity from the 3rd-last footfall to the final footfall, whereas the young exhibit these reductions from the penultimate footfall.

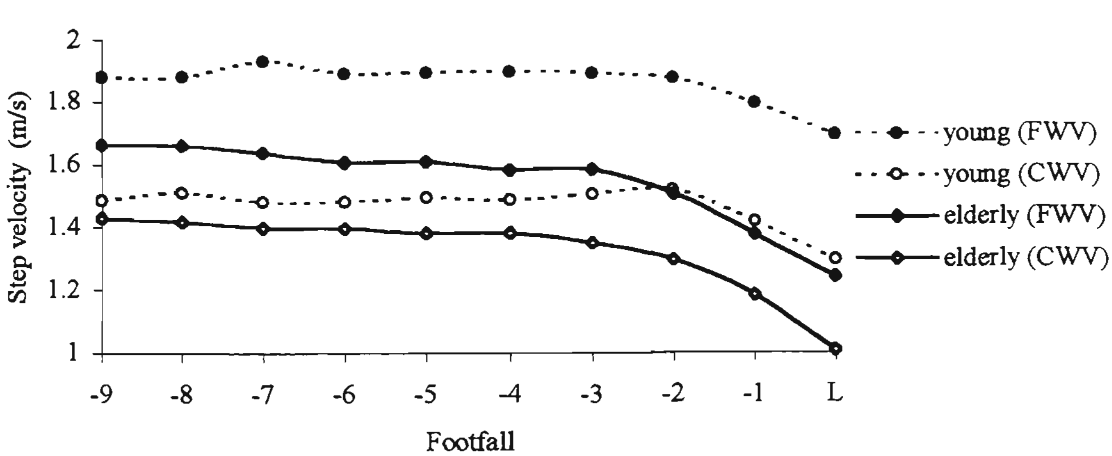


Figure 6.5.4.7.2 Plots of mean step velocity (1st trial).

6.6 Ascent task

6.6.1 Descriptive statistics (1st trial)

The outcome variables (with labels and descriptors) collected in this phase of the investigation are listed in table 6.6.1.1.

Table 6.6.1.1 Outcome variables collected (listed alphabetically) in this phase of the investigation.

Variable	Description
ART (ms)	Available response time.
ASL (cm)	Approach step lengths (ipsilateral heel contact to contralateral heel contact).
AST (s)	Approach step times (ipsilateral heel contact to contralateral heel contact).
CSL (cm)	Crossing step length (determined from lead and trail toe position).
CST (s)	Lead limb crossing swing time (toe-off to foot land).
DFST (s)	Double foot support time (trail limb crossing stride).
HA (°)	Head pitch angle (approach and crossing phases).
HCD (cm)	Horizontal displacement of trunk marker from the trail toe when the lead toe crosses the step.
HCV ($m{\cdot}s^{-1}$)	Horizontal crossing velocity of trunk marker when the lead toe crosses the step.
HLD (cm)	Horizontal displacement of trunk marker from the trail toe when the lead foot lands.
LCA (°)	Lead foot angle (orientation) at step crossing.
LFM (%)	Lead foot focal movement trajectory (crossing step).
LHC (cm)	Lead heel-step-clearance (vertical).
LHD (cm)	Lead heel horizontal displacement from step (after crossing)
LLA (°)	Lead foot landing angle (orientation) in crossing step.
LLV ($m{\cdot}s^{-1}$)	Lead foot horizontal landing velocity (crossing step).
LTC (cm)	Lead toe-step-clearance (vertical).
TCA (cm)	Trail foot angle (orientation) at step crossing
TD (cm)	Trail toe horizontal displacement from step (single limb support phase before crossing).
TSED	Toe-to-step-edge displacement (horizontal)
THC (cm)	Trail heel-step-clearance (vertical).
TRKCA (°)	Trunk orientation (relative to horizontal) at lead foot crossing.
TTC (cm)	Trail toe-step-clearance (vertical).

Non-normal data sets were identified by the Shapiro-Wilks test of normality. Attempts were made to normalise these data sets by (1) removing outliers, and/or (2) by performing data transformations (Afifi & Clark, 1990). These attempts failed to produce a satisfactory outcome for two reasons: (1) the majority of the non-normal data could not be normalised; and, (2) some data sets could be normalised by a specific transformation (e.g. logarithmic), but the application of this transformation to the equivalent data set from the other age group, needed for comparison purposes, led to non-normality.

In this investigation, outliers were retained on the basis that there was no demonstrable proof that they were truly aberrant or that they were not representative of any observations in the population (Hair et al., 1998).

Descriptive statistics and measures of normality are listed in tables 6.6.1.2 to 6.6.1.5. Note that the number of cases (n) for some variables is less than 48. The reason being that some participants placed their lead foot so that it straddled the step (foot partially supported by step), therefore, no pertinent lead foot focal movement trajectory (*LFM*) or lead heel-step-clearance data (*LHC*) could be extracted for these participants. Table 6.5.1.1.2, for example, only shows 37 cases for these variables because 11 participants placed the lead foot on the step edge.

The tables show 6 of the 76 data sets to exhibit significant levels of skewness and/or kurtosis ($p < .05$); that is, measures fall outside the 95% confidence interval bounded by $\pm$ 1.96. The Shapiro-Wilks normality test results show that 30 of the 76 data sets exhibit non-normality.

Table 6.6.1.2 Descriptive statistics and normality values for the elderly group in the ascent task (comfortable walking velocity). Test of normality: Shapiro-Wilks (SW).

Elderly	Mean	SD	Min.	Max.	Skew.	Kurt.	SW Sig.	n
ART (ms)	105	66	-12	310	-.786	.884	.128	48
CSL (cm)	63.7	10.2	44.6	93.4	0.636	0.534	.417	48
CST (s)	0.41	0.04	0.34	0.54	0.826	1.339	.019	48
DFST (s)	0.14	0.03	0.04	0.2	-0.282	0.195	.091	48
HCD (cm)	-10.6	5.1	-20.5	1.8	0.258	-0.145	.666	48
HCV ($m \cdot s^{-1}$)	1.13	0.26	0.62	1.79	0.339	-0.233	.698	48
HLD (cm)	7.5	6.5	-3.3	28.7	0.908	1.124	.079	48
LCA (°)	0.5	9.9	-26.0	17.1	-0.361	-0.223	.491	48
LFM (%)	97.0	3.8	81.8	100	-2.066	5.879	.01	37
LHC (cm)	3.7	2.3	0.1	10.0	0.817	1.028	.145	37
LHD (cm)	7.5	9.8	-8.2	35.4	0.891	0.897	.028	48
LLA (°)	12.7	8.1	-8.6	25.3	-0.838	0.03	.01	48
LLV ($m \cdot s^{-1}$)	0.81	0.62	-0.14	2.09	0.620	-0.578	.01	48
LTC (cm)	7.2	1.8	2.6	11.6	-0.086	0.37	.929	48
TCA (°)	-53.7	12.1	-91.8	-35.6	-1.177	1.447	.01	48
TD (cm)	-33.8	12.5	-63.8	-5.8	-0.404	0.352	.388	48
THC (cm)	18.0	5.7	10.3	33.2	1.056	0.865	.01	48
TRKCA (°)	85.6	5.5	74.6	96.3	-0.024	-0.855	.305	48
TTC (cm)	4.4	2.1	0.1	10.2	0.149	0.346	.99	48

Table 6.6.1.3 Descriptive statistics and normality values for the young group in the ascent task (comfortable walking velocity). Test of normality: Shapiro-Wilks (SW).

Young	Mean	SD	Min.	Max.	Skew.	Kurt.	SW Sig.	n
ART (ms)	57	41	-27	152	-.481	.214	.236	48
CSL (cm)	82.7	8.2	65.8	103.5	0.164	-0.068	.932	48
CST (s)	0.42	0.03	0.34	0.48	-0.407	-0.428	.039	48
DFST (s)	0.11	0.03	0.04	0.2	0.192	1.102	.044	48
HCD (cm)	-7.1	4.6	-18.5	4.9	-0.045	0.289	.99	48
HCV ($m \cdot s^{-1}$)	1.34	0.22	0.89	1.93	0.216	-0.249	.842	48
HLD (cm)	16.0	4.8	4.2	26.9	0.125	-0.477	.372	48
LCA (°)	4.0	15.3	-36.3	28.5	-0.819	0.154	.016	48
LFM (%)	96.9	5.0	79.4	100	-2.3	4.598	.01	44
LHC (cm)	4.2	2.9	0.1	12.9	1.089	1.469	.01	44
LHD (cm)	14.7	13.7	1.5	53.4	1.396	1.221	.01	48
LLA (°)	25.3	5.8	14.9	40.9	0.662	0.524	.119	48
LLV ($m \cdot s^{-1}$)	0.88	0.62	-0.24	2.34	0.343	0.210	.037	48
LTC (cm)	8.8	2.5	4.7	13.3	0.186	-1.137	.021	48
TCA (°)	-59.6	17.8	-107.8	-38.2	-1.218	0.863	.01	48
TD (cm)	-44.2	16.2	-77.1	-7.6	0.409	-0.096	.427	48
THC (cm)	20.4	6.3	10.8	35.1	0.62	-0.491	.01	48
TRKCA (°)	86.0	5.7	74.8	99.1	-0.075	-0.412	.694	48
TTC (cm)	4.3	3.1	0.2	17	2.024	5.604	.01	48

Table 6.6.1.4 Descriptive statistics and normality values for the elderly group in the ascent task (fast walking velocity). Test of normality: Shapiro-Wilks (SW).

Elderly	Mean	SD	Min.	Max.	Skew.	Kurt.	SW Sig.	n
ART (ms)	76	58	-26	190	-0.312	-0.600	.143	48
CSL (cm)	68.5	11.7	40.1	96.4	-0.093	0.105	.938	48
CST (s)	0.38	0.04	0.3	0.48	0.577	1.049	.01	48
DFST (s)	0.11	0.04	0	0.18	-0.347	0.325	.207	48
HCD (cm)	-8.7	5.9	-19.3	4.1	0.255	-0.136	.322	48
HCV ($m \cdot s^{-1}$)	1.32	0.32	0.78	2.09	0.387	-0.42	.384	48
HLD (cm)	11.7	7.2	-1.4	28.4	0.295	-0.333	.208	48
LCA (°)	-1.2	13.7	-26	28.6	-0.132	-0.791	.255	48
LFM (%)	97.8	3.7	82.5	97.8	-2.538	7.177	.01	38
LHC (cm)	5.0	2.3	0.7	9.7	0.066	-0.586	.706	38
LHD (cm)	10.8	13.8	-11.1	45.2	0.626	-0.035	.089	48
LLA (°)	14.8	8.8	-6.6	30.5	-0.812	0.232	.01	48
LLV ($m \cdot s^{-1}$)	0.99	0.74	-0.03	3.27	0.755	0.396	.022	48
LTC (cm)	7.3	2.4	2.0	13.5	0.221	0.062	.936	48
TCA (°)	-58.4	13.9	-87.4	-31.9	-0.365	-0.655	.087	48
TD (cm)	-35.6	14.8	-63.0	-7.2	0.175	-1.096	.05	48
THC (cm)	19.9	6.7	9.1	33.2	0.347	-0.914	.042	48
TRKCA (°)	83.5	5.8	71.6	98.8	0.4	0.149	.684	48
TTC (cm)	4.7	2.2	1.1	10.3	0.238	-0.477	.357	48

Table 6.6.1.5 Descriptive statistics and normality values for the young group in the ascent task (fast walking velocity). Test of normality: Shapiro-Wilks (SW).

Young	Mean	SD	Min.	Max.	Skew.	Kurt.	SW Sig.	n
ART (ms)	38	39	-36	130	0.096	-0.706	.224	48
CSL (cm)	88.3	7.5	71.7	114.3	0.677	2.174	.375	48
CST (s)	0.39	0.04	0.32	0.5	0.626	0.576	.025	48
DFST (s)	0.07	0.03	0.02	0.14	0.198	-0.21	.047	48
HCD (cm)	-5.8	6.2	-20.0	7.7	0.228	-0.455	.37	48
HCV ($m \cdot s^{-1}$)	1.67	0.32	1.21	2.6	1.224	1.254	.01	48
HLD (cm)	22.3	6.9	8.6	41.4	0.607	0.84	.341	48
LCA (°)	3.5	17.2	-28.4	38.4	0.187	-0.726	.28	48
LFM (%)	96.7	4.4	79.4	100	-2.264	5.65	.01	44
LHC (cm)	6.3	3.2	0.9	12.8	0.29	-0.663	.165	44
LHD (cm)	21.5	16.7	-0.4	63.7	0.561	-0.608	.012	48
LLA (°)	26.2	5.5	14.4	40.9	0.338	0.362	.628	48
LLV ($m \cdot s^{-1}$)	0.85	0.67	-0.52	2.71	0.661	0.355	.270	48
LTC (cm)	9.5	2.6	5.3	16.8	1.083	1.132	.01	48
TCA (°)	-65.2	17.2	-104.6	-33.5	-0.46	-0.339	.291	48
TD (cm)	-43.4	18.8	-81.8	-10.5	-0.126	-0.841	.338	48
THC (cm)	23.0	6.7	10.8	35.1	-0.036	-1.073	.15	48
TRKCA (°)	84.1	5.2	73.9	94.3	0.253	-0.962	.085	48
TTC (cm)	4.9	2.4	1.2	11.9	0.676	0.306	.161	48

Figures 6.6.1.1 to 6.6.1.4 are plots of the descriptive statistics listed in tables 6.6.1.2 to 6.6.1.5. The plots are organised so that variables are grouped in the following categories: (1) foot placement measures; (2) measures of dynamic stability upon landing and at the time of crossing; (3) measures of foot-step-clearance; and, (4) measures of foot orientation at crossing. Significant age differences ($p < .05$) are indicated by an asterisk (*) positioned between age-group bars. Significant velocity differences ($p < .05$) are indicated by an asterisk (*) above the bars of an age-group.

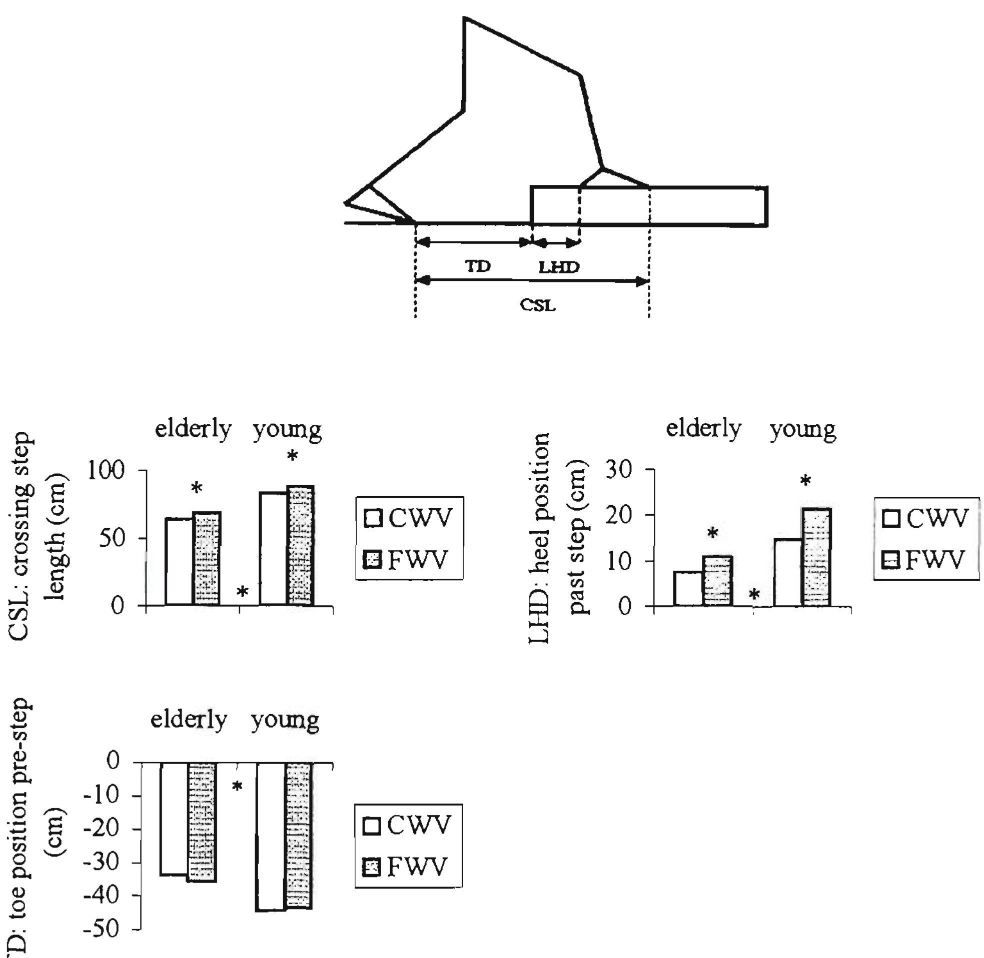


Figure 6.6.1.1 Measures of foot placement (*TD*, *LHD*) and crossing step length (*CSL*) found across age, step and velocity conditions. CWV: comfortable walking velocity; FWV: fast walking velocity. Significant age differences ($p < .05$) are indicated by an asterisk (*) positioned between age-group bars. Significant velocity differences ($p < .05$) are indicated by an asterisk (*) above the bars of an age-group.

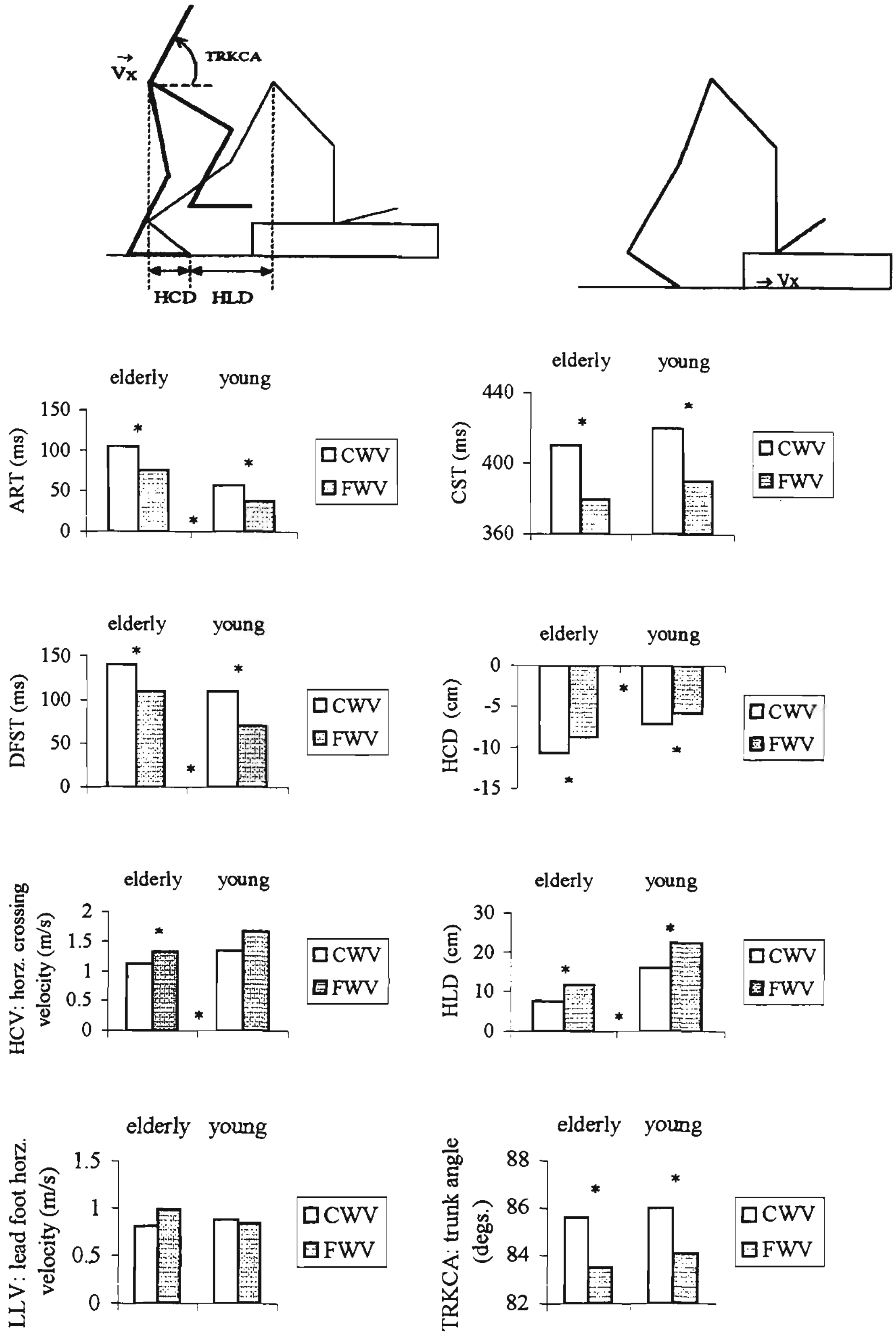


Figure 6.6.1.2 Measures of dynamic stability (*ART*, *CST*, *DFST*, *HCD*, *HCV*, *HLD*, *LLV*, *TRKCA*) found across age, step and velocity conditions. CWV: comfortable walking velocity. FWV: fast walking velocity. Significant age differences ($p < .05$) are indicated by an asterisk (*) positioned between age-group bars. Significant velocity differences ($p < .05$) are indicated by an asterisk (*) above the bars of an age-group.

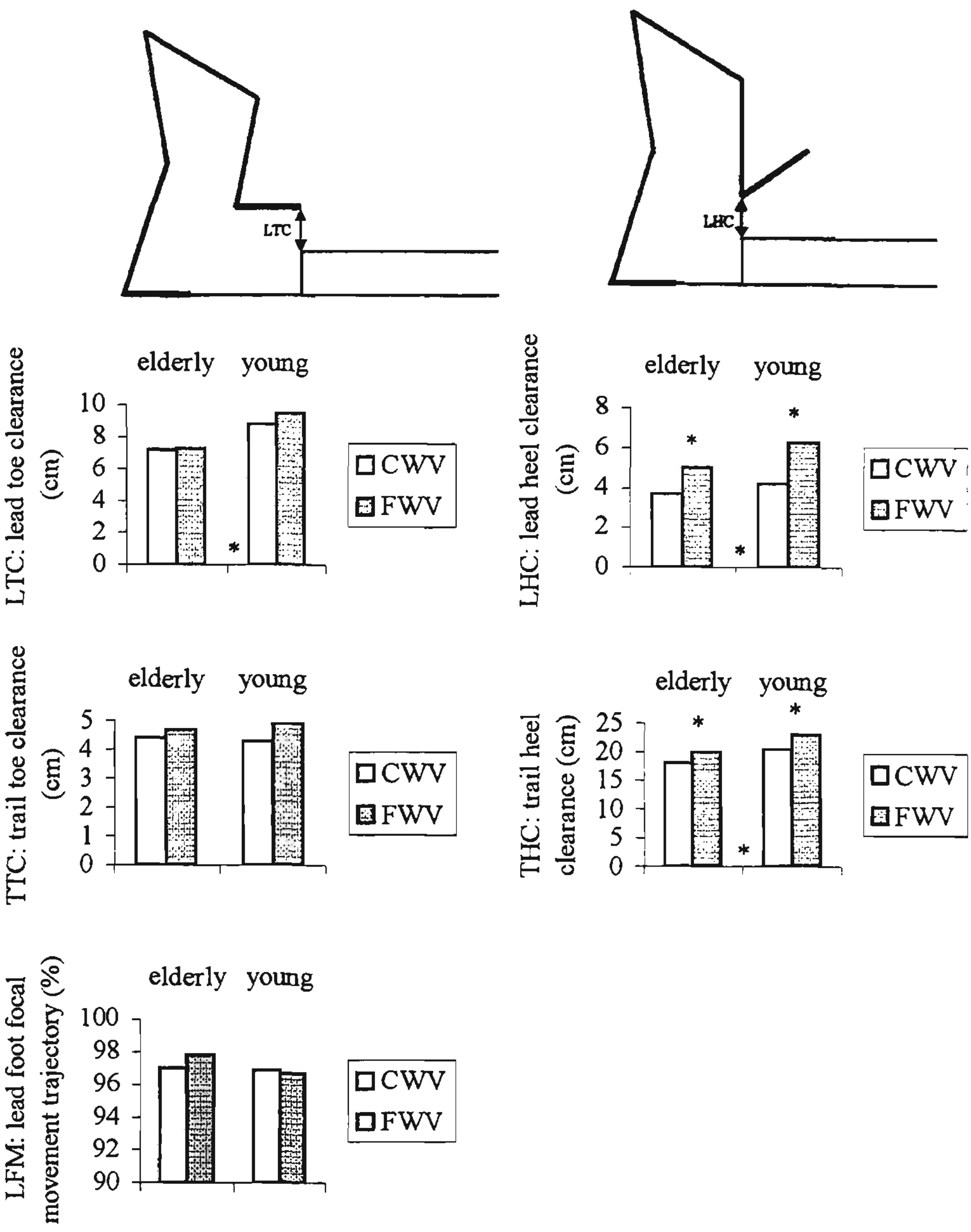


Figure 6.6.1.3 Measures of foot clearance (*LTC*, *LHC*, *TTC*, *THC*) and lead foot focal movement trajectory (*LFM*) found across age, step and velocity conditions. CWV: comfortable walking velocity. FWV: fast walking velocity. Significant age differences ($p < .05$) are indicated by an asterisk (*) positioned between age-group bars. Significant velocity differences ($p < .05$) are indicated by an asterisk (*) above the bars of an age-group. N.B. The *LHC* variable was only significantly different across age for the FWV condition.

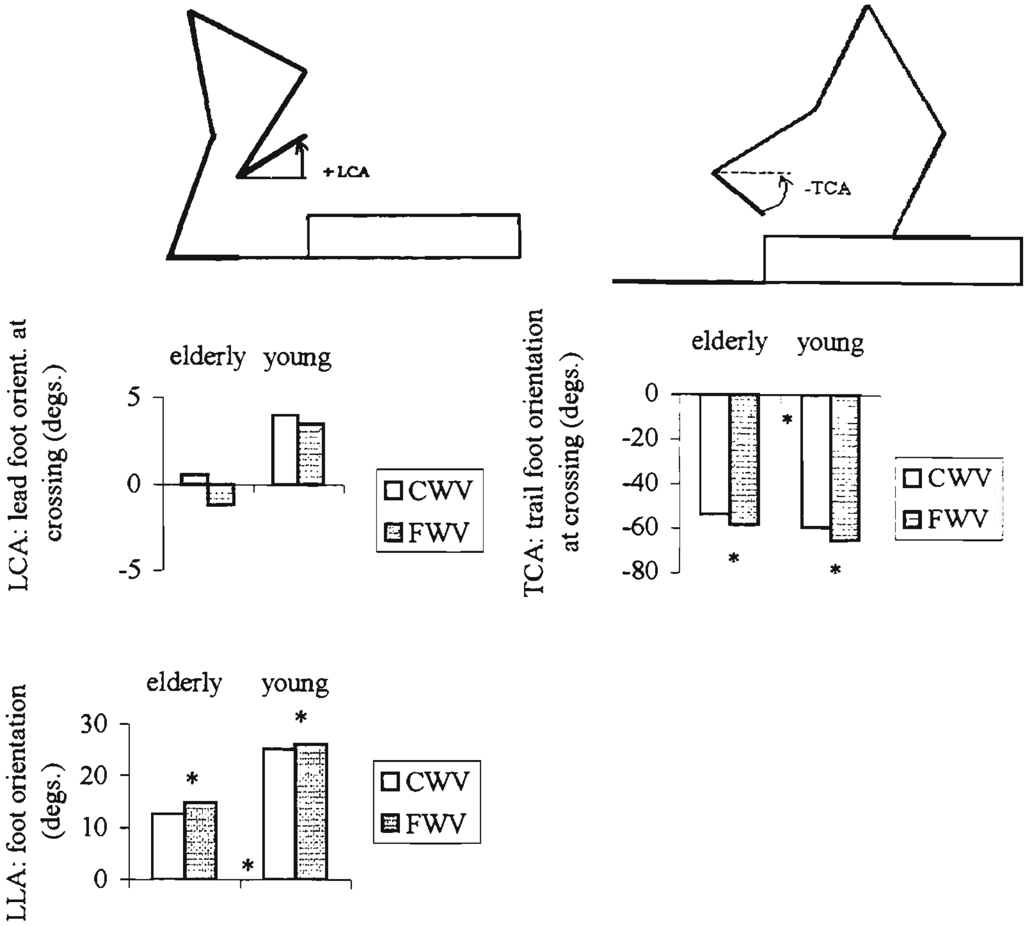


Figure 6.6.1.4 Measures of lead foot orientation (*LCA*, *TCA*, *LLA*) found across age, step and velocity conditions. CWV: comfortable walking velocity. FWV: fast walking velocity. Significant age differences ($p < .05$) are indicated by an asterisk (*) positioned between age-group bars. Significant velocity differences ($p < .05$) are indicated by an asterisk (*) above the bars of an age-group.

6.6.2 Inferential statistics (1st trial)

6.6.2.1 Age effects

The size (n) of the MANOVA cells was greater than 30 and of equal magnitude (i.e. $n_1 = n_2 = n_3 = n_4$). Since these criteria were met, any violations of normality and homogeneity of variance (refer to table 6.6.2.1.1) were considered as being of little concern (Coakes & Steed, 2000).

Table 6.6.2.1.1 Levene's test of equality of error variances (between age groups) in the ascent task (comfortable and fast walking velocity).

CWV	Sig.	FWV	Sig.
ART	.019	*ART*	.013
CSL	.185	*CSL*	.006
CST	.195	*CST*	.433
DFST	.429	*DFST*	.046
HCD	.453	*HCD*	.383
HCV	.438	*HCV*	.739
HLD	.093	*HLD*	.485
LCA	.006	*LCA*	.102
LFM	.468	*LFM*	.44
LHC	.223	*LHC*	.011
LHD	.031	*LHD*	.082
LLA	.018	*LLA*	.011
LLV	.969	*LLV*	.371
LTC	.002	*LTC*	.977
TCA	0.01	*TCA*	.207
TD	.096	*TD*	.096
THC	.172	*THC*	.872
TRKCA	.976	*TRKCA*	.694
TTC	.261	*TTC*	.661

A three-stage approach was used to analyse the data and the reader is referred to section 5.5.3.1 for a more detailed discussion of this approach. The first stage examined the age and velocity effects on the variables that had 48 cases (n). The second stage examined the effect of age on the outcome variables that contained missing cases, and the third stage examined the effect of velocity upon these variables.

The first stage of this analysis revealed a significant main effect of age ($F(18, 78) = 11.587, p < .001$). Bartlett's test of sphericity did reveal the presence of significant correlations among at least some of the dependent variables ($p < .001$). Note that Mauchly's test of sphericity could not be conducted since there were only two levels on the repeated measures factor (Vincent, 1995).

The Box M's test for homogeneity of variance-covariance matrices was found to be significant ($p < .001$). This was most probably due to the presence of the non-normal data sets: the test is highly sensitive to such data sets. Since the cell sizes, however, were greater than 30, and equal, violation of this assumption was considered to have minimal impact (Hair et al., 1998; Coakes & Steed, 2000).

Tables 6.6.2.1.2 and 6.6.2.1.3 list the main effects of age for each outcome variable. Main effects of age are illustrated in figures 6.6.1.1 to 6.6.1.4. The following outcome measures were not found to differ across age:

- trail foot toe clearance (*TTC*);
- lead foot cross angle (*LCA*);
- lead foot horizontal landing velocity (*LLV*);
- lead limb crossing swing time (*CST*);
- trunk orientation at crossing (*TRKCA*);
- lead foot focal movement trajectory (*LFM*) in both velocity conditions;
- lead heel-step-clearance (*LHC*) in both velocity conditions (CWV condition only).

All other outcome variables were found to significantly differ ($p < .05$) across age.

Table 6.6.2.1.2 Main effects of age on variables analysed in the first stage.

Combined Variable	Sig.	Observed Power
ART	.001	.993
CSL	.001	1.000
CST	.110	.358
DFST	.001	1.000
HCD	.001	.918
HCV	.001	1.000
HLD	.001	1.000
LCA	.080	.418
LHD	.001	.970
LLA	.001	1.000
LLV	.767	.060
LTC	.001	.996
TCA	.016	.684
TD	.001	.928
THC	.014	.699
TRKCA	.633	.076
TTC	.843	.054

Table 6.6.2.1.3 Main effects of age on variables analysed in the second stage.

Variable	Velocity	Sig.	Observed Power
LFM	CWV	.909	0.051
LHC	CWV	.428	0.124
LFM	FWV	.243	0.213
LHC	FWV	.045	0.522

In both velocity conditions, the young exhibited smaller *HLD* (CWV: EA = -10.6 cm, YA = -7.1 cm; FWV: EA = -8.7 cm, YA = -5.8 cm) and *ART* values than the elderly (CWV: EA = 105 ms, YA = 57 ms; FWV: EA = 76 ms, YA = 38 ms). These differences were significant ($p < .001$)

In the comfortable velocity condition, the elderly exhibited significant reductions ($p < .05$) compared to the young in the following variables:

- crossing step length (*CSL*: EA = 63.7 cm, YA = 82.7 cm);
- double foot support time (*DFST*: EA = 0.14 s, YA = 0.11 s);
- horizontal crossing velocity (*HCV*: EA = 1.13 $m{\cdot}s^{-1}$, YA = 1.34 $m{\cdot}s^{-1}$);

- horizontal displacement of trunk marker relative to the toe of trail limb when the lead foot landed (*HLD*: EA = 7.5 cm, YA = 16.0 cm);
- heel placement past the step edge (*LHD*: EA = 7.5 cm, YA = 14.7 cm);
- lead foot landing angle (*LLA*: EA = 12.7°, YA = 25.3°);
- lead toe-step-clearance (*LTC*: EA = 7.2 cm, YA = 8.8 cm);
- trail foot crossing angle (*TCA*: EA = -53.7°, YA = -59.6°);
- trail toe pre-step distance (*TD*: EA = -33.8 cm, YA = -44.2 cm);

In the fast velocity condition, the elderly exhibited significant reductions ($p < .05$) compared to the young in the following variables:

- crossing step length (*CSL*: EA = 68.5 cm, YA = 88.3 cm);
- double foot support time (*DFST*: EA = 0.11 s, YA = 0.07 s);
- horizontal crossing velocity (*HCV*: EA = 1.32 $m{\cdot}s^{-1}$, YA = 1.67 $m{\cdot}s^{-1}$);
- horizontal displacement of trunk marker relative to the toe of trail limb when the lead foot landed (*HLD*: EA = 11.7 cm, YA = 22.3 cm);
- trail foot crossing angle (*LCA*: EA = -58.4°, YA = -65.2°);
- heel placement past the step edge (*LHD*: EA = 10.8 cm, YA = 21.5 cm);
- lead foot landing angle (*LLA*: EA = 14.8°, YA = 26.2°);
- lead toe-step-clearance (*LTC*: EA = 7.3 cm, YA = 9.5 cm);

- trail toe pre-step distance (*TD*: EA = -35.6 cm, YA = -43.4 cm);

- trail heel-step-clearance (*THC*: EA = 19.9 cm, YA = 23.0 cm).

Tables 6.6.2.1.4 and 6.6.2.1.5 list the descriptive statistics (and frequency count) of the foot clearance data found to be less than or equal to a value of 1.0 cm.

Table 6.6.2.1.4 Descriptive statistics (and frequency count) of the foot clearance data found to be less than or equal to a value of 1.0 cm in the comfortable velocity condition.

YA	Mean	SD	Min.	Max	n	EA	Mean	SD	Min.	Max	n
LTC	-	-	-	-	0	*LTC*	-	-	-	-	0
LHC	0.5	0.4	0.1	1.0	5	*LHC*	-	-	0.1	0.6	2
TTC	-	-	0.2	0.3	2	*TTC*	-	-	0.1	1.0	2
THC	-	-	-	-	0	*THC*	-	-	-	-	0

Table 6.6.2.1.5 Descriptive statistics (and frequency count) of the foot clearance data found to be less than or equal to a value of 1.0 cm in the fast velocity condition.

YA	Mean	SD	Min.	Max	n	EA	Mean	SD	Min.	Max	n
LTC	-	-	-	-	0	*LTC*	-	-	-	-	0
LHC	-	-	0.9	1.0	2	*LHC*	-	-	0.7	-	1
TTC	-	-	-	-	0	*TTC*	-	-	-	-	0
THC	-	-	-	-	0	*THC*	-	-	-	-	0

In 86.5% of the elderly trials and 94.5% of the young trials, the position of the trunk marker was located posterior to, or behind, the support toe of the trail limb (*HCD*) at the moment the lead toe crossed the step. In 6.3% of the elderly trials, the position of the trunk marker was located posterior to, or behind, the support toe of the trail limb (*HLD*) at the moment the lead foot landed on the raised surface: none of the young trials exhibited this characteristic.

In both velocity conditions, approximately 20% of the elderly (n_{CWV} = 10, n_{FWV} = 9), placed their lead foot on the step edge: that is, their foot straddled the step (foot partially supported by the step). Only three of the young participants used this strategy (in the fast velocity condition). Further analysis of these data revealed that on average the elderly placed the lead foot so that about 76% (range: ≈ 50% to 98%) of it (foot length) was supported by the step, whereas the young exhibited a value of 98.4% (range: ≈ 0.7%).

The lead foot orientation at the time of crossing (*LCA*) was found to differ significantly ($p < .05$) across age and velocity conditions. The data shows that both groups, except for the elderly in the fast velocity condition, crossed the step edge with an upward orientation of the foot (CWV: EA = 0.5°, YA = 4.0°; FWV: EA = -1.2°, YA = 3.5°). Upon landing, the majority of the elderly (n_{CWV} = 90%, n_{FWV} = 92%) and all of the young landed on the heel.

6.6.2.2 Velocity effects

The MANOVA analyses revealed significant main effects of velocity in both the 1st and 2nd stages (1st stage: $F(17, 78) = 18.022$, $p < .001$; 2nd stage; $F(2, 70) = 11.590$, $p < .001$). Main effects of velocity are illustrated in figures 6.5.1.1 and 6.5.1.5. The results of univariate comparisons are listed in table 6.6.2.2.1. This table shows significant differences ($p < .05$) on thirteen of the variables. The following measures were not found to significantly differ:

- lead toe-step- clearance (*LTC*);
- trail toe-step-clearance (*TTC*);
- trail toe pre-step distance (*TD*);
- lead foot cross angle (*LCA*);

- lead foot horizontal landing velocity (*LLV*);
- lead foot focal movement trajectory (*LFM*).

Across velocity conditions, significant reductions in double foot support time (*DFST*), crossing swing time (*CST*), available response time (*ART*) and the *HCD* variable were found for both the elderly and young. For the elderly, significant increases ($p < .05$) were found in the following variables:

- trail heel-step-clearance (*THC*: CWV = 18.0 cm, FWV = 19.9 cm);
- crossing step length (*CSL*: CWV = 63.7 cm, FWV = 68.5 cm);
- heel placement past the step (*LHD*: CWV = 7.5 cm, FWV = 10.8 cm);
- lead foot landing angle (*LLA*: CWV = 12.7°, FWV = 14.8°);
- trail foot crossing angle (*TCA*: CWV = -53.7°, FWV = -58.4°);
- horizontal crossing velocity (*HCV*: CWV = 1.13 $m \cdot s^{-1}$, FWV = 1.32 $m \cdot s^{-1}$);
- trunk crossing angle (*TRKCA*: CWV = 85.6°, FWV = 83.5°);
- horizontal displacement of trunk marker relative to the toe of trail limb when the lead foot landed (*HLD*: CWV = 7.5 cm, FWV = 11.7 cm);
- lead heel-step-clearance (*LHC*: CWV = 3.5 cm, FWV = 4.7 cm).

Significant increases ($p < .05$) were found across velocity for the young in the following variables:

- trail heel-step-clearance (*THC*: CWV = 20.4 cm, FWV = 23.0 cm);
- crossing step length (*CSL*: CWV = 82.3 cm, FWV = 88.3 cm);
- heel placement past the step edge (*LHD*: CWV = 14.7 cm, FWV = 21.5 cm);
- lead foot landing angle (*LLA*: CWV = 25.3°, FWV = 26.2°);
- trail foot crossing angle (*TCA*: CWV = -59.6°, FWV = -65.2°);
- horizontal crossing velocity (*HCV*: CWV = 1.34 $m \cdot s^{-1}$, FWV = 1.67 $m \cdot s^{-1}$);
- trunk crossing angle (*TRKCA*: CWV = 86.0°, FWV = 84.1°);
- horizontal displacement of trunk marker relative to the toe of trail limb when the lead foot landed (*HLD*: CWV = 16.0 cm, FWV = 22.3 cm);
- lead heel-step-clearance (*LHC*: CWV = 4.2 cm, FWV = 6.3 cm).

Table 6.6.2.2.1 Main effects of velocity.

Variable	Sig.	Observed Power
ART (ms)	.001	.993
CSL (cm)	.001	1.000
CST (s)	.001	1.000
DFST (s)	.001	1.000
HCD (cm)	.008	.758
HCV ($m \cdot s^{-1}$)	.001	1.000
HLD (cm)	.001	1.000
LCA (°)	.540	.093
LFM (%)	.580	.085
LHC (cm)	.001	.995
LHD (cm)	.002	.891
LLA (°)	.036	.560
LLV ($m \cdot s^{-1}$)	.328	.164
LTC (cm)	.138	.316
TCA (°)	.005	.805
TD (cm)	.790	.058
THC (cm)	.001	.907
TRKCA (°)	.002	.885
TTC (cm)	.117	.347

An interesting outcome of the repeated measures analysis was that both age groups' trail toe pre-step distance (*TD*) were not significantly affected by velocity. Further inspection of this data showed that the *TD* measures were of equivalent magnitude across velocity conditions. The elderly measures for the comfortable and fast velocity conditions, for example, were -33.8 cm (SD = 12.5 cm) and -35.6 cm (SD = 14.8 cm) respectively, and the equivalent young measures were -44.2 cm (SD = 16.2 cm) and -43.4 cm (SD = 18.8 cm). The elderly and young, therefore, appear to target different regions for trail foot placement irrespective of the velocity of approach or crossing.

6.6.2.3 Velocity-age interaction

No velocity-age interaction effects were found.

6.6.2.4 Group membership

Discriminant (stepwise) analyses with cross-validation procedures were conducted in order to determine which of the variables accounted the most for the differences in the average score profiles of the two groups. In the comfortable velocity condition the analysis identified four significant variables ($p \leq .001$) in the following order:

1. Lead limb crossing step length (*CSL*);
2. Lead foot landing angle (*LLA*);
3. Double foot support time (*DFST*);
4. Lead limb crossing swing time (*CST*).

In the fast velocity condition the analysis identified four significant variables ($p < .001$) in the following order:

1. Lead limb crossing step length (*CSL*);
2. Double foot support time (*DFST*);
3. Lead foot landing angle (*LLA*).

In the comfortable velocity condition (refer to table 6.6.2.4.1) the identified variables (*CSL, LLA, DFST, CST*) correctly classified 87.5% of the elderly and 91.7% of the young. In the fast velocity condition (refer to table 6.6.2.4.2) the identified variables (*CSL, LLA, DFST*) correctly classified 83.5% of the elderly and 93.8% of the young.

Table 6.6.2.4.1 Accuracy of predicted group membership (comfortable velocity) using a stepwise discriminant analysis.

Classification Results					
			Predicted Group Membership		
		AGE	YA	EA	Total
Original	**Count**	YA	44	4	48
		EA	6	42	48
	%	YA	91.7	8.37	100
		EA	12.5	87.5	100
Cross-validated	**Count**	YA	43	5	48
		EA	6	42	48
	%	YA	89.6	10.4	100
		EA	12.5	87.5	100

Table 6.6.2.4.2 Accuracy of predicted group membership (fast velocity) using a stepwise discriminant analysis.

Classification Results					
			Predicted Group Membership		
		AGE	YA	EA	Total
Original	**Count**	YA	46	2	48
		EA	8	40	48
	%	YA	95.8	4.2	100
		EA	16.7	83.5	100
Cross-validated	**Count**	YA	45	3	48
		EA	9	39	48
	%	YA	93.8	6.3	100
		EA	18.8	81.3	100

6.6.2.5. Variable association (correlation)

Correlation analyses were conducted in order to examine the relationship between variables. The results are listed in appendices N and O and will be referred to throughout other sections of this thesis.

6.6.3 Ensemble average patterns (1st trial)

6.6.3.1 Lead foot orientation

Figures 6.6.3.1.1 and 6.6.3.1.2 are the ensemble average plots of the orientation of the lead foot (with respect to an earth-based horizontal axis system) in the crossing step (toe-off to foot land). On each plot the approximate position of the mean percentage value of the time at which the lead toe crossed the step edge is shown by a dashed line. For each velocity condition, and across both age groups, this value showed little variation ranging from 61.5% to 64.9%. The reader is referred to Appendix P for each age group and velocity condition ensemble average plot.

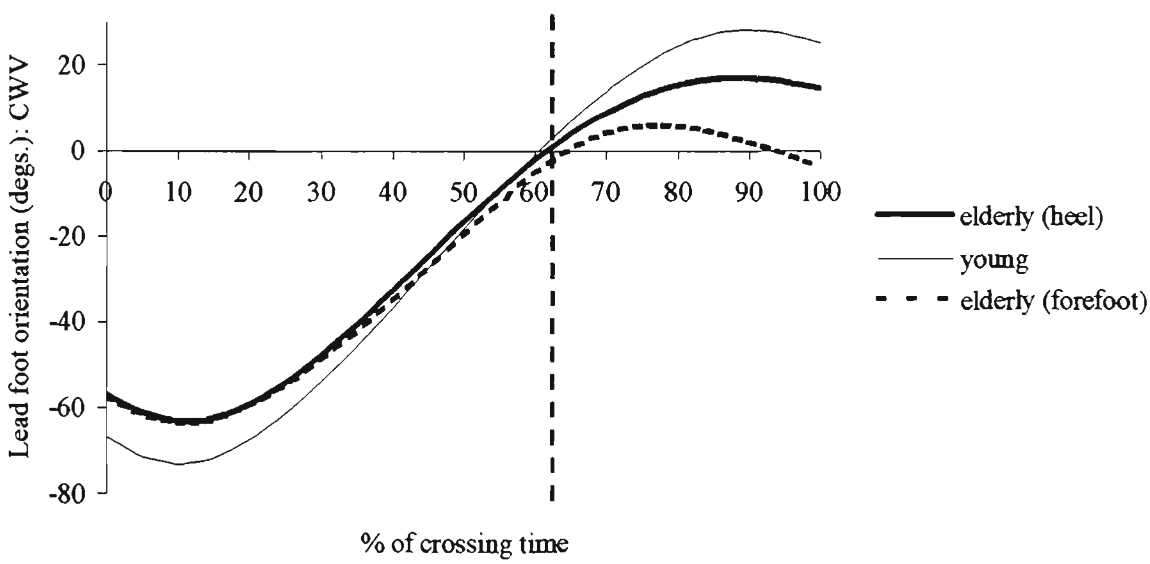


Figure 6.6.3.1.1 Ensemble average plot of the lead foot orientation for participants (EA = 43, YA = 48) who adopted a heel landing strategy in the comfortable velocity condition. Mean percent cross time (approximate position shown by dashed line) of the step edge by the lead toe (EA = 62.5%, YA = 63.2%). Plot of elderly participants who landed on the forefoot (n = 5) is also shown (cross time = 64.9%).

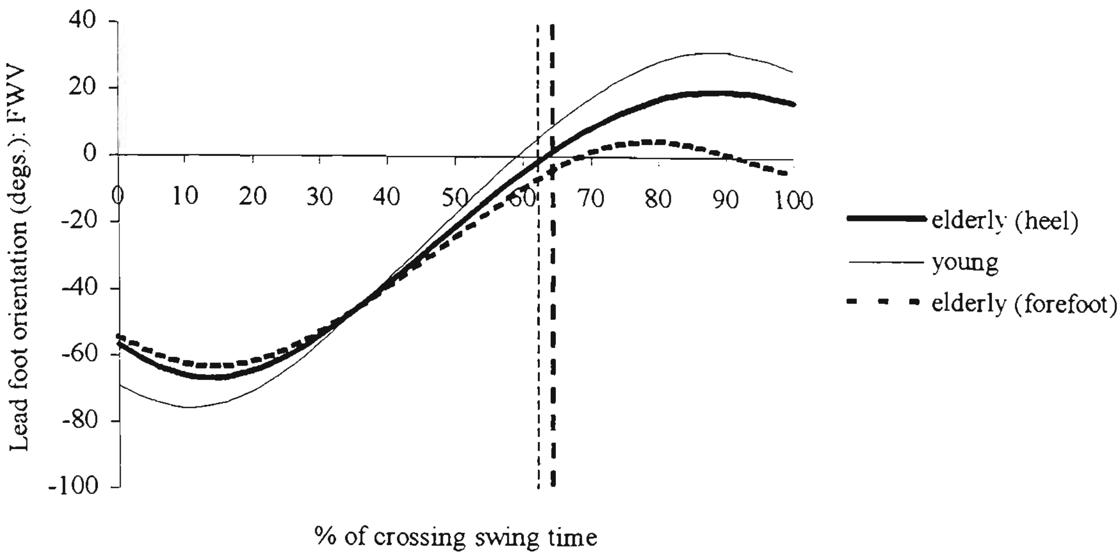


Figure 6.6.3.1.2 Ensemble average plot of the lead foot orientation for participants (EA = 44, YA = 48) who adopted a heel landing strategy in the fast velocity condition. Mean percent cross time (approximate position shown by dashed lines) of the step edge by the lead toe (EA = 63.3%, YA = 61.5%). Plot of elderly participants who landed on the forefoot (n = 4) is also shown (cross time = 63.2%).

In 91% of the elderly trials and all of the young trials a heel landing strategy was employed. The plots also show the young take the foot through a large angular range of motion compared to the elderly participants. A comparison of the take-off angle across the groups revealed that the young (-67.9°, SD = 10.9°) had a significantly greater angle ($p < .001$) than the elderly (-56.7°, SD = 9.4°).

Of the elderly participants who landed on the forefoot, 2 used this strategy in both velocity conditions.

In the comfortable velocity condition, 46% of the elderly and 33% of the young participants exhibited a lead foot crossing strategy where the foot was oriented down (EA = -8.3°, SD = 6.1°; YA = -14.0°, SD = 10.7°). The remaining participants exhibited a strategy where the foot was orientated up (EA = 8.0°, SD = 5.1°; YA = 13.0°, SD = 7.2°).

In the fast velocity condition, 48% of the elderly and 44% of the young participants exhibited a lead foot crossing strategy where the foot was oriented down (toe-down) over the step edge (EA = -13.1°, SD = 8.2°; YA = -12.7°, SD = 7.6°). The remaining participants exhibited a strategy where the toe was orientated up (toe-up) over the step edge (EA = 9.7°, SD = 6.9°; YA = 16.1°, SD = 10.8°).

Interestingly, the time of lead foot crossing (percent of crossing swing time) was not found to differ (statistically) across age or velocity. The descriptive statistics for this variable are listed in table 6.6.3.1.1.

Table 6.6.3.1.1 Mean percent crossing time of the lead foot.

	Elderly				**Young**			
Velocity	Mean (%)	SD (%)	Min (%)	Max (%)	Mean (%)	SD (%)	Min (%)	Max (%)
CWV	62.7	7.1	40.7	78.9	63.2	7.4	45.0	82.6
FWV	63.3	7.1	45.8	76.5	61.5	7.4	47.6	73.7

6.6.3.2 Lead foot vertical trajectory

Figures 6.6.3.2.1 and 6.6.3.2.2 are the ensemble average plots of the vertical displacement of the marker located on the lead toe. The displacement of the marker was calculated relative to step height (15 cm) for the crossing step (toe-off to foot land). On each plot the approximate position of the mean percentage value of the time at which the lead toe crossed the step edge is shown by a dashed line. For each velocity condition, and across both age groups, this value showed little variation ranging from 61.5% to 64.9%. The reader is referred to Appendix Q for each age group and velocity condition ensemble average plot.

In 91% of the elderly trials a heel landing strategy was adopted; 9% adopted a forefoot landing strategy. All of the young participants adopted a heel landing strategy.

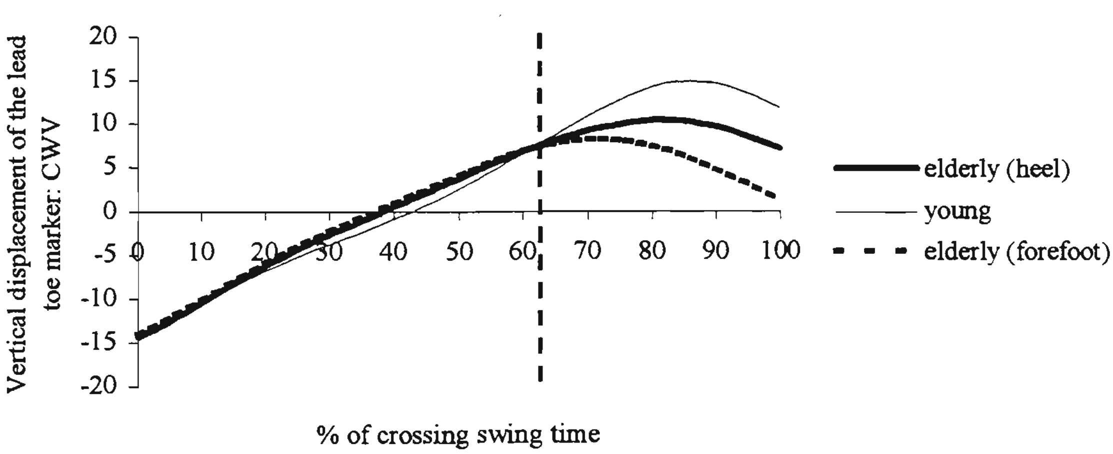


Figure 6.6.3.2.1 Ensemble average plot of the vertical displacement of the lead toe marker (relative to step height) for participants (EA = 43, YA = 48) who adopted a heel landing strategy in the comfortable velocity condition. Mean percent cross time of the step edge (approximate position shown by dashed line) by the lead toe (EA = 62.5%, YA = 63.2%). A plot of elderly participants who landed on the forefoot (n = 5) is also shown (% cross time = 64.9%).

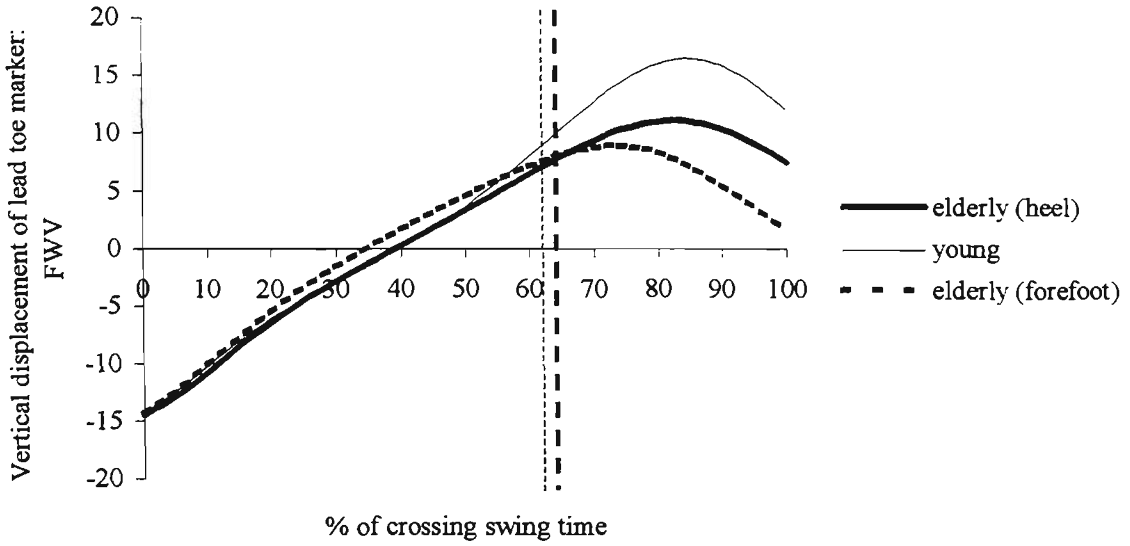


Figure 6.6.3.2.2 Ensemble average plot of the vertical displacement of the lead toe marker (relative to step height) for participants (EA = 44, YA = 48) who adopted a heel landing strategy in the fast velocity condition. Mean percent cross time of the step edge (approximate position shown by dashed lines) by the lead toe (EA = 63.3%, YA = 61.5%). A plot of elderly participants who landed on the forefoot (n = 4) is also shown. Mean percent cross time of the step edge by the lead toe (63.2%).

6.6.3.3 Head pitch

Figures 6.6.3.3.1 to 6.6.3.3.5 are the ensemble average plots of the head pitch for each age group. Head pitch was recorded from the 3rd-last step until midstance past the step (refer to figure 5.3.2.1). Head pitch was normalised to the value found at midstance in the 9th-last step of approach. A positive magnitude indicates the head is rotated upwards, whereas a negative magnitude indicates the head is rotated downwards. On each plot the events of heel contact (*HC*), foot landing past the step (*FL*), lead toe-step-clearance (*LTC*), lead toe-off (*LTO*), and trail toe-off (*TTO*) are shown.

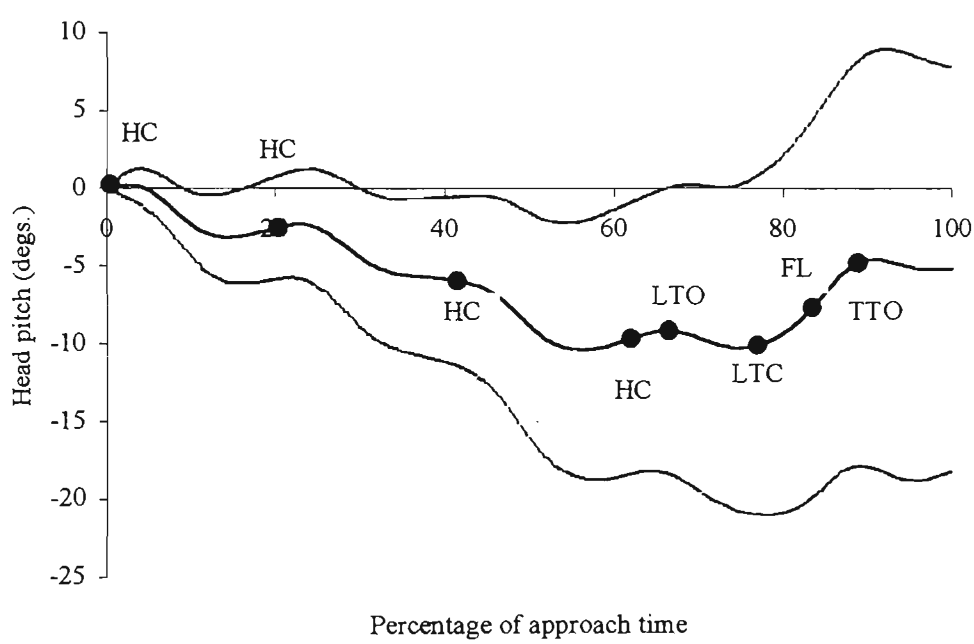


Figure 6.6.3.3.1 Elderly ensemble average plot of head pitch in the comfortable velocity condition. The events of heel contact (*HC*; occurring at 0, 21, 41 & 62%), foot landing past step (*FL*; 84%), lead toe-step-clearance (*LTC*; 77%), lead toe-off (*LTO*; 67%), and trail toe-off (*TTO*; 89%) are shown.

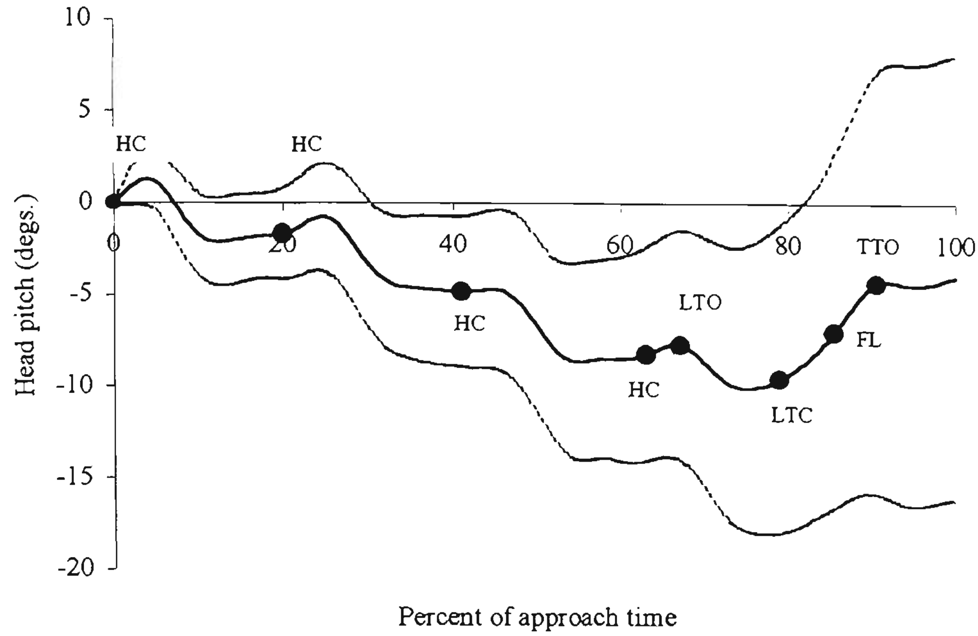


Figure 6.6.3.3.2 Elderly ensemble average plot of head pitch in the fast velocity condition. The events of heel contact (*HC*; occurring at 0, 19, 41 & 63%), foot landing past step (*FL*; 86%), lead toe-step-clearance (*LTC*; 79%), lead toe-off (*LTO*; 67%), and trail toe-off (*TTO*; 91%) are shown.

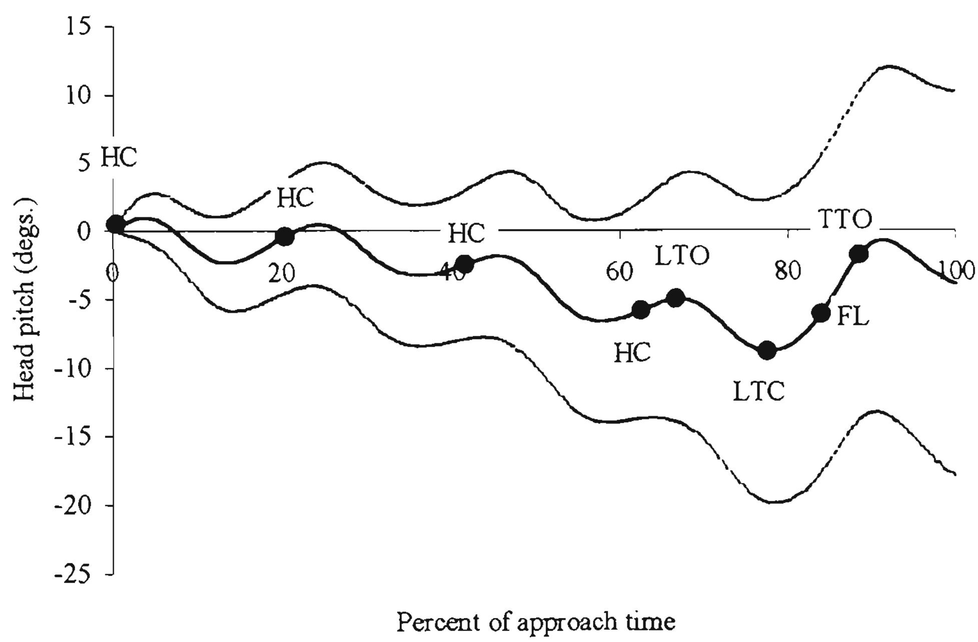


Figure 6.6.3.3.3 Young ensemble average plot of head pitch in the comfortable velocity condition. The events of heel contact (*HC*; occurring at 0, 21, 41 & 62%), foot landing past step (*FL*; 84%), lead toe-step-clearance (*LTC*; 77%), lead toe-off (*LTO*; 67%), and trail toe-off (*TTO*; 88%) are shown.

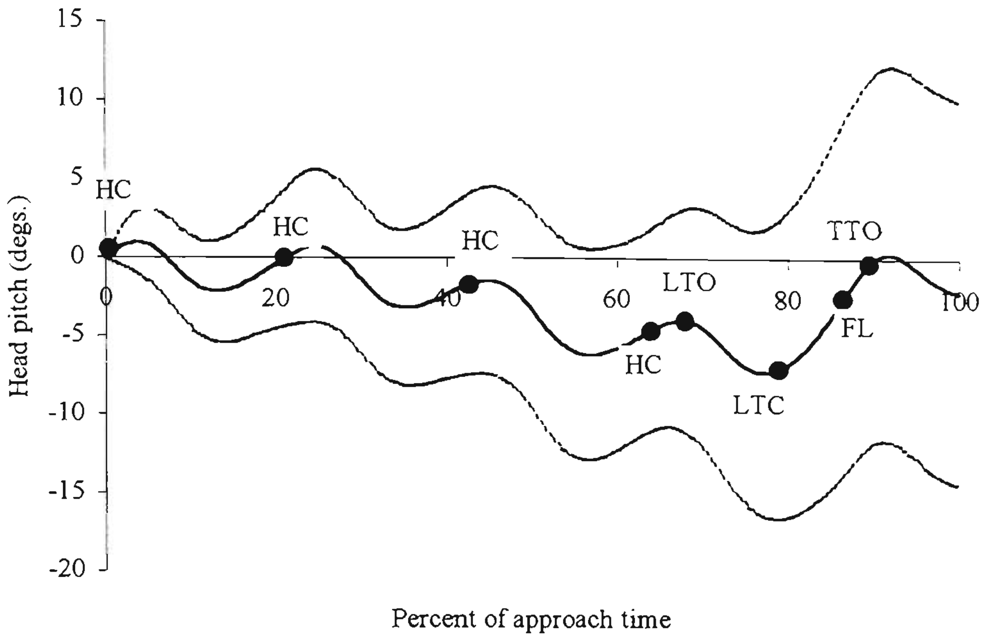


Figure 6.6.3.3.4 Young ensemble average plot of head pitch in the fast velocity condition. The events of heel contact (*HC*; occurring at 0, 21, 43 & 64%), foot landing past step (*FL*; 86%), lead toe-step-clearance (*LTC*; 79%), lead toe-off (*LTO*; 68%), and trail toe-off (*TTO*; 90%) are shown.

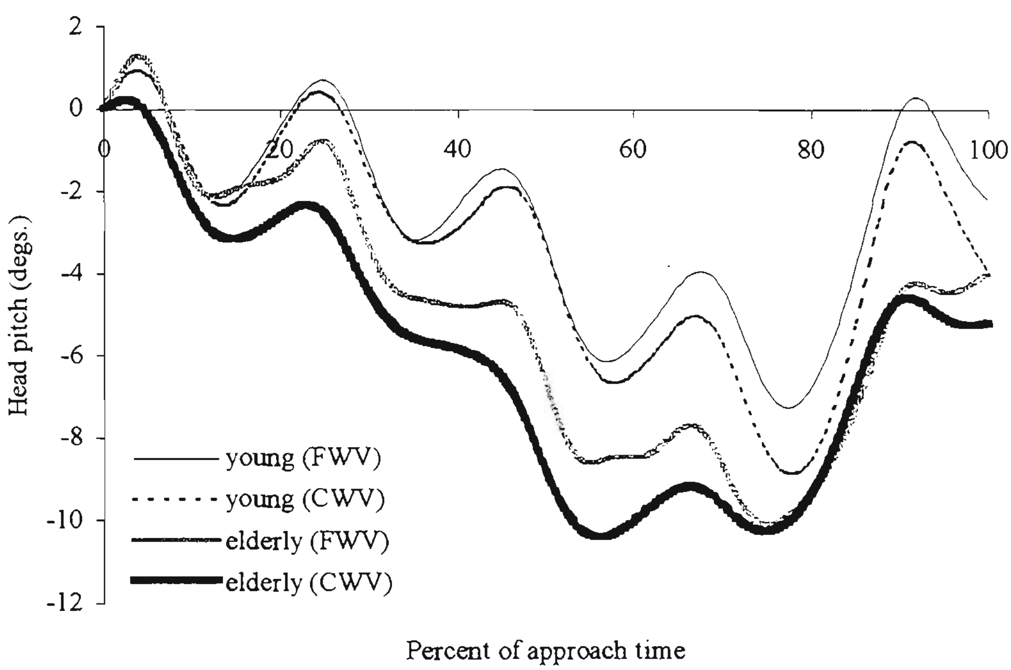


Figure 6.6.3.3.5 Ensemble average plots of head pitch for both groups.

The plots show the elderly implement a marked and systematic reduction in head pitch (rotate the head downwards) earlier than the young (EA ≈ 5%, YA ≈

25%). The elderly also show greater head pitch reductions than the young. The minimum value (EA $\approx$ -10°, YA $\approx$ -7 to -9°) was found to occur just prior to the last heel contact ($\approx$ 60%) before the step. After this event, the elderly show a marked and systematic increase in head pitch, whereas the young exhibit this phase later ($\approx$ 80%). Overall the elderly were found to exhibit greater head rotation throughout the approach and accommodation phases.

6.6.4 Footfall adjustments

6.6.4.1 Footfall variability (all trials)

Toe-to-step-edge displacement (*TSED*) was calculated for each participant's footfalls in the 3 comfortable and 3 fast walking velocity trials. Footfall variability values were derived from these data. These data were then used to derive mean values of footfall variability for each age group. Ensemble average plots of footfall variability across age and velocity conditions are shown in figure 6.6.4.1.1. The reader is referred to Appendix R for the plots of each age group.

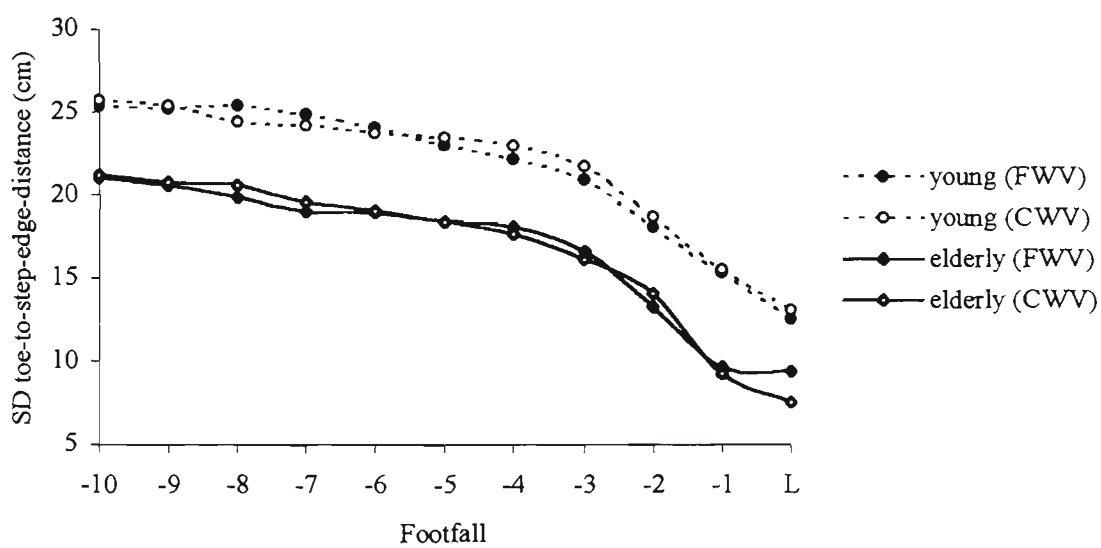


Figure 6.6.4.1.1 Plots of footfall variability for each age group and velocity condition (all trials).

The plots show small systematic reductions (0.2 to 1.5 cm) from the 10th to 3rd-last footfall. Larger reductions (2 to 4.8 cm) occur from the 3rd-last to final footfall followed by a smaller reductions (0.2 to 2.4 cm) in the final footfall.

The figure also shows the elderly exhibit less variability than the young in the approach and accommodation phases.

One-way (factor: age) MANOVAs were conducted in order to statistically validate some of the above observations. The analyses revealed significant age differences ($p < .05$) in mean footfall variability in the following intervals: (1) 6th-last footfall to final footfall (CWV); and, (2) 2nd-last footfall to final footfall (FWV).

Inspection of the individual plots of footfall variability revealed the existence of three distinct patterns (refer to figures 6.6.4.1.2 to 6.6.4.1.3). In the comfortable walking velocity condition, for example, 38% of the participants exhibited an ascending-descending pattern, whereas 61% exhibited a descending trend from the 10th-last footfall. One young participant displayed very low variability. This participant's data was checked. No significant differences were found in this participant's data (e.g. foot-obstacle-clearance, foot placement or crossing step length) compared to group data.

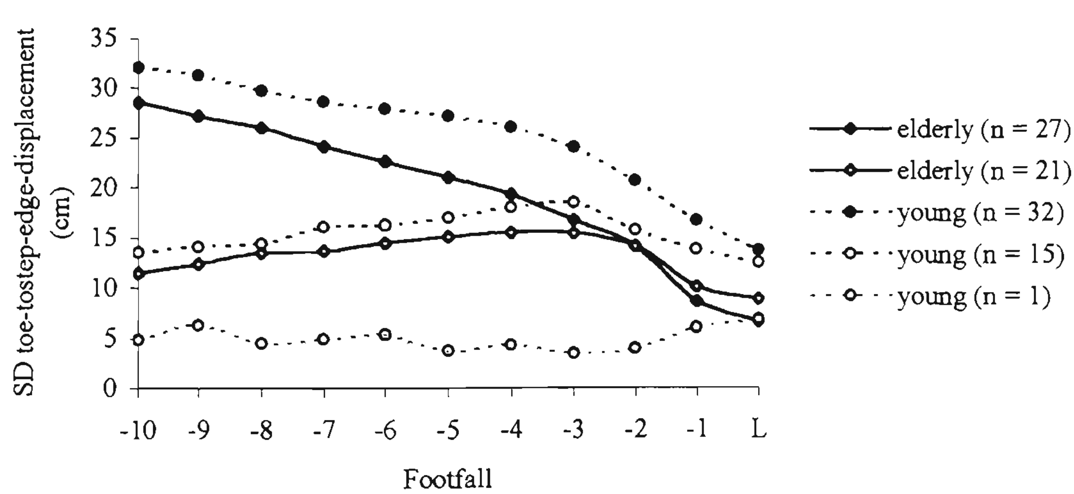


Figure 6.6.4.1.2 Plots of footfall variability showing three distinct patterns (comfortable walking velocity).

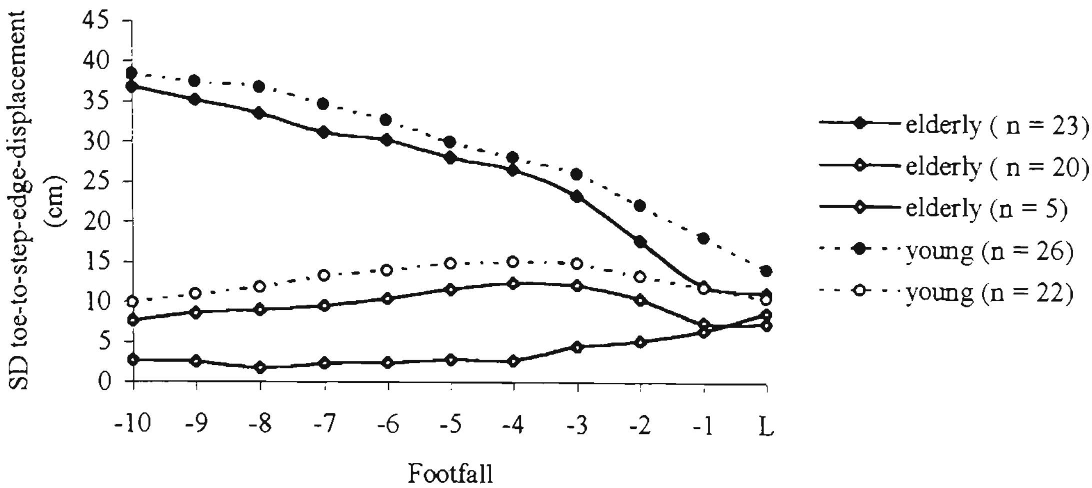


Figure 6.6.4.1.3 Plots of footfall variability showing three distinct patterns (fast walking velocity).

6.6.4.2 Foot placement (1st trial)

After crossing the step (refer to figures 6.6.4.2.1 and 6.6.4.2.2), the elderly placed the heel of the lead limb closer (*LHD*) to the step (EA ≈ 9.2 cm, YA ≈ 18.1 cm, $p < .001$). In about 20% of the elderly trials the lead foot was placed on the edge (foot partially supported by step), whereas this figure fell to 3% for the young adults. In fact, none of the young adults placed the foot on the edge in the comfortable velocity condition. Further analysis of these data revealed the elderly, on average, placed the lead foot so that about 76% (SD = 12.4%) of it (foot length) was supported by the step, whereas the young exhibited a value of 98.4% (SD = 0.4%). The elderly values were found to range from approximately 50 to 98% with the smallest values found in the fast velocity condition (CWV = 81%, FWV = 71%). The elderly were also found to place the toe of the trail limb (*TD*) closer to the step (EA ≈ 35 cm, YA ≈ 44 cm, $p < .001$).

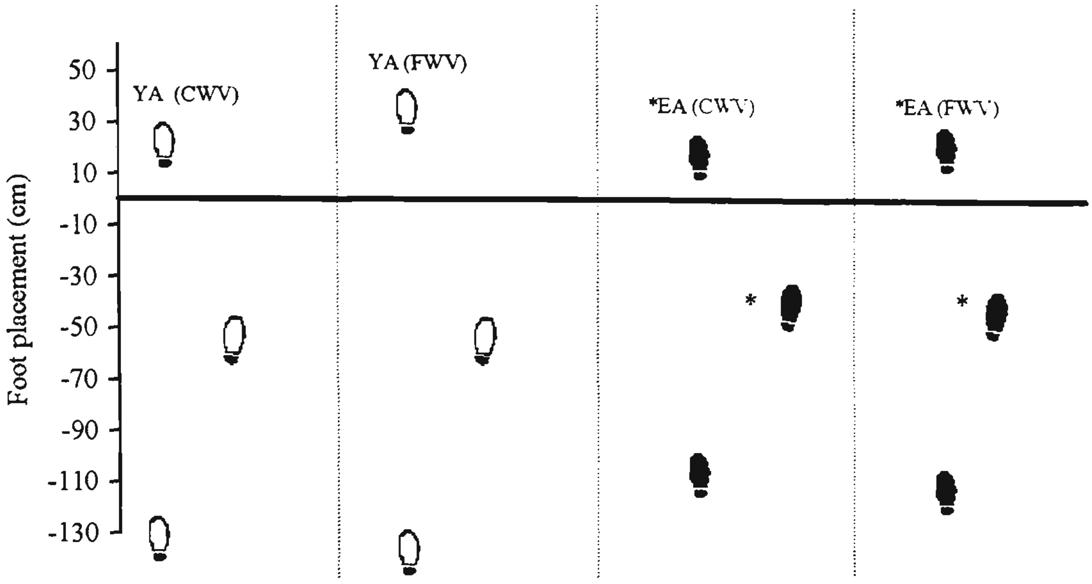


Figure 6.6.4.2.1 Plan view of lead and trail foot placement in the crossing stride for the ascent task. CWV: comfortable walking velocity; FWV: fast walking velocity. An asterisk (*) indicates an age effect ($p < .05$).

The elderly exhibited less variability in the placement of the lead heel (*LHD*) in the comfortable velocity condition (EA = 9.8 cm, YA = 13.7 cm, $p < .025$). The variability in the placement of the trail foot did not differ across age.

Foot placement data (time and displacement) were normalised across age by expressing it as a percentage of lead limb crossing swing time (lead limb toe-off to foot landing) and as a percentage of crossing stride length (operationally defined as pre-step toe-off to post-step heel position). Significant age and velocity differences ($p < .03$) were found for the normalised stride length data (refer to table 6.6.4.2.1 and 6.6.4.2.2). On average, the elderly allowed about 8% of stride length, compared to approximately 13% for the young adults, in which to position the lead foot after crossing the step. No differences, however, were found in the normalised crossing time data.

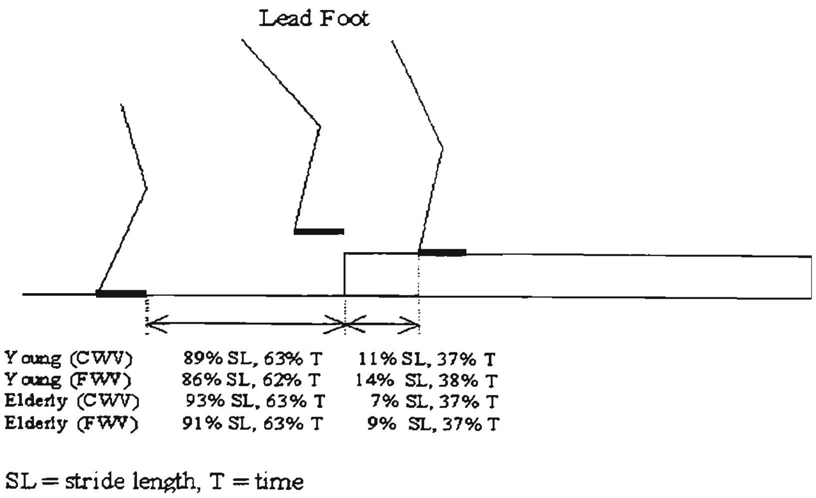


Figure 6.6.4.2.2 Lead foot pre-step and post-step crossing percentage distances and times for the ascent task. SL: stride length; T: time.

Table 6.6.4.2.1 Crossing time (expressed as a percentage of lead limb swing time).

	Elderly				Young			
Velocity	**Mean (%)**	**SD (%)**	**Min (%)**	**Max (%)**	**Mean (%)**	**SD (%)**	**Min (%)**	**Max (%)**
CWV	62.7	7.1	40.7	78.9	63.2	7.4	45.0	82.6
FWV	63.2	7.1	45.8	76.5	61.5	7.4	47.6	73.7

Table 6.6.4.2.2 Step crossing (expressed as a percentage of lead limb stride length).

	Elderly				Young			
Velocity	**Mean (%)**	**SD (%)**	**Min (%)**	**Max (%)**	**Mean (%)**	**SD (%)**	**Min (%)**	**Max (%)**
CWV	92.9	9.0	65.3	106.6	89.1	10.3	58.8	98.9
FWV	90.9	12.1	57.7	110.8	85.8	10.8	60.1	100.3

6.6.4.3 Step length (all trials)

Step length values were calculated for each participant's footfalls from the 3 comfortable and 3 fast walking velocity trials. Mean step length values were derived from these data for each age group and velocity condition. The plots of these mean values are shown in figure 6.6.4.3.1. The reader is referred to Appendix S for each age group plot.

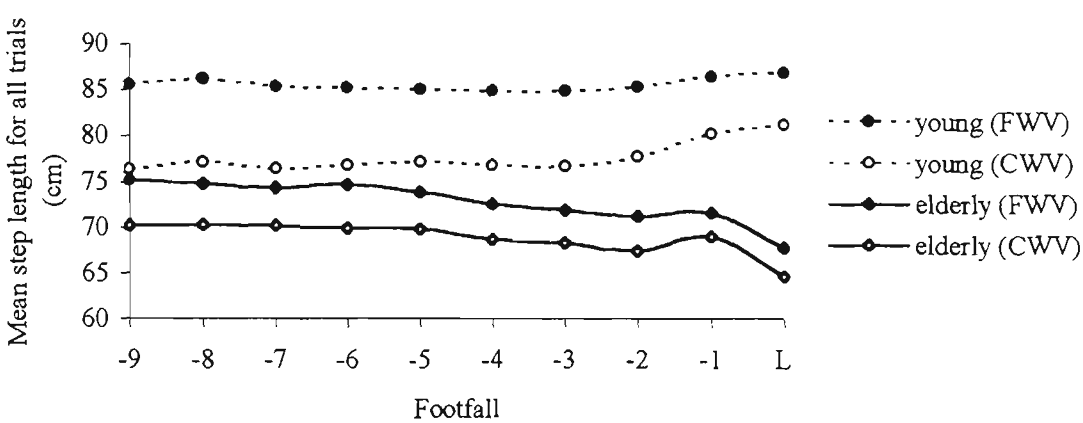


Figure 6.6.4.3.1 Mean step length plots (all trials).

The elderly plots show an increase in step length at the penultimate footfall followed by a reduction in the final footfall. The young plots show systematic increases in step length from the 3rd-last to final footfall. The elderly also exhibit small reductions from the 5th to 2nd-last footfall.

6.6.4.4 Step length (1st trial)

Step length values were calculated for each participant's footfalls from the 1st trial of each velocity condition. Mean step length values were derived from these data for each age group and velocity condition. The plots of these mean values are shown in figure 6.6.4.4.1. The reader is referred to Appendix T for each age group plot.

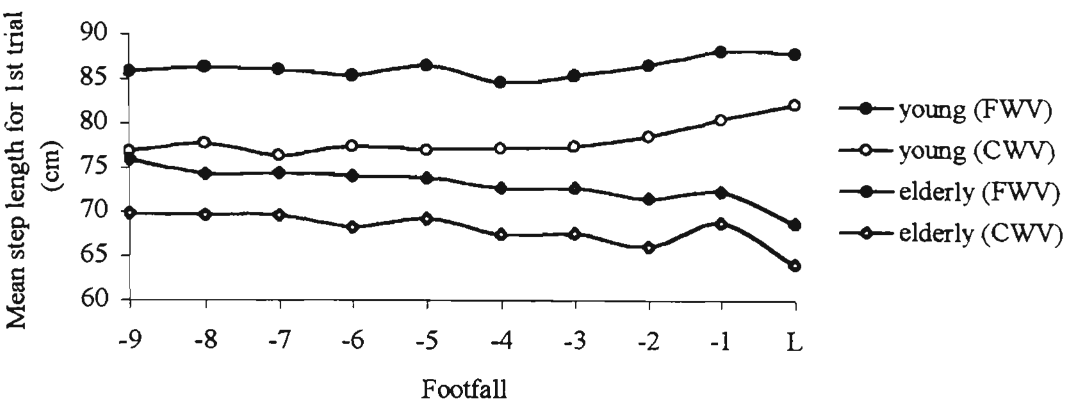


Figure 6.6.4.4.1 Mean step length plots (1st trial).

The elderly plots show reductions from the 3rd to 2nd-last footfall, then an increase in step length at the penultimate footfall, followed by a reduction in the final footfall. The young plots show systematic increases in step length from the 3rd-last to final footfall.

Figures 6.6.4.4.2 and 6.6.4.4.3 are comparison plots of the mean percentage step length adjustment (absolute value) made by each age group in the 1st trial. In both velocity conditions each group exhibit marked and systematic step length adjustments from the 3rd-last footfall. The elderly exhibit greater adjustments (refer to figures 6.6.4.4.4 and 6.6.4.4.5) in the penultimate and final footfall compared to the young. In the penultimate footfall, the elderly made adjustments ranging from 20 to 40% more than the young, and in the final footfall they made adjustments 2 to 2 1/2 times of that made by the young.

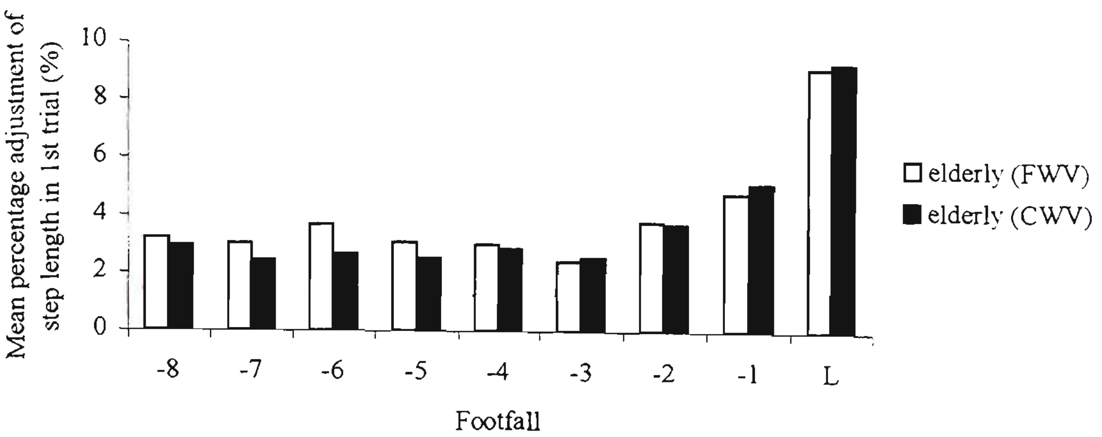


Figure 6.6.4.4.2 Mean percentage step length adjustment (absolute) made by the elderly in the 1st trial (velocity comparison).

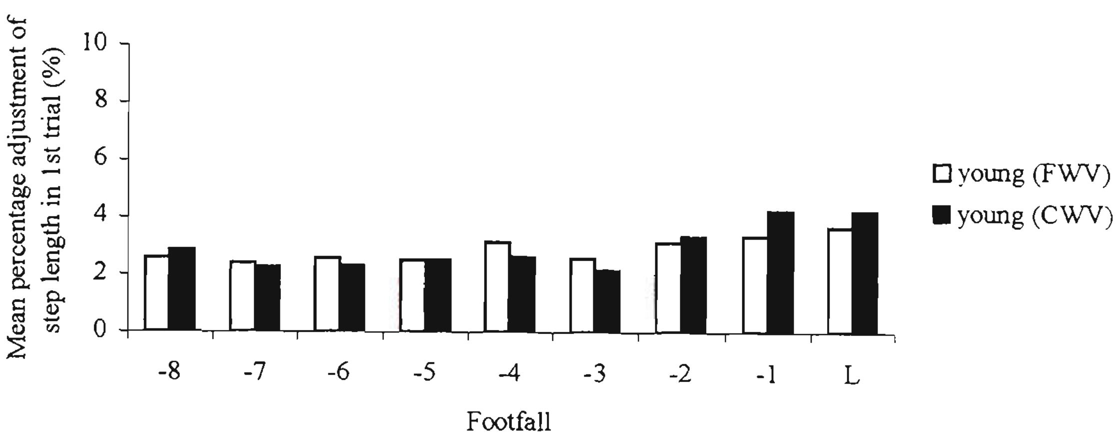


Figure 6.6.4.4.3 Mean percentage step length adjustment (absolute) made by the young in the 1st trial (velocity comparison).

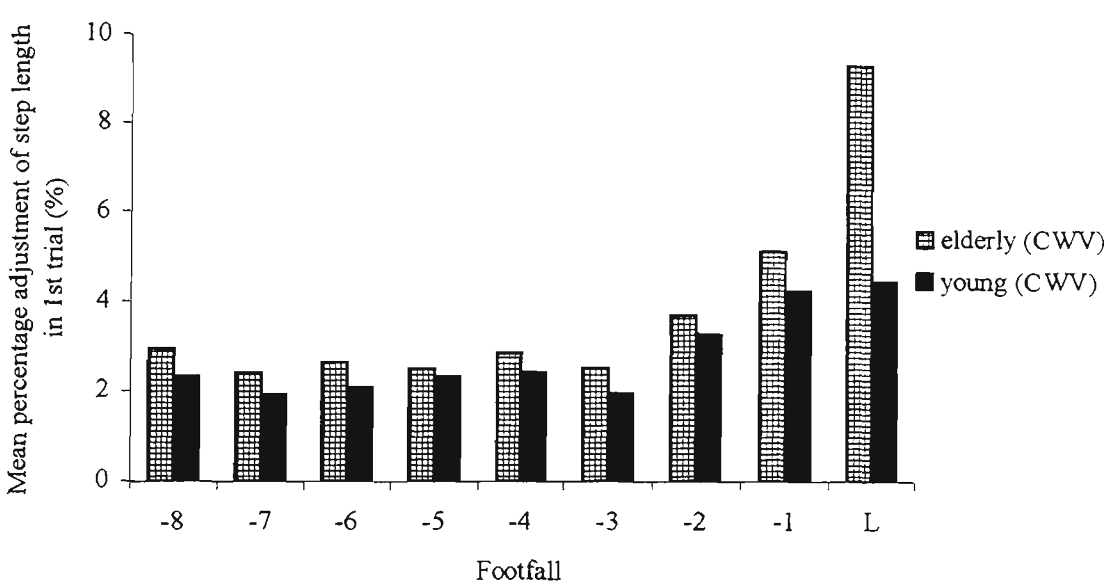


Figure 6.6.4.4.4 Age comparison plot of mean percentage step length adjustment (absolute) made by the elderly and young in the 1st trial (CWV).

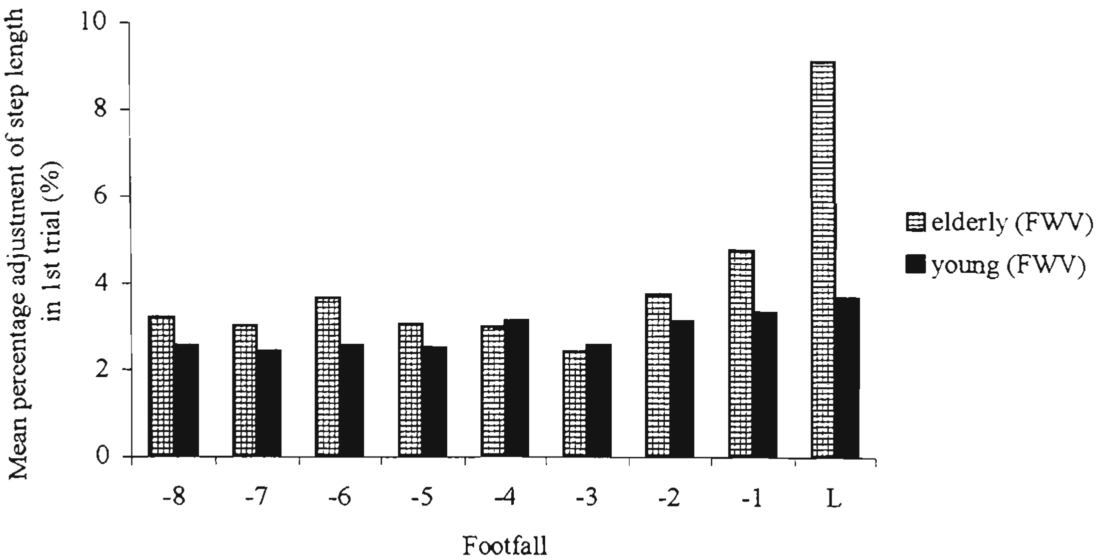


Figure 6.6.4.4.5 Age comparison plot of mean percentage step length adjustment (absolute) made by the elderly and young in the 1st trial (FWV).

6.6.4.5 Stepping strategies (1st trial)

Table 6.6.4.5.1 lists the step strategies adopted by each group (refer to section 5.4.3). A chi-square analysis revealed a significant age difference in the frequency of the stepping strategies ($p < .001$). The strategies employed were: (1) a long step strategy (*LSS*); (2) short step strategy (*SSS*); (3) a mixture of short and long steps; and, (4) a normal step strategy.

Table 6.6.4.5.1 Frequency count of step strategies adopted

Step Strategy	CWV Elderly	CWV Young	FWV Elderly	FWV Young
Long	8	25	4	17
Mixed	2	4	4	0
Short	27	2	24	5
Normal	11	17	16	26
Total	48	48	44	48

In the comfortable velocity condition, 11 of the elderly and 17 of the young "took it in their stride" (normal step strategy), whereas in the fast velocity condition 16 of the elderly and 26 of the young "took it in their stride"; that is, these subjects did not make significant step adjustments in approaching and accommodating the step.

Overall, the elderly favoured a short step strategy. In 53% of the trials the elderly employed a short step strategy compared to 7% for the young. The young tended to favour a long step strategy (44%) compared to the elderly (13%).

6.6.4.6 Step time and velocity (1st trial)

Plots of the mean step times (1st trial) are shown in figure 6.6.4.6.1. The reader is referred to Appendix U for each age group plot. Each plot exhibits the same pattern; there is a marked step time increase in the final footfall (L). The elderly exhibit smaller step times compared to the young in the approach for the comfortable velocity condition, whereas in the fast velocity condition the step times are similar except for the crossing step where the elderly show a significant increase in step time compared to the young.

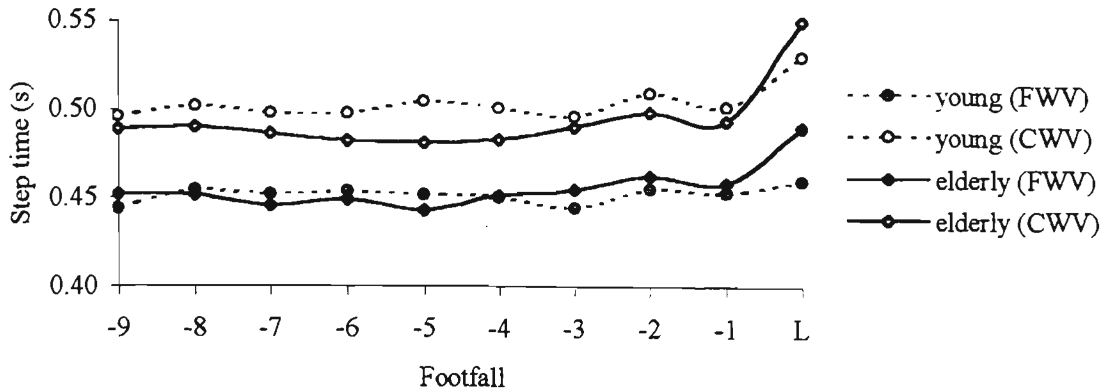


Figure 6.6.4.6.1 Plots of mean step time (1st trial).

Plots of mean step velocity (1st trial) are shown in figure 6.6.4.6.2. In both velocity conditions the young exhibit higher velocities. The elderly show marked and systematic reductions in step velocity from the 4th-last footfall to the final footfall in both velocity conditions, whereas the young do not exhibit any significant reductions in step velocity.

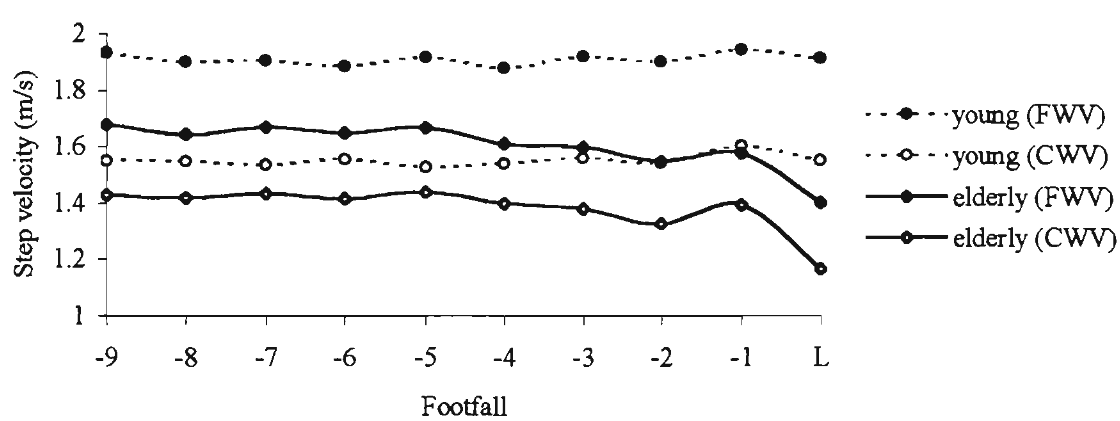


Figure 6.6.4.6.2 Plots of mean step velocity (1st trial).

6.7 Effect of surface height condition

Six one-way repeated measures MANOVAs were conducted in order to identify main effects of surface height condition (descent - ascent). Descriptive and inferential statistics are listed in tables 6.7.1 and 6.7.2. These tables also show the variable groupings for each analysis. Items shown in the same boxes were grouped for analysis. Refer to section 5.5.3.2 for further explanation.

Table 6.7.1 Comparison of surface height condition (CWV).

	Descent		Ascent				
Variable	Mean	SD	Mean	SD	n	Sig.	Observed β
ART (ms) *	84	61	77	54	96	.318	.168
CSL (cm)	68.1	14.2	73.0	13.2	96	.001	0.999
CST (s)	0.47	0.07	0.41	0.04	96	.001	1.000
DFST (s)	0.08	0.03	0.12	0.03	96	.001	1.000
HCD (cm)	-8.9	4.9	-8.7	4.9	96	.635	.076
HCV ($m \cdot s^{-1}$)	1.25	0.33	1.25	0.26	96	.849	.054
HLD (cm)	29.8	10.7	11.8	7.1	96	.001	1.000
LCA (°)	-23.8	9.1	2.1	12.5	96	.001	1.000
LHD (cm)	36.8	16.1	11.1	12.4	96	.001	1.000
LLA (°)	-6.8	17.3	19.0	9.6	96	.001	1.000
LLV ($m \cdot s^{-1}$)	0.27	0.45	0.85	0.62	96	.001	1.000
LTC (cm)	2.7	1.5	8.0	2.4	96	.001	1.000
TD (cm)	-8.1	11.0	-38.8	14.6	96	.001	1.000
TRKCA (°)	89.9	4.3	85.9	5.5	96	.001	.999
LFM (%)**	93.4	4.7	97.0	4.5	81	.545	.092
LHC (cm)	3.9	2.2	4.1	2.7	81	.001	1.000
TCA (°)***	-68.8	11.0	-55.4	15.5	65	.031	.584
THC (cm)	20.5	4.1	18.4	5.8	65	.001	1.000
TTC (cm)	1.5	1.4	4.3	2.8	65	.001	1.000

*$F(14, 82) = 117.84, p \leq .001, \beta = 1.000$

**$F(2, 79) = 13.6, p \leq .001, \beta = .997$

***$F(3, 62) = 62.5, p \leq .001, \beta = 1.000$

Table 6.7.2 Comparison of surface height condition (FWV).

	Descent		Ascent				
Variable	**Mean**	**SD**	**Mean**	**SD**	**n**	**Sig.**	**Observed β**
ART (ms) *	46	39	56	50	96	.069	.444
CSL (cm)	76.9	15.7	78.3	14.0	96	.225	0.227
CST (s)	0.43	0.04	0.39	0.04	96	.001	1.000
DFST (s)	0.05	0.03	0.09	0.04	96	.001	1.000
HCD (cm)	-6.5	5.3	-7.2	6.0	96	.276	.197
HCV ($m \cdot s^{-1}$)	1.59	0.37	1.49	0.36	96	.015	.685
HLD (cm)	37.6	11.1	17.0	8.6	96	.001	1.000
LCA (°)	-26.4	8.8	0.8	15.3	96	.001	1.000
LHD (cm)	45.5	17.4	16.3	16.3	96	.001	1.000
LLA (°)	-4.5	18.4	20.5	9.5	96	.001	1.000
LLV ($m \cdot s^{-1}$)	0.44	0.52	0.94	0.71	96	.001	.999
LTC (cm)	2.7	1.6	8.3	2.7	96	.001	1.000
TD (cm)	-8.2	9.9	-39.3	16.9	96	.001	1.000
TRKCA (°)	88.3	4.6	83.8	5.3	96	.001	.963
LFM (%)**	94.8	3.4	97.2	4.2	79	.05	.504
LHC (cm)	4.8	2.4	5.7	2.9	79	.001	1.001
TCA (°)***	-73.9	11.2	-61.0	15.5	68	.073	.435
THC (cm)	22.5	3.4	21.2	7.0	68	.001	1.000
TTC (cm)	1.9	1.4	5.0	2.4	68	.001	1.000

* $F(12, 84) = 114.46, p \leq .001, \beta = 1.000$
** $F(2, 77) = 9.29, p \leq .001, \beta = 0.974$
*** $F(3, 65) = 85.9, p \leq .001, \beta = 1.000$

Each analysis revealed significant main effects of surface height condition. Tables 6.7.1 and 6.7.2 list the main surface height condition effects for each outcome variable. In the comfortable velocity condition, the *HCD*, *HCV* and *LHC* variables were not found to significantly differ. In the fast velocity condition, the *CSL*, *HCD* and *THC* variables were not found to significantly differ. All other variables however were found to significantly differ ($p < .05$).

In the comfortable velocity condition, the following variables were found to increase significantly ($p \leq .05$) across surface height condition (descent - ascent):

- crossing step length (*CSL*: descent = 68.1 cm, ascent = 73.0 cm);
- crossing swing time (*CST*: descent = 0.47 s, ascent = 0.41 s);
- double foot support time (*DFST*: descent = 0.08 s, ascent = 0.12 s);
- horizontal displacement of the hip marker from the toe of the trail limb at the instant the lead foot landed (*HLD*: descent = 29.8 cm, ascent = 11.8 cm);
- lead foot crossing angle (*LCA*: descent = -23.8°, ascent = 2.1°);
- lead foot heel placement past the step edge (*LHD*: descent = 36.8 cm, ascent = 11.1 cm);
- lead foot landing angle (*LLA*: descent = -6.8°, ascent = 19.0°);
- lead foot horizontal landing velocity (*LLV*: descent = 0.27 $m \cdot s^{-1}$, ascent = 0.85 $m \cdot s^{-1}$);

- lead toe-step-clearance (*LTC*: descent = 2.7 cm, ascent = 8.0 cm);

- trail foot toe pre-distance (*TD*: descent = -8.0 cm, ascent = -38.8 cm);

- focal movement trajectory of the lead foot (*LFM*: descent = 93.5%, ascent = 96.9%);

- lead heel-step-clearance (*LHC*: descent = 3.9 cm, ascent = 4.1 cm);

- trail foot crossing angle (*TCA*: descent = -73.9°, ascent = -61.0°);

- trail toe-step-clearance (*TTC*: descent = 1.5 cm, ascent = 4.3 cm).

Trunk orientation upon landing (*TRKCA*) was found to reduce ($p < .001$) across surface height conditions (descent - ascent): *TRKCA*: descent = 89.9°, ascent = 85.9°).

In the fast velocity condition, the following variables were found to increase significantly ($p < .05$) across surface height condition (descent - ascent):

- crossing swing time (*CST*: descent = 0.43 s, ascent = 0.39 s);

- double foot support time (*DFST*: descent = 0.05 s, ascent = 0.09 s);

- horizontal crossing velocity (*HCV*: descent = 1.59 $m \cdot s^{-1}$, ascent = 1.49 $m \cdot s^{-1}$);

- horizontal displacement of the hip marker from the toe of the trail limb at the instant the lead foot landed (*HLD*: descent = 37.6 cm, ascent = 17.0 cm);

- lead foot crossing angle (*LCA*: descent = -26.4°, *ON* = 0.8°);

- lead foot heel placement past the step edge (*LHD*: descent = 45.5 cm, ascent = 16.3 cm);

- lead foot landing angle (*LLA*: descent = -4.5°, ascent = 20.5°);

- lead toe-step-clearance (*LTC*: descent = 2.7 cm, ascent = 8.3 cm);

- trail foot toe pre-distance (*TD*: descent = -8.2 cm, ascent = -39.3 cm);

- focal movement trajectory of the lead foot (*LFM*: descent = 94.8%, ascent = 97.2%);

- lead heel-step- clearance (*LHC*: descent = 4.9 cm, ascent = 5.7 cm);

- lead foot horizontal landing velocity (*LLV*: descent = 0.44 $m \cdot s^{-1}$, ascent = 0.94 $m \cdot s^{-1}$); trail foot crossing angle (*TCA*: descent = -73.9°, ascent = -61.0°);

- trail heel-step-clearance (*THC*: descent = 22.5 cm, ascent = 21.2 cm);

- trail toe-step-clearance (*TTC*: descent = 1.9 cm, ascent = 5.0 cm).

Trunk orientation upon landing (*TRKCA*) was found to reduce ($p < .001$) across surface height condition (descent - ascent): *TRKCA*: descent = 89.3°, ascent = 83.8°.

CHAPTER 7 DISCUSSION

The format of this chapter is as follows. There are five major sections that focus upon key issues related to this project. These include: (1) participant screening and trial protocol; (2) regulation of gait velocity; (3) footfall adjustments; (4) dynamic stability; and, (5) foot trajectory and orientation. Each section primarily focuses upon results that are linked. Some results, however, appear in more than one section. This outcome is inevitable since some variables such as foot placement and foot-step-clearance are intrinsically linked.

The first section primarily focuses upon methodological issues relevant to investigations in obstructed gait. Issues such as the worth or applicability of screening tests, the adoption of blocked or single trial methods and lead limb selection. The primary aim of this section was to provide more knowledge about these issues in order to assist future studies.

The second section specifically focuses upon the walking velocities exhibited by the participants. This is important since "hurrying" or fast walking velocity has been linked to falls (e.g., Pauls, 1985; Australian Bureau of Statistcs, 1995a; Lilley et al., 1995; Berg et al., 1997). To date, only one investigation of obstructed gait has examined the effect of speed on the ability of a person to step over an obstacle (Liu et al., 1996). Consequently, the effect of walking velocity was examined in both surface height conditions employed in this project.

Footfall issues are extensively discussed in the third section. The primary aim was to ascertain the likelihood of a misstep on a step. Such an outcome is undesirable since it may lead to a stumble or fall (e.g., Pauls, 1985; Lilley et al, 1995; Berg et al., 1997). As such, issues relating to perception-action coupling, foot placement (pattern, amount and variability) and step adjustment (time and length) were examined. A new method drawn from previous work involving the long jump (e.g., Lee et al., 1982; Scott et al., 1997) was employed to examine footfall positions. The adoption of this method is a unique aspect of this project.

The dynamic stability section specifically focuses on aspects of the crossing step. Measures were predominantly drawn from previous studies of obstructed gait (Patla & Rietdyk, 1993; Liu et al., 1996; Lythgo & Begg, 1999c). These include measures of (1) support time, (2) trunk marker position and velocity, (3) available response time, and (4) foot velocity and orientation upon landing

The final section focuses on the vertical trajectory and orientation of the lead foot in the crossing stride. The aim was to ascertain whether the elderly exhibit behaviour that may heighten the chance of unwanted foot-ground or foot-step contact. Few studies have examined these patterns.

7.1 Participant screening and trial protocol issues

7.1.1 Screening

Overall, it appears that rigorous screening methods have been adopted in age-related studies of gait (e.g., Chen et al., 1991; 1994a; 1994b; Simoneau et al., 1991; Pavol et al., 1999). Projects, however, have not reported information such as the incidence of participant exclusion nor have they provided a detailed description of screening measures. Failure to report this information makes it difficult to ascertain the most relevant or useful tests. As a result, researchers may employ tests that are unnecessarily costly in terms of labour and monetary measures; some tests are labour intensive or may require the paid expertise of other colleagues or professionals. A project, therefore, may be impeded or restricted (e.g., reduced sample size) because of a reliance on other professionals (e.g., trained assistants or medical), hence, it would be beneficial for studies to provide more information so that the most discerning or relevant screening measures can be identified.

Rigorous screening procedures improve the validity of a project by reducing or eliminating the effects of confounding or extraneous variables. In this project, 11% of the elderly adults screened were excluded. None of the young adults, however, failed the screening process. Reasons for exclusion were: (1) musculo-skeletal impairment (n = 3); (2) failure on the vestibular stepping test (n = 2); and, (3) failure on both the Romberg and vestibular stepping tests (n = 1).

These findings confirm the need to screen elderly adults but not young adults when examining age-related issues in gait. Additionally, it shows that only a few of the screening measures were effective in identifying participants for exclusion; hence, these measures may be the most reliable or discerning.

It is recognized that some underlying pathologies may not have been detected by the screening items employed in this project. As such, the issue of screening warrants further investigation. Ideally, a common standard or battery of screening measures should be adopted so that consistency can be achieved across age-related investigations of gait.

7.1.2 Trial selection

This project (refer to section 6.5.4.1) found significant evidence of a practice effect when a blocked trial method (12 repeat trials) was employed in an accommodation task (stepping off a step). Footfall variability (in the approach and crossing phases) in the 1st trial, for example, was greater than in the 6th or 11th trials ($p < .006$). In addition, footfall variability was greater in trials 1-3 than in the remaining trials ($p < .001$). These findings suggest that participants implemented a learned response (less variable) or stereotypical behaviour in the later trials (Scott et al., 1997). In the early trials, however, their response to the travel path was quite novel or unique (highly variable).

Past studies of obstructed gait have reported practice effects in obstacle avoidance tasks involving blocked trial methods (e.g., Chen et al., 1991; 1994a;

1996; Hreljac, 1993). These findings, coupled with the suggestions of other investigators (e.g., Patla et al., 1996), support the notion that clinical or experimental assessment of dynamic stability is most likely confounded by adaptive changes that occur during repeated or blocked testing. This is a major concern since many studies have involved numerous repeat trials (average of about 9) presented in either blocked (e.g., McFadyen & Winter, 1988; Livingston et al., 1991; Patla et al., 1996; Riener et al., 2002; McFadyen & Prince, 2002) or randomised conditions (e.g., Chen et al., 1991; 1996; Patla et al., 1991; Patla & Rietdyk, 1993; Patla & Prentice, 1995; Liu et al., 1996; Sparrow et al., 1996; Patla & Vickers, 1997; Stemmons Mercer et al., 1997; Lythgo & Begg, 1999a; Sims & Brauer, 2000). These studies have sought to attain a high level of statistical power by employing repeat trial methods. Although this increases mathematical power (by reducing the standard error), such methods actually reduce the "real" power of a test since the first response is different to subsequent responses. The influence of the first response ("true affect") on a comparison test, therefore, will be diminished or "washed out" by subsequent trials. Put simply, the real effects of independent variables (e.g., age) upon outcome measures such as foot-obstacle-clearance may be obscured.

The later findings suggest that studies may profitably gain by focusing more upon the first compensatory responses to a novel travel path or disturbance. The adoption of such a practice may improve the power of a study to identify age-related differences in gait. This project, for example, found age-related differences in foot-step-clearance, whereas a past study (e.g., Chen et al., 1991) involving a repeat trial method did not find significant age differences in foot-obstacle-clearance.

7.1.3 Lead limb selection (all trials)

Although the majority of participants (≈ 78%) exhibited a lead limb preference when accommodating the surface height conditions (used one limb more than the other), only about 10% were found to exhibit limb dominance (used the same lead limb). In addition, the frequencies of right and left limb preference across tasks fell close to a value of 50%. As such, these findings support an important hypothesis; that is, methods involving pre-determined or constrained lead limb protocols may confound the outcomes of obstructed gait studies. Put simply, participants may be forced to employ atypical gait adjustments or footfall patterns. Although, a significant number of adults exhibited a limb preference in this project, a large proportion did not. As such, the adoption of a protocol where the lead limb is pre-determined or constrained (e.g., Chen et al., 1991; Patla et al., 1991; McFayden et al., 1993; Patla & Rietdyk, 1993; Patla & Prentice, 1995; Chou & Draganich, 1997; Austin et al., 1999) may compromise the ecological validity of a study. Such a protocol assumes gait is symmetrical in obstructed terrain. This may not be the case since evidence of asymmetry in able-bodied gait has been reported by Sadeghi, Allard, Prince and Labelle (2000).

No genuine age differences in the frequency of lead limb preference or dominance were found. In the ascent task, however, both age groups exhibited a 20% increase in limb dominance (same limb) in the fast walking velocity condition. In the descent task, the elderly increased dominance with velocity (≈ 20%), whereas the young exhibited a small decline (≈ 2%).

The previous findings show the elderly relied more upon a particular limb (increased limb dominance) when walking fast and descending the step. This suggests the elderly are more cautious when stepping down at fast velocity. This makes sense since investigations have reported steps and stairs to be the most common sites of a fall (≈ 34%) with approximately 80% occurring in descent (Templer, 1992; National Safety Council, 1985; 1994; Simoneau et al., 1991; Australian Bureau of Statistics, 1995a). In addition, fallers have cited "hurrying too much" as a reason for a fall (Australian Bureau of Statistics, 1995a; Berg et al., 1997).

To date, no investigation of obstructed gait has focused upon the issue of limb dominance or preference. It seems highly likely, however, that any population (e.g., elderly) who exhibits asymmetry in lower limb strength or functionality may exhibit greater limb dominance in obstructed terrain; for example: (1) elderly populations, or fallers in general, may exhibit limb dominance or asymmetry in obstructed gait. Interestingly, a longitudinal study by Hill et al. (1999) found a measure of gait symmetry (time difference between right and left stance duration) to be a strong predictor in identifying multiple fallers amongst a group of elderly; (2) there may be a threshold height of an obstacle or step where limb dominance becomes more or less prevalent; or (3) populations that favour a limb may be at greater risk of a fall or stumble. Future falls research should focus on these issues.

7.2 Regulation of gait velocity

7.2.1 Unobstructed condition

As expected, the young walked faster (≈ 6%) than the elderly in the unobstructed condition ($p < .01$). This finding merely supports previous work which has reported age-related reductions in walking velocity (e.g., Hageman & Blanke, 1986; Blanke & Hageman, 1989; Smidt, 1990; Whittle, 1991; Öberg et al., 1993; 1994; Ostrosky et al., 1994; McGibbon & Krebbs, 2001).

Each group's walking velocity fell within the normal range reported by past studies (e.g., Hageman & Blanke, 1986; Kaneko, Morimoto, Kimura, Fuchimoto & Fuchimoto, 1991; Whittle, 1991; Karst et al., 1999). This shows that participants were representative of their respective sub-groups within the general population.

7.2.2 Surface height condition

In this project, participants were instructed to complete the step tasks (descent and ascent) whilst walking at comfortable and fast velocities (both velocities were self-selected). Compared to the comfortable walking velocity condition, participants increased ($p < .001$) velocity by about 25% in the fast condition in both surface height conditions. This value falls within the range (20-25% increase) reported by previous studies (Cunningham et al., 1982; Smidt, 1990; Waters & Yakura, 1989; Karst et al., 1999).

In both surface height conditions, the step velocity of the elderly was found to be significantly lower ($p < .001$) than the young adults (refer to figure 7.2.2.1) throughout the approach (≈ 15% reduction) and crossing phases (≈ 33% reduction). This finding is supported by McFadyen and Prince (2002) who found elderly adult males to exhibit lower step velocities (1.28 $m{\cdot}s^{-1}$) than young adult males (1.55 $m{\cdot}s^{-1}$) when ascending a platform ($p < .01$).

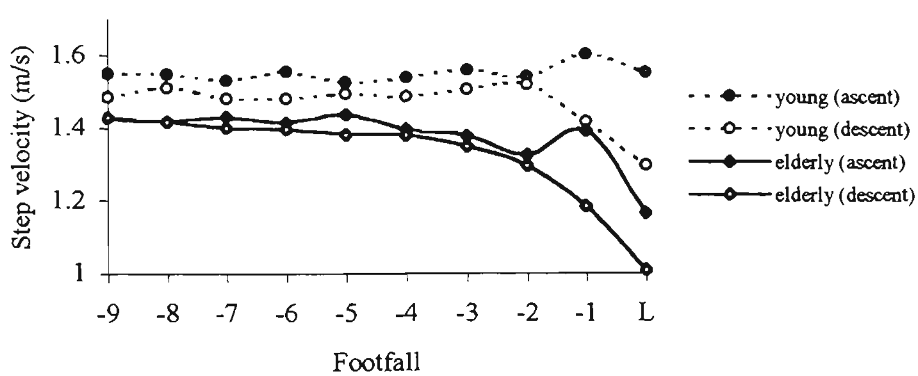


Figure 7.2.2.1 Step velocity for both surface height conditions (comfortable walking velocity).

Walking velocity was also estimated from a trunk marker as the lead foot crossed the step and landed. Again, these results show the elderly were slower (≈ 20-25%) in these phases ($p < .001$). In the comfortable velocity condition, the magnitude (1.4 $m{\cdot}s^{-1}$) of the young adults' horizontal crossing velocity was found to be greater than that (0.9 to 1.17 $m{\cdot}s^{-1}$) reported in previous obstacle avoidance and platform accommodation studies (e.g., Patla et al., 1996; Begg &

Lythgo, 1999c; Chou et al., 2001). The elderly adults' velocity of 1.1 $m \cdot s^{-1}$, however, fell within the range previously reported (e.g., Patla et al., 1996; Begg & Lythgo, 1999c; Chou et al., 2001).

The patterns of step velocity (refer to figure 7.2.2.1) throughout the approach and crossing phases were uniquely different across age but not velocity condition. In the descent task, the elderly showed small but systematic reductions (≈ 1.5%) from the 8th-last footfall with comparatively larger reductions (≈ 7%) in the last two steps. The young, however, only reduced step velocity (≈ 9%) in the penultimate and final steps. In the ascent task, the elderly showed small but systematic reductions (≈ 1.5%) in step velocity from the 4th-last footfall followed by an increase (≈ 4%) in the penultimate footfall, and a comparatively large reduction in the final footfall (≈ 14%). The young increased velocity in the penultimate footfall (≈ 3%) followed by a reduction (≈ 2.5%) in the final step.

The previous findings show that the young may be able to deal with steps better than the elderly since they can leave adjustment until the last moment. The elderly, however, exert more control or need more time in order to reduce velocity to accommodate a change in surface height. Descent appears to challenge the elderly more since step velocity adjustments began early in approach.

In the descent task, the elderly landed with less (≈ 25%) vertical velocity ($p < .001$). This parameter, however, increased by about 10% in the fast condition ($p < .001$). Interestingly, the magnitudes of this parameter are about double the magnitude reported for normal gait or when stepping over ($\approx$ -0.2 $m \cdot s^{-1}$ to -0.35 $m \cdot s^{-1}$) an obstacle (Chou et al., 2001). This supports the notion that a descent task involves greater load carriage or weight acceptance since greater vertical momentum (downward) must be arrested. This may heighten the risk of a fall or stumble in populations (e.g., elderly) who exhibit reduced lower limb strength or musculoskeletal control limitations (Whipple et al., 1987; Gehlsen & Whaley, 1990; Porter, Vandervoort & Lexell, 1995; Thelen, Schultz, Alexander & Ashton-Miller, 1996; Lamoureux et al., 2002) since they may not be able to safely attenuate an increased load (particularly under time critical conditions).

It has been shown that factors such as age, gender, gait speed, response time and lower extremity strength can affect a person's ability to regain balance after the onset of an unexpected perturbation (e.g., Thelen et al., 1997; Wojcik et al., 1999; 2001; Pavol et al., 2001). These studies also suggest the elderly have difficulty in suddenly accepting (with the recovery limb) weight forces greater than body weight; that is, the elderly have difficulty, or may even refuse, to rapidly load (eccentrically) the lower limb musculature. This was evidenced in a series of forward lean studies (Thelen et al., 1997; Wojcik et al., 1999; 2001) where it was proposed that the elderly may have improved their success rate if allowed to take more than one step to regain balance. It would be interesting to examine the number of footfalls or amount of time required for individuals to return to a normal walking pattern after accommodating a step or obstacle.

These measures may provide further insight into the integrity of the locomotor system. Unfortunately, this matter was outside the scope of this project.

The results support the findings of previous work; that is, comfortable or natural walking velocity reduces with age (Hageman & Blanke, 1986; Blanke & Hageman, 1989; Smidt, 1990; Whittle, 1991; Öberg et al., 1993; 1994; Ostrosky et al., 1994; McGibbon & Krebbs, 2001). In addition, this project found age-related reductions in walking velocity to occur in terrain containing a step representative of a door threshold or kerb.

7.3 Footfall

7.3.1 Footfall variability (amount and pattern)

To date, no study has comprehensively examined footfall patterns of elderly adults in obstructed terrain. As such, this project is unique since it is the first investigation to examine this issue across age and walking velocity. Another unique aspect of this project was the adoption of a method to examine how gait is regulated in an accommodation task. This method was drawn from investigations of the long jump that found an ascending-descending pattern of footfall variability (refer to figure 2.3.3.3.2) across three jumps (e.g., Lee et al., 1982; Hay, 1988; Berg et al., 1994; Berg & Greer, 1995; Scott et al., 1997; Galloway & Connor, 1999; Montagne et al., 2000). According to investigators, the ascending part of this pattern (accelerative phase) reflects small inconsistencies in stride length which cause a build-up of footfall variability (Lee et al., 1982; Scott et al., 1997), whereas the descending part represents a zeroing-in or targeting phase where gait is regulated or controlled by the visual system. The point of maximum footfall variability was defined to be the "visual switch point" or the point where gait is regulated by the visual system. This point was found to about 4 to 5 steps from the take-off board.

In each step-velocity condition, small reductions (2 to 3% reductions) in mean footfall variability were exhibited by both age groups from the 10th to 3rd-last footfall (refer to figures 7.3.1.1 and 7.3.1.2). Large reductions (average reduction of 21%), however, were found from the 3rd-last to penultimate footfall with the elderly exhibiting a larger average reduction (26%) than the young (16%) in this interval. The magnitude of the early reductions may reflect variation in the adopted start position coupled with minor inconsistencies in stride length. Equally, these reductions may represent a period where gait is gradually and continuously regulated. The period of large reductions, however, suggest gait is being regulated by the visual system with the "visual switch point" occurring at the 3rd-last footfall.

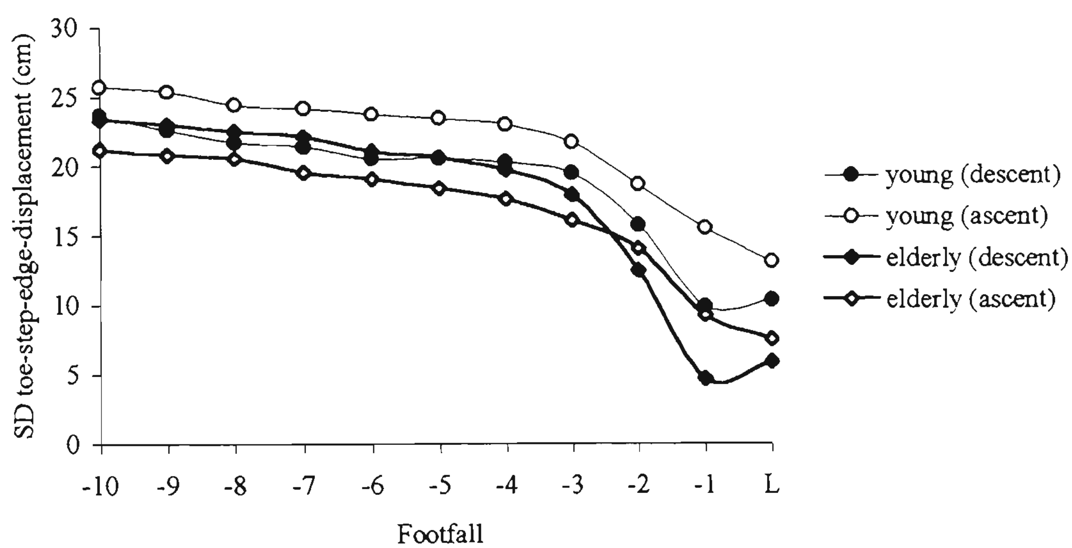


Figure 7.3.1.1 Mean variability plots of toe-to-step-edge displacement for the step ascent and descent tasks (comfortable walking velocity).

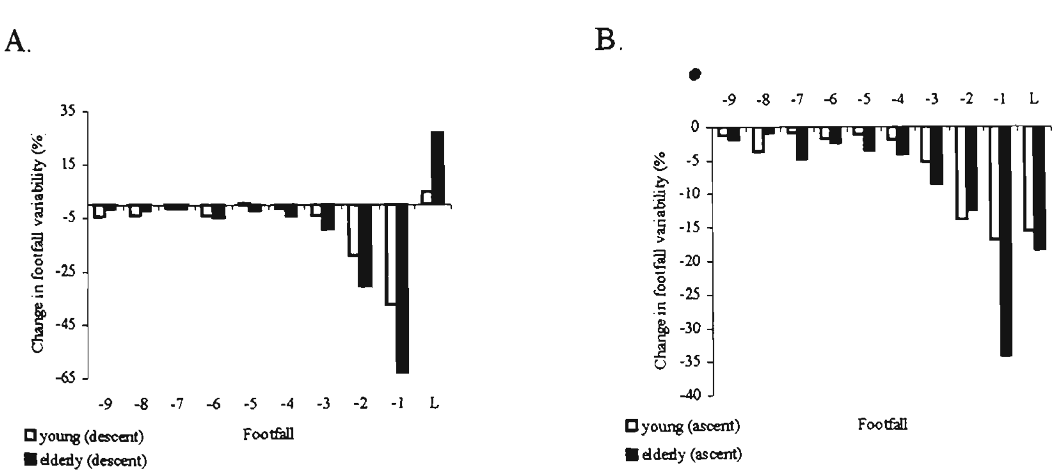


Figure 7.3.1.2 Mean percentage change in footfall variability found across age and step tasks (comfortable walking velocity). A. Descent task. B. Ascent task.

Inspection of the individual plots of footfall variability revealed four distinct patterns (refer to figure 7.3.1.3). In general, these patterns were not more prevalent within an age group or step-velocity condition. Firstly, 52% of the plots displayed a descending pattern with small reductions (≈ 5%) from the 10th to 3rd-last footfall followed by larger reductions (21 to 35%) from the 3rd-last to penultimate footfall. Secondly, 45% displayed the ascending-descending pattern described by Lee et al. (1982). This pattern showed small increases (≈ 5%) from the 10th to 4th-last footfall followed by reductions (1 to 31%) from the 4th -last to penultimate footfall. Thirdly, 3% displayed relatively low variability (≈ 4 cm) but showed large increases (20 to 44%) from the 2nd-last to final footfall. Lastly, in the fast-velocity descent condition, a young participant exhibited high variability (≈ 40 cm) with only small changes (less than 4%) throughout.

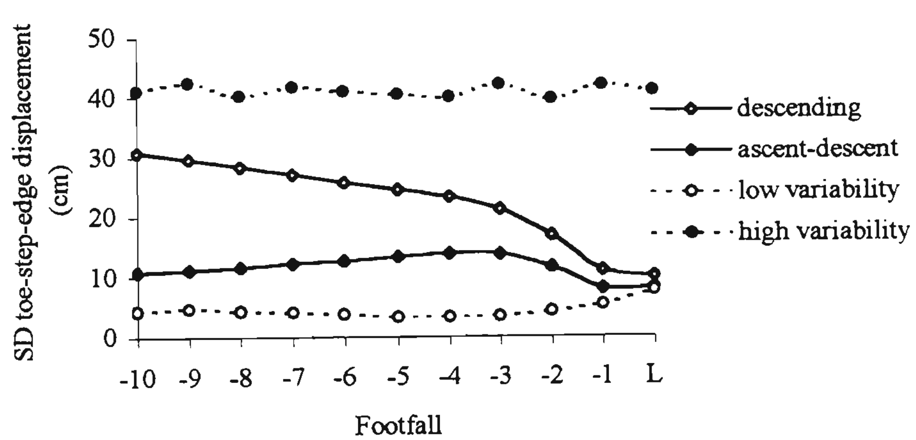


Figure 7.3.1.3 The four patterns of footfall variability exhibited by participants in this project.

The descending pattern of footfall variability most likely reflects high variation in the adopted starting position coupled with early visual regulation of gait in order to spread adjustment throughout the approach to the step. The ascending-descending pattern, however, most likely reflects small variation in the adopted start position coupled with late regulation of gait from the 3rd-last footfall. The ascent part of this pattern may also represent a period of acceleration since footfall accuracy should reduce with speed. This is consistent with the speed-accuracy trade-off principle in the field of motor control (Bradshaw & Sparrow, 2000; 2001).

It is recognized that experimental error contributed to the variation found in the footfall data. An instrument reliability study conducted in the early stages of this project (refer to Chapter 4) found the likely error to be about 5 mm (SD = 2.5 mm). It is highly unlikely, however, that the variation (10 to 25 mm) found in footfall variability was significantly affected by experimental error since it is 5 to 10 times the magnitude of the error. Additionally, the adjustments are systematic, hence it seems reasonable to conclude that the majority of participants made minor adjustments in the early stages of the step tasks.

The pattern of low footfall variability shown in figure 7.3.1.3 is representative of stereotypic behaviour; that is, a learned response has been employed in each trial. Interestingly, the pattern does not display a reduction in the last few footfalls. The low variability employed throughout the approach, however, most likely negates the necessity for a reduction in the last few steps (Scott et al., 1997). Variability in the final footfall (7.5 cm) is similar to the previous patterns (9.1 cm) discussed. This suggests that gait was still regulated by the visual system.

The pattern of high variation (refer to figure 7.3.1.3) exhibited by a young participant in the descent task suggests diminished visual control. High variation adopted from the starting position is maintained throughout the task. This suggests that the participant's behaviour is not stereotypical but highly variable.

The differing patterns of footfall variability observed in this project have been reported in the long jump literature (e.g., Lee et al., 1982; Hay, 1988; Hay & Koh, 1988; Berg et al., 1994; Berg & Greer, 1995; Scott et al., 1997; Galloway & Connor, 1999; Montagne et al., 2000). The most ubiquitous being an ascending-descending pattern coupled with marked and systematic reductions from the 4th or 5th-last footfall. Gait regulation strategies used to perform the long jump, therefore, are adopted in accommodation tasks (e.g., stepping off a kerb). This makes sense since both activities require targeting. In a step task, people need to target an area near the step in order to safely cross it (e.g., avoid a misstep), whereas in the long jump event the take-off board needs to be targeted in order to maximize performance.

Compared to the long jump approach, the onset of visual control occurred a step or two later (3rd-last footfall) in the step tasks. This difference in the position of the "visual switch point" is most likely related to the differing gait velocities of the activities. It follows that control would be established earlier in the long jump approach since higher gait velocities are achieved. Such velocities reduce the time available, particularly in the last few steps, to make the necessary adjustments in order to place the preferred limb within the bounds of the take-off board. Visual control, therefore, emerges a step earlier so as to allow adequate time for step adjustment (Bradshaw & Sparrow, 2001).

In this project, footfall variability was generally not affected by walking velocity. The elderly, however, showed an average 18% reduction ($p < .001$) in the interval bounded by the 10^{th} to 2^{nd}-last footfall in the fast-velocity-descent condition. This finding suggests the elderly exert more control over gait or are more cautious in this activity. This makes sense since this task has been directly linked to falls (Templer, 1992; National Safety Council, 1985; 1994; Simoneau et al., 1991; Australian Bureau of Statistics, 1995a; Berg et al., 1997).

The elderly were found (compared to the young) to exhibit significantly less footfall variability ($p < .05$) throughout various stages of the step tasks. This was especially the case in the interval bounded by the 2^{nd}-last to final footfall. Once again, these findings support the notion that the elderly exerted more control. This outcome is not surprising since the consequences of a misstep (e.g., a fall or stumble) are more serious for the elderly (e.g., Lord, 1990).

For the majority of participants, it is reasonable to conclude that the onset of visual control occurs around 2 to 3 steps from the edge of the step. This supports the previous work conducted by Crosbie (1996), Lythgo and Begg (1999b) and Bradshaw and Sparrow (2001). In addition, this finding is partly supported by the head orientation data extracted in this project. These data showed both groups rotated the head downwards 2 to 3 steps from the step edge. The elderly were found to begin this movement earlier (a step duration ≈ 0.5 s) than the young adults.

Any distraction or division of attention near the point of visual control may jeopardize dynamic stability. Any delay in exerting control may result in a misstep or loss of balance. This danger is heightened when walking fast since less time would be available to make adjustments.

7.3.2 Foot placement in the crossing stride

In the descent task (comfortable and fast walking velocity), the elderly were found to place the heel of the lead foot (*LHD* ≈ 32 cm) closer to the step ($p < .001$) than the young adults (≈ 50 cm). The placement of the trail foot (*TD*), however, was found to be relatively consistent or invariant across age and velocity (refer to figure 7.3.2.1). Participants placed the trail foot close to the step or about 8 cm from it. Interestingly, the young adults exhibited more variability in this parameter ($p < .05$). This explains the high incidence of partial foot placement on the step (foot partly supported by the step) exhibited by the young adults (33% of trials) compared to the elderly (16% of trials). Interestingly, neither of these sub-groups were at greater risk of a misstep (foot collapse due to inadequate step support) since both placed the foot so that approximately 90% of it was supported by the step.

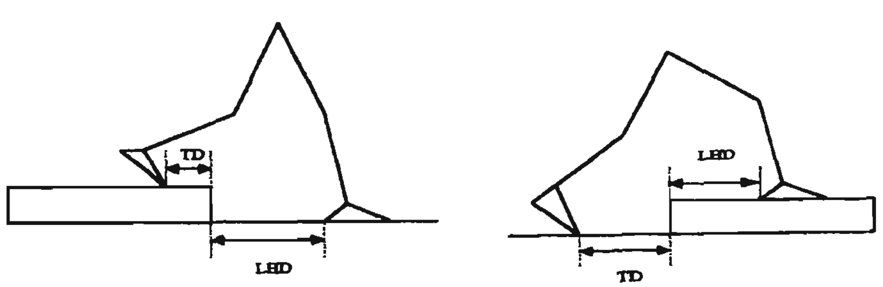


Figure 7.3.2.1 Measures of foot placement (*TD*, *LHD*) collected in this project.

The closer placement of the lead foot to the step (*LHD*) by the elderly can be partly explained by their reduced crossing step length. In both velocity conditions highly significant correlations (CWV: $r = 0.74$; FWV: $r = 0.84$, $p < .001$) were found between these variables. Interestingly, however, the leg lengths of the young and elderly were not found to differ, hence, the elderly appear to deliberately land the foot closer to the step.

The findings show that adults (young and elderly) target a specific region near a step for the placement of the trail foot. Such an action most likely affords more crossing options since the lead foot can be placed further from the step (reducing the chance of a misstep) or be orientated for a forefoot or heel landing. It appears that the elderly as a group are more cautious or exert more control in the placement of the trail limb. Compared to the young adults, the elderly reduced the incidence of the foot being partly supported by the step and targeted a narrower region near the step. This makes sense as partial foot placement on the step may heighten the risk of a stumble or fall since the trail limb may collapse due to inadequate support.

In the ascent task, the elderly placed their feet (*TD* $\approx$ 35 cm, *LHD* $\approx$ 9 cm) closer ($\approx$ 9 cm) to the step than the young adults ($p < .001$). In addition, more of the elderly (20%) exhibited partial foot placement (lead foot partly supported by the step) on the step compared to the young adults (3%). On average (across all conditions), this sub-group of the elderly placed the foot so that 76% (SD = 12.4%) of it was supported by the step, whereas the sub-group of young adults placed the foot so that 98.4 % (SD = 0.4%) of it was supported. Overall, these findings suggest the elderly as a group are at greater risk of misstep since they target a region near the step for the placement of the lead foot. Additionally, a sub-group of the elderly appear to be at greater risk of a misstep since they target the step edge. A perceptual error (misjudging the step position) may lead to inadequate support of the foot that may result in a stumble or fall.

Recently, in a platform ascent task (height: 11.75 cm), McFadyen and Prince (2002) found adult males (elderly and young) to place the trail foot (*TD*) about 34 cm from the step and land the heel of the lead foot (*LHD*) about 26 cm (SD $\approx$ 8 cm) past it. This finding, coupled with the outcomes of this study, suggests female adults are at greater risk of a misstep since they land the lead foot closer to a step. This outcome may be related to the short crossing stride of the females. In this study, the females' crossing strides were about 10 cm less than the male participants in the study by McFadyen and Prince.

This research found the elderly to take shorter crossing steps (about 23% shorter) than the young adults ($p < .001$). In fact, discriminant analyses revealed crossing step length to account the most for age differences in the average score profiles across all step conditions. Any restriction of step length constrains foot placement. In order to employ a short crossing step, for example, the trail or lead foot must be placed close to a step. Such actions, however, are undesirable since they have been directly linked to missteps and unwanted foot contact with an obstacle (Chen et al., 1991; Chou & Draganich, 1998a; 1998b). Once again, it appears that the elderly are at greater risk of a misstep because of a reduced capacity or unwillingness to take a crossing step of similar magnitude to the young. This was aptly demonstrated when an elderly participant accidentally lowered the lead foot onto the step so that only 10% of the foot was supported (a misstep). This caused the foot to suddenly plantarflex (plantarflexion moment) and led to a stumble but not a fall.

In the descent task, forefoot landings occurred in 97% and 62% of the elderly and young adult trials respectively. Although both groups chose to land on the heel (positive foot orientation) in the ascent task, the foot orientation of the elderly was about half the magnitude ($\approx 14°$) of the young ($\approx 26°$). Interestingly, the foot orientation exhibited by the elderly can only be achieved by employing a short crossing step. As such, this partly explains their shortened crossing step.

The previous findings suggest that trail foot placement further from the step coupled with a desire to land on the forefoot may increase the chance of a misstep. This is supported by the fact that the elderly adult who accidentally lowered the lead foot onto the step (descent task) placed the trail foot 22.5 cm (*TD*) from the step and then attempted to ground the forefoot of the lead limb. On average, participants placed the trail foot about 8 cm from the step.

Further inspection of lead foot clearance and placement data for the descent task (refer to table 6.5.3.1.1.3) revealed significant differences between the participants who exhibited a forefoot and heel landing. In the comfortable velocity condition, lead toe clearance was found to be significantly less in the group who landed on the forefoot (forefoot landing = 2.5 cm; heel landing = 3.4 cm, $p < .025$). Forefoot landers also placed the heel closer (about 25 cm) to the step than the heel landers ($p < .001$) after crossing the step. These findings suggest that forefoot landers may be at greater risk of unwanted foot contact or a misstep since both lead foot clearance and placement are reduced.

A unique aspect of this project involved walking velocity variation (comfortable and fast). Essentially, lead heel-step-distance (*LHD*) and crossing step length increased with velocity ($p < .01$), whereas trail foot placement (*TD*) was unaffected. The later finding reinforces the idea that trail foot placement is essentially invariant in accommodation tasks; that is, specific regions near a step are targeted irrespective of walking velocity.

The findings of this study are consistent with the outcomes of previous accommodation work (e.g., Lythgo & Begg, 1999c; Begg & Sparrow, 2000; McFadyen & Prince, 2002); that is, elderly adults (compared to young adults): (1) place the lead foot (in the crossing step) close to a step; (2) exhibit less footfall variability; and, (3) primarily employ a short crossing step. Finally, compared to an ascent task, adults (young and elderly) place the trail foot close to a step ($\approx$ 7 to 8 cm) when descending it.

7.3.3 Stepping strategies

As expected, each participant employed a transport phase (negligible step length adjustment) in the early stages of the approach. This phase continued in 30% of the trials and shows that some participants accommodate a step (ascent and descent) with minimal adjustment. Put simply, these participants "took it in their stride". In the remaining trials three distinct patterns of step adjustment emerged in the last few footfalls (refer to tables 6.5.4.6.1 and 6.6.4.5.1). Participants modified normal step length by either taking (1) long steps, (2) short steps or (3) a combination of short and long steps (refer to figure 7.3.3.1). On average, step adjustment emerged in the penultimate step with some participants making adjustments as early as the 4th-last step. No age or velocity differences in the point of this emergent behaviour were evident.

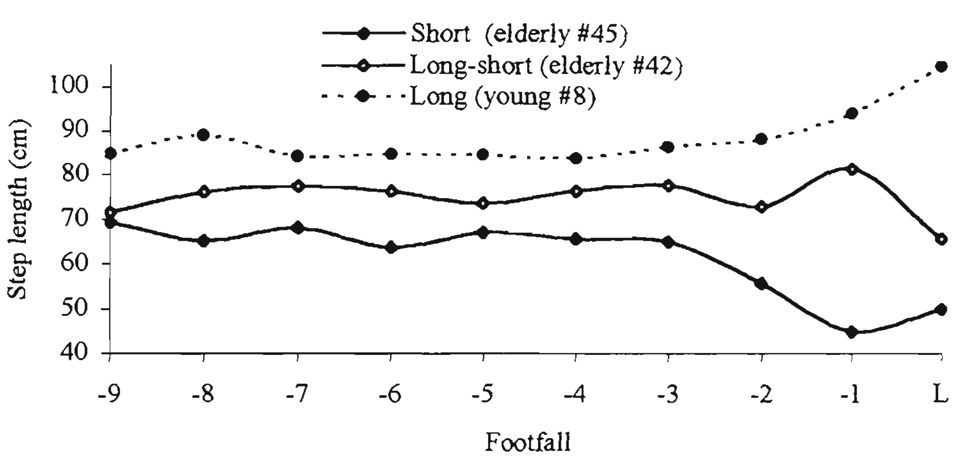


Figure 7.3.3.1 Examples of the three distinct patterns of step adjustment exhibited by 3 participants. Last footfall (L).

The predominant stepping responses (refer to table 7.3.3.1) employed by the elderly were a short (60% of trials) and normal (25%) step strategy. On the other hand, the predominant stepping responses employed by the young were a long (37% of trials) and normal (35%) step strategy. The young only employed a short step strategy in 19% of the trials. These findings are important since previous obstacle avoidance work has suggested that the chances of a misstep are heightened when a short step strategy is employed (Chen et al., 1994b). It has also been suggested that a short step strategy is inherently dangerous since the body may be placed in an unstable position where the centre of mass is further forward of the base of support.

Table 7.3.3.1 Frequency of stepping strategies.

Step Strategy	**Elderly(%)**	**Young (%)**
Long	9%	37%
Mixed (short-long)	6%	9%
Short	60%	19%
Normal	25%	35%

The short step strategy commonly employed by the elderly appears to heighten the chance of a fall. Such a strategy increases the risk of a misstep or stumble from which they may not be able to regain balance as readily as young adults. Previous work involving sudden stop and turn tasks has shown the elderly need more time to arrest or control forward momentum (Cao et al., 1997; 1998a; 1998b). Studies have also shown that elderly females have a reduced capacity (lower step velocity and longer reaction times) to recover from an unexpected release from a forward leaning position (Wojcik et al., 1999), therefore, should a misstep occur, it is reasonable to conclude that an elderly person may experience more difficulty in regaining balance.

The elderly were found to make large step adjustments (up to twice the magnitude of the young) over the last few footfalls in both step tasks (refer to figures 6.5.4.5.4 and 6.6.4.4.4). This may be the result of a failure to exert adequate control early in the approach to the step or it may represent a gradual slowing of the body since the elderly's predominant stepping response was a short step strategy (refer to table 7.3.3.1). This makes sense since it is probably easier to make these adjustments (or even stop) when moving at slower velocities. In addition, the slower velocity most likely allows greater control of the position of the body's centre of mass; that is, the centre of mass could be "held back" within the base of support until the lead limb is firmly grounded. This action, however, may also be dangerous since a shortened step may inadvertently place the centre of mass outside the base of support, or a over a smaller base of support, when a person is near a step edge.

The step strategies found in this project are generally consistent with the findings reported in previous work (Chen et al., 1994b; Crosbie, 1996; Lythgo & Begg 1999b). Interestingly, a study by Crosbie (1996) only found (1) a short-long step strategy when ascending a kerb (height: 15 cm), and (2) a long step strategy when descending the kerb. The differing strategies observed in this project are most likely due to the larger sample size (n = 96) and age range of the participants (18 to 77 yrs.). Crosbie's work involved 20 adults who were 50 years of age or less.

7.4 Dynamic stability

7.4.1 Landing

In this project, participants (particularly the elderly) primarily landed on the forefoot when descending the step (elderly ≈ 97%, young ≈ 62%) and the heel when ascending it (elderly ≈ 91%, young ≈ 100%). These findings suggest greater caution or control is exerted (particularly by the elderly) when descending a step since a forefoot landing most likely: (1) allows greater attenuation of impact forces (Scholten, Stergiou, Hreljac, Houser, Blanke & Alberts, 2002); (2) provides more options (e.g., braking and propulsive) should a slip or loss of balance occur (Lythgo & Begg, 1999a); (3) provides a longer period of double foot support in the crossing stride. Forefoot landers exhibited periods of double foot support about 20% longer (≈ 12 ms) than heel landers; and, (4) lessens the vertical momentum attained by the body. The last notion is readily supported by the fact that forefoot landers exhibited less (average reductions ≈ 20%, $p < .05$) vertical velocity of the trunk marker (v_y) than those who landed on the heel (refer to figure 7.4.1.1).

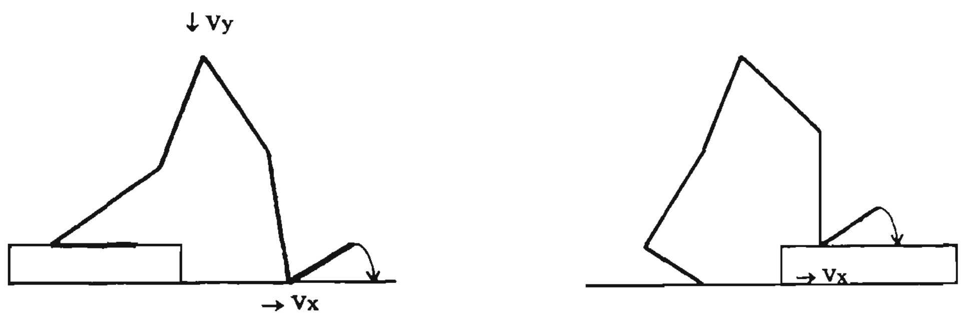


Figure 7.4.1.1 Landing measures collected in this study for the descent (left panel) and ascent tasks.

Upon landing, the magnitude of the horizontal velocity of the lead foot (v_x) was found to differ across age, landing strategy (forefoot or heel) and step task (refer to figure 7.4.1.1). When descending the step, for example, the elderly landed with a foot velocity about a third of the magnitude ($\approx 0.16\ m \cdot s^{-1}$) of the young adults ($p < .001$). The velocity of the young adults who landed on the forefoot was also found to be less or about two-thirds the magnitude exhibited by the young adults who landed on the heel ($p < .05$). When ascending the step, the velocity did not differ across age but was about 5 to 6 times the magnitude exhibited by the elderly in descent. Overall, these findings show that when descending a step a forefoot landing minimizes the horizontal velocity of the foot Clearly, this demonstrates greater caution (particularly by the elderly) in this task since it is recognized that lower horizontal foot velocities upon landing minimize the chance of a slip (Patla & Rietdyk, 1993; Winter, 1987).

In the ascent task, foot velocity (v_x) remained essentially unchanged across walking velocity conditions (comfortable and fast). In descent, however, participants increased foot velocity by about 60% ($p < .002$). Hence, it is reasonable to conclude that fast walking velocities increase the chance of a slip when descending a step.

The foot velocities (v_x) found in both step tasks are significantly higher ($\approx$ 3 to 20 times) than those reported in an obstacle avoidance study (Patla & Rietdyk, 1993). Values of about $-0.05\ m \cdot s^{-1}$ were reported for a group of young adults avoiding obstacles of varying height and width (6.7, 13.4, 26.8 cm). This suggests that the chance of slip may be greater in accommodation tasks (compared to avoiding obstacles) since these tasks elicit higher foot velocities.

In the descent task, the foot velocity (v_x) exhibited by the participants was significantly lower than velocities (0.5 to 1.0 $m \cdot s^{-1}$) reported for young and elderly adults whilst free walking (Winter, 1987; Karst et al., 1999). In ascent, however, foot velocity was essentially maintained or was similar to that exhibited in free walking. Overall, this supports the notion that descent tasks are more challenging or pose a greater threat to dynamic stability since the response is more cautious.

7.4.2 Crossing

Figure 7.4.2.1 illustrates the variables discussed in this section. As such the reader should refer to this figure for the following discussion.

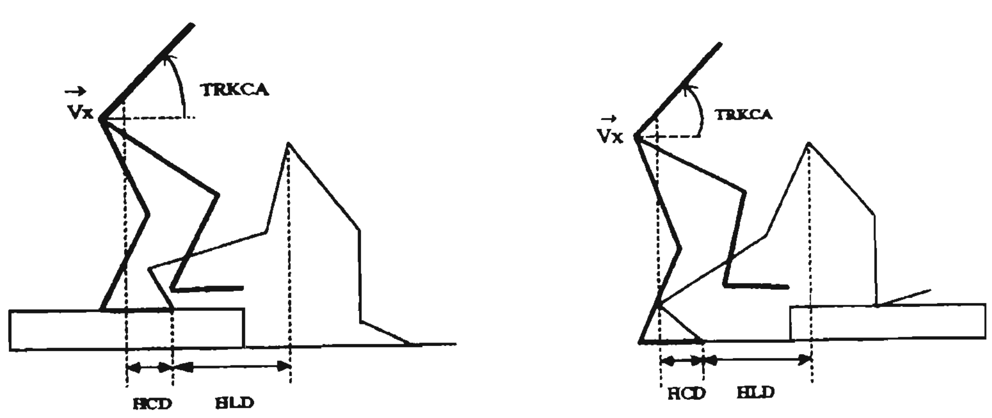


Figure 7.4.2.1 Some of the dynamic stability measures (*HCD*, *HLD*, *TRKCA*) collected in this study. Left panel: descent task. Right panel: ascent task.

In this study, a single point on the trunk was used to represent the location of the whole body centre of mass (*COM*). Although this appears to be a limitation, previous work has shown that single points on the trunk (sacrum region) provide reliable information about the motion of the centre of mass in walking tasks (e.g., Thirunarayan et al., 1996). In fact, studies of gait have commonly employed methodologies where a marker on the trunk (sacrum, hip or pelvis regions) has been used to represent the body's centre of mass (e.g., Cotes, & Meade, 1960; Patla & Rietdyk, 1993; Kerrigan et al., 1995; Duff-Raffaele et al., 1996; Saini et al., 1998; Lythgo & Begg, 1999c).

The trunk marker was found to be "held back" or within the base of support (i.e., over the trail foot) as the lead toe crossed the step (*HCD*). As expected, the elderly "held it" further back (elderly ≈ 9.3 cm, young ≈ 6.5 cm, $p < .05$) and exhibited less forward trunk lean (*TRKCA*) than the young adults; the forward trunk lean of the elderly was only significantly less (or about 3° less) in the descent task ($p < .001$). These findings suggest the participants were cautious (particularly the elderly) when accommodating the step since they held the trunk marker behind or within the base of support as the lead foot crossed the step. Such an action serves to increase the time available to regain balance should unwanted foot contact occur.

The trunk marker positions (at the time of lead foot crossing) found in this project are consistent with previous work. Lythgo and Begg (1999c), for example, similarly found elderly adults (compared to young adults) to hold a trunk marker (nominal *COM* position) further back or within the base of support when accommodating a step. Significant age differences, however, were not found in this study and was probably due to the small number of participants (n = 12). Similar findings have been reported in obstacle avoidance studies involving young adults. These studies found a hip marker as the body's centre of mass and to be "held back" or behind the location of the toe of the trail foot until the lead toe reached the top of an obstacle (Patla & Rietdyk, 1993; Liu et al., 1996).

The position of the trunk marker was found to be well forward of the base of support (trail toe) by the time the lead foot landed (*HLD*) with the young positioning it further forward (≈ 10 cm) in both step tasks ($p < .001$). Interestingly, a small group of the elderly (n = 5) held the trunk marker within the base of support (≈ 1.3 cm) until the lead foot was grounded in the ascent task. A comparison of the position of this group's trunk marker at the time of lead foot crossing (*HCD*) to the remainder of the elderly participants (n = 43) revealed significant differences ($p < .002$). This group positioned the trunk marker about 17 cm behind the trail toe whilst the remaining elderly adults positioned it about 10 cm behind. These findings suggest some elderly act with greater caution since they hold the body further back or within the base of support throughout the crossing stride. This strategy probably lessens the threat to stability should the lead foot unexpectedly contact the step. That is, a person may be able to use the support limb to regain balance should unwanted foot contact occur.

The elderly were found to allow more time to respond to an unexpected perturbation (e.g., unwanted foot-step contact). Essentially, they employed a crossing strategy where the available response time (*ART*) was about twice the magnitude of the young ($p < .001$). The available response time is simply the amount of time (predicted from walking velocity and horizontal displacement of the trunk marker from the trail toe) until the trunk marker moves forward of the base of support (refer to Figure 5.4.1.1). In the comfortable velocity condition, the *ART* of the elderly and young was approximately 105 ms and 61 ms respectively. In the fast velocity conditions, these values reduced to around 68 ms and 36 ms respectively. Both age groups exhibited a significant reduction in *ART* ($p < .001$) with velocity. As expected, this shows that the time available to respond to an unexpected perturbation reduces as walking velocity increases.

Clearly, the elderly's increased available response time can be related to the reduced crossing velocity (v_x) exhibited by them ($p < .001$). However, it may also demonstrate that the elderly allow more time to regain balance (by positioning the trunk marker further back) should unwanted lead foot contact occur with the step. Past studies have demonstrated that elderly adults need more time (≈ 30 to 80 ms) to deal with a perturbation. Studies, for example, have shown the elderly need more time to: (1) suddenly turn or arrest forward momentum (Cao et al., 1997; 1998a; 1998b); (2) avoid the sudden appearance of an obstacle (Chen et al., 1994a; 1996; Pavol et al., 1999); or (3) complete a single-rapid-step-up task (Stemmons Mercer et al., 1997). Other studies have shown the elderly exhibit lower step velocity and longer reaction times (about 20 ms longer) when recovering from an unexpected release from a forward leaning position (e.g., Wojcik et al., 1999). Hence, the increased available response time exhibited by the elderly may reflect their need to provide more time to deal with a perturbation.

Compared to the ascent task, the participants were found to spend less time (≈ 40 ms) of the crossing stride in double foot support ($p < .001$) and more time in single limb support (≈ 60 ms) when descending the step ($p < .001$). Significant reductions (≈ 30 ms) in these parameters were found with increased walking velocity across both step tasks ($p < .001$). Hence, it would appear that a descent task is a greater challenge to dynamic stability (particularly when walking fast) since it reduces the period of double foot support and increases the period of single limb support.

It is important to recognize that the measures of double foot support time most likely contain large error due to the sample rate (50 Hz) of the cameras used in this study to capture motion. Generally, these measures were found to fall around 90 ms. Failure to capture the actual event of foot landing or take-off, however, would result in an over or underestimation of *DFST*; this error may reach magnitudes of up to 20 ms (≈ 22% error). The likely error contained in the measure of single limb support time, however, falls below 5% since the magnitude of this parameter fell around 430 ms.

Lastly, the young adults (compared to the elderly) showed greater stabilization of the head throughout the step tasks. They exhibited head pitches of about -10° (head tilted forward) whereas the young exhibited pitches of -7 to -9°. This suggests the elderly may be more cautious or may have a reduced ability to attenuate head movement. The later outcome is undesirable since large head movements may result in a loss of balance or degrade visual information required to prevent a misstep (Grossman et al., 1988, Patla, 1997; Cromwell & Wellmon, 2001). Interestingly, the head orientations exhibited by the participants were lower (about half) than those reported for stair climbing (Cromwell & Wellmon, 2001). Hence, it appears that a single step doesn't require the magnitude of head movement needed for staircase climbing.

7.5 Foot trajectory and orientation

7.5.1 Foot-step-clearance

Foot clearance measures were only marginally affected by walking velocity. For instance, toe and heel-step-clearances increased by around 0.3 and 1.6 cm ($p < .001$) respectively in both step tasks. Interestingly, the variability of the elderly's lead toe-step-clearance (*LTC*) measure increased with velocity by a factor of 33% in ascent ($p < .05$) and 20% in descent. Variability, however, remained essentially unchanged for the young adults and for all other measures of foot clearance (e.g., heel step-clearance). These findings suggest the elderly exhibit less control (or more variability) of the lead limb endpoint when accommodating a step at fast velocity, whereas the young adults control is unaffected. This finding is partly supported by an investigation conducted by

Karst et al. (1999) who found the variability of toe-ground-clearance in a group of elderly females to increase (≈ 8%) with walking velocity over level ground.

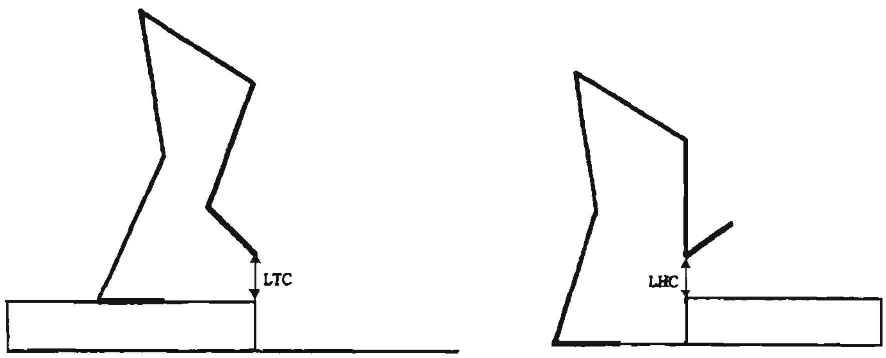


Figure 7.5.1.1 Foot clearance measures (*LTC*, *LHC*) collected in this project. Left panel: descent task. Right panel: ascent task.

The risk of unwanted foot contact with the step was found to be greater in the descent task. Significantly lower ($p < .001$) lead toe-step-clearances, for example, were found in descent (*LTC* ≈ 2.7 cm) than in ascent (*LTC* ≈ 8.2 cm). Although no significant age difference in lead toe-step-clearance was found in the descent task, the elderly did exhibit clearances (2.9 cm) around 0.4 cm higher than the young adults (2.5 cm). The chance of unwanted toe contact (refer to section 5.5.3.5) when descending the step was estimated to be about 4% across both age groups (both age group's data were found to exhibit normality). Hence, neither group appears to be at greater risk of unwanted lead toe contact when descending a step.

Overall, the trail toe was found to clear the step by the lowest margin in both step tasks (descent = 1.8 cm, ascent = 4.6 cm). Interestingly, whilst descending the step the elderly cleared it (with the trail toe) by a lesser margin (≈ 0.5 cm less) in both velocity conditions. When walking at comfortable velocity the elderly, for example, cleared it by 1.3 cm, whereas the young adults cleared it by 1.9 cm ($p < .003$). An examination of the distribution of these data showed the elderly distribution to be non-normal ($p < .01$) and exhibit a positive skewness and kurtosis (leptokurtic), whereas the young data exhibited normality. This shows that the elderly as a group are at greater risk of trail toe contact since the majority of them clear the step by a small margin. If normality was assumed for the elderly data, the chance of trail toe contact would fall around 16% compared to 10% for the young adults.

Lead and trail heel-step-clearances fell around 5 and 21 cm respectively across step tasks. Interestingly, the lowest lead heel-step-clearances were exhibited by the elderly in descent ($p < .05$). Hence, they appear to be a greater risk of lead heel contact since they cleared the step by a smaller margin (≈ 3.9 cm) than the young (≈ 4.7 cm). Since both age group's data exhibited normality, the probability of lead heel contact was estimated to fall around 3.8% for the elderly and 2.9% for the young.

A limitation of this project involved the adoption of planar analysis (2D motion analysis) to extract foot clearance measures. Although this method is suitable for extracting clearance measures from markers located on the lateral aspect of a crossing foot (anatomical toe and heel regions), some error is introduced when clearance measures are extracted from markers located on the medial aspect of a crossing foot (refer to section 7.1.3). Since it is widely accepted that the foot is slightly supinated or inverted (≈ 1°) in the midswing of the gait cycle (e.g., Smidt, 1990; Whittle, 1991), it is reasonable to assume that the lateral aspect of the foot will clear a step by the least margin. Hence, clearances obtained from the markers located on the medial aspect of the crossing foot may overestimate measures of foot clearance. This error, however, is likely to be small or in the order of 1.0 mm since lateral and medial foot markers (toe and heel regions) were located about 6 cm apart. Unfortunately, this is a limitation of both 2D and 3D motion analysis. The toe and heel regions of the foot, however, have been commonly used to extract foot clearances in obstructed and unobstructed gait (e.g., Winter et al., 1990; Simoneau et al., 1991; Winter, 1991; 1992; McFadyen et al., 1993; Patla & Rietdyk, 1993; Patla et al., 1996; Sparrow et al., 1997; Austin et al., 1999; Karst et al., 1999; Begg & Sparrow, 2000; Krell & Patla, 2002; McFadyen & Prince, 2002).

Overall, the foot clearances found in this project are consistent with the literature. Riener et al. (2002), for example, reported toe clearance for a group of young adults to be about 7 cm in stair ascent, whereas Simoneau et al. (1991) reported foot clearance (sole of foot) for a group of elderly adults to be about 2.6 cm in stair descent. As with this project, Begg and Sparrow (2000) found measures of foot clearance to be lower in platform descent (≈ 2 cm) compared to ascent (≈ 9 cm). In a recent study involving a platform ascent task (male participants), McFadyen and Prince (2002) found an age-related reduction ($p < .05$) in lead toe-step-clearance (elderly ≈ 6 cm, young ≈ 7.5 cm) but no significant age difference was found in trail toe-step-clearance (elderly ≈ 2 cm, young ≈ 3 cm). Obstacle avoidance studies have reported toe-obstacle-clearances of about 10 cm (Chen et al., 1991; Watanabe & Miyakawa, 1991; Patla &

Rietdyk, 1993; Patla & Prentice, 1995; Patla et al., 1996; Austin et al., 1999; McFadyen & Prince, 2002). These values are similar to the toe-step-clearances reported for platform ascent tasks. Hence, it appears that platform (or step) ascent and obstacle avoidance tasks elicit similar foot clearance responses. This shows that platform (or step) descent tasks are probably more dangerous since the margin for clearance is relatively small.

Generally, this project found the elderly to exhibit the lowest foot clearances. This finding suggests that they are at greater risk of unwanted foot contact with a step. This is especially so when descending a step, where toe clearances were at least half the magnitude found in ascent. Lead limb toe contact in ascent, however, still poses a serious threat to dynamic stability since forward progression of the foot would be fully arrested, whereas in descent the forward progression of the foot may not be fully arrested but slowed as the foot drags along or "brushes" the top surface of the step. A misstep, however, may result in the downward motion of the foot being arrested in descent. In fact, a misstep by an elderly participant led to the lead heel being grounded on the step. This caused the participant to stumble but not fall.

7.5.2 Foot trajectory

Ensemble average plots of the vertical trajectory of the lead toe (centre of toe marker) show unique differences across step tasks (refer to figures 7.5.2.1 and 7.5.2.2). Maximum toe-step-clearances, for example, were achieved early in the swing phase (≈ 22%) of descent but late in the swing phase (≈ 80%) of ascent (≈ 12 cm). In the descent task, the maximum toe-step-clearances achieved by both age groups were similar (≈ 6 cm) and fell close to the clearances at the step edge (≈ 4 cm). In the ascent task, however, the elderly exhibited lower maximum clearances (≈ 8 to 10 cm) than the young adults (≈ 16 cm). In addition, the elderly (especially the forefoot landers) exhibited crossing clearances (≈ 7 cm) that fell close to their maximum clearance values (≈ 10 cm), whereas the young exhibited maximum clearances about twice the magnitude of the clearances at the step edge. This suggests the elderly may be unable or unwilling to elevate the toe as much as the young. It also suggests the elderly employ a near optimal crossing strategy in ascent since the foot is close to maximum elevation at the time of crossing. It may, however, simply reflect more cautious behaviour (i.e. establish a new base of support as soon as possible) since the elderly were found to land the lead limb earlier or closer to the step edge than the young adults ($p < .001$).

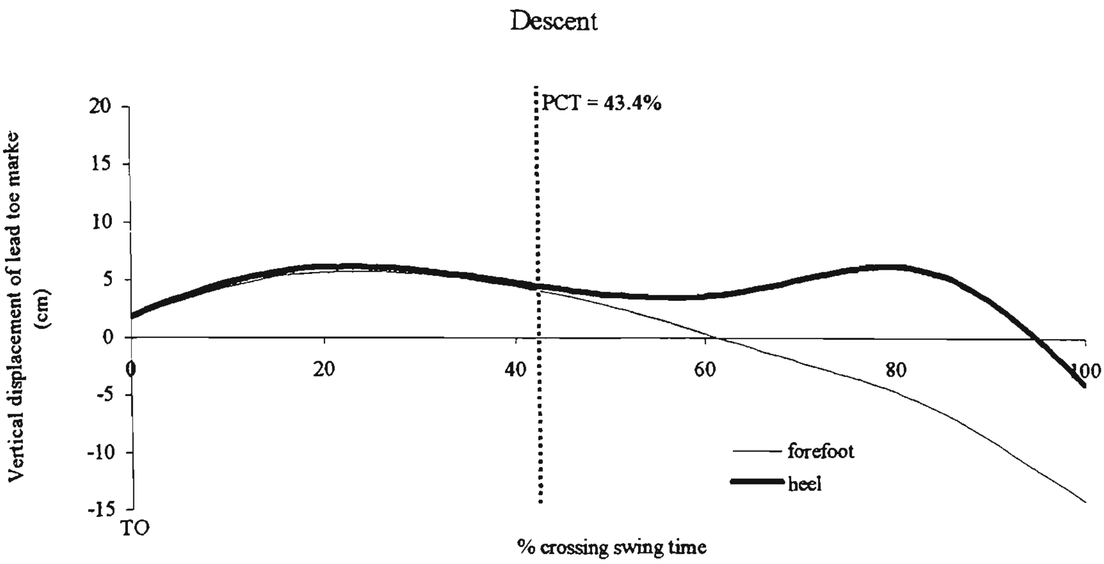


Figure 7.5.2.1 Ensemble average plots of the vertical trajectory of the lead toe marker in the descent task from toe-off (*TO*) to foot landing (*FL*) for those trials where participants employed a forefoot (79%) and heel (21%) landing strategy. Both velocity conditions were incorporated because the plots were qualitatively similar. Mean percent cross time of the step edge (*PCT*) by the lead toe was about 43.4% (SD = 5.6%) for both landing strategies.

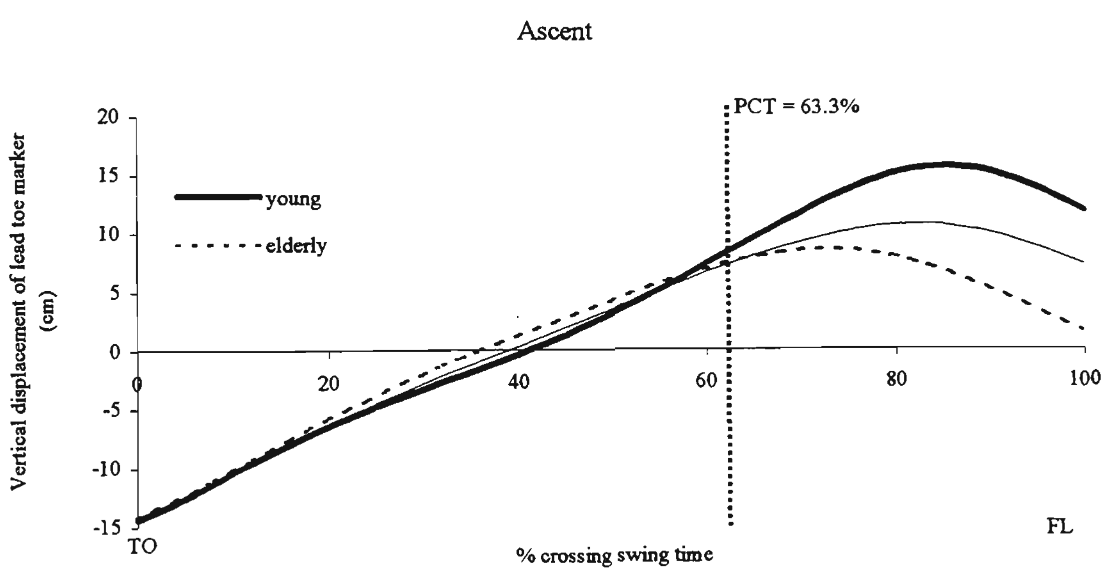


Figure 7.5.2.2 Ensemble average plots of the vertical trajectory of the lead toe marker in the ascent task from toe-off (*TO*) to foot landing (*FL*) for those trials where participants' employed a forefoot (5%) and heel (95%) landing strategy. Mean percent cross time of the step edge (*PCT*) by the lead toe was about 63.3% (SD = 7.2%) for both groups.

The reduced maximum toe elevation exhibited by the elderly in the ascent task may be evidence of a diminished capacity to elevate the foot. As such, the elderly may experience more difficulty in regaining balance from unwanted foot contact with a step riser. A diminished capacity to rapidly elevate the limb endpoint may result in a trip-induced fall. Equally, it may force a person to land the foot on the edge of a step which results in partial support of the foot. These notions are partly supported by the fact that the elderly cleared the step by a lesser margin and landed the foot on the step edge more often (20%) than the young (3%). Such outcomes are undesirable since they may lead to a stumble or trip-induced fall.

The plots also show the time of crossing (expressed as a percentage of swing time) to be earlier in descent (43.4%) than ascent (63.3%). This outcome is expected since participants placed the trail foot close to the step when descending the step. Interestingly, crossing time expressed as a percentage (*PCT*) of the time period from toe-off (*TO*) to foot landing (*FL*) was found to be essentially invariant (across age and walking velocity) and is indicative of rigid control being exerted in the crossing stride. Additionally, it demonstrates the existence of a ubiquitous strategy used by humans to accommodate a step.

In descent, the shape of the trajectory patterns of the heel and forefoot landers are essentially the same until the lead toe crosses the step (refer to figure 7.5.2.1). At this point, however, the forefoot landers (79% of trials) continue to lower the toe to the ground, whereas the heel landers orientate the foot for a heel landing. The forefoot landers were found to exhibit lower foot clearances (2.6 cm) than the heel landers (3.2 cm) and placed the lead heel about 25 cm closer to the step upon landing ($p < .001$). As such, it is reasonable to suggest that these participants may be at greater risk of unwanted foot contact or a misstep since they clear the step by a lesser margin and land the heel closer to the step. Either outcome is undesirable since it may lead to a fall or a stumble.

Overall, the trajectory (from crossing to landing) of the first lead limb endpoint (heel or toe) to land was found to exhibit a high degree of linearity (*LFM* ≈ 95%). The elderly participants exhibited less smoothness or linearity ($p < .001$) in the trajectory of the lead foot when descending the step (elderly = 92.5%, young = 95.1%) but exhibited similar smoothness in ascent (97%). This suggests a reduced control or awareness of the position of the limb endpoint when descending a step. Equally, it may reflect the different muscular contractions required to complete these tasks. Stair descent is primarily achieved through eccentric contractions of the lower limb musculature, whereas stair ascent mainly involves the pulling and pushing of the body through concentric contractions of this same musculature (McFadyen and Winter, 1988; McFadyen & Carnahan, 1997). The elderly, therefore, may have a reduced capacity to lower the limb endpoint smoothly due to the differing muscular contractions (i.e. eccentric) required to lower the body in a descent task.

The lead focal movement trajectory values (*LFM*) found in this project (≈ 95%) were much greater than those (74%) reported for a rapid single step onto a platform (Stemmons Mercer et al., 1997). The larger values are probably due to the lower platform and step velocities employed in this project. It may also indicate that the rapid step task (as fast as possible) employed by Stemmons Mercer et al. reduces the accuracy of foot placement. It is widely recognized that movement accuracy reduces with movement velocity (Bradshaw & Sparrow, 2000; 2001). In fact, this project found movement accuracy reduced by about 3% with velocity in the descent task ($p < .01$). More research of the movement of the lower limb endpoint is warranted. The control of the limb endpoint, for example, may be reduced when a person is distracted or suddenly confronted by an obstacle.

7.5.3 Foot orientation

Figure 7.5.3.1 shows the lead foot orientation measures discussed in this section. The reader is also referred to section 7.4.1 for a previous discussion about the lead foot orientation upon landing.

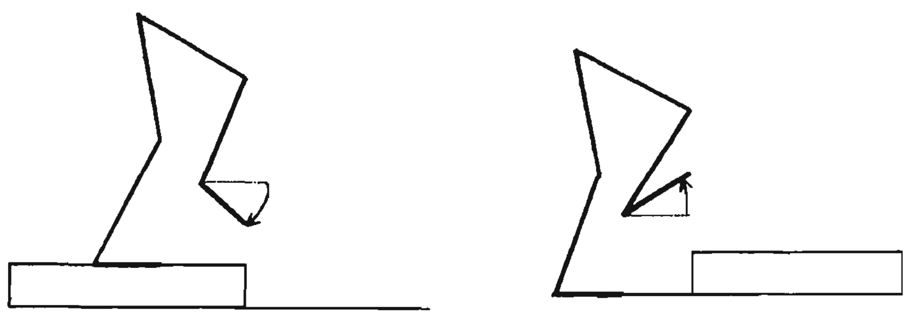


Figure 7.5.3.1 Examples of foot orientation measures collected in this project. The left panel shows a lead foot orientation of negative magnitude ($-\theta$) in the descent task. The right panel shows a lead foot orientation of positive magnitude (θ) in the ascent task.

Essentially, the foot orientation measures found in this project are consistent with previous work (Lythgo & Begg, 1999a). In the descent task, for example, both groups crossed the step with the lead and trail foot orientated downward (lead ≈ -26°, trail ≈ -73°). In the ascent task, the participants crossed the step with the lead foot in a relatively neutral position (≈ 1.7°) whereas the trail foot was orientated down (≈ -60°). Further inspection of this data, however, revealed the lead foot to be in a downward orientation (≈ -12°) in 43% of the trials (elderly ≈ 24%, young ≈ 19%) and an upward orientation (≈ 12°) in the remaining trials. This finding shows that a greater proportion of the elderly have the foot in a downward orientation when ascending a step. Such an orientation is dangerous since the toe would be fully arrested (forward direction) should contact with the step-riser be made.

Figures 7.5.3.2 to 7.5.3.3 are the plots (ensemble average) of the lead foot orientation throughout the crossing stride. Both velocity conditions have been incorporated in the plots since the patterns were found to be qualitatively similar (refer to sections 6.5.3.1 and 6.6.3.1). The plots show an age-related reduction in the range of foot motion. This suggests that the elderly are unable or unwilling, especially in ascent, to take the foot through the range of motion exhibited by the young. The plots of ascent also show the foot to be in a neutral position at the step. If the position of the step is misjudged, however, the foot may be orientated downward at the time of crossing. Such an outcome would occur if a person unknowingly or accidentally crossed the step earlier in the swing phase (e.g., 30-40% of the swing phase). This action is inherently dangerous since it has been shown that the toe is below the level of the step at this point (refer to figure 7.5.2.1), hence, the toe would contact the step. This outcome poses a serious threat to dynamic stability since the foot would have to be rapidly elevated or lowered to the ground to recover balance.

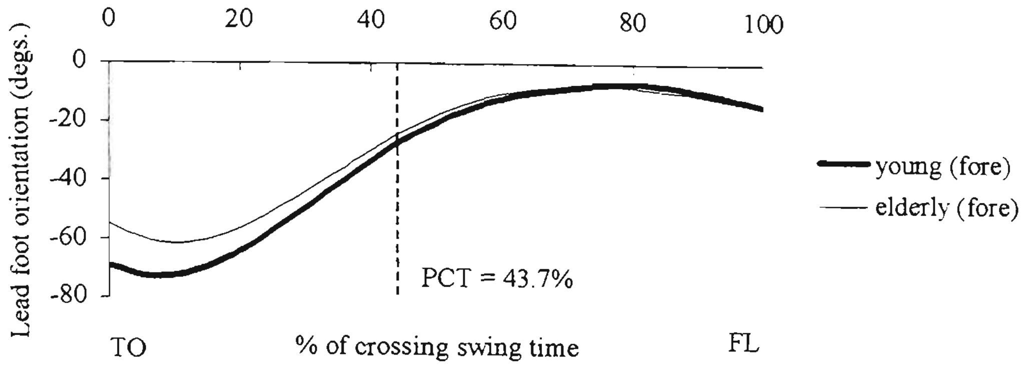


Figure 7.5.3.2 Ensemble average plots of the lead foot orientation in the descent task from toe-off (*TO*) to foot landing (*FL*) for those trials (79%) where participants' employed a forefoot landing strategy. Both velocity conditions were incorporated. Mean percent cross time of the step edge (*PCT*) by the lead toe was 43.7% for both landing strategies.

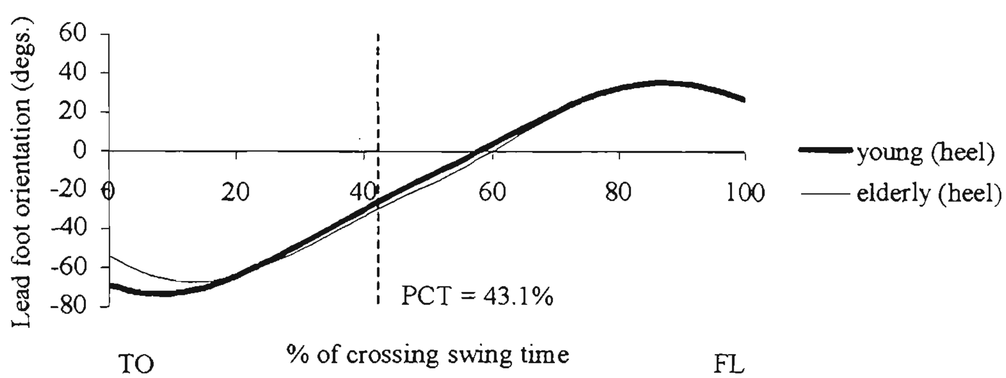


Figure 7.5.3.3 Ensemble average plots of the lead foot orientation in the descent task from toe-off (*TO*) to foot landing (*FL*) for those trials where participants' employed a heel landing strategy (21%). Both velocity conditions were incorporated. Mean percent cross time of the step edge (*PCT*) by the lead toe was about 43.1% for both landing strategies.

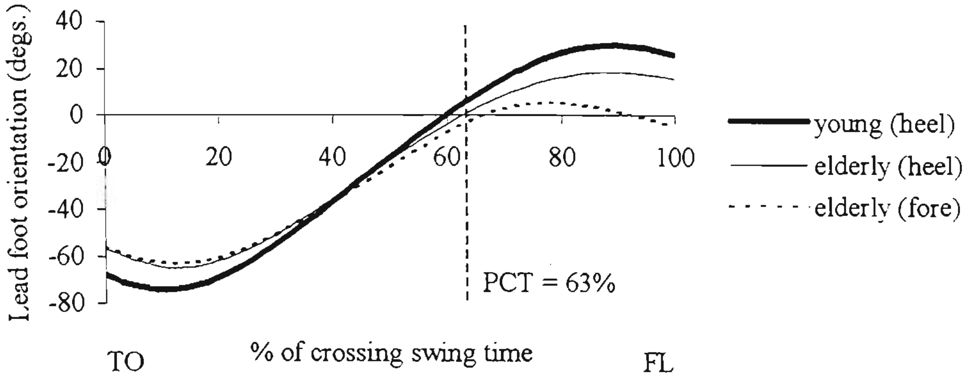


Figure 7.5.3.4 Ensemble average plots of the lead foot orientation in the ascent task from toe-off (*TO*) to foot landing (*FL*) for those trials where participants' employed forefoot (5%) and heel (95%) landing strategies. Both velocity conditions were incorporated. Mean percent cross time of the step edge (*PCT*) by the lead toe was about 63% for both landing strategies.

More work examining foot orientation is warranted in obstructed gait. Fallers, for example, may exhibit more downward orientation (magnitude and frequency) of the lead foot over a number of trials when ascending a step. Downward orientation of the foot coupled with low step-clearances heightens the risk of a trip-induced fall.

CHAPTER 8 CONCLUSION

The primary aim of this study was to extend work in the field of obstructed gait in order to better understand the biomechanical mechanisms or reasons for the high rate of falling behaviour exhibited by the elderly adult female population in terrain containing surface height changes (i.e. kerbs or door thresholds). As such, this study specifically: (1) focused upon young and elderly adult females; (2) examined the gait adjustments made to approach (over distance) and accommodate (descend and ascend) terrain representative of a single step, kerb or door threshold; and, (3) ascertained the effect of walking velocity ("hurrying") upon a person's ability to safely accommodate this terrain.

As part of this investigation, an instrument reliability study was conducted in order to ascertain the experimental setup (camera location and field of view) needed to minimize the effects of perspective, parallax and digitization error associated with 2D planar analyses. The setup found to be the most suitable and reliable for the main phase of this investigation (step tasks) involved: (1) four cameras; (2) a camera location of 10 m from the 2D measurement plane; (3) a 2.8 m (width) camera field of view; and, (4) a 20 cm camera field of view overlap (width). This setup was found to minimize the likely error to be contained in the spatio-temporal data collected in the main part of this investigation. Average errors in the linear and angular spatio-temporal data, for example, were found to fall around 4 mm and 0.5° respectively. These were the typical errors expected to be contained in the data collected in the main part of this investigation.

In this study, significant reductions in perspective error were found as the camera was located further from the 2D measurement plane (from 5 m to 10 m with 1 m increments). This demonstrates that the accuracy of 2D planar motion analysis is significantly affected by camera location. This is an important finding since gait studies have employed camera locations of 5 or 6 m (e.g., Prince et al., 1994; Redfern & DiPasquale, 1997; Cutlip et al., 2000). Large errors (up to 40 mm) may be contained in the data reported in these studies. In fact, Cutlip et al. (2000) evaluated the accuracy of an instrumented walkway (GAITRite system) by comparing its measured footfall data (e.g., step length) to data collected (through digitization) from the same footfalls (on film) by a camera located 5 m from the mat. A camera location of 7 m or more should have been employed to test the accuracy of the instrumented walkway. A camera location of 5 m is unsatisfactory since it is associated with large errors in 2D spatial data (as shown by this study).

Extensive screening measures were conducted in this investigation. The findings confirmed the need to screen elderly adults but not young adults when examining age-related issues in gait. Additionally, it was shown that only a few of the screening measures were effective in identifying elderly participants for exclusion. Reasons for exclusion were: (1) musculo-skeletal impairment (n = 3); (2) failure on the vestibular stepping test (n = 2); or, (3) failure on both the Romberg and vestibular stepping tests (n = 1). These screening items, therefore, may be the most reliable or discerning. Future studies, therefore, might profitably focus on items of this nature when screening participants. This may help researchers to reduce the costs (labour and monetary measures) associated with rigorous screening methods.

The issue of screening warrants further investigation. Ideally, a common standard or battery of screening items should be adopted so that consistency can be achieved across age-related investigations of gait.

As with previous work (e.g., Chen et al., 1991; 1994a; 1994b; Hreljac, 1993), this project found significant evidence of a practice effect when employing a blocked trial method (12 repeat trials). This finding suggests that studies may profitably gain by focusing more upon the first compensatory responses to a novel travel path or disturbance. The adoption of such a practice may improve the power of a study to identify age-related differences in gait. This project, for example, found age-related differences in measures of foot-step-clearance, whereas a past study of obstructed gait (e.g., Chen et al., 1991) involving a repeat trial method did not find significant age differences in measures of foot-obstacle-clearance. It is recognised, however, that the later study may have failed to find age differences as a result of the smaller sample size (n = 48) and reduced homogeneity of the sample (involved males and females) compared to this study which involved 96 participants of the same gender (females).

Overall, the main findings of this investigation show that step tasks (in particular a descent task) perturb the gait of elderly females more than the gait of young adult females. Essentially, this was evidenced by the manifestation of gait behaviour indicative of more rigid control or caution when accommodating (ascending and descending) the step. The elderly, for example, compared to the young: (1) made earlier adjustments to the gait pattern (e.g., step length); (2) made larger step adjustments (up to $2\frac{1}{2}$ times). In fact, they primarily took short steps or employed a short stepping strategy (60% of trials) when approaching and accommodating (ascending and descending) the step, whereas the young adults primarily employed long or normal stepping strategies (72% of trials); (3) exhibited less footfall variability in both step tasks ($p < .05$) and minimized the chance of a misstep (foot collapse due to inadequate step support) in the descent task by targeting a narrow region near the step; (4) moved slower in the approach and crossing phases ($p < .001$). They also landed with less vertical velocity (about 25%) in the descent task ($p < .001$); and, (5) exhibited more forward head tilt throughout the approach and crossing stride. This action most likely allows the elderly to visually monitor the terrain for a longer period of time.

The step tasks appeared to challenge the dynamic stability of the elderly more so than the young. The elderly, for example, compared to the young: (1) preferred to land on the forefoot, as opposed to the heel region, in the descent task ($p < .001$). This action or response allows greater attenuation of impact forces (e.g., Scholten et al., 2002) and most likely provides more options (e.g., braking and propulsive) should a slip or loss of balance occur; (2) lessened the chance of a slip (crossing stride) in the descent task by minimizing the horizontal velocity of the foot upon landing ($p < .001$); (3) increased the time available to deal with unwanted foot-step/ground contact by holding the body's trunk marker further back or behind the support foot at the time the lead foot crossed the step ($p < .05$). This was also associated with less forward tilt of the trunk in the descent task ($p < .001$); (4) spent a longer time in double foot support when ascending the step ($p < .001$). Interestingly, the descent task involved (all participants) a reduced time period of double foot support ($p < .001$) coupled with an increased time period of single limb support throughout the crossing stride ($p < .001$). This may heighten the risk of a fall or stumble when descending a step in populations (e.g., elderly) who exhibit reduced lower limb strength or musculoskeletal control limitations (Whipple et al., 1987; Gehlsen & Whaley, 1990; Porter et al., 1995; Thelen et al., 1996; Lamoureux et al., 2002).

It is reasonable to conclude that some of the gait strategies (e.g., short step strategy, lower foot clearances) employed by the elderly heighten the risk of a stumble or trip-induced fall in terrain containing a single step. The elderly's short crossing steps (about 23% shorter than the young adults, $p < .001$), for example, resulted in the lead and trail feet being placed closer ($p < .001$) to the step edge than the young adults (except for the descent task where both groups placed the trail foot about 8 cm from the step). This suggests the elderly are at greater risk of a misstep (foot partially supported by the step) where the support limb may collapse due to inadequate support. In fact, this was aptly demonstrated in the descent task when an elderly participant accidentally lowered the lead foot onto the step so that only 10% of the foot was supported (a misstep). This caused the foot to suddenly plantarflex (plantarflexion moment) and led to a stumble but not a fall.

Further analysis of the participant's footfall patterns revealed the elderly to be at greater risk of a misstep in the ascent task. The elderly, for example, landed the foot closer to the step edge ($p < .001$). In fact, only 3% of the young adults stepped on the edge with 98.4% (SD = 0.4%) of the lead foot supported, whereas 20% of the elderly stepped on the edge with 76.0% (SD = 12.4%) of the lead foot supported. In the descent task, however, sub-groups of the young (33%) and elderly (16%) were found to place the support foot (trail limb) on the step edge (foot partly supported by the step) so that approximately 90% of the foot was supported by the step. Importantly, these findings suggest the existence of a sub-group of elderly adults who are at greater risk of a misstep (limb collapse due to inadequate step support) in an ascent task. As such, future work in the field of obstructed gait could profitably gain by focusing on issues such as: (1) the likelihood of a misstep leading to the collapse of the support limb; (2) the amount of foot support required to safely climb a step; and, (3) the role of lower limb musculature (e.g., plantarflexors and dorsiflexors) in preventing the collapse of the support limb in the event of a misstep.

Generally, this project found the elderly to exhibit the lowest foot-step-clearances. This supports the notion that they are at greater risk of unwanted foot contact with a step. This is especially so when descending a step, where toe clearances (lead foot = 2.7 ± 1.6 cm, trail foot = 1.8 ± 1.4 cm) were at least half the magnitude found in ascent. In fact, minimum toe clearances fell around

0.2 cm. Lead limb toe contact in ascent, however, still poses a serious threat to dynamic stability since forward progression of the foot would be fully arrested, whereas in descent the forward progression of the foot may not be fully arrested but slowed as the foot drags along or "brushes" the top surface of the step. A misstep, however, may result in the downward motion of the foot being arrested in descent. In fact, the misstep by the elderly participant discussed earlier led to the lead heel being grounded or fully arrested on the step.

Interestingly, the participants (elderly ≈ 97%, young ≈ 61%) who elected to land on the forefoot in the descent task cleared the step edge by a lower margin ($p < .001$) than heel landers. On average, forefoot landers cleared the step by 2.6 cm (SD = 1.5 cm), whereas heel landers cleared it by 3.2 cm (SD = 1.7 cm). As such, it is reasonable to conclude that these participants (particularly the elderly as a group) are at greater risk of unwanted foot contact.

In the ascent task the elderly exhibited lower maximum clearances (lead toe clearances ≈ 8 to 10 cm) than the young adults (≈ 16 cm). In addition, the elderly (especially the forefoot landers) exhibited crossing clearances (lead toe clearance ≈ 7 cm) that fell close to their maximum clearance values (≈ 10 cm), whereas the young exhibited maximum clearances about twice the magnitude of the clearances at the step edge. This suggests the elderly may be unable or unwilling to elevate the toe as much as the young. It also suggests the elderly employ a near optimal crossing strategy in ascent since the foot is close to maximum elevation at the time of crossing. It may, however, simply reflect more cautious behaviour (i.e. establish a new base of support as soon as possible) since the elderly were found to land the lead limb earlier or closer to the step edge (about 9 cm closer) than the young adults ($p < .001$).

Interestingly, this project found evidence of a reduced capacity of the elderly to control the lead limb end-point when descending a step. Essentially, the elderly were found to exhibit less smoothness or linearity ($p < .001$) in the trajectory of the lead foot. This suggests a reduced control or awareness of the position of the limb endpoint when descending a step. This is inherently dangerous since the feet (lead and trail) clear the step by a small margin.

As expected, the fast walking velocity condition evoked (1) longer approach and crossing steps ($p < .001$) and (2) shorter double and single limb support ($p < .001$). In addition, the lead foot landed further past the step edge ($p < .002$) and there was more reliance on a particular limb to lead the crossing. Interestingly, however, trail foot placement (near the step) and toe clearances (lead and trail feet) were not affected by walking velocity; that is, the same region was targeted for the placement of the trail foot and similar toe clearances were exhibited across velocity conditions.

The most important or critical changes elicited by the fast velocity conditions involved a reduction in measures associated with dynamic stability, for example: (1) the horizontal landing velocity of the lead foot and the body's vertical landing velocity increased in the descent task ($p < .001$); (2) the body's trunk marker was closer to the support toe (i.e. closer to the boundary of the base of support) at the time the lead foot crossed the step and landed past it ($p < .001$);

that is, the trunk marker was held relatively further back ($\approx$ 2 cm) or within the base of support (at the time the lead foot crossed the step edge) in the comfortable velocity condition; and, (3) the available response time was less ($p < .001$). The available response time is simply the amount of time (predicted from walking velocity and horizontal displacement of the trunk marker from the trail toe) until the trunk marker moves forward of the base of support. Essentially, these measures of dynamic stability are important since they are associated with factors such as the propensity to slip, the force encountered upon landing (weight acceptance), and the capacity to regain balance should the lead limb accidentally contact the step or ground.

Lastly, this study found evidence of a "visual switch point" occurring at the 3rd-last footfall prior to the step. This finding shows that gait in terrain containing surface height changes is primarily regulated by the visual system in the last few footfalls. In addition, it provides evidence of a perception-action coupling previously found in other tasks such as the long jump, hence, accommodation tasks involve a transport phase followed by a targeting or "zeroing in" phase. This strategy appears to be ubiquitous since both the elderly and young adult females exhibited this behaviour.

In conclusion, this study found evidence to suggest that elderly adult females are at greater risk (compared to young adult females) of fall in terrain containing surface height changes. Stair or step descent appears to be particularly hazardous (especially when walking fast) since foot clearances are small and foot placement is close to the step edge. Both of these actions increase the chance of a stumble or trip-induced fall. These actions appear to be directly related to the short crossing step employed by elderly adult females, hence, any decline in step length capacity (due to the ageing process) may indicate a heightened risk of a fall on a stair or step. Finally, future work in this field would gain profitably by focusing on issues such as: (1) the likelihood of a misstep (partial foot support on a step or failure to ground the foot on a step) in terrain containing surface height changes; (2) the probability of limb collapse due to inadequate foot support on a step; and, (3) minimum lower limb strength and power required to prevent limb collapse or regain balance on a step should the foot be inadequately supported. Once this information is acquired, exercise-based intervention programs could be developed and administered to large groups of at-risk elderly female adults in order to minimise falling behaviour.

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Appendix A

Screening questionnaire

AUSTRALIAN CATHOLIC UNIVERSITY

RESEARCH QUESTIONAIRE - Biomechanical characteristics of gait.

Principal Investigator: Noel Lythgo

1. Personal Details

Name:

Address:

Telephone: (AH) (W)

Date of Birth: Gender: ☐ F ☐ M

Height: cm

Weight: kg

Have you ever been hospitalised? If yes, when and why?

Have you ever had any fractures? ☐ No ☐ Yes If yes, please specify:

Have you had any falls in the last 12 months ? ☐ No ☐ Yes

If yes, how many falls? ☐

If yes, specify the environment in which the fall occurred (e.g. stair, footpath etc.) and how it occurred (e.g. as a result of a trip or loss of balance)

Do you currently experience pain in any of the following areas?

No Yes If yes, specify frequency and type of pain

	No	Yes
Lower back	☐	☐
Hips	☐	☐
Legs	☐	☐
Knees	☐	☐
Ankles	☐	☐
Feet	☐	☐

Do you experience pain when walking? ☐ No ☐Yes

Do you consider yourself to be: ☐ Inactive (no exercise)

☐ Slightly active (exercise 1-2 times per week

☐ Active (exercise 3-4 times per week)

☐ Very active (exercise 5-7 times per week)

Do you have any of the following conditions?

	No	Yes	If yes, specify
Musculo-skeletal dysfunction	☐	☐	
Neuromuscular dysfunction☐	☐		
Overuse injuries	☐	☐	
Vascular disorders	☐	☐	
Traumatic injuries/surgeries	☐	☐	
Diabetes	☐	☐	
Arthritis	☐	☐	
Visual impairment	☐	☐	
Persistent vertigo	☐	☐	
Lightheadedness	☐	☐	
Other	☐	☐	

Are you currently on medication which affects your balance (e.g. hypnotics, sedatives such as benzodiepines)? ☐ No ☐Yes

If yes, please specify.

2. Melbourne Edge Test

Visual Acuity — Test distance: 6m + ☐ – ☐

Last line read ☐

Melbourne Edge Test ☐

3. Anthropometric Measures (cm)

Left leg height (greater trochanter) ☐ iliac crest ☐

Right leg height (greater trochanter) ☐ iliac crest ☐

4. Cognition ☐

5. Vibration Sense — left tibial tuberosity, right tibial tuberosity, left lateral malleolus, right lateral malleolus.

6. Lower limb Joint Proprioception

Left limb	Right limb
1.	1.
2.	2.
3.	3.
4.	4.
5.	5.

7. Vestibular Stepping Test - positive ☐ No ☐Yes

8. Blood Pressure and Pulse

Activity	Blood Pressure (mm Hg)
Supine	
Standing after 1 minute	
Standing after 2 minutes	
Standing after 5 minutes	

9. Romberg test – positive ☐ No ☐Yes

Appendix B

Computer software program (C language) used to extract data for the descent task

This program extracts the majority of spatio-temporal variables collected in this project. Variables such as foot-step-clearances, foot orientations, trunk marker position, available response time, step length and time etc...

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <string.h>  // For strcpy....

#define MAXLL    300  // Most lines are about 250 chars in length....
// Number of points in the spatial model == number of points on each line of the file....
#define SPATIALMODELPOINTS  12
#define MAXIMUMFRAMES       300

struct point  {
   float x, y;
   };
typedef    struct point      Point;

// Point p[MAXIMUMFRAMES][SPATIALMODELPOINTS];

float ara[MAXIMUMFRAMES][SPATIALMODELPOINTS*3];
int M = 0, N = 0;   // Size of array read in from file...
float mmark[3][9];

//Subroutine to estimate foot clearance.........................................................................

float minimum(float x1, float x2, float y1, float y2,float min, float step_edge_x_coordinate)
                    {
                    min = ((step_edge_x_coordinate - x1)*(y2-y1)/(x2-x1)) + y1;
                    return (min);
                    }

//Variable declaration..........................................................................................

main()

{
        FILE *data;
        FILE *fp;

float   step_edge_x_coordinate, step_edge_y_coordinate;
float   lead_toe_clearance, lead_toe_minimum_clearance,
        lead_heel_clearance,lead_heel_minimum_clearance;
float   lead_crossing_stride_length, percent_of_lead_stride_length_at_crossing,
        percent_time_of_lead_at_crossing;
float   lead_crossing_step_length, percent_of_lead_step_length_at_crossing, lead_crossing_step_time,
        increment_step_time;
float   lead_toe_pre_step_distance, lead_toe_landing_distance_past_edge;
float   lead_foot_hor_land_velocity, lead_foot_vert_land_velocity;
float   cross_lead_foot_angle, land_lead_foot_angle, lead_foot_angle_before_land,
        lead_foot_angular_velocity_at_landing;
float   trail_toe_clearance, trail_heel_clearance, trail_toe_pre_step_distance;
float   cross_trail_foot_angle;
float   ART, hor_linear_velocity_of_COM, hor_linear_dist_to_edge, COM_relative_base_of_support,
        s1, s2;
```

```
float   COM_horz_velocity_at_landing, COM_vertical_velocity_at_landing,
        COM_relative_to_lead_foot_land_position, time_estimate_til_COM_passes_lead_toe,
        crossing_double_foot_support_time, time_til_foot_grounded_from_toe_clearance_event,
        COM_relative_base_of_support_at_lead_foot_landing;
float   min,x1,x2,y1,y2;
float   x_toe, y_toe, x_heel, y_heel, foot_angle, true_gradient, left_marker_y_coordinate,
        right_marker_y_coordinate, horizontal_distance_between_markers, foot_gradient;
float   min_lead_heel_height, min_lead_toe_height;
float   lead_toe_position_at_midstance_past_edge;
float   lead_toe_position_before_edge, trail_toe_position_before_edge;
int     row, col,lead_toe_x_column, trail_toe_x_column, left_toe_past_frame, right_toe_past_frame;
int     lead_toe_y_column, trail_toe_y_column;
int     lead_heel_clearance_frame, lead_toe_clearance_frame, lead_toe_position_before_edge_frame,
        trail_heel_clearance_frame, trail_toe_position_before_edge_frame, trail_toe_clearance_frame;
int     lead_toe_take_off_frame, trail_toe_take_off_frame, min_lead_heel_height_frame, min_
        lead_toe_height_frame;
int     lead_foot_land_frame,lead_toe_midstance_frame_past_edge;
char    filename[50], midmarker[50], filesave1[50], filesave2[50], filesave3[50], filesave4[50],
        filesave5[50];
int     lineNo = 0, pointNo = 0;
int     i = 0, j = 0;
float   x, y, r;
```

//Filenames...
//The first two lines open the datafiles produced from the digitization process.
//The nap4.txt file refers to the datafile (for participant S1) described in table 5.3.3.1.
//The markof.txt file contains information about the location of the midmarkers described in section 5.2.2.3.
//The remaining files describe where calculated data is sent.
//leadfoot.txt; lead foot angular data: trajtoe.txt; coordinate data for lead toe marker; trajhip.txt;
//coordinate data for hip COM marker; trajknee.txt; coordinate data for knee marker;
//normoff.txt; remaining data such lead toe clearance etc...........

```
(void) strcpy( filename, "c:\\doctor\\data\\old\\stepoff\\S1\\nap4.txt");
(void) strcpy( midmarker,"c:\\doctor\\data\\midmark\\off\\markof.txt");
(void) strcpy( filesave1,"c:\\doctor\\data\\old\\results\\normoff\\leadfoot.txt");
(void) strcpy( filesave2,"c:\\doctor\\data\\old\\results\\normoff\\trajtoe.txt");
(void) strcpy( filesave3,"c:\\doctor\\data\\old\\results\\normoff\\trajhip.txt");
(void) strcpy( filesave4,"c:\\doctor\\data\\old\\results\\normoff\\trajknee.txt");
(void) strcpy( filesave5,"c:\\doctor\\data\\old\\results\\normoff\\normoff.txt");
```

//Opens and scans mid-maker array...

```
if ((data=fopen(midmarker,"r"))==NULL)
   {printf("\n\n*** That file does not exit***\n");
   exit(0);}
else
{
        for (row=0;row < 4; row++)
        for (col=0;col < 9; col++)
        fscanf(data,"%f", &mmark[row][col]);
}
```

//Opens and scans data array...

```
printf("Name of file being analysed? %s\n", filename);
```

```
                if ( (data = fopen( filename, "r")) == NULL ) {
                   printf("\n\n*** That file does not exist you idiot ***\n");
                   exit(1);
                   }

#ifdef COMMENT
                lineNo = 0;
                while ( fgets( line, MAXLL, data) != NULL ) {
                   lineNo++;
                   printf("Line number : %d,  Length : %d\n",  lineNo, strlen( line ));
                   printf("Line : %s", line);

                   while ( sscanf( line, "%f %f %f", &x, &y, &r)  == 3 )  {
                   printf("GOT SUMMAT : %4.1f, %4.1f, %4.1f\n", x, y, r);
                   getchar();
                      }
                   getchar();
                   }

#endif // COMMENT

                lineNo = 0;
                pointNo = 0;
                while ( fscanf( data, "%f %f %f", &x, &y, &r)  == 3 )  {

        ara[lineNo][pointNo*3+0] = x;
        ara[lineNo][pointNo*3+1] = y;
        ara[lineNo][pointNo*3+2] = r;

        if ( (pointNo+1)  == SPATIALMODELPOINTS ) {
           lineNo++;      // Increment the line number...
           pointNo = 0;   // Reset the point number on this line...

           }
        else  {
           pointNo++;
           }

        if ( lineNo >= MAXIMUMFRAMES  )  {
           printf("What !!  Too many lines in the data file........\n");
           printf("Please change the MAXIMUMFRAMES constant.  Exiting.\n");
           exit( 1 );
           }
        // getchar();
                  }

                fclose(data);

// Keep track of the number of rows and columns read from the file.......................................

     M = lineNo;
     N = SPATIALMODELPOINTS * 3;
     printf("Array is :  %3d Rows  *  %3d Columns\n", M, N);
          for ( i = 0;  i  <  M;  i++ )  {
             for ( j = 0;  j <  N;  j = j+3 ){
             }
             }

printf("Step edge sagittal plane coordinates = %f m, %f m\n", mmark[3][0], mmark[3][2]);
```

```
                step_edge_x_coordinate = mmark[3][0];
                step_edge_y_coordinate = mmark[3][2];

printf("\tstep_edge_x_coordinate = %.4f m\n",step_edge_x_coordinate);
printf("\tstep_edge_y_coordinate = %.4f m\n",step_edge_y_coordinate);
```

// Lead limb identified when both heel and toe are past step. This is required in case the trail foot is placed half on and off the edge (partially supported by step)..

```
        for (row = 0;  row < M;  row++ )  {

        if((ara[row][6] > step_edge_x_coordinate) && (ara[row][3] > step_edge_x_coordinate))
            {right_toe_past_frame = row-1;
            printf("\tx_value = %.4f\n", ara[row][6]);
            printf("\tFrame = %i\n", right_toe_past_frame);
            break;}
          }

        for (row = 0;  row < M;  row++ )  {

        if((ara[row][12] > step_edge_x_coordinate) && (ara[row][9] > step_edge_x_coordinate))
            {left_toe_past_frame = row-1;
            printf("\tx_value = %.4f\n", ara[row][12]);
            printf("\tFrame = %i\n", left_toe_past_frame);
            break;}
          }
                if (right_toe_past_frame < left_toe_past_frame){
                printf("\tLead limb is the right limb!\n\n");
                lead_toe_x_column = 6;
                trail_toe_x_column = 12;
                printf("\tlead toe column = %i\n", lead_toe_x_column);
                printf("\ttrail toe column = %i\n", trail_toe_x_column);
                lead_toe_y_column = lead_toe_x_column + 1;
                trail_toe_y_column = trail_toe_x_column + 1;
                }

                else
                {printf("\tLead limb is the left limb!\n\n");
                lead_toe_x_column = 12;
                trail_toe_x_column = 6;
                lead_toe_y_column = lead_toe_x_column + 1;
                trail_toe_y_column = trail_toe_x_column +1;
                printf("\tlead toe column = %i\n", lead_toe_x_column);
                printf("\ttrail toe column = %i\n", trail_toe_x_column);
                }
```

//Routines to calculate minimum lead heel and toe clearance of step..

//Lead heel-step-clearance (LHC)...

```
                for (row = 0;  row < M;  row++ )  {
                if((ara[row][lead_toe_x_column-3] < step_edge_x_coordinate) &&
                (ara[row + 1][lead_toe_x_column-3] > step_edge_x_coordinate))
                 break;
                }

                x1 = ara[row][lead_toe_x_column-3];
                x2 = ara[row+1][lead_toe_x_column-3];
```

```
                y1 = ara[row][lead_toe_x_column-2];
                y2 = ara[row+1][lead_toe_x_column-2];
                min = minimum(x1, x2, y1, y2, min, step_edge_x_coordinate);
                lead_heel_clearance = 100*(min - step_edge_y_coordinate);
                lead_heel_clearance_frame = row;
printf("\t%.4f,\t%.4f,\t%.4f,\t%.4f\n",x1,x2,y1,y2);
printf("\tLead heel clearance of step edge = %.2f cm, %i\t\n", lead_heel_clearance, row);

//Minimum lead heel height near step (in approach phase)..........................................

min_lead_heel_height = 1000;
for (row = lead_heel_clearance_frame - 20;  row < lead_heel_clearance_frame + 1;  row++ )  {

if ((ara[row][lead_toe_x_column-2] < min_lead_heel_height) && (ara[row][lead_toe_x_column-2] !=
0))
   {min_lead_heel_height = ara[row][lead_toe_x_column-2]; min_lead_heel_height_frame = row;}
   lead_heel_minimum_clearance = (min_lead_heel_height - step_edge_y_coordinate)*100        }

if (min_lead_heel_height_frame = lead_heel_clearance_frame )
        {lead_heel_minimum_clearance = lead_heel_clearance;}
        printf("\tLead heel minimum clearance of raised surface in approach = %.2f cm, %i\t\n",
        lead_heel_minimum_clearance,min_lead_heel_height_frame);

//Lead toe-step-clearance (LTC) ..................................................................

for (row = 0;  row < M;  row++ )  {
if ((ara[row][lead_toe_x_column] < step_edge_x_coordinate) && (ara[row + 1][lead_toe_x_column] >
step_edge_x_coordinate))
                break;
                }

                lead_toe_clearance_frame = row;
                x1 = ara[row][lead_toe_x_column];
                x2 = ara[row+1][lead_toe_x_column];
                y1 = ara[row][lead_toe_y_column ];
                y2 = ara[row+1][lead_toe_y_column];
                min = minimum(x1, x2, y1, y2, min, step_edge_x_coordinate);
                lead_toe_clearance = 100*(min - step_edge_y_coordinate);
                increment_step_time = (step_edge_x_coordinate - x1)/((x2-x1)/0.02);
                printf("increment step time = %.4f sec\n", increment_step_time);
                printf("\tLead toe minimum clearance of step edge = %.2f cm,
                %i\t\n",lead_toe_clearance, lead_toe_clearance_frame);
printf("%.4f %.4f %.4f %.4f",ara[row][lead_toe_x_column],ara[row+1][lead_toe_x_column],
ara[row][lead_toe_y_column],ara[row+1][lead_toe_y_column]);

//Minimum lead toe height over step platform......................................................

 min_lead_toe_height = 1000;

for (row = lead_toe_clearance_frame - 20;  row < lead_toe_clearance_frame + 1;  row++ )  {

if ((ara[row][lead_toe_y_column] < min_lead_toe_height) && (ara[row][lead_toe_y_column] != 0))
        {min_lead_toe_height = ara[row][lead_toe_y_column]; min_lead_toe_height_frame = row;}
        lead_toe_minimum_clearance = (min_lead_toe_height - step_edge_y_coordinate)*100;}

 if (min_lead_toe_height = lead_toe_clearance)
        {lead_toe_minimum_clearance = lead_toe_clearance;}
printf("\tLead toe minimum clearance of raised surface in appraoch = %.2f cm,
%i\t\n\n",lead_toe_minimum_clearance, min_lead_toe_height_frame);
```

//Routines to calculate minimum TRAIL heel and toe-step-clearance....................................

//Trail heel-step-clearance (THC)..

```
for (row = 0;  row < M;  row++ )  {

if ((ara[row][trail_toe_x_column-3] < step_edge_x_coordinate) &&
(ara[row + 1][trail_toe_x_column-3] > step_edge_x_coordinate))
                    break;
                    }
                    trail_heel_clearance_frame = row;
                    x1 = ara[row][trail_toe_x_column-3];
                    x2 = ara[row+1][trail_toe_x_column-3];
                    y1 = ara[row][trail_toe_y_column-3];
                    y2 = ara[row+1][trail_toe_y_column-3];
                    min = minimum(x1, x2, y1, y2, min, step_edge_x_coordinate);
                    trail_heel_clearance = 100*(min - step_edge_y_coordinate);
                    printf("\tTrail heel clearance of step edge = %.2f cm, %i\n",trail_heel_clearance,
                    trail_heel_clearance_frame);
```

//Trail toe-step-clearance (TTC). If trail foot straddles step (foot partially supported) in support phase, trail_toe_clearance_frame is assigned a default value of 1000, and trail_toe_clearance is assigned a default value of 1000..

```
for (row = 0;  row < M;  row++ )  {

if ((ara[row][trail_toe_x_column] < step_edge_x_coordinate) && (ara[row + 1][trail_toe_x_column] >
step_edge_x_coordinate))
                             break;
                    }
                    if (ara[row][trail_toe_x_column] == 0)
                    {trail_toe_clearance_frame = 1000;
                    trail_toe_clearance = 1000;
                    printf("\n\tTrail foot straddles edge\n\n");
                    }

                    else {
                    trail_toe_clearance_frame = row;
                    x1 = ara[row][trail_toe_x_column];
                    x2 = ara[row+1][trail_toe_x_column];
                    y1 = ara[row][trail_toe_y_column];
                    y2 = ara[row+1][trail_toe_y_column];
                    min = minimum(x1, x2, y1, y2, min, step_edge_x_coordinate);
                    trail_toe_clearance = 100 * (min - step_edge_y_coordinate);
printf("\tTrail toe minimum clearance of step edge = %.2f cm, %i\n\n",trail_toe_clearance,
trail_toe_clearance_frame);
printf("%.4f %.4f %.4f %.4f",ara[row][trail_toe_x_column], ara[row+1][trail_toe_x_column],
ara[row][trail_toe_y_column],ara[row+1][trail_toe_y_column]);
          }
```

//Routines to estimate toe position from step: pre and post crossing.......................................

//Lead toe pre-step distance..

```
        for (row = 0;  row < M;  row++ )  {
        if  ((ara[row][lead_toe_x_column] > 0) && (ara[row][lead_toe_x_column - 3] > 0))
                {lead_toe_take_off_frame = row;
                printf("\tFrame lead toe take off = %i\n", lead_toe_take_off_frame);
```

```
                break;}
            }

        lead_toe_position_before_edge = 0;
        for (row = 0;  row < lead_toe_take_off_frame;  row++ )  {

if (ara[row][lead_toe_x_column] > lead_toe_position_before_edge)
        {lead_toe_position_before_edge =
        ara[row][lead_toe_x_column];lead_toe_position_before_edge_frame = row;}
            }

printf("\tFrame lead toe pre step = %i\n", lead_toe_position_before_edge_frame);
printf("\tLead toe pre step x coordinate = %.4f\n", lead_toe_position_before_edge);

lead_toe_pre_step_distance = 100 * (ara[lead_toe_position_before_edge_frame][lead_toe_x_column] -
step_edge_x_coordinate );

printf("\tLead toe pre step distance = %.2f cm, %i\t\n", lead_toe_pre_step_distance,
lead_toe_position_before_edge_frame);
```

//Lead toe landing position (midstance) past edge..

```
for (row = lead_toe_take_off_frame;  row < M;  row++ )  {
        if ((ara[row][lead_toe_x_column] > 0) && (ara[row+1][lead_toe_x_column] == 0))
                break;
                }
        lead_foot_land_frame = row;
        printf("\tLead foot landing frame = %i\n", lead_foot_land_frame);

        for (row = lead_foot_land_frame + 1;  row < M;  row++ )  {
        if (ara[row][lead_toe_x_column] > 0)
                break;
                }

lead_toe_position_at_midstance_past_edge = ara[row][lead_toe_x_column];
lead_toe_midstance_frame_past_edge = row;

printf("\tLead foot midstance frame = %i\n", lead_toe_midstance_frame_past_edge);
printf("\tLead foot midstance position = %.4f\n", lead_toe_position_at_midstance_past_edge);

lead_toe_landing_distance_past_edge = 100 * (lead_toe_position_at_midstance_past_edge -
step_edge_x_coordinate);
printf("\tLanding distance of lead toe past step (midstance) = %.2f cm, %i\t\n ",
lead_toe_landing_distance_past_edge, lead_toe_midstance_frame_past_edge);
```

//Lead crossing stride length: percent at crossing...

```
lead_crossing_stride_length =  lead_toe_landing_distance_past_edge - lead_toe_pre_step_distance;

percent_of_lead_stride_length_at_crossing =
fabs(lead_toe_pre_step_distance/lead_crossing_stride_length) * 100;

printf("\tLead crossing stride length = %.2f cm\n", lead_crossing_stride_length);
printf("\tPercent of lead stride length at crossing = %.1f\n\n",
percent_of_lead_stride_length_at_crossing);
```

//Trail toe pre-step distance (TD)...

```
for (row = 0;  row < M;  row++ )  {
```

```
        if ((ara[row][trail_toe_x_column] > 0) && (ara[row][trail_toe_x_column - 3] > 0))
                {trail_toe_take_off_frame = row;
                printf("\tFrame trail toe take off = %i\n", trail_toe_take_off_frame);
                break;}
            }

          trail_toe_position_before_edge = 0;

        for (row = 0;  row < trail_toe_take_off_frame;  row++ )  {
        if  (ara[row][trail_toe_x_column] > trail_toe_position_before_edge)
         {trail_toe_position_before_edge =
        ara[row][trail_toe_x_column];trail_toe_position_before_edge_frame = row;}
                                }
printf("\tTrail toe pre step x coordinate = %.4f\n", trail_toe_position_before_edge);

trail_toe_pre_step_distance = 100 * (ara[trail_toe_position_before_edge_frame][trail_toe_x_column] -
step_edge_x_coordinate );
printf("\tTrail toe pre step distance = %.2f cm, %i\n", trail_toe_pre_step_distance,
trail_toe_position_before_edge_frame);

//Lead crossing step length (CSL: toe to toe) and step time (CST: toe-off to foot contact): percent at
crossing....

lead_crossing_step_length = lead_toe_landing_distance_past_edge - trail_toe_pre_step_distance;
percent_of_lead_step_length_at_crossing =
fabs(trail_toe_pre_step_distance/lead_crossing_step_length)*100;

printf("\tLead crossing step length = %.2f cm\n", lead_crossing_step_length);
printf("\tPercent of lead step length at crossing = %.1f\n\n", percent_of_lead_step_length_at_crossing);

lead_crossing_step_time = lead_foot_land_frame - lead_toe_take_off_frame;
percent_time_of_lead_at_crossing = (((lead_toe_clearance_frame - lead_toe_take_off_frame)*0.02 +
increment_step_time) / (lead_crossing_step_time * 0.02))*100;

        printf("\tLead crossing step time = %.2f\n", lead_crossing_step_time * 0.02);
        printf("\tTime percentage of lead foot at crossing = %.2f\n\n",
        percent_time_of_lead_at_crossing);
        printf("\tlead toe clearance frame = %2i\n", lead_toe_clearance_frame);
        printf("\tlead toe takeoff frame = %2i\n", lead_toe_take_off_frame);
        printf("\tlead toe land frame = %2i\n", lead_foot_land_frame);

//Foot orientation at step edge. Angles are estimated from data before toe crosses step..................

//Lead foot angle at step  crossing edge(LCA).........................................................................

        x_heel = ara[lead_toe_clearance_frame][lead_toe_x_column-3];
        y_heel = ara[lead_toe_clearance_frame][lead_toe_x_column-2];
        x_toe = ara[lead_toe_clearance_frame][lead_toe_x_column];
        y_toe = ara[lead_toe_clearance_frame][lead_toe_x_column + 1];
        left_marker_y_coordinate = mmark[0][6];
        right_marker_y_coordinate = mmark[0][7];
        horizontal_distance_between_markers = mmark[0][8];
        true_gradient = ((right_marker_y_coordinate –
        left_marker_y_coordinate))/(horizontal_distance_between_markers);
        printf("true gradient = %.4f\n", true_gradient);
        printf("%f %f %f %f", x_heel, y_heel, x_toe, y_toe);
        printf("%f %f %f",left_marker_y_coordinate, right_marker_y_coordinate,
        horizontal_distance_between_markers);
```

```
        if(x_heel == x_toe)
        {foot_angle = 90;}

        else {
        foot_gradient = (y_toe - y_heel)/(x_toe - x_heel);
        printf("foot gradient = %.2f\n", foot_gradient);
        foot_angle = (atan((foot_gradient - true_gradient)/(1 + foot_gradient * true_gradient)) *
        180/3.14159);
        }

        cross_lead_foot_angle = foot_angle;
        printf("\n\tLead foot angle = %.2f degs, %i\n", cross_lead_foot_angle,
        lead_toe_clearance_frame);
```

//Lead foot angle upon landing (LLA)...

```
        x_heel = ara[lead_foot_land_frame][lead_toe_x_column-3];
        y_heel = ara[lead_foot_land_frame][lead_toe_x_column-2];
        x_toe = ara[lead_foot_land_frame][lead_toe_x_column];
        y_toe = ara[lead_foot_land_frame][lead_toe_x_column + 1];

printf("%f %f %f %f", x_heel, y_heel, x_toe, y_toe);
printf("%f %f %f",left_marker_y_coordinate, right_marker_y_coordinate,
horizontal_distance_between_markers);

    foot_gradient = (y_toe - y_heel)/(x_toe - x_heel);
    foot_angle = (atan((foot_gradient - true_gradient)/(1 + foot_gradient * true_gradient)) *
    180/3.14159);
    land_lead_foot_angle = foot_angle;

printf("\tLead foot angle at landing = %.2f degs, %i\n", land_lead_foot_angle, lead_foot_land_frame);
```

//Lead foot angle from toe-off to landing...

```
                        fp = fopen(filesave1, "a+");

                        if (fp == NULL)
                                {printf("Error opening file.\n");}
                        else
                                {fprintf(fp,"\n%s\t", filename);}
                                fclose(fp);

for (row = lead_toe_take_off_frame;  row < lead_foot_land_frame + 1;  row++ )  {

        x_heel = ara[row][lead_toe_x_column-3];
        y_heel = ara[row][lead_toe_x_column-2];
        x_toe = ara[row][lead_toe_x_column];
        y_toe = ara[row][lead_toe_x_column + 1];

printf("%f %f %f %f", x_heel, y_heel, x_toe, y_toe);
printf("%f %f %f",left_marker_y_coordinate, right_marker_y_coordinate,
horizontal_distance_between_markers);

if(x_heel == x_toe)
  {foot_angle = 90;}

        else  {
        foot_gradient = (y_toe - y_heel)/(x_toe - x_heel);
```

```
        foot_angle = (atan((foot_gradient - true_gradient)/(1 + foot_gradient * true_gradient)) *
        180/3.14159);

printf("\tLead foot angle = %.2f degs\t\n", foot_angle);
                              }
                              fp = fopen(filesave1, "a+");
                              if (fp == NULL)
                                        {printf("Error opening file.\n");}
                              else
                                        {fprintf(fp,"%.2f\t", foot_angle);}
                                        fclose(fp);
        }
```

//Lead foot linear velocity (LLV) upon landing (frame prior to contact with the ground)...............

```
if(ara[lead_foot_land_frame][lead_toe_y_column] < ara[lead_foot_land_frame][lead_toe_y_column - 3])

        {lead_foot_hor_land_velocity = (ara[lead_foot_land_frame][lead_toe_x_column] -
        ara[lead_foot_land_frame - 2][lead_toe_x_column])/0.04;
        lead_foot_vert_land_velocity = (ara[lead_foot_land_frame][lead_toe_y_column] -
        ara[lead_foot_land_frame - 2][lead_toe_y_column])/0.04;

printf("\tLead foot (toe) horz. land velocity = %.2f m.s-1\n",lead_foot_hor_land_velocity);
printf("%.4f,%.4f\n",ara[lead_foot_land_frame][lead_toe_x_column],ara[lead_foot_land_frame –
      2][lead_toe_x_column]);
printf("\tLead foot (toe) vert.land velocity = %.2f m.s-1\n",lead_foot_vert_land_velocity);
printf("%.4f,%.4f\n",ara[lead_foot_land_frame][lead_toe_y_column],ara[lead_foot_land_frame –
      2][lead_toe_y_column]);
        }

else {
lead_foot_hor_land_velocity = (ara[lead_foot_land_frame][lead_toe_x_column - 3] –
ara[lead_foot_land_frame - 2][lead_toe_x_column - 3])/0.04;
lead_foot_vert_land_velocity = (ara[lead_foot_land_frame][lead_toe_y_column - 3] –
ara[lead_foot_land_frame - 2][lead_toe_y_column - 3])/0.04;
printf("%.4f,%.4f\n",ara[lead_foot_land_frame][lead_toe_x_column - 3], ara[lead_foot_land_frame –
      2][lead_toe_x_column - 3]);
printf("\tLead foot (heel) horz. land velocity = %.2f m.s-1\n",lead_foot_hor_land_velocity);
printf("%.4f,%.4f\n",ara[lead_foot_land_frame][lead_toe_y_column - 3], ara[lead_foot_land_frame –
      2][lead_toe_y_column - 3]);
printf("\tLead foot (heel) vert.land velocity = %.2f m.s-1\n",lead_foot_vert_land_velocity);
        }
```

//Lead foot angular velocity upon landing (frame prior to contact with the ground)........................

```
        x_heel = ara[lead_foot_land_frame - 2][lead_toe_x_column-3];
        y_heel = ara[lead_foot_land_frame - 2][lead_toe_x_column-2];
        x_toe = ara[lead_foot_land_frame - 2][lead_toe_x_column];
        y_toe = ara[lead_foot_land_frame - 2][lead_toe_x_column + 1];

printf("%f %f %f %f", x_heel, y_heel, x_toe, y_toe);
printf("%f %f %f",left_marker_y_coordinate, right_marker_y_coordinate,
horizontal_distance_between_markers);

foot_gradient = (y_toe - y_heel)/(x_toe - x_heel);
foot_angle = (atan((foot_gradient - true_gradient)/(1 + foot_gradient * true_gradient)) * 180/3.14159);
lead_foot_angle_before_land = foot_angle;
printf("\tLead foot angle before landing = %.2f degs, %i\n", lead_foot_angle_before_land,
      lead_foot_land_frame);
```

```
lead_foot_angular_velocity_at_landing = (land_lead_foot_angle - lead_foot_angle_before_land)/0.04;
printf("\tLead foot angular velocity at landing = = %.2f degs.s-1\n",
        lead_foot_angular_velocity_at_landing);

// Trail foot orientation (TCA).....................................................................

 if (trail_toe_clearance_frame == 1000)
          {cross_trail_foot_angle = 1000;
          printf("\n\tTrail foot angle = %.2f degs\t Frame number = %i\n", cross_trail_foot_angle,
                  trail_toe_clearance_frame);
          printf("\tTrail foot straddles edge in support phase\n\n");
                  }
                  else{
         x_heel = ara[trail_toe_clearance_frame][trail_toe_x_column-3];
         y_heel = ara[trail_toe_clearance_frame][trail_toe_x_column-2];
         x_toe = ara[trail_toe_clearance_frame][trail_toe_x_column];
         y_toe = ara[trail_toe_clearance_frame][trail_toe_x_column + 1];

printf("%i, %i\n",trail_toe_clearance_frame, trail_toe_x_column);
printf("\n%f %f %f %f", x_heel, y_heel, x_toe, y_toe);
printf("\n%f %f %f",left_marker_y_coordinate, right_marker_y_coordinate,
       horizontal_distance_between_markers);

if(x_heel == x_toe)
          {foot_gradient = 10000000;}
 else{foot_gradient = (y_toe - y_heel)/(x_toe - x_heel);}

// This section ensures that a foot angle past vertical (i.e. toe is behind heel) is computed correctly.
// In an original program large velocities were being calculated. An angle past the vertical was
// computed as a positive value, hence moving past the vertical caused a negative then positive
// foot angle therefore resulting in false velocities.


 if (x_toe < x_heel)

 {foot_angle = (atan((foot_gradient - true_gradient)/(1 + foot_gradient * true_gradient)) * 180/3.14159 -
 180);
 cross_trail_foot_angle = foot_angle;
 printf("\tTrail foot angle = %.2f degs.\t Frame number = %i\n",
 cross_trail_foot_angle,trail_toe_clearance_frame);
          }
          else
          {foot_angle = (atan((foot_gradient - true_gradient)/(1 + foot_gradient * true_gradient)) *
          180/3.14159);
          cross_trail_foot_angle = foot_angle;
 printf("\tTrail foot angle = %.2f degs.\t Frame number = %i\n",
          cross_trail_foot_angle,trail_toe_clearance_frame);
          }

          }

//Available response time (ART) and trunk marker (HCD, HLD) characteristics.......................

          s1 = ara[lead_toe_clearance_frame - 1][15];
          s2 = ara[lead_toe_clearance_frame + 1][15];
          hor_linear_velocity_of_COM = (s2-s1)/0.04;
          hor_linear_dist_to_edge = mmark[3][0] - ara[lead_toe_clearance_frame][15];
          ART = hor_linear_dist_to_edge/hor_linear_velocity_of_COM;
```

```
COM_relative_base_of_support = (ara[lead_toe_clearance_frame][15] –
trail_toe_position_before_edge)*100;
COM_relative_base_of_support_at_lead_foot_landing = (ara[lead_foot_land_frame][15] –
trail_toe_position_before_edge)*100;

printf("\n\tCOM Vx = %.4f m.s-1\n", hor_linear_velocity_of_COM);
printf("\tCOM Sx = %.4f m\n", hor_linear_dist_to_edge);
printf("\tAvailable Response Time = %.4f\n", ART);
printf("\tCOM distance from base of support = %.2f cm\n", COM_relative_base_of_support);
printf("\tCOM distance from base of support at landing = %.2f cm\n",
COM_relative_base_of_support_at_lead_foot_landing);

s1 = ara[lead_foot_land_frame-2][16];
s2 = ara[lead_foot_land_frame][16];
COM_vertical_velocity_at_landing = (s2-s1)/0.04;
printf("\t%.4f, %.4f\n", s1, s2);
s1 = ara[lead_foot_land_frame-2][15];
s2 = ara[lead_foot_land_frame][15];
printf("\t%.4f, %.4f\n", s1, s2);
COM_horz_velocity_at_landing = (s2-s1)/0.04;
printf("\tCOM vertical velocity at landing = %.4f m.s-1\n",
COM_vertical_velocity_at_landing);
printf("\tCOM horizontal velocity at landing = %.4f m.s-1\n",
COM_horz_velocity_at_landing);

//Trunk marker (COM) position calculated relative to foot landing (i.e. heel or toe position)..........

if(ara[lead_foot_land_frame][lead_toe_y_column] < ara[lead_foot_land_frame][lead_toe_y_column - 3])
{
COM_relative_to_lead_foot_land_position =  ara[lead_foot_land_frame][15] -
lead_toe_position_at_midstance_past_edge;
printf("\tCOM horz. position relative to lead toe landing position = %.4f m\n",
COM_relative_to_lead_foot_land_position );
time_estimate_til_COM_passes_lead_toe =  fabs(COM_relative_to_lead_foot_land_position
)/COM_horz_velocity_at_landing;
printf("\tTime (estimate) til COM passes lead toe = %.2f sec\n",
time_estimate_til_COM_passes_lead_toe);
}

    else  {
    COM_relative_to_lead_foot_land_position =  ara[lead_foot_land_frame][15] –
    ara[lead_foot_land_frame][lead_toe_x_column - 3];
    printf("\tCOM horz. position relative to lead heel landing position = %.4f m\n",
    COM_relative_to_lead_foot_land_position );
    time_estimate_til_COM_passes_lead_toe =  fabs(COM_relative_to_lead_foot_land_position
    )/COM_horz_velocity_at_landing;
    printf("\tTime (estimate) til COM passes lead toe = %.2f sec\n",
    time_estimate_til_COM_passes_lead_toe);
        }

    if((lead_foot_land_frame < trail_toe_take_off_frame)||(lead_foot_land_frame ==
    trail_toe_take_off_frame))
    {crossing_double_foot_support_time = (trail_toe_take_off_frame - lead_foot_land_frame)*0.02;
    printf("\tDouble foot support time for accommodation step = %.2f sec\n",
    crossing_double_foot_support_time);
    }

    else{crossing_double_foot_support_time = 1000;
    printf("\tFlight phase = %.2f sec\n", crossing_double_foot_support_time);}
```

```
time_til_foot_grounded_from_toe_clearance_event = (lead_toe_midstance_frame_past_edge –
lead_foot_land_frame)*0.02;
printf("\tActual time til COM passes lead toe %.2f sec\n",
time_til_foot_grounded_from_toe_clearance_event);

//Lead toe trajectory ..........................................................................................

// Lead toe ..x ..coordinate saved to file.....................................................................

        fp = fopen(filesave2, "a+");

                if (fp == NULL)
                        {printf("Error opening file.\n");}
                else
                        {fprintf(fp,"\n%s\t", filename);}
                        fclose(fp);

        for (row = lead_toe_take_off_frame;  row < lead_foot_land_frame + 1;  row++ )  {

                fp = fopen(filesave2, "a+");

                if (fp == NULL)
                        {printf("Error opening file.\n");}
                else
                        {fprintf(fp,"%.4f\t", ara[row][lead_toe_x_column]);}
                        fclose(fp);
}

//Lead toe..y..coordinate saved to datafile ..................................................................

fp = fopen(filesave2, "a+");

                if (fp == NULL)
                        {printf("Error opening file.\n");}
                else
                        {fprintf(fp,"\n%s\t", filename);}
                        fclose(fp);

        for (row = lead_toe_take_off_frame;  row < lead_foot_land_frame + 1;  row++ )  {


                fp = fopen(filesave2, "a+");

                if (fp == NULL)
                        {printf("Error opening file.\n");}
                else
                        {fprintf(fp,"%.4f\t", ara[row][lead_toe_y_column]);}
                        fclose(fp);
}

//Hip trajectory ..........................................................................................

// Hip ..x ..coordinate saved to file.......................................................................

        fp = fopen(filesave3, "a+");

                if (fp == NULL)
                        {printf("Error opening file.\n");}
```

```
			else
				{fprintf(fp,"\n%s\t", filename);}
				fclose(fp);

		for (row = lead_toe_take_off_frame;  row < lead_foot_land_frame + 1;  row++ )  {

			fp = fopen(filesave3, "a+");

			if (fp == NULL)
				{printf("Error opening file.\n");}
			else
				{fprintf(fp,"%.4f\t", ara[row][0]);}
				fclose(fp);
	}
```

//Hip..y..coordinate saved to datafile ....

```
  fp = fopen(filesave3, "a+");

			if (fp == NULL)
				{printf("Error opening file.\n");}
			else
				{fprintf(fp,"\n%s\t", filename);}
				fclose(fp);

		for (row = lead_toe_take_off_frame;  row < lead_foot_land_frame + 1;  row++ )  {

			fp = fopen(filesave3, "a+");

			if (fp == NULL)
				{printf("Error opening file.\n");}
			else
				{fprintf(fp,"%.4f\t", ara[row][1]);}
				fclose(fp);
	}
```

// Knee ..x ..coordinate saved to file..

```
		fp = fopen(filesave4, "a+");

			if (fp == NULL)
				{printf("Error opening file.\n");}
			else
				{fprintf(fp,"\n%s\t", filename);}
				fclose(fp);

		for (row = lead_toe_take_off_frame;  row < lead_foot_land_frame + 1;  row++ )  {


			fp = fopen(filesave4, "a+");

			if (fp == NULL)
				{printf("Error opening file.\n");}
			else
				{fprintf(fp,"%.4f\t", ara[row][30]);}
				fclose(fp);
	}
```

//Knee..y..coordinate saved to datafile ....

```
fp = fopen(filesave4, "a+");

                if (fp == NULL)
                        {printf("Error opening file.\n");}
                else
                        {fprintf(fp,"\n%s\t", filename);}
                        fclose(fp);

        for (row = lead_toe_take_off_frame;  row < lead_foot_land_frame + 1;  row++ )  {

                fp = fopen(filesave4, "a+");

                if (fp == NULL)
                        {printf("Error opening file.\n");}
                else
                        {fprintf(fp,"%.4f\t", ara[row][31]);}
                        fclose(fp);
    }

//Data sent to datafiles ******************************************************

fp = fopen(filesave5, "a+");

    if (fp == NULL)
    {printf("Error opening file.\n");}
    else

{fprintf(fp,"\n%s, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f,
%.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f,
%.4f, %.4f, %.4f", filename, step_edge_x_coordinate, step_edge_y_coordinate, lead_toe_clearance,
lead_toe_minimum_clearance, lead_heel_clearance, lead_heel_minimum_clearance,
lead_crossing_stride_length, percent_of_lead_stride_length_at_crossing,
percent_time_of_lead_at_crossing,lead_crossing_step_length, percent_of_lead_step_length_at_crossing,
lead_crossing_step_time,lead_toe_pre_step_distance,lead_toe_landing_distance_past_edge,
lead_foot_hor_land_velocity, lead_foot_vert_land_velocity, trail_toe_clearance, trail_heel_clearance,
trail_toe_pre_step_distance,cross_lead_foot_angle, land_lead_foot_angle, lead_foot_angle_before_land,
lead_foot_angular_velocity_at_landing, cross_trail_foot_angle, ART, hor_linear_velocity_of_COM,
hor_linear_dist_to_edge, COM_relative_base_of_support, COM_horz_velocity_at_landing,
COM_vertical_velocity_at_landing, COM_relative_to_lead_foot_land_position ,
time_estimate_til_COM_passes_lead_toe, time_til_foot_grounded_from_toe_clearance_event,
crossing_double_foot_support_time);}

fclose(fp);

    return(0);

}
```

Appendix C

Computer software program (C language) used to extract data for the descent condition

This program calculates footfall position relative to step edge. It also extracts parameters such as head angle, knee angle, trunk angle and hip angle.

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>  // For strcpy....
#include <math.h>
#define M 150
#define N 6
#define P 15
#define Q 36

float mmark[M][9];
float ara1[M][N];
float ara2[M][N];
float ara3[M][P];
float ara4[M][Q];

main()

{
        FILE *fp;
        FILE *data;
        int row, col;

char    approach1[50], approach2[50], approach3[50], approach4[50], midmark[50], filesave1[50],
        filesave2[50], filesave3[50], filesave4[50], filesave5[50], filesave6[50];
float   max_head_down_angle_in_FOV3, max_head_down_angle_in_FOV4,
        land_hip_angle, land_lead_knee_angle, knee_angle_at_midstance,
        knee_angle_change_to_midstance, max_knee_flexion_angle;
float   land_trunk_angle, trunk_angle_at_midstance, trunk_angle_at_lead_toe_clearance,
        min_trunk_angle, max_trunk_angle;
float   knee_angle, head_angle, trunk_angle, x_hip, y_hip, x_knee, y_knee, x_ankle, y_ankle,
        x_shoulder, y_shoulder, x_head_front, y_head_front, x_head_back, y_head_back, x_canthus,
        y_canthus;
float   true_gradient4, true_gradient3,true_horz_angle4, true_horz_angle3, lower_leg_gradient,
        trunk_gradient,  thigh_gradient, head_gradient, lead_toe_position_at_midstance_past_edge,
        trail_toe_position_near_edge, trail_toe_position_in_straddle, lead_heel_position_past_edge;
float   trail_foot_length, lead_foot_length;
float   step_edge_x_coordinate, step_edge_y_coordinate;
float   toe_position, first_right_toe_position, first_left_toe_position;
float   right_marker_y_coordinate, left_marker_y_coordinate, horizontal_distance_between_markers;
float   canthus_horz_position_FOV3, canthus_horz_position_FOV4;
float   x_heel, y_heel, x_toe, y_toe;
int     LineNo, H, I, J, K;
int     lead_toe_take_off_frame, lead_toe_midstance_frame_past_edge, lead_foot_land_frame,
        max_knee_flexion_frame;
int     lead_toe_x_column, lead_toe_y_column, trail_toe_x_column, trail_toe_y_column ;
int     right_toe_past_frame, left_toe_past_frame, lead_toe_clearance_frame,
        min_trunk_angle_frame, max_trunk_angle_frame ;
int     heel_contact_frame_before_edge, max_head_down_angle_in_FOV3_frame,
        max_head_down_angle_in_FOV4_frame, end_of_file,
        head_start_frame_in_FOV4, trail_toe_take_off_frame;

//printf("Name of file being analysed?\n");
```

//Filenames...
//The first four lines open the datafiles produced from the digitization process of the film recorded
//by the four cameras (nap1.txt, nap2.txt, nap3.txt, nap4.txt). The markoff.txt file contains
//information about the location of the midmarkers described in section 5.2.2.3.
//The remaining files describe where calculated information is sent.
//tersdnof.txt; footfall position: hdangnof.txt; head angle data; taunoff.txt; tau data;
//noff.txt; data such as maximum trunk or minimum knee angle etc...; kneenoff.txt; knee
//angle data; trunknof.txt; trunk angle data.

```
(void) strcpy( approach1, "c:\\doctor\\data\\young\\stepoff\\S1\\nap1.txt");
(void) strcpy( approach2, "c:\\doctor\\data\\young\\stepoff\\S1\\nap2.txt");
(void) strcpy( approach3, "c:\\doctor\\data\\young\\stepoff\\S1\\nap3.txt");
(void) strcpy( approach4, "c:\\doctor\\data\\young\\stepoff\\S1\\nap4.txt");
(void) strcpy( midmark,   "c:\\doctor\\data\\midmark\\off\\markoff.txt");
(void) strcpy( filesave1, "c:\\doctor\\data\\young\\results\\normoff\\tersdnof.txt");
(void) strcpy( filesave2, "c:\\doctor\\data\\young\\results\\normoff\\hdangnof.txt");
(void) strcpy( filesave3, "c:\\doctor\\data\\young\\results\\normoff\\taunoff.txt");
(void) strcpy( filesave4, "c:\\doctor\\data\\young\\results\\normoff\\noff.txt");
(void) strcpy( filesave5, "c:\\doctor\\data\\young\\results\\normoff\\kneenoff.txt");
(void) strcpy( filesave6, "c:\\doctor\\data\\young\\results\\normoff\\trunknof.txt");

printf("%s\n", approach4);
//printf("\n");
```

//* Routine to calculate footfall position*****

//Places a name in data file...................................

```
                    fp = fopen(filesave1, "a+");

            if (fp == NULL)
                    {printf("Error opening file.\n");}
            else
                    {fprintf(fp,"\n%s\t", approach4);}
                    fclose(fp);
```

//Opens and scans mid-maker array (approach4) - incline calculated..

```
        if ((data=fopen(midmark,"r"))==NULL)
          {printf("\n\n*** That file does not exist***\n");
          exit(0);}

        else
             {
            for (row=0;row < M; row++)

            for (col=0;col < 9; col++)
                    fscanf(data,"%f", &mmark[row][col]);
      }

    left_marker_y_coordinate = mmark[0][6];
    right_marker_y_coordinate = mmark[0][7];
    horizontal_distance_between_markers = mmark[0][8];
    true_gradient4 = ((right_marker_y_coordinate -
    left_marker_y_coordinate))/(horizontal_distance_between_markers);
    true_horz_angle4 = true_gradient4 * 180.00/3.14159;
```

//Opens and scans mid-maker array (approach3) - incline calculated...

```
if ((data=fopen(midmark,"r"))==NULL)
   {printf("\n\n*** That file does not exist***\n");
   exit(0);}

else
         {
         for (row=0;row < M; row++)

         for (col=0;col < 9; col++)
                 fscanf(data,"%f", &mmark[row][col]);
   }
         left_marker_y_coordinate = mmark[0][3];
   right_marker_y_coordinate = mmark[0][4];
   horizontal_distance_between_markers = mmark[0][5];
   true_gradient3 = ((right_marker_y_coordinate -
   left_marker_y_coordinate))/(horizontal_distance_between_markers);
   true_horz_angle3 = true_gradient3 * 180/3.14159;

  //printf("\tGradients = %.4f degs., %.4f degs.\n", true_horz_angle4, true_horz_angle3);
```

//Opens and scans 1st file into array...

```
if ( (data = fopen( approach1, "r")) == NULL ) {
   printf("\n\n*** That file does not exist you idiot ***\n");
   exit(1);
   }

else

         {
         for (row=0;row < M; row++)

         for (col=0;col < N; col++)
               · fscanf(data,"%f", &ara1[row][col]);
   }
```

//Routine to identify which foot lands first ....

```
for (row=0;row < M; row++) {
         if(ara1[row][0]>0)
         break;
         }
         first_right_toe_position = ara1[row][0];
         //printf("%.4f\n", first_right_toe_position);

         for (row=0;row < M; row++) {
         if(ara1[row][3]>0)
         break;
         }
   first_left_toe_position = ara1[row][3];
  //printf("%.4f\n", first_left_toe_position);
```

```
if (first_right_toe_position < first_left_toe_position)

            {H=0;I=3;J=6;K=12;}

else {H=3;I=0;J=12;K=6;}


                  for (row=0;row < M; row++) {
              if(ara1[row][H]>0)
              {
              LineNo = row;
              toe_position = mmark[0][0] - ara1[LineNo][H] + mmark[0][1];
              printf("\t%.4f\n",toe_position);

              fp = fopen(filesave1, "a+");

                  if (fp == NULL)
                          {printf("Error opening file.\n");}
                  else
                          {fprintf(fp,"%.4f\t", toe_position);}
                          fclose(fp);
              }


              if(ara1[row][I]>0)
              {
              LineNo = row;
              toe_position = mmark[0][0] - ara1[LineNo][I] + mmark[0][1];
              printf("\t%.4f\n",toe_position);

              fp = fopen(filesave1, "a+");

                  if (fp == NULL)
                          {printf("Error opening file.\n");}
                  else
                          {fprintf(fp,"%.4f\t", toe_position);}
                          fclose(fp);
              }
              }
```

//Opens and scans 2nd file into array ....

```
if ((data=fopen(approach2,"r"))==NULL)
              {printf("\n\n*** That file does not exit***\n");
              exit(0);}

          else
                  {
                  for (row=0; row < M; row++)

                  for (col=0; col < N; col++)
                          fscanf(data,"%f", &ara2[row][col]);
                  }

              for (row=0;row < M; row++) {
              if(ara2[row][H]>0)
              {
              LineNo = row;
              toe_position = mmark[1][0] - ara2[LineNo][H] + mmark[1][1];
```

```
                    printf("\t%.4f\n",toe_position);

                    fp = fopen(filesave1, "a+");

                            if (fp == NULL)
                                    {printf("Error opening file.\n");}
                            else
                                    {fprintf(fp,"%.4f\t", toe_position);}
                                    fclose(fp);
                    }

                    if(ara2[row][I]>0)
                    {
                    LineNo = row;
                    toe_position = mmark[1][0] - ara2[LineNo][I] + mmark[1][1];
                    //printf("\t%.4f\n",toe_position);

                    fp = fopen(filesave1, "a+");

                            if (fp == NULL)
                                    {printf("Error opening file.\n");}
                            else
                                    {fprintf(fp,"%.4f\t", toe_position);}
                                    fclose(fp);
                    }
                    }
```

//Opens and scans 3rd file into array ....

```
if ((data=fopen(approach3,"r"))==NULL)
                    {printf("\n\n*** That file does not exit***\n");
                    exit(0);}

                else
                            {

                            for (row=0; row < M;row++)

                            for (col=0; col < P;col++)

                                    fscanf(data,"%f", &ara3[row][col]);


                            }

        for (row=0; row < M;row++) {
                            if((ara3[row][14] > 0) && (ara3[row+1][14]==0))
                            break;
                            }
                            end_of_file = row;
                            //printf("\tEnd of file (row) %i\n", end_of_file);


                    for (row=0;row < M; row++) {
                    if(ara3[row][H]>0)
                    {
                    LineNo = row;
                    toe_position = mmark[2][0] - ara3[LineNo][H] + mmark[2][1];
                    //printf("\t%.4f\n",toe_position);
```

```
        fp = fopen(filesave1, "a+");

                if (fp == NULL)
                        {printf("Error opening file.\n");}
                else
                        {fprintf(fp,"%.4f\t", toe_position);}
                        fclose(fp);
        }

        if(ara3[row][I]>0)
        {
        LineNo = row;
        toe_position = mmark[2][0] - ara3[LineNo][I] + mmark[2][1];
        //printf("\t%.4f\n",toe_position);

        fp = fopen(filesave1, "a+");

                if (fp == NULL)
                        {printf("Error opening file.\n");}
                else
                        {fprintf(fp,"%.4f\t", toe_position);}
                        fclose(fp);
        }
        }
```

//Opens and scans 4th file into array ....

```
 if ((data=fopen(approach4,"r"))==NULL)
        {printf("\n\n*** That file does not exit***\n");
         exit(0);}

       else
                {
                for (row=0; row < M;row++)

                for (col=0; col < Q;col++)
                        fscanf(data,"%f", &ara4[row][col]);

                }

        for (row=0;row < M; row++) {
         if((ara4[row-1][J]==0) && (ara4[row][J]>0) && (ara4[row+1][J]==0))
         {
         LineNo = row;
         toe_position = mmark[3][0] - ara4[LineNo][J] + mmark[3][1];
         //printf("\t%.4f\n",toe_position);

         fp = fopen(filesave1, "a+");

                if (fp == NULL)
                        {printf("Error opening file.\n");}
                else
                        {fprintf(fp,"%.4f\t", toe_position);}
                        fclose(fp);
         }

         if((ara4[row-1][K]==0) && (ara4[row][K]>0) && (ara4[row+1][K]==0))
```

```
                {
                LineNo = row;
                toe_position = mmark[3][0] - ara4[LineNo][K] + mmark[3][1];
                //printf("\t%.4f\n",toe_position);

                fp = fopen(filesave1, "a+");

                      if (fp == NULL)
                            {printf("Error opening file.\n");}
                      else
                            {fprintf(fp,"%.4f\t", toe_position);}
                            fclose(fp);
                }
                }

//printf("Step edge sagittal plane coordinates = %f m, %f m\n", mmark[3][0], mmark[3][2]);
        step_edge_x_coordinate = mmark[3][0];step_edge_y_coordinate = mmark[3][2];
//printf("\tstep_edge_x_coordinate = %.4f m\n",step_edge_x_coordinate);
//printf("\tstep_edge_y_coordinate = %.4f m\n",step_edge_y_coordinate);

// Lead limb identified when both heel and toe are past step edge. This is required in case the trail
// foot is placed half on and off the edge (partially supported).

        for (row = 0; row < M; row++ ) {

   if((ara4[row][6] > step_edge_x_coordinate) && (ara4[row][3] > step_edge_x_coordinate))
            {right_toe_past_frame = row-1;
            //printf("\tx_value = %.4f\n", ara4[row][6]);
            //printf("\tFrame = %i\n", right_toe_past_frame);
            break;}

            }

        for (row = 0; row < M; row++ ) {

        if((ara4[row][12] > step_edge_x_coordinate) && (ara4[row][9] > step_edge_x_coordinate))
            {left_toe_past_frame = row-1;
            //printf("\tx_value = %.4f\n", ara4[row][12]);
            //printf("\tFrame = %i\n", left_toe_past_frame);
            break;}

            }

              if (right_toe_past_frame < left_toe_past_frame){
              //printf("\tLead limb is the right limb!\n\n");
              lead_toe_x_column = 6;
              trail_toe_x_column = 12;
              //printf("\tlead toe column = %i\n", lead_toe_x_column);
              //printf("\ttrail toe column = %i\n", trail_toe_x_column);
              lead_toe_y_column = lead_toe_x_column + 1;
              trail_toe_y_column = trail_toe_x_column + 1;
              }

              else
              {//printf("\tLead limb is the left limb!\n\n");
              lead_toe_x_column = 12;
              trail_toe_x_column = 6;
              lead_toe_y_column = lead_toe_x_column + 1;
              trail_toe_y_column = trail_toe_x_column +1;
```

```
            //printf("\tlead toe column = %i\n", lead_toe_x_column);
            //printf("\ttrail toe column = %i\n", trail_toe_x_column);
            }
```

//Identification of events (e.g., toe-off, foot landing etc...)..

```
    for (row = 0;  row < M;  row++ )  {
    if ((ara4[row][lead_toe_x_column] > 0) && (ara4[row][lead_toe_x_column - 3] > 0))
            break;
              }
      lead_toe_take_off_frame = row;
//printf("\tFrame lead toe take off = %i\n", lead_toe_take_off_frame);

    for (row = lead_toe_take_off_frame;  row < M;  row++ )  {
    if ((ara4[row][lead_toe_x_column] > 0) && (ara4[row+1][lead_toe_x_column] == 0))
            break;
            }
    lead_foot_land_frame = row;
//printf("\tLead foot landing frame = %i\n", lead_foot_land_frame);

    for (row = lead_foot_land_frame + 1;  row < M;  row++ )  {
        if  (ara4[row][lead_toe_x_column] > 0)
                    break;
                    }
lead_toe_position_at_midstance_past_edge = ara4[row][lead_toe_x_column];
lead_toe_midstance_frame_past_edge = row;

//printf("\tLead foot midstance frame = %i\n", lead_toe_midstance_frame_past_edge);
//printf("\tLead foot midstance position = %.4f\n", lead_toe_position_at_midstance_past_edge);

for (row = 0;  row < M;  row++ )  {
if ((ara4[row][lead_toe_x_column] < step_edge_x_coordinate) && (ara4[row + 1][lead_toe_x_column]
> step_edge_x_coordinate))
             break;
            }
     lead_toe_clearance_frame = row;
     //printf("\tLead toe clearance frame = %i\n",  row);

     for (row = 0;  row < M;  row++ )  {
                    if (ara3[row][9] > 0)
                break;
            }
     heel_contact_frame_before_edge = row;
     //printf("\tHeel contact before edge (frame) = %i\n",  row);

   for (row = 0;  row < M;  row++ )  {
                    if (ara4[row][24] > 0)
                break;
            }
     head_start_frame_in_FOV4 = row;
     //printf("\tHead start frame in FOV4 (frame) = %i\n",  row);

   for (row = 0;  row < M;  row++ )  {
     if ((ara4[row][trail_toe_x_column] > 0) && (ara4[row][trail_toe_x_column - 3] > 0))
            {trail_toe_take_off_frame = row;
            //printf("\tFrame trail toe take off = %i\n", trail_toe_take_off_frame);
            break;}
         }
```

```
for (row = 0;  row < trail_toe_take_off_frame; row++)
  if ((ara4[row][trail_toe_x_column] > 0) && (ara4[row + 1][trail_toe_x_column] == 0))
            {trail_toe_position_near_edge = ara4[row][trail_toe_x_column];}
            //printf("\tTrail toe position = %.4f", trail_toe_position_near_edge);
```

///Trail foot length calculation and position of trail toe if straddling edge.....

```
if (trail_toe_position_near_edge > step_edge_x_coordinate)
{//printf("\tTrail foot straddles edge\n");
   x_heel = ara4[row + 2][trail_toe_x_column - 3];
   y_heel = ara4[row + 2][trail_toe_y_column - 3];
   x_toe = ara4[row + 2][trail_toe_x_column];
   y_toe = ara4[row + 2][trail_toe_y_column];

   trail_foot_length = sqrt((x_toe - x_heel)*(x_toe - x_heel) + (y_toe - y_heel)*(y_toe - y_heel));
   //printf("\t Trail foot length = %.4f\n", trail_foot_length);

   trail_toe_position_in_straddle =  trail_toe_position_near_edge - step_edge_x_coordinate;
   printf("\tTrail toe position (straddle) past edge = %.4f m\n", trail_toe_position_in_straddle);
      }
```

//Lead foot length calculation and position of lead heel at landing relative to edge (LHD)

```
    x_heel = ara4[lead_foot_land_frame][lead_toe_x_column - 3];
    y_heel = ara4[lead_foot_land_frame][lead_toe_y_column - 3];
    x_toe = ara4[lead_foot_land_frame][lead_toe_x_column];
    y_toe = ara4[lead_foot_land_frame][lead_toe_y_column];

    lead_foot_length = sqrt((x_toe - x_heel)*(x_toe - x_heel) + (y_toe - y_heel)*(y_toe - y_heel));
    //printf("\t Lead foot length = %.4f\n", lead_foot_length);
    lead_heel_position_past_edge = (lead_toe_position_at_midstance_past_edge - lead_foot_length)
    - step_edge_x_coordinate;
    //printf("\t Lead heel position past edge = %.4f m\n", lead_heel_position_past_edge);
```

//Knee angle at foot contact and maximum knee flexion (foot contact to midstance)................
//Knee angle is measured counter-clockwise from thigh segment ....

```
    x_hip = ara4[lead_foot_land_frame][0];
    y_hip = ara4[lead_foot_land_frame][1];
    x_knee = ara4[lead_foot_land_frame][30];
    y_knee = ara4[lead_foot_land_frame][31];
    x_ankle = ara4[lead_foot_land_frame][33];
    y_ankle = ara4[lead_foot_land_frame][34];
```

//Knee variables are not calculated for Approach4 datafiles that do not have knee or ankle data....

```
if (x_knee == 0)

  {
    //printf("\n\tNO KNEE OR ANKLE DATA\n\n\n");
    land_lead_knee_angle = 1000;
    max_knee_flexion_angle = 1000;
    knee_angle_at_midstance =  1000;
    knee_angle_change_to_midstance = 1000;
    land_hip_angle = 1000;
    //printf("\t%.0f, %.0f, %.0f, %.0f, %.0f", land_lead_knee_angle, max_knee_flexion_angle,
    //knee_angle_at_midstance, land_hip_angle, knee_angle_change_to_midstance);
  }
```

```
else

{

        thigh_gradient = (y_knee - y_hip)/(x_knee - x_hip);
        lower_leg_gradient = (y_ankle - y_knee)/(x_ankle - x_knee);
       //printf("\t%.4f, %.4f, %.2f\n", thigh_gradient, lower_leg_gradient, true_horz_angle4);
        knee_angle = atan((lower_leg_gradient - thigh_gradient)/(1 +
        lower_leg_gradient*thigh_gradient))*180/3.14159;
       //printf("\tLead knee angle at landing = %.2f degs\n", knee_angle);
```

//Calculates knee angle when knee is in flexion (< 180 degs.), else when hyperextended (e.g. at foot contact).......

```
        land_lead_knee_angle = knee_angle + 180;

        //printf("\tLead knee angle at landing = %.2f degs\n", land_lead_knee_angle);
```

//Maximum knee flexion (landing to midstance) ....

```
 fp = fopen(filesave5, "a+");

                        if (fp == NULL)
                                {printf("Error opening file.\n");}
                        else
                                {fprintf(fp,"\n%s\t", approach4);}
                                fclose(fp);

 max_knee_flexion_angle = 1000;

for (row = lead_foot_land_frame;  row < lead_toe_midstance_frame_past_edge + 1;  row++ )  {

       x_hip = ara4[row][0];
       y_hip = ara4[row][1];
       x_knee = ara4[row][30];
       y_knee = ara4[row][31];
       x_ankle = ara4[row][33];
       y_ankle = ara4[row][34];

       if (x_knee == x_hip )       .
        {thigh_gradient = 10000000;}

       else {thigh_gradient = (y_knee - y_hip)/(x_knee - x_hip);}

       if (x_knee == x_ankle)
        {lower_leg_gradient = 10000000;}

       else {lower_leg_gradient = (y_ankle - y_knee)/(x_ankle - x_knee);}

       //printf("\t%.4f, %.4f\n", thigh_gradient, lower_leg_gradient);
       //printf("\t%.4f %.4f %.4f %.4f %.4f %.4f\n", x_hip, y_hip, x_knee, y_knee, x_ankle, y_ankle);

        knee_angle = atan((lower_leg_gradient - thigh_gradient)/(1 +
        lower_leg_gradient*thigh_gradient))*180/3.14159;
        //printf("\tLead knee angle at landing = %.2f degs\n", knee_angle);

        knee_angle = knee_angle + 180;

        fp = fopen(filesave5, "a+");
```

```
                    if (fp == NULL)
                            {printf("Error opening file.\n");}
                    else
                            {fprintf(fp,"%.4f\t", knee_angle);}
                            fclose(fp);

                    //printf("\tKnee angle = %.2f degs\n", knee_angle);

                    if (knee_angle < max_knee_flexion_angle)
                    {max_knee_flexion_angle = knee_angle;
                    max_knee_flexion_frame = row;}

            }

                    knee_angle_at_midstance = knee_angle;
     knee_angle_change_to_midstance = knee_angle_at_midstance - land_lead_knee_angle;
    //printf("\tLead knee angle at landing = %.2f degs\n", land_lead_knee_angle);
    printf("\tMaximum knee flexion angle  = %.2f degs, %i\n", max_knee_flexion_angle,
           max_knee_flexion_frame);
    //printf("\tKnee angle at midstance  = %.2f degs\n", knee_angle_at_midstance);
    //printf("\tChange in knee angle from landing to midstance  = %.2f degs\n",
     knee_angle_change_to_midstance);

//Hip angle at landing.....Note..............................
//Hip angle is relative to thigh segment and measured counter - clockwise ......
//Trunk angle is relative to incline and measured counter-clockwise (positive magnitude) from
  incline ...

    x_hip = ara4[lead_foot_land_frame][0];
    y_hip = ara4[lead_foot_land_frame][1];
    x_knee = ara4[lead_foot_land_frame][30];
    y_knee = ara4[lead_foot_land_frame][31];
    x_shoulder = ara4[lead_foot_land_frame][18];
    y_shoulder = ara4[lead_foot_land_frame][19];

    //printf("\t%.4f %.4f %.4f %.4f %.4f %.4f\n", x_hip, y_hip, x_knee, y_knee, x_ankle, y_ankle);
    thigh_gradient = (y_knee - y_hip)/(x_knee - x_hip);
    trunk_gradient = (y_hip - y_shoulder)/(x_hip - x_shoulder);
    //printf("\t%.4f,%.4f, %.4f\n", thigh_gradient, trunk_gradient, true_gradient4);

    land_hip_angle = (atan((thigh_gradient - trunk_gradient)/(1 + trunk_gradient*thigh_gradient))
    * 180/3.14159);
    land_hip_angle  = 180 - land_hip_angle;
    //printf("\n\tHip angle at landing = %.2f degs\n", land_hip_angle);

 }

//Trunk angle at landing (trunk angle placed in same convention as step down condition).....

    x_hip = ara4[lead_foot_land_frame][0];
    y_hip = ara4[lead_foot_land_frame][1];
    x_shoulder = ara4[lead_foot_land_frame][18];
    y_shoulder = ara4[lead_foot_land_frame][19];

// This step required to prevent program from crashing - division by zero...

    if(x_shoulder == x_hip)  {
    land_trunk_angle = 90;
```

```
}
            else {
            trunk_gradient = (y_hip - y_shoulder)/(x_hip - x_shoulder);
    //printf("\t%.4f, %.4f\n", trunk_gradient, true_gradient4);
    land_trunk_angle = atan((trunk_gradient - true_gradient4)/(1 + trunk_gradient*true_gradient4))
    * 180/3.14159;
    }

    if(land_trunk_angle < 0)
    {land_trunk_angle = 180 + land_trunk_angle;}
    printf("\tLand trunk angle = %.2f degs. %.2f\n", land_trunk_angle, true_horz_angle4);
```

//Trunk angle at lead foot clearance ....

```
    x_hip = ara4[lead_toe_clearance_frame][0];
    y_hip = ara4[lead_toe_clearance_frame][1];
    x_shoulder = ara4[lead_toe_clearance_frame][18];
    y_shoulder = ara4[lead_toe_clearance_frame][19];
     //printf("\t%.4f %.4f %.4f %.4f\n", x_hip, y_hip, x_shoulder, y_shoulder);
```

// This step required to prevent program from crashing - division by zero...

```
    if(x_shoulder == x_hip)  {
    trunk_angle = 90;
    }
            else {
            trunk_gradient = (y_hip - y_shoulder)/(x_hip - x_shoulder);
    //printf("\t%.4f, %.4f\n",trunk_gradient, true_gradient4);
    trunk_angle = atan((trunk_gradient - true_gradient4)/(1 + trunk_gradient*true_gradient4)) *
    180/3.14159;
    }

    if(trunk_angle < 0)
    {trunk_angle = 180 + trunk_angle;}

    trunk_angle_at_lead_toe_clearance = trunk_angle;
    //printf("\tTrunk angle at lead toe clearance = %.2f degs\n", trunk_angle);

 fp = fopen(filesave6, "a+");

                    if (fp == NULL)
                            {printf("Error opening file.\n");}
                    else
                            {fprintf(fp,"\n%s\t", approach4);}
                            fclose(fp);

    max_trunk_angle = 0;
    min_trunk_angle = 1000;

 for (row = lead_toe_take_off_frame;  row < lead_toe_midstance_frame_past_edge + 1;  row++ )  {

    x_hip = ara4[row][0];
    y_hip = ara4[row][1];
    x_shoulder = ara4[row][18];
    y_shoulder = ara4[row][19];
    //printf("\t%.4f %.4f %.4f %.4f\n", x_shoulder, y_shoulder, x_hip, y_hip);
```

// This step required to prevent program from crashing - division by zero...

```
	if(x_shoulder == x_hip) {
	trunk_angle = 90;
	}

	else {
	trunk_gradient = (y_hip - y_shoulder)/(x_hip - x_shoulder);
	//printf("\t%.4f, %.4f\n",trunk_gradient, true_gradient4);
	trunk_angle = atan((trunk_gradient - true_gradient4)/(1 + trunk_gradient*true_gradient4)) *
	180/3.14159;
	}

	if(trunk_angle < 0)
	{trunk_angle = 180 + trunk_angle;}

	if(trunk_angle < min_trunk_angle) {
	min_trunk_angle = trunk_angle;
	min_trunk_angle_frame = row;}

	if(trunk_angle > max_trunk_angle) {
	max_trunk_angle = trunk_angle;
	max_trunk_angle_frame = row;}

	//printf("%i, Trunk angle  = %.2f degs\n", row, trunk_angle);

	fp = fopen(filesave6, "a+");

			if (fp == NULL)
				{printf("Error opening file.\n");}
			else
				{fprintf(fp,"%.4f\t", trunk_angle);}
				fclose(fp);
	}

	trunk_angle_at_midstance = trunk_angle;
	//printf("\tTrunk angle at midstance = %.2f degs\n", trunk_angle);
	//printf("\tMinimum trunk angle (toe-off to midstance) = %.2f degs , %i\n", min_trunk_angle,
	  min_trunk_angle_frame);
	//printf("\tMaximum trunk angle (toe-off to midstance) = %.2f degs , %i\n", max_trunk_angle,
	  max_trunk_angle_frame);
```

//Head angle in FOV3 ....

```
 fp = fopen(filesave2, "a+");

			if (fp == NULL)
				{printf("Error opening file.\n");}
			else
				{fprintf(fp,"\n%s\t", approach4);}
				fclose(fp);

max_head_down_angle_in_FOV3 = 1000;

for (row = heel_contact_frame_before_edge;  row < end_of_file + 1;  row++ )  {

	x_head_front = ara3[row][9];
	y_head_front = ara3[row][10];
	x_head_back = ara3[row][12];
	y_head_back = ara3[row][13];
```

```
//printf("\t%.4f %.4f %.4f %.4f\n", x_head_front, y_head_front, x_head_back, y_head_back);

 head_gradient = (y_head_front - y_head_back )/(x_head_front - x_head_back);
//printf("\t%.4f,%.4f\n", head_gradient, );

head_angle = atan((head_gradient - true_gradient3)/(1 + head_gradient*true_gradient3)) *
180/3.14159;
//printf("\tHead angle = %.2f\n", head_angle);

if(head_angle < max_head_down_angle_in_FOV3) {
max_head_down_angle_in_FOV3 = head_angle;
max_head_down_angle_in_FOV3_frame = row;
}
//printf("\tMaximum head angle (head down) = %.2f degs , %i\n",
 max_head_down_angle_in_FOV3,  max_head_down_angle_in_FOV3_frame);

fp = fopen(filesave2, "a+");

                if (fp == NULL)
                        {printf("Error opening file.\n");}
                else
                        {fprintf(fp,"%.4f\t", head_angle);}
                        fclose(fp);

}

//printf("\tMaximum head angle (head down) in FOV3 = %.2f degs, %i\n",
  max_head_down_angle_in_FOV3,  max_head_down_angle_in_FOV3_frame);
```

//Head angle in FOV4 ....

```
max_head_down_angle_in_FOV4 = 1000;

for (row = head_start_frame_in_FOV4;  row < lead_toe_midstance_frame_past_edge + 1;  row++ )  {

 x_head_front = ara4[row][27];
 y_head_front = ara4[row][28];
 x_head_back = ara4[row][24];
 y_head_back = ara4[row][25];

 //printf("\t%.4f %.4f %.4f %.4f\n", x_head_front, y_head_front, x_head_back, y_head_back);
   head_gradient = (y_head_front - y_head_back )/(x_head_front - x_head_back);
 //printf("\t%.4f,%.4f\n", head_gradient, true_gradient4);

 head_angle = atan((head_gradient - true_gradient3)/(1 + head_gradient*true_gradient3)) *
 180/3.14159;
 //printf("\tHead angle = %.2f\n", head_angle);

 if(head_angle < max_head_down_angle_in_FOV4) {
 max_head_down_angle_in_FOV4 = head_angle;
 max_head_down_angle_in_FOV4_frame = row;
 }

 //printf("\tMaximum head angle (head down) = %.2f degs , %i\n",
   max_head_down_angle_in_FOV4,  max_head_down_angle_in_FOV4_frame);

 fp = fopen(filesave2, "a+");

                 if (fp == NULL)
```

```
                {printf("Error opening file.\n");}
        else
                {fprintf(fp,"%.4f\t", head_angle);}
                fclose(fp);

    }

    //printf("\tMaximum head angle (head down) in FOV4 = %.2f degs, %i\n",
     max_head_down_angle_in_FOV4, max_head_down_angle_in_FOV4_frame);
```

//Tau in FOV3 ....

```
 fp = fopen(filesave3, "a+");

        if (fp == NULL)
                {printf("Error opening file.\n");}
        else
                {fprintf(fp,"\n%s\t", approach4);}
                fclose(fp);

     for (row = heel_contact_frame_before_edge;  row < end_of_file + 1;  row++ )  {

    x_canthus = ara3[row][6];
    y_canthus = ara3[row][7];

    canthus_horz_position_FOV3 =  mmark[2][0] - x_canthus + mmark[2][1];
    //printf("\t%.4f %.4f %.4f\n", x_canthus, y_canthus, canthus_horz_position_FOV3);
    //printf("\t%.4f %.4f\n", mmark[2][0], mmark[2][1]);

    fp = fopen(filesave3, "a+");

        if (fp == NULL)
                {printf("Error opening file.\n");}
        else
                {fprintf(fp,"%.4f\t",canthus_horz_position_FOV3);}
                fclose(fp);
    }
```

//Tau in FOV4 ....

```
     for (row = head_start_frame_in_FOV4;  row < lead_foot_land_frame + 1;  row++ )  {

    x_canthus = ara4[row][21];
    y_canthus = ara4[row][22];

    canthus_horz_position_FOV4 =  mmark[3][0] - x_canthus + mmark[3][1];
    //printf("\t%.4f %.4f %.4f\n", x_canthus, y_canthus, canthus_horz_position_FOV4);
    //printf("\t%.4f %.4f\n", mmark[3][0], mmark[3][1]);

    fp = fopen(filesave3, "a+");

        if (fp == NULL)
                {printf("Error opening file.\n");}
        else
                {fprintf(fp,"%.4f\t",canthus_horz_position_FOV4);}
                fclose(fp);

    }
```

```
fp = fopen(filesave4, "a+");

        if (fp == NULL)
        {printf("Error opening file.\n");}
        else

{fprintf(fp,"\n%s, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f, %.4f,%i, %i, %i,
%i, %i, %i, %.4f, %.4f, %.4f, %.4f", approach4, max_head_down_angle_in_FOV3,
max_head_down_angle_in_FOV4, land_hip_angle, land_lead_knee_angle,
knee_angle_at_midstance, knee_angle_change_to_midstance, max_knee_flexion_angle,
land_trunk_angle, trunk_angle_at_midstance, trunk_angle_at_lead_toe_clearance, min_trunk_angle,
max_trunk_angle, min_trunk_angle_frame, max_trunk_angle_frame, lead_toe_clearance_frame,
heel_contact_frame_before_edge, lead_foot_land_frame, head_start_frame_in_FOV4, trail_foot_length,
lead_foot_length, trail_toe_position_in_straddle, lead_heel_position_past_edge);} fclose(fp);


        return(0);

}
```

Appendix D

Computer software program (C language) used for ensemble averaging of data

This program was used to ensemble average (50 points) the lead foot orientation and vertical displacement (toe trajectory) data.

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>  // For strcpy....
#include <math.h>
#define M 45
#define N 48
#define START 0
float ara[M][N];

main()

{
        FILE    *fp;
        FILE    *data;
        int      row, col, integer, count,   number_of_frames;
        float   factor, ensemble_point,  interpolation;
        char    filename1[50], filesave[60];

(void) strcpy(filename1, "c:\\doctor\\data\\old\\results\\normoff\\data.txt");
(void) strcpy(filesave, "c:\\doctor\\data\\old\\results\\normoff\\enof.txt");

// File scanned
..........................................................................................................

                if ((data=fopen(filename1,"r"))==NULL)
                   {printf("\n\n*** That file does not exist***\n");
                   exit(0);}

                else {

                        for (row = 0; row  <  M; row++)
                                for (col = 0; col <  48; col++)
                                fscanf(data,"%f", &ara[row][col]);
                         }

        for (col =  0; col <  48; col++)
                for (row = 0; row <  M; row++)

                if( (ara[row][col]  >  0)  &&  (ara[row + 1][col] ==  0))
                {
                number_of_frames = row+1;
                factor  =   (number_of_frames - 1)*0.02;
                printf("\tEnd of file (row) %i\n", number_of_frames);
                printf("\tfactor =  %.4f\n", factor);

                fp = fopen(filesave, "a+");
                    if (fp == NULL)
                          {printf("Error opening file.\n");}
                    else
                          {fprintf(fp,"%.4f \t",ara[0][col]);
                          fclose(fp);}

                for(count = 1; count < 50; count++)
                                        {
                integer = factor*count;
```

```
                row = START + integer;
                interpolation = factor*count;

ensemble_point = (ara[row+1][col]-ara[row][col])*(interpolation-integer) + ara[row][col];
printf("Count = %i, Integer = %i, row = %i, ensemble point = %.4f\n \t",count, integer, row,
        ensemble_point);

                fp = fopen(filesave, "a+");
                if (fp == NULL)
                        {printf("Error opening file.\n");}
                else
                        {fprintf(fp,"%.4f \t",ensemble_point);}
                        fclose(fp);

                                        }

                        fp = fopen(filesave, "a+");
                        if (fp == NULL)
                                printf("Error opening file.\n");}
                        else
                                {fprintf(fp,"%.4f\n",ara[number_of_frames - 1][col]);}
                                fclose(fp);
                                break;}

        else { printf("%.4f\n", ara[row][col]); }

        return(0);

}
```

Appendix E

Computer software program used for calculating lead foot focal movement trajectory (*LFM*)

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <string.h>  // For strcpy....


#define MAXLL     300  // Most lines are about 250 chars in length....
// Number of points in the spatial model == number of points on each line of the file....
#define SPATIALMODELPOINTS  12
#define MAXIMUMFRAMES      300


struct point  {
   float x, y;
   };
typedef   struct point    Point;

// Point p[MAXIMUMFRAMES][SPATIALMODELPOINTS];

float     ara[MAXIMUMFRAMES][SPATIALMODELPOINTS*3];
int       M = 0, N = 0;  // Size of array read in from file...
float     mmark[3][9];

//Subroutine to estimate foot clearance.........................

float minimum(float x1, float x2, float y1, float y2,float min, float step_edge_x_coordinate)
                    {

                    min = ((step_edge_x_coordinate - x1)*(y2-y1)/(x2-x1)) + y1;
                    return (min);

                    }

main()

{

FILE     *data;
FILE     *fp;

float    step_edge_x_coordinate, step_edge_y_coordinate;
float    lead_toe_clearance,lead_heel_clearance;
float    lead_toe_pre_step_distance;
float    cross_lead_foot_angle, land_lead_foot_angle;
float    x_toe_initial, x_toe_final, y_toe_initial, y_toe_final, x_difference, y_difference,
         toe_displacement, gross_displacement, net_displacement, ratio;
float    min,x1,x2,y1,y2;
float    x_toe, y_toe, x_heel, y_heel, foot_angle, true_gradient, left_marker_y_coordinate,
         right_marker_y_coordinate, horizontal_distance_between_markers, foot_gradient;
float    lead_toe_position_before_edge;
int      row, col,lead_toe_x_column, trail_toe_x_column, left_toe_past_frame, right_toe_past_frame;
int      lead_toe_y_column, trail_toe_y_column;
int      lead_heel_clearance_frame, lead_toe_clearance_frame, lead_toe_position_before_edge_frame;
int      lead_toe_take_off_frame;
int      lead_foot_land_frame;
char     filename[50], midmarker[50], filesave1[50];

         int lineNo = 0, pointNo = 0;
         int i = 0, j = 0;
```

```
        float x, y, r;

  (void) strcpy( filename, "c:\\doctor\\data\\old\\stepoff\\mk\\nap4.txt");
  (void) strcpy( midmarker,"c:\\doctor\\data\\midmark\\off\\markof18.txt");
  (void) strcpy( filesave1,"c:\\doctor\\data\\old\\results\\normoff\\noffratio.txt");
```

//Opens and scans mid-maker array...

```
                if ((data=fopen(midmarker,"r"))==NULL)
                  {printf("\n\n*** That file does not exit***\n");
                  exit(0);}

                else
                          {
                          for (row=0;row < 4; row++)

                          for (col=0;col < 9; col++)
                                  fscanf(data,"%f", &mmark[row][col]);
              }
```

//Opens and scans data (accommodation phase) array...

```
        printf("Name of file being analysed? %s\n", filename);

                if ( (data = fopen( filename, "r")) == NULL ) {
                  printf("\n\n*** That file does not exist you idiot ***\n");
                  exit(1);
                  }

#ifdef COMMENT
                lineNo = 0;
                while ( fgets( line, MAXLL, data) != NULL ) {

                  lineNo++;
                  //printf("Line number : %d, Length : %d\n", lineNo, strlen( line ));
                  //printf("Line : %s", line);

                  while ( sscanf( line, "%f %f %f", &x, &y, &r) == 3 ) {
                    //printf("GOT SUMMAT : %4.1f, %4.1f, %4.1f\n", x, y, r);
                    getchar();
                    }

                  getchar();
                  }

#endif // COMMENT

                lineNo = 0;
                pointNo = 0;
                while ( fscanf( data, "%f %f %f", &x, &y, &r) == 3 ) {

        ara[lineNo][pointNo*3+0] = x;
        ara[lineNo][pointNo*3+1] = y;
        ara[lineNo][pointNo*3+2] = r;

        if ( (pointNo+1) == SPATIALMODELPOINTS ) {
          lineNo++;      // Increment the line number...
          pointNo = 0;   // Reset the point number on this line...
```

```
        }
      else {
        pointNo++;
        }

      if ( lineNo >= MAXIMUMFRAMES ) {
        //printf("What !! Too many lines in the data file........\n");
        //printf("Please change the MAXIMUMFRAMES constant. Exiting.\n");
        exit( 1 );
        }
      // getchar();
                }

                fclose(data);
```

// Keep track of the number of rows and columns read from the file...

```
    M = lineNo;
    N = SPATIALMODELPOINTS * 3;
    //printf("Array is : %3d Rows * %3d Columns\n", M, N);
          for ( i = 0; i < M; i++ ) {
             for ( j = 0; j < N; j = j+3 ){
             }
             }
    //printf("Step edge sagittal plane coordinates = %f m, %f m\n", mmark[3][0], mmark[3][2]);

                step_edge_x_coordinate = mmark[3][0];
                step_edge_y_coordinate = mmark[3][2];

    //printf("\tstep_edge_x_coordinate = %.4f m\n",step_edge_x_coordinate);
    //printf("\tstep_edge_y_coordinate = %.4f m\n",step_edge_y_coordinate);
```

// Lead limb identified when both heel and toe are past step edge. This is required in case the trail foot is placed half on and off the edge.

```
  for (row = 0; row < M; row++ ) {

        if((ara[row][6] > step_edge_x_coordinate) && (ara[row][3] > step_edge_x_coordinate))
           {right_toe_past_frame = row-1;
           //printf("\tx_value = %.4f\n", ara[row][6]);
           //printf("\tFrame = %i\n", right_toe_past_frame);
           break;}
           }

  for (row = 0; row < M; row++ ) {
        if((ara[row][12] > step_edge_x_coordinate) && (ara[row][9] > step_edge_x_coordinate))
           {left_toe_past_frame = row-1;
           //printf("\tx_value = %.4f\n", ara[row][12]);
           //printf("\tFrame = %i\n", left_toe_past_frame);
           break;}

           }

        if (right_toe_past_frame < left_toe_past_frame){
           printf("\tLead limb is the right limb!\n\n");
           lead_toe_x_column = 6;
           trail_toe_x_column = 12;
        //printf("\tlead toe column = %i\n", lead_toe_x_column);
```

```
//printf("\ttrail toe column = %i\n", trail_toe_x_column);
    lead_toe_y_column = lead_toe_x_column + 1;
    trail_toe_y_column = trail_toe_x_column + 1;
    }

else
{printf("\tLead limb is the left limb!\n\n");
    lead_toe_x_column = 12;
    trail_toe_x_column = 6;
    lead_toe_y_column = lead_toe_x_column + 1;
    trail_toe_y_column = trail_toe_x_column +1;
//printf("\tlead toe column = %i\n", lead_toe_x_column);
//printf("\ttrail toe column = %i\n", trail_toe_x_column);
    }
```

//Routine to calculate minimum lead heel and toe clearance of step edge

//Lead heel clearance of step edge......................................

```
for (row = 0;  row < M;  row++ )  {
        if((ara[row][lead_toe_x_column-3] < step_edge_x_coordinate) &&
        (ara[row + 1][lead_toe_x_column-3] > step_edge_x_coordinate))
                break;
        }

        x1 = ara[row][lead_toe_x_column-3];
        x2 = ara[row+1][lead_toe_x_column-3];
        y1 = ara[row][lead_toe_x_column-2];
        y2 = ara[row+1][lead_toe_x_column-2];
        min = minimum(x1, x2, y1, y2, min, step_edge_x_coordinate);
        lead_heel_clearance = 100*(min - step_edge_y_coordinate);
        lead_heel_clearance_frame = row;
        //printf("\t%.4f,\t%.4f,\t%.4f,\t%.4f\n",x1,x2,y1,y2);
        printf("\tLead heel clearance of step edge = %.2f cm, %i\t\n",lead_heel_clearance, row);
```

//Lead toe clearance of step edge......................................

```
for (row = 0;  row < M;  row++ )  {
        if ((ara[row][lead_toe_x_column] < step_edge_x_coordinate) && (ara[row +
        1][lead_toe_x_column] >  step_edge_x_coordinate))
                break;
                }

                lead_toe_clearance_frame = row;
                x1 = ara[row][lead_toe_x_column];
                x2 = ara[row+1][lead_toe_x_column];
                y1 = ara[row][lead_toe_y_column ];
                y2 = ara[row+1][lead_toe_y_column];
                min = minimum(x1, x2, y1, y2, min, step_edge_x_coordinate);
                lead_toe_clearance = 100*(min - step_edge_y_coordinate);
                printf("\tLead toe minimum clearance of step edge = %.2f cm,
                %i\t\n",lead_toe_clearance, lead_toe_clearance_frame);
        printf("%.4f %.4f %.4f %.4f",ara[row][lead_toe_x_column],ara[row+1][lead_toe_x_column],
        ara[row][lead_toe_y_column],ara[row+1][lead_toe_y_column]);
```

//Routines to estimate toe position from step: pre and post crossing.

//Lead toe pre-step distance

```
        for (row = 0;  row < M;  row++ )  {
        if  ((ara[row][lead_toe_x_column] > 0) && (ara[row][lead_toe_x_column - 3] > 0))
                {lead_toe_take_off_frame = row;
                //printf("\tFrame lead toe take off = %i\n", lead_toe_take_off_frame);
                break;}
            }

lead_toe_position_before_edge = 0;
for (row = 0;  row < lead_toe_take_off_frame;  row++ )  {
if  (ara[row][lead_toe_x_column] > lead_toe_position_before_edge)
{lead_toe_position_before_edge = ara[row][lead_toe_x_column];lead_toe_position_before_edge_frame
= row;}
                                                    }

//printf("\tFrame lead toe pre step = %i\n", lead_toe_position_before_edge_frame);
//printf("\tLead toe pre step x coordinate = %.4f\n", lead_toe_position_before_edge);

lead_toe_pre_step_distance = 100 * (ara[lead_toe_position_before_edge_frame][lead_toe_x_column] -
step_edge_x_coordinate );
//printf("\tLead toe pre step distance = %.2f cm, %i\t\n", lead_toe_pre_step_distance,
lead_toe_position_before_edge_frame);

//Lead toe landing position past edge......................................

for (row = lead_toe_take_off_frame;  row < M;  row++ )  {
        if ((ara[row][lead_toe_x_column] > 0) && (ara[row+1][lead_toe_x_column] == 0))
                break;
                }
            lead_foot_land_frame = row;
            //printf("\tLead foot landing frame = %i\n", lead_foot_land_frame);

for (row = lead_foot_land_frame + 1;  row < M;  row++ )  {
        if (ara[row][lead_toe_x_column] > 0)
                break;
                }

//Lead foot angle at edge.......................................................

        x_heel = ara[lead_toe_clearance_frame][lead_toe_x_column-3];
        y_heel = ara[lead_toe_clearance_frame][lead_toe_x_column-2];
        x_toe = ara[lead_toe_clearance_frame][lead_toe_x_column];
        y_toe = ara[lead_toe_clearance_frame][lead_toe_x_column + 1];
        left_marker_y_coordinate = mmark[0][6];
        right_marker_y_coordinate = mmark[0][7];
        horizontal_distance_between_markers = mmark[0][8];

//printf("%f %f %f %f", x_heel, y_heel, x_toe, y_toe);
//printf("%f %f %f",left_marker_y_coordinate, right_marker_y_coordinate,
horizontal_distance_between_markers);

        if(x_heel == x_toe)
        {foot_angle = 90;}

        else {
        foot_gradient = (y_toe - y_heel)/(x_toe - x_heel);
        //printf("foot gradient = %.2f\n", foot_gradient);
        true_gradient = ((right_marker_y_coordinate -
        left_marker_y_coordinate))/(horizontal_distance_between_markers);
        //printf("true gradient = %.4f\n", true_gradient);
```

```
        foot_angle = (atan((foot_gradient - true_gradient)/(1 + foot_gradient * true_gradient)) *
        180/3.14159);
                        }

        cross_lead_foot_angle = foot_angle;
        printf("\n\tLead foot angle = %.2f degs, %i\n", cross_lead_foot_angle,
        lead_toe_clearance_frame);
```

//Lead foot angle upon landing

```
        x_heel = ara[lead_foot_land_frame][lead_toe_x_column-3];
        y_heel = ara[lead_foot_land_frame][lead_toe_x_column-2];
        x_toe = ara[lead_foot_land_frame][lead_toe_x_column];
        y_toe = ara[lead_foot_land_frame][lead_toe_x_column + 1];

//printf("%f %f %f %f", x_heel, y_heel, x_toe, y_toe);
//printf("%f %f %f",left_marker_y_coordinate, right_marker_y_coordinate,
        horizontal_distance_between_markers);

foot_gradient = (y_toe - y_heel)/(x_toe - x_heel);
foot_angle = (atan((foot_gradient - true_gradient)/(1 + foot_gradient * true_gradient)) * 180/3.14159);
land_lead_foot_angle = foot_angle;
printf("\tLead foot angle at landing = %.2f degs, %i\n", land_lead_foot_angle, lead_foot_land_frame);
```

//Routine to calculate net/gross displacement ratio (LFM) ....
//If toe lands first, ratio is calculated for toe trajectory, otherwise heel trajectory.

```
        if ((land_lead_foot_angle < 0)||(land_lead_foot_angle == 0))
           {x_toe_initial = ara[lead_toe_clearance_frame][lead_toe_x_column];
            x_toe_final = ara[lead_foot_land_frame][lead_toe_x_column];
            y_toe_initial = ara[lead_toe_clearance_frame][lead_toe_y_column];
            y_toe_final = ara[lead_foot_land_frame][lead_toe_y_column];
            x_difference = x_toe_final - x_toe_initial;
            y_difference = y_toe_final - y_toe_initial;
            net_displacement = sqrt(pow(x_difference,2) + pow(y_difference,2));
            printf("%f\n", net_displacement);}

        else {x_toe_initial = ara[lead_heel_clearance_frame][lead_toe_x_column - 3];
            x_toe_final = ara[lead_foot_land_frame][lead_toe_x_column - 3];
            y_toe_initial = ara[lead_heel_clearance_frame][lead_toe_y_column - 3];
            y_toe_final = ara[lead_foot_land_frame][lead_toe_y_column - 3];
            x_difference = x_toe_final - x_toe_initial;
            y_difference = y_toe_final - y_toe_initial;
            net_displacement = sqrt(pow(x_difference,2) + pow(y_difference,2));
            printf("%f\n", net_displacement);}

        gross_displacement = 0;

         if (land_lead_foot_angle < 0) {
         for (row = lead_toe_clearance_frame; row < lead_foot_land_frame; row++) {
         x_toe_initial = ara[row][lead_toe_x_column];
         x_toe_final = ara[row + 1][lead_toe_x_column];
         y_toe_initial = ara[row][lead_toe_y_column];
         y_toe_final = ara[row + 1][lead_toe_y_column];
         x_difference = x_toe_final - x_toe_initial;
         y_difference = y_toe_final - y_toe_initial;
         toe_displacement = sqrt(pow(x_difference,2) + pow(y_difference,2));
         gross_displacement = gross_displacement + toe_displacement;
         printf("%f %f\n", toe_displacement, gross_displacement);}
```

```
        }

        else {
        for (row = lead_heel_clearance_frame; row < lead_foot_land_frame; row++) {
        x_toe_initial = ara[row][lead_toe_x_column - 3];
        x_toe_final = ara[row + 1][lead_toe_x_column - 3];
        y_toe_initial = ara[row][lead_toe_y_column - 3];
        y_toe_final = ara[row + 1][lead_toe_y_column - 3];
        x_difference = x_toe_final - x_toe_initial;
        y_difference = y_toe_final - y_toe_initial;
        toe_displacement = sqrt(pow(x_difference,2) + pow(y_difference,2));
        gross_displacement = gross_displacement + toe_displacement;
        printf("%f %f\n", toe_displacement, gross_displacement);}
        }

       ratio = net_displacement/gross_displacement*100;
       printf("%f", ratio);

//Data sent to datafiles********************************************************

fp = fopen(filesave1, "a+");

         if (fp == NULL)
         {printf("Error opening file.\n");}
         else
          {fprintf(fp,"\n%s, %.4f", filename, ratio);}
          fclose(fp);

          return(0);

}
```

Appendix F

Correlations found for the descent condition (CWV)

Table F-1 Correlations among variables

		ART	CSL	CST	DFST	HCD	HCV	HLD	HLV	LCA	LFM	LHC	LHD	LLA	LLV	LTC	TCA	TD	THC	TRKCA	TTC	VLV
ART	Pearson Correlation	1.00	0.63	-0.50	-0.29	0.87	0.80	0.76	0.73	-0.23	0.28	0.25	0.39	0.17	0.36	-0.02	-0.05	-0.19	0.64	0.54	0.36	-0.32
	Sig. (2-tailed)	.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.10	0.00	0.88	0.71	0.06	0.00	0.00	0.00	0.00
CSL	Pearson Correlation	0.63	1.00	-0.07	-0.34	0.62	0.69	0.89	0.87	-0.09	0.26	0.26	0.74	0.63	0.49	0.11	0.01	-0.15	0.74	0.31	0.48	-0.52
	Sig. (2-tailed)	0.00	.	0.52	0.00	0.00	0.00	0.00	0.00	0.36	0.01	0.01	0.00	0.00	0.00	0.28	0.97	0.15	0.00	0.00	0.00	0.00
CST	Pearson Correlation	-0.50	-0.07	1.00	0.02	-0.22	-0.44	-0.06	-0.32	0.53	-0.52	-0.28	-0.27	-0.02	-0.37	0.14	-0.03	-0.34	-0.24	-0.21	0.20	0.20
	Sig. (2-tailed)	0.00	0.52	.	0.84	0.03	0.00	0.54	0.00	0.00	0.00	0.01	0.01	0.88	0.00	0.17	0.78	0.00	0.05	0.04	0.10	0.05
DFST	Pearson Correlation	-0.29	-0.34	0.02	1.00	-0.24	-0.35	-0.49	-0.47	0.15	-0.03	-0.27	-0.31	-0.16	-0.01	-0.08	-0.09	-0.04	-0.40	0.05	-0.39	0.12
	Sig. (2-tailed)	0.00	0.00	0.84	.	0.02	0.00	0.00	0.00	0.14	0.74	0.01	0.00	0.13	0.93	0.42	0.47	0.73	0.00	0.66	0.00	0.23
HCD	Pearson Correlation	0.87	0.62	-0.22	-0.24	1.00	0.64	0.78	0.68	-0.04	0.12	0.18	0.27	0.13	0.30	0.04	-0.11	-0.37	0.59	0.48	0.52	-0.29
	Sig. (2-tailed)	0.00	0.00	0.03	0.02	.	0.00	0.00	0.00	0.69	0.25	0.08	0.01	0.20	0.00	0.70	0.36	0.00	0.00	0.00	0.00	0.00
HCV	Pearson Correlation	0.80	0.69	-0.44	-0.35	0.64	1.00	0.75	0.80	-0.11	0.29	0.12	0.42	0.25	0.40	-0.05	-0.01	-0.20	0.59	0.42	0.41	-0.34
	Sig. (2-tailed)	0.00	0.00	0.00	0.00	0.00	.	0.00	0.00	0.29	0.00	0.25	0.00	0.01	0.00	0.66	0.95	0.05	0.00	0.00	0.00	0.00
HLD	Pearson Correlation	0.76	0.89	-0.06	-0.49	0.78	0.75	1.00	0.85	-0.08	0.17	0.24	0.58	0.39	0.35	0.04	-0.01	-0.24	0.75	0.43	0.57	-0.38
	Sig. (2-tailed)	0.00	0.00	0.54	0.00	0.00	0.00	.	0.00	0.44	0.10	0.02	0.00	0.00	0.00	0.71	0.95	0.02	0.00	0.00	0.00	0.00
HLV	Pearson Correlation	0.73	0.87	-0.32	-0.47	0.68	0.80	0.85	1.00	-0.17	0.25	0.29	0.60	0.43	0.42	0.03	-0.03	-0.18	0.74	0.33	0.47	-0.51
	Sig. (2-tailed)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.	0.10	0.01	0.00	0.00	0.00	0.00	0.75	0.81	0.08	0.00	0.00	0.00	0.00
LCA	Pearson Correlation	-0.23	-0.09	0.53	0.15	-0.04	-0.11	-0.08	-0.17	1.00	-0.57	-0.68	-0.59	-0.04	-0.47	0.38	-0.27	-0.77	-0.33	-0.07	0.18	0.28
	Sig. (2-tailed)	0.02	0.36	0.00	0.14	0.69	0.29	0.44	0.10	.	0.00	0.00	0.00	0.69	0.00	0.00	0.02	0.00	0.01	0.52	0.13	0.01
LFM	Pearson Correlation	0.28	0.26	-0.52	-0.03	0.12	0.29	0.17	0.25	-0.57	1.00	0.26	0.61	0.38	0.71	-0.17	0.10	0.56	0.25	0.10	-0.23	-0.32
	Sig. (2-tailed)	0.00	0.01	0.00	0.74	0.25	0.00	0.10	0.01	0.00	.	0.01	0.00	0.00	0.00	0.09	0.42	0.00	0.04	0.31	0.06	0.00
LHC	Pearson Correlation	0.25	0.26	-0.28	-0.27	0.18	0.12	0.24	0.29	-0.68	0.26	1.00	0.54	0.06	0.30	0.21	0.13	0.46	0.37	0.04	0.06	-0.34
	Sig. (2-tailed)	0.01	0.01	0.01	0.01	0.08	0.25	0.02	0.00	0.00	0.01	.	0.00	0.59	0.00	0.04	0.28	0.00	0.00	0.70	0.62	0.00
LHD	Pearson Correlation	0.39	0.74	-0.27	-0.31	0.27	0.42	0.58	0.60	-0.59	0.61	0.54	1.00	0.65	0.70	-0.05	0.17	0.54	0.74	0.17	0.11	-0.50
	Sig. (2-tailed)	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	.	0.00	0.00	0.66	0.16	0.00	0.00	0.10	0.38	0.00
LLA	Pearson Correlation	0.17	0.63	-0.02	-0.16	0.13	0.25	0.39	0.43	-0.04	0.38	0.06	0.65	1.00	0.43	0.23	-0.04	0.14	0.33	0.07	0.10	-0.43
	Sig. (2-tailed)	0.10	0.00	0.88	0.13	0.20	0.01	0.00	0.00	0.69	0.00	0.59	0.00	.	0.00	0.02	0.73	0.16	0.01	0.50	0.44	0.00
LLV	Pearson Correlation	0.36	0.49	-0.37	-0.01	0.30	0.40	0.35	0.42	-0.47	0.71	0.30	0.70	0.43	1.00	-0.15	0.06	0.43	0.34	0.13	-0.04	-0.52
	Sig. (2-tailed)	0.00	0.00	0.00	0.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.	0.14	0.63	0.00	0.00	0.21	0.75	0.00
LTC	Pearson Correlation	-0.02	0.11	0.14	-0.08	0.04	-0.05	0.04	0.03	0.38	-0.17	0.21	-0.05	0.23	-0.15	1.00	-0.26	-0.25	-0.02	-0.02	-0.02	0.00
	Sig. (2-tailed)	0.88	0.28	0.17	0.42	0.70	0.66	0.71	0.75	0.00	0.09	0.04	0.66	0.02	0.14	.	0.03	0.01	0.86	0.86	0.89	0.99
TCA	Pearson Correlation	-0.05	0.01	-0.03	-0.09	-0.11	-0.01	-0.01	-0.03	-0.27	0.10	0.13	0.17	-0.04	0.06	-0.26	1.00	0.23	-0.72	-0.02	-0.38	0.13
	Sig. (2-tailed)	0.71	0.97	0.78	0.47	0.36	0.95	0.95	0.81	0.02	0.42	0.28	0.16	0.73	0.63	0.03	.	0.05	0.00	0.90	0.00	0.29
TD	Pearson Correlation	-0.19	-0.15	-0.34	-0.04	-0.37	-0.20	-0.24	-0.18	-0.77	0.56	0.46	0.54	0.14	0.43	-0.25	0.23	1.00	-0.02	-0.11	-0.50	-0.10
	Sig. (2-tailed)	0.06	0.15	0.00	0.73	0.00	0.05	0.02	0.08	0.00	0.00	0.00	0.00	0.16	0.00	0.01	0.05	.	0.87	0.28	0.00	0.32
THC	Pearson Correlation	0.64	0.74	-0.24	-0.40	0.59	0.59	0.75	0.74	-0.33	0.25	0.37	0.74	0.33	0.34	-0.02	-0.72	-0.02	1.00	0.30	0.44	-0.42
	Sig. (2-tailed)	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.00	0.01	0.00	0.86	0.00	0.87	.	0.01	0.00	0.00
TRKCA	Pearson Correlation	0.54	0.31	-0.21	0.05	0.48	0.42	0.43	0.33	-0.07	0.10	0.04	0.17	0.07	0.13	-0.02	-0.02	-0.11	0.30	1.00	0.20	-0.15
	Sig. (2-tailed)	0.00	0.00	0.04	0.66	0.00	0.00	0.00	0.00	0.52	0.31	0.70	0.10	0.50	0.21	0.86	0.90	0.28	0.01	.	0.10	0.13
TTC	Pearson Correlation	0.36	0.48	0.20	-0.39	0.52	0.41	0.57	0.47	0.18	-0.23	0.06	0.11	0.10	-0.04	-0.02	-0.38	-0.50	0.44	0.20	1.00	-0.22
	Sig. (2-tailed)	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.13	0.06	0.62	0.38	0.44	0.75	0.89	0.00	0.00	0.00	0.10	.	0.07
VLV	Pearson Correlation	-0.32	-0.52	0.20	0.12	-0.29	-0.34	-0.38	-0.51	0.28	-0.32	-0.34	-0.50	-0.43	-0.52	0.00	0.13	-0.10	-0.42	-0.15	-0.22	1.00
	Sig. (2-tailed)	0.00	0.00	0.05	0.23	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.99	0.29	0.32	0.00	0.13	0.07	.

Appendix G

Correlations found for the descent condition (FWV)

Table G-1 Correlations among variables

		ART	CSL	CST	DFST	HCD	HCV	HLD	HLV	LCA	LFM	LHC	LHD	LLA	LLV	LTC	TCA	TD	THC	TRKCA	TTC	VLV
ART	Pearson Correlation	1.00	0.61	-0.12	-0.34	0.93	0.66	0.75	0.61	0.04	0.21	0.07	0.33	0.24	0.33	-0.06	-0.57	-0.37	0.35	0.34	0.47	-0.42
	Sig. (2-tailed)	.	0.00	0.23	0.00	0.00	0.00	0.00	0.00	0.70	0.04	0.53	0.00	0.02	0.00	0.58	0.00	0.00	0.00	0.00	0.00	0.00
CSL	Pearson Correlation	0.61	1.00	0.01	-0.35	0.42	0.75	0.84	0.86	-0.14	0.48	0.19	0.84	0.64	0.54	-0.08	-0.73	0.00	0.74	0.23	0.36	-0.60
	Sig. (2-tailed)	0.00	.	0.94	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.06	0.00	0.00	0.00	0.44	0.00	0.99	0.00	0.02	0.00	0.00
CST	Pearson Correlation	-0.12	0.01	1.00	0.10	-0.05	-0.26	-0.06	-0.20	0.37	-0.21	-0.14	-0.13	0.01	-0.24	0.23	0.02	-0.29	-0.07	0.10	0.11	0.13
	Sig. (2-tailed)	0.23	0.94	.	0.34	0.65	0.01	0.54	0.05	0.00	0.05	0.17	0.19	0.89	0.02	0.02	0.85	0.00	0.55	0.32	0.38	0.19
DFST	Pearson Correlation	-0.34	-0.35	0.10	1.00	-0.27	-0.42	-0.52	-0.50	0.04	-0.02	-0.12	-0.28	-0.16	0.08	-0.02	0.31	0.04	-0.30	0.10	-0.27	0.17
	Sig. (2-tailed)	0.00	0.00	0.34	.	0.01	0.00	0.00	0.00	0.69	0.86	0.23	0.00	0.11	0.46	0.82	0.01	0.70	0.01	0.34	0.02	0.11
HCD	Pearson Correlation	0.93	0.42	-0.05	-0.27	1.00	0.46	0.61	0.44	0.13	0.08	0.04	0.11	0.13	0.21	0.05	-0.48	-0.48	0.17	0.32	0.49	-0.35
	Sig. (2-tailed)	0.00	0.00	0.65	0.01	.	0.00	0.00	0.00	0.22	0.46	0.70	0.29	0.21	0.04	0.60	0.00	0.00	0.16	0.00	0.00	0.00
HCV	Pearson Correlation	0.66	0.75	-0.26	-0.42	0.46	1.00	0.83	0.79	-0.13	0.38	0.06	0.58	0.42	0.46	-0.25	-0.56	-0.08	0.52	0.23	0.41	-0.40
	Sig. (2-tailed)	0.00	0.00	0.01	0.00	0.00	.	0.00	0.00	0.22	0.00	0.53	0.00	0.00	0.00	0.01	0.00	0.44	0.00	0.03	0.00	0.00
HLD	Pearson Correlation	0.75	0.84	-0.06	-0.52	0.61	0.83	1.00	0.80	-0.17	0.37	0.19	0.67	0.41	0.39	-0.17	-0.66	-0.07	0.55	0.36	0.43	-0.44
	Sig. (2-tailed)	0.00	0.00	0.54	0.00	0.00	0.00	.	0.00	0.10	0.00	0.07	0.00	0.00	0.00	0.10	0.00	0.49	0.00	0.00	0.00	0.00
HLV	Pearson Correlation	0.61	0.86	-0.20	-0.50	0.44	0.79	0.80	1.00	-0.09	0.33	0.19	0.67	0.44	0.44	-0.05	-0.70	-0.09	0.71	0.05	0.34	-0.57
	Sig. (2-tailed)	0.00	0.00	0.05	0.00	0.00	0.00	0.00	.	0.37	0.00	0.06	0.00	0.00	0.00	0.64	0.00	0.41	0.00	0.65	0.00	0.00
LCA	Pearson Correlation	0.04	-0.14	0.37	0.04	0.13	-0.13	-0.17	-0.09	1.00	-0.45	-0.72	-0.50	0.01	-0.36	0.41	0.11	-0.73	-0.37	-0.04	0.17	0.09
	Sig. (2-tailed)	0.70	0.17	0.00	0.69	0.22	0.22	0.10	0.37	.	0.00	0.00	0.00	0.91	0.00	0.00	0.38	0.00	0.00	0.69	0.17	0.37
LFM	Pearson Correlation	0.21	0.48	-0.21	-0.02	0.08	0.38	0.37	0.33	-0.45	1.00	0.28	0.68	0.44	0.73	-0.24	-0.24	0.48	0.34	0.16	0.11	-0.35
	Sig. (2-tailed)	0.04	0.00	0.05	0.86	0.46	0.00	0.00	0.00	0.00	.	0.01	0.00	0.00	0.00	0.02	0.04	0.00	0.00	0.11	0.37	0.00
LHC	Pearson Correlation	0.07	0.19	-0.14	-0.12	0.04	0.06	0.19	0.19	-0.72	0.28	1.00	0.40	-0.06	0.25	0.16	-0.22	0.45	0.41	0.00	0.13	-0.20
	Sig. (2-tailed)	0.53	0.06	0.17	0.23	0.70	0.53	0.07	0.06	0.00	0.01	.	0.00	0.57	0.01	0.12	0.06	0.00	0.00	0.97	0.27	0.05
LHD	Pearson Correlation	0.33	0.84	-0.13	-0.28	0.11	0.58	0.67	0.67	-0.50	0.68	0.40	1.00	0.60	0.63	-0.25	-0.58	0.53	0.75	0.19	0.13	-0.53
	Sig. (2-tailed)	0.00	0.00	0.19	0.00	0.29	0.00	0.00	0.00	0.00	0.00	0.00	.	0.00	0.00	0.02	0.00	0.00	0.00	0.06	0.29	0.00
LLA	Pearson Correlation	0.24	0.64	0.01	-0.16	0.13	0.42	0.41	0.44	0.01	0.44	-0.06	0.60	1.00	0.38	0.14	-0.40	0.08	0.38	0.11	0.18	-0.52
	Sig. (2-tailed)	0.02	0.00	0.89	0.11	0.21	0.00	0.00	0.00	0.91	0.00	0.57	0.00	.	0.00	0.18	0.00	0.44	0.00	0.29	0.14	0.00
LLV	Pearson Correlation	0.33	0.54	-0.24	0.08	0.21	0.46	0.39	0.44	-0.36	0.73	0.25	0.63	0.38	1.00	-0.21	-0.38	0.32	0.40	0.12	0.03	-0.47
	Sig. (2-tailed)	0.00	0.00	0.02	0.46	0.04	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	.	0.04	0.00	0.00	0.00	0.26	0.79	0.00
LTC	Pearson Correlation	-0.06	-0.08	0.23	-0.02	0.05	-0.25	-0.17	-0.05	0.41	-0.24	0.16	-0.25	0.14	-0.21	1.00	-0.03	-0.37	-0.06	-0.29	0.26	0.00
	Sig. (2-tailed)	0.58	0.44	0.02	0.82	0.60	0.01	0.10	0.64	0.00	0.02	0.12	0.02	0.18	0.04	.	0.79	0.00	0.65	0.00	0.03	1.00
TCA	Pearson Correlation	-0.57	-0.73	0.02	0.31	-0.48	-0.56	-0.66	-0.70	0.11	-0.24	-0.22	-0.58	-0.40	-0.38	-0.03	1.00	0.23	-0.71	-0.07	-0.37	0.42
	Sig. (2-tailed)	0.00	0.00	0.85	0.01	0.00	0.00	0.00	0.00	0.38	0.04	0.06	0.00	0.00	0.00	0.79	.	0.06	0.00	0.59	0.00	0.00
TD	Pearson Correlation	-0.37	0.00	-0.29	0.04	-0.48	-0.08	-0.07	-0.09	-0.73	0.48	0.45	0.53	0.08	0.32	-0.37	0.23	1.00	0.13	0.00	-0.41	-0.03
	Sig. (2-tailed)	0.00	0.99	0.00	0.70	0.00	0.44	0.49	0.41	0.00	0.00	0.00	0.00	0.44	0.00	0.00	0.06	.	0.30	0.99	0.00	0.81
THC	Pearson Correlation	0.35	0.74	-0.07	-0.30	0.17	0.52	0.55	0.71	-0.37	0.34	0.41	0.75	0.38	0.40	-0.06	-0.71	0.13	1.00	-0.06	0.34	-0.49
	Sig. (2-tailed)	0.00	0.00	0.55	0.01	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.00	0.30	.	0.61	0.00	0.00
TRKCA	Pearson Correlation	0.34	0.23	0.10	0.10	0.32	0.23	0.36	0.05	-0.04	0.16	0.00	0.19	0.11	0.12	-0.29	-0.07	0.00	-0.06	1.00	0.13	-0.17
	Sig. (2-tailed)	0.00	0.02	0.32	0.34	0.00	0.03	0.00	0.65	0.69	0.11	0.97	0.06	0.29	0.26	0.00	0.59	0.99	0.61	.	0.27	0.11
TTC	Pearson Correlation	0.47	0.36	0.11	-0.27	0.49	0.41	0.43	0.34	0.17	0.11	0.13	0.13	0.18	0.03	0.26	-0.37	-0.41	0.34	0.13	1.00	-0.22
	Sig. (2-tailed)	0.00	0.00	0.38	0.02	0.00	0.00	0.00	0.00	0.17	0.37	0.27	0.29	0.14	0.79	0.03	0.00	0.00	0.00	0.27	.	0.07
VLV	Pearson Correlation	-0.42	-0.60	0.13	0.17	-0.35	-0.40	-0.44	-0.57	0.09	-0.35	-0.20	-0.53	-0.52	-0.47	0.00	0.42	-0.03	-0.49	-0.17	-0.22	1.00
	Sig. (2-tailed)	0.00	0.00	0.19	0.11	0.00	0.00	0.00	0.00	0.37	0.00	0.05	0.00	0.00	0.00	1.00	0.00	0.81	0.00	0.11	0.07	.

Appendix H

Ensemble average plots of lead foot orientation (crossing step) in the descent condition (1st trial)

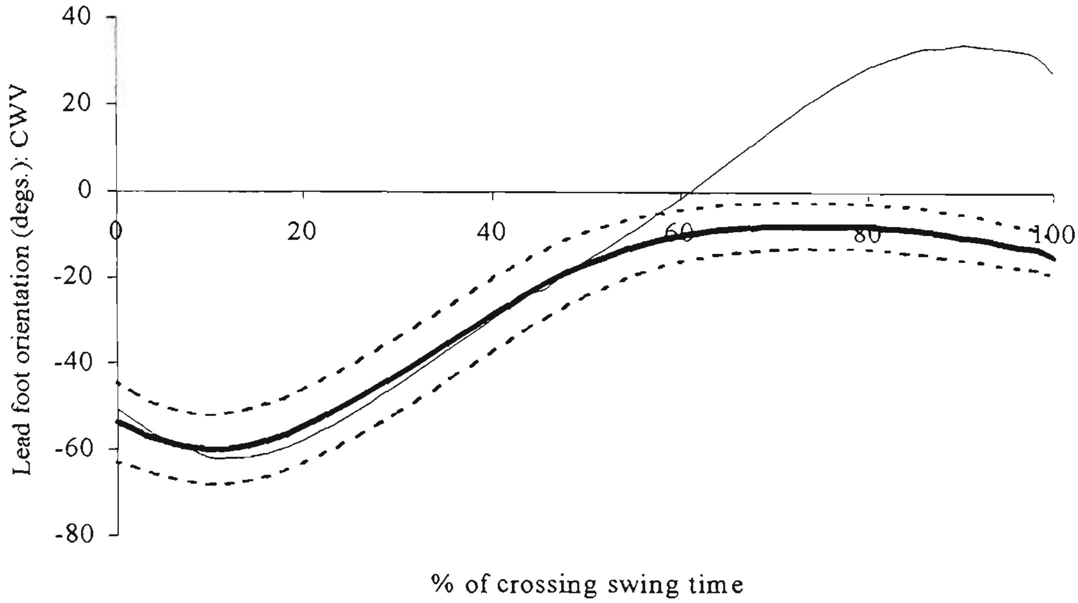


Figure H-1 (━) ensemble average plot (± SD) of the lead foot orientation for the elderly participants who adopted a forefoot landing strategy (n = 47) in the CWV condition. (-) plot of lead foot orientation for the elderly participant (n = 1) who adopted a heel landing strategy.

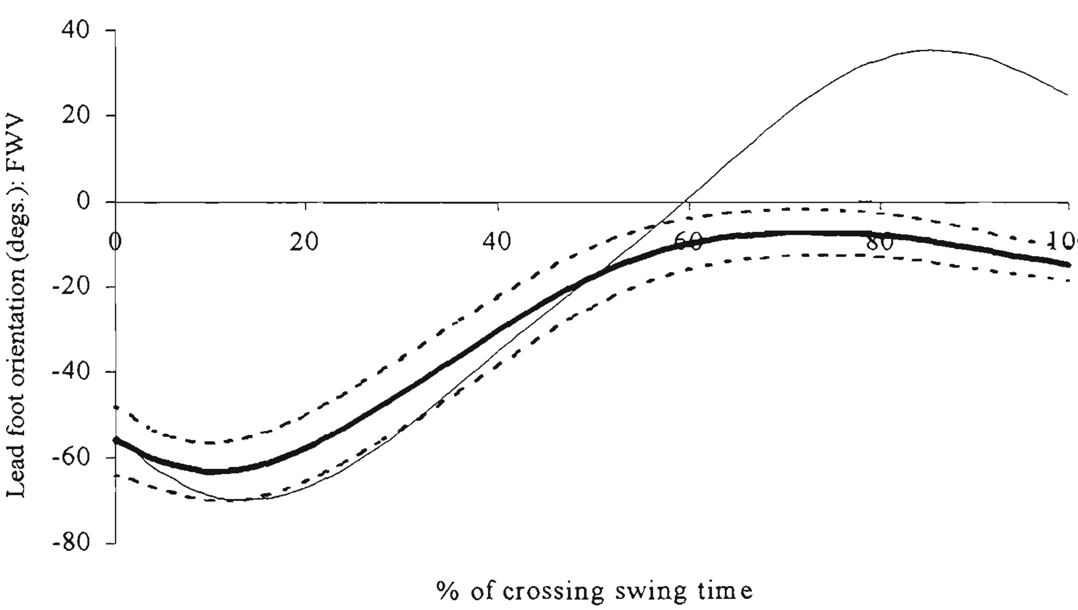
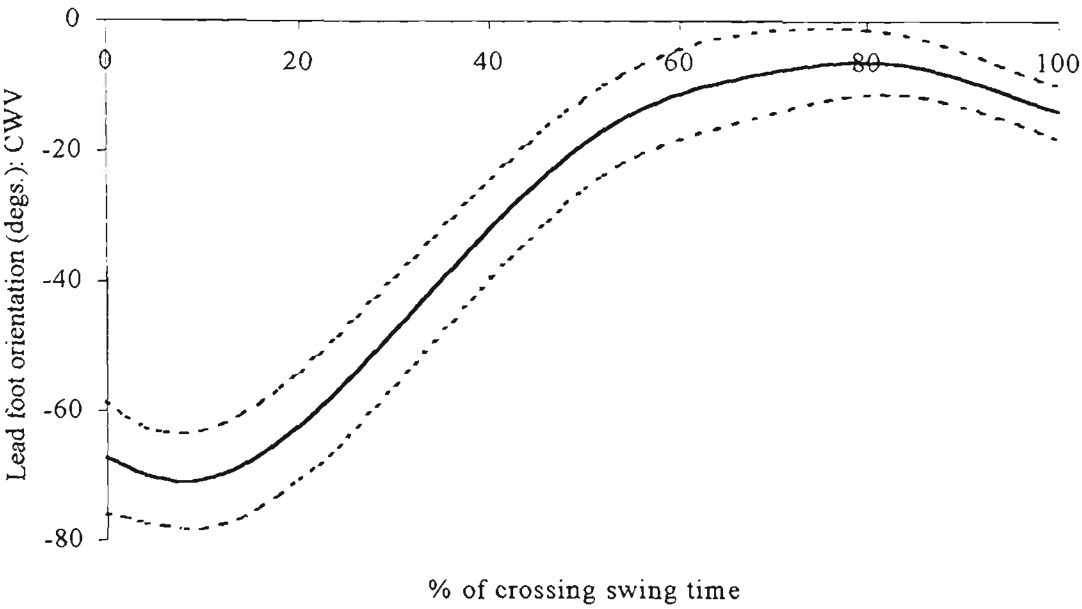
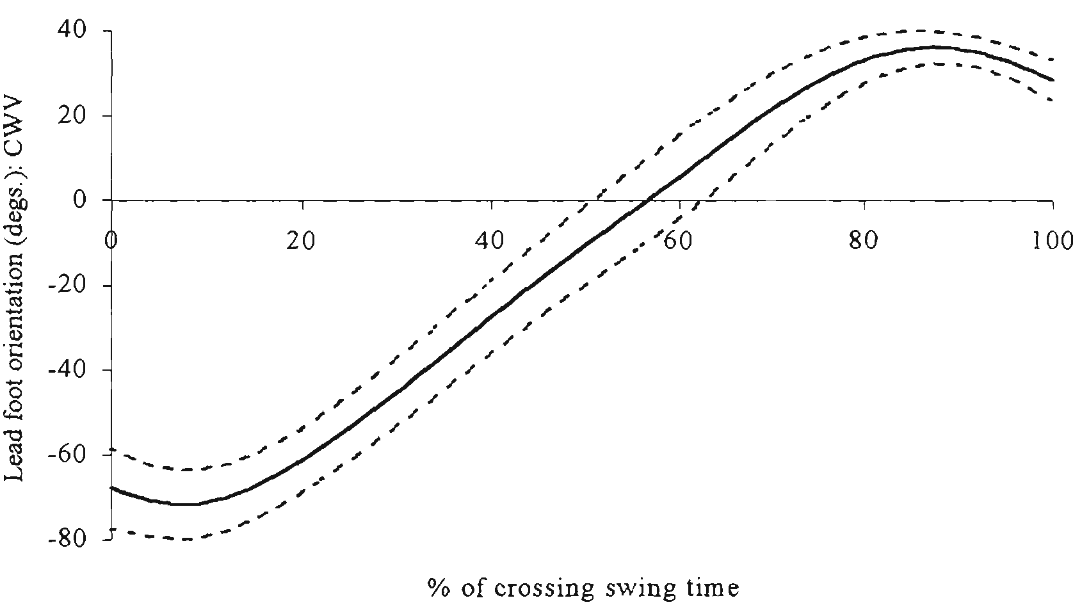


Figure H-2 (━) ensemble average plot (± SD) of the lead foot orientation for the elderly participants who adopted a forefoot landing strategy (n = 46) in the FWV condition. (-) ensemble average plot of lead foot orientation for the elderly participants (n = 2) who adopted a heel landing strategy.



<u>Figure H-3</u> Ensemble average plot (± SD) of lead foot orientation plot for the young participants (n = 32) who adopted a forefoot landing strategy in the CWV condition.



<u>Figure H-4</u> Ensemble average plot (± SD) of the lead foot orientation for the young participants (n = 16) who adopted a heel landing strategy in the CWV condition.

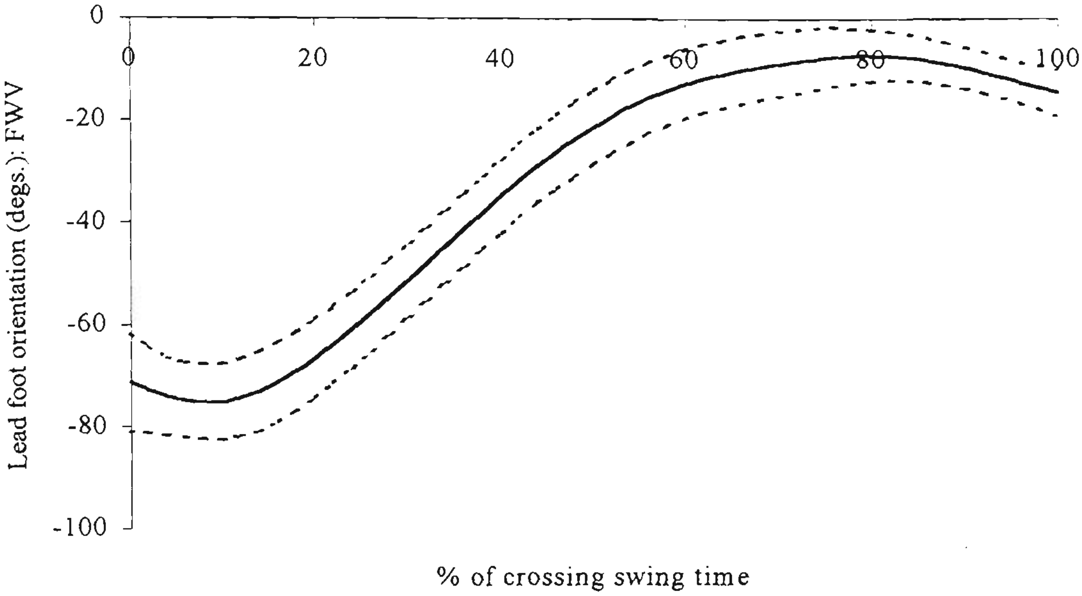


Figure H-5 Ensemble average plot (± SD) of the lead foot orientation for the young participants (n = 27) who adopted a forefoot landing strategy in the FWV condition.

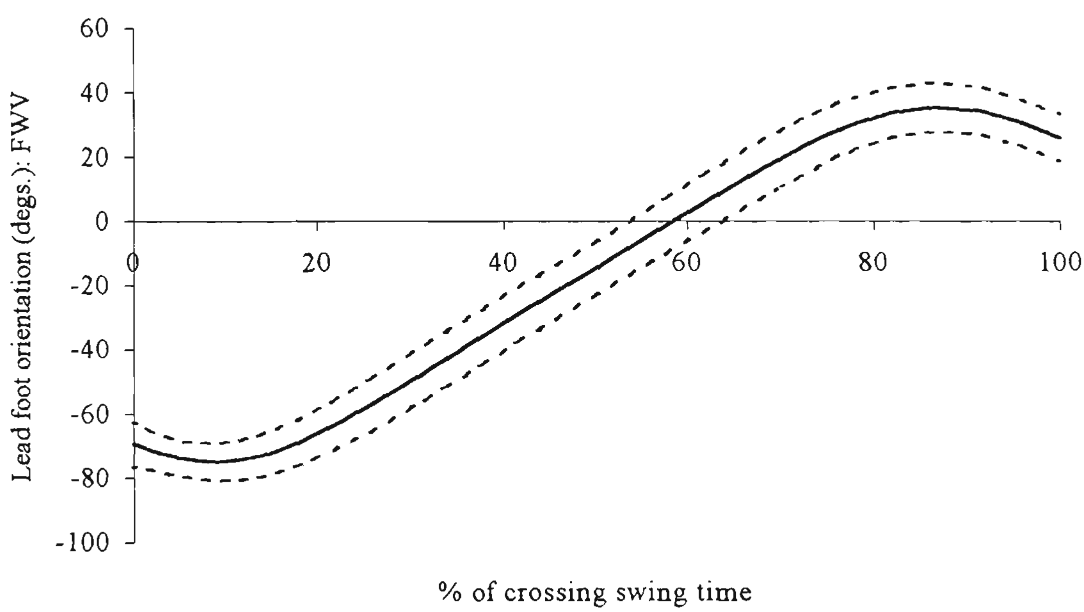


Figure H-6 Ensemble average plot (± SD) of the lead foot orientation for the young participants (n = 21) who adopted a heel landing strategy in the FWV condition.

Appendix I

Ensemble average plots of vertical displacement of lead toe marker (crossing step) in the descent condition (1^{st} trial)

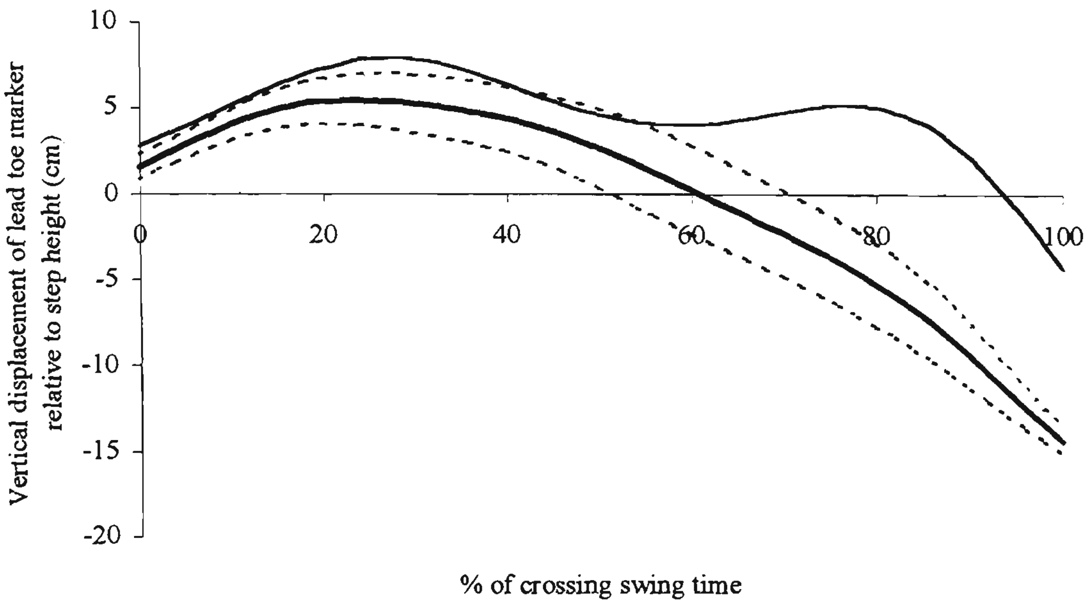


Figure I-1 (▬) Ensemble average plot (± SD) of the vertical displacement of the lead toe marker (relative to step height) for the elderly participants who adopted a forefoot landing strategy (n = 47) in the CWV condition. (-) plot of lead foot orientation for the elderly participant (n = 1) who adopted a heel landing strategy.

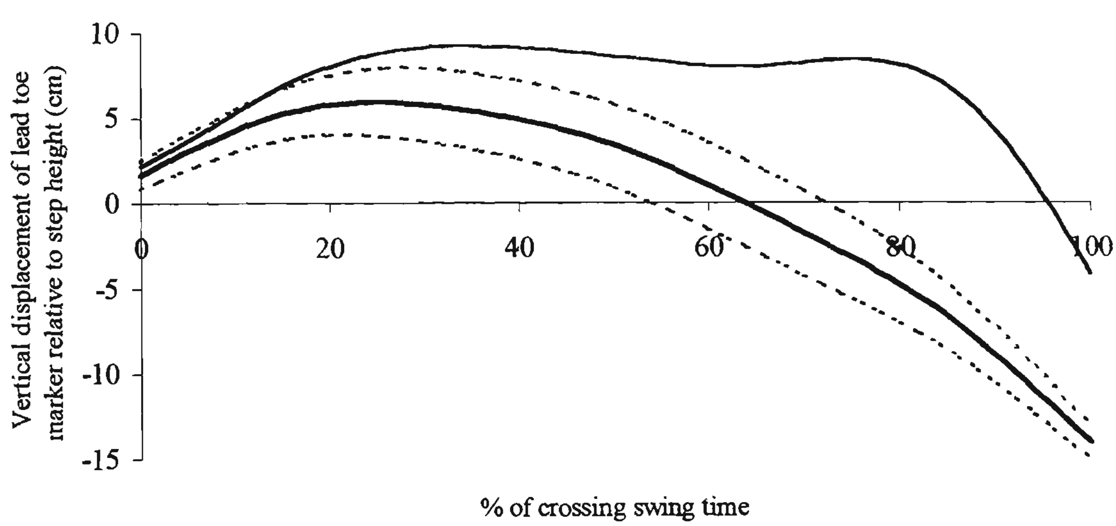


Figure I-2 (▬) Ensemble average plot (± SD) of the lead toe marker (relative to step height) for the elderly participants who adopted a forefoot landing strategy (n = 46) in the FWV condition. (-) ensemble average plot of lead foot orientation for the elderly participants (n = 2) who adopted a heel landing strategy.

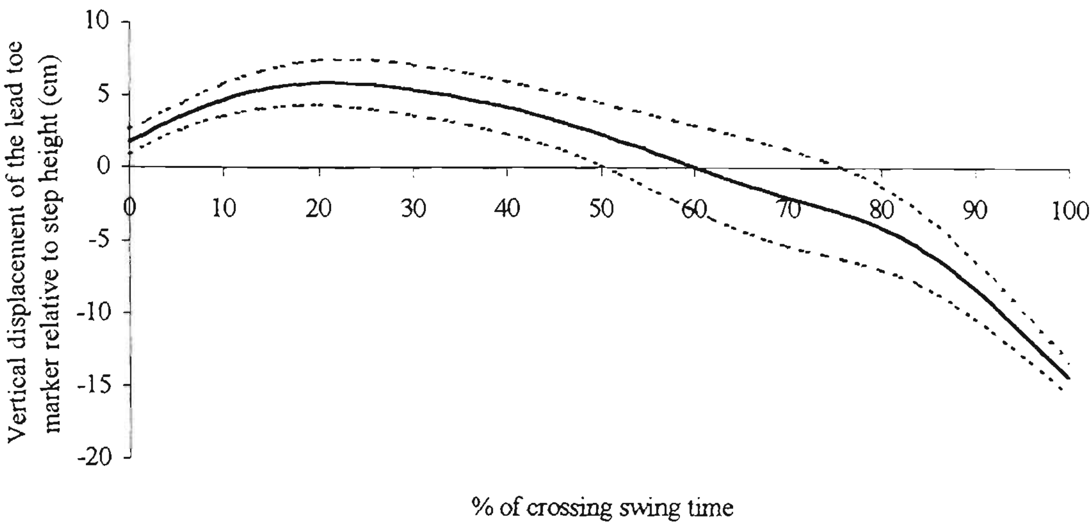


Figure I-3 Ensemble average plot (± SD) of the lead toe marker (relative to step height) for the young participants (n = 32) who adopted a forefoot landing strategy in the CWV condition.

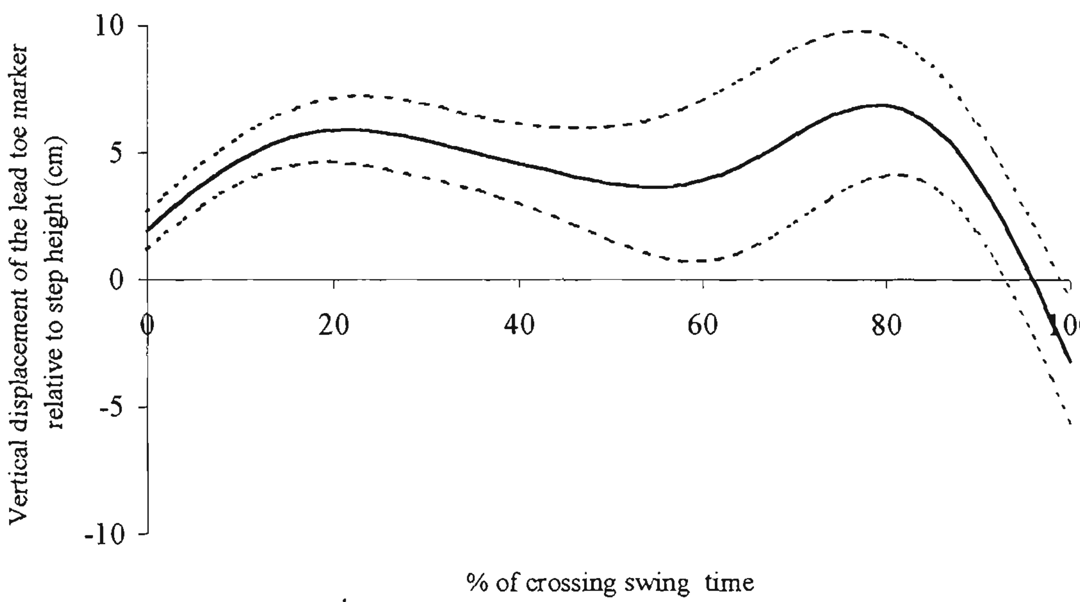


Figure I-4 Ensemble average plot (± SD) of the lead toe marker (relative to step height) for the young participants (n = 16) who adopted a heel landing strategy in the CWV condition.

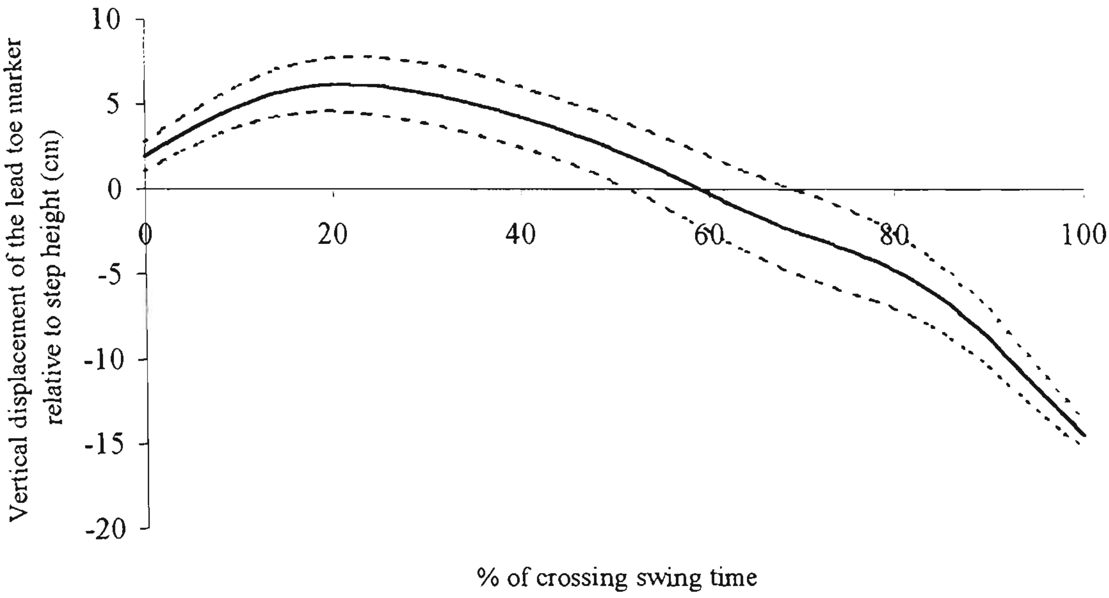


Figure I-5 Ensemble average plot (± SD) of the lead toe marker (relative to step height) for the young participants (n = 27) who adopted a forefoot landing strategy in the FWV condition.

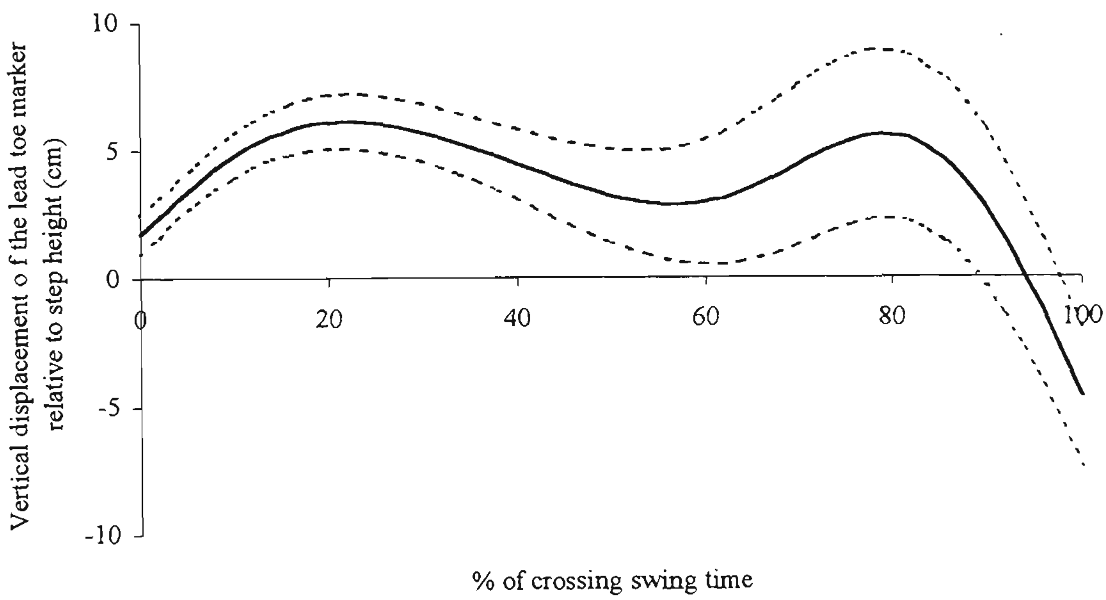


Figure I-6 Ensemble average plot (± SD) of the lead toe marker (relative to step height) for the young participants (n = 21) who adopted a heel landing strategy in the FWV condition.

Appendix J

Plots of footfall variability (approach and crossing phases) in the descent condition (all trials)

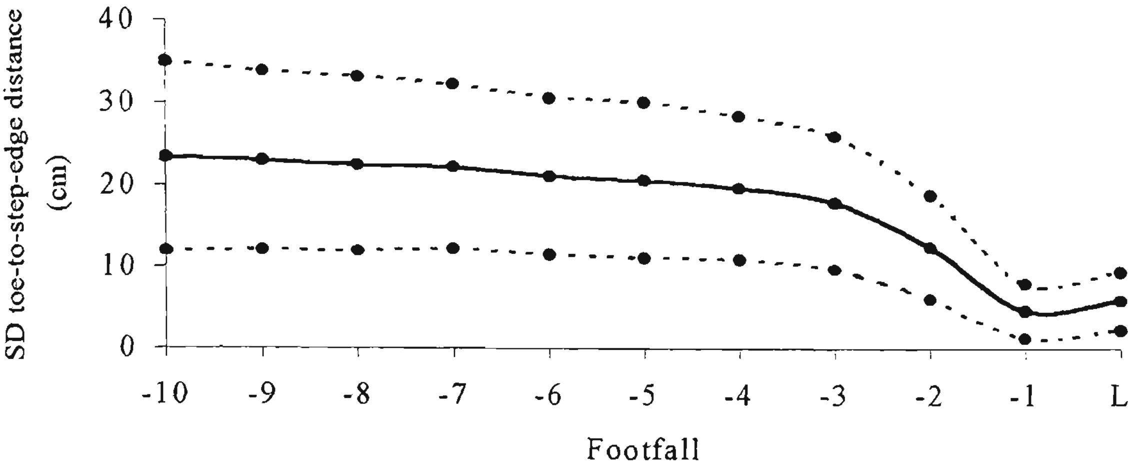


Figure J-1 Mean plot (± SD) of footfall variability for the elderly in the CWV condition.

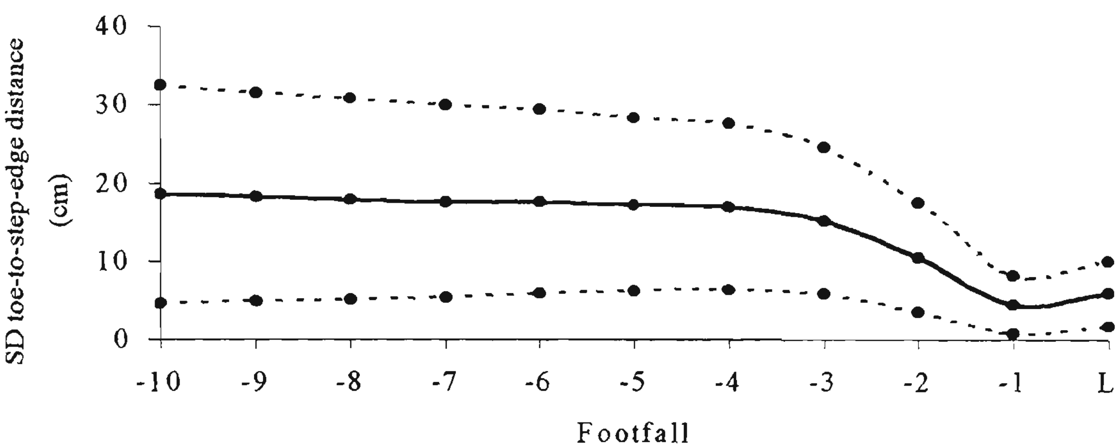


Figure J-2 Mean plot (± SD) of footfall variability for the elderly in the FWV condition.

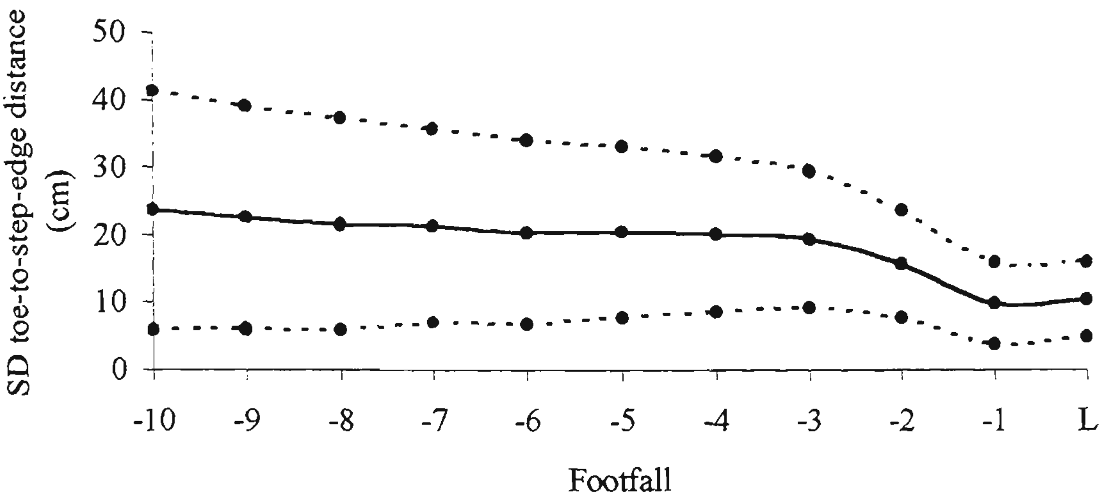


Figure J-3 Mean plot (± SD) of footfall variability for the young in the CWV condition.

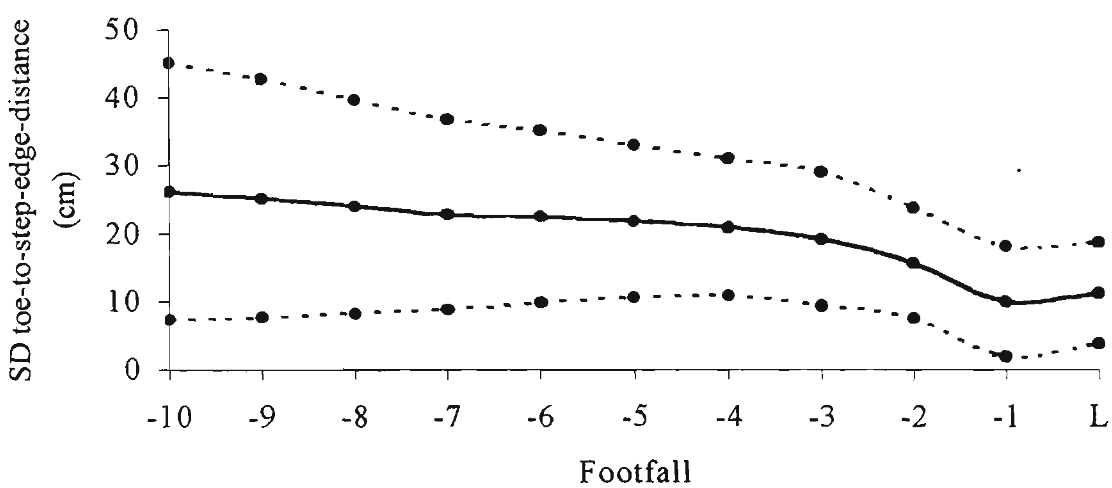


Figure J-4 Mean plot (± SD) of footfall variability for the young in the FWV condition.

Appendix K

Mean plots of step lengths (all trials) in the descent condition

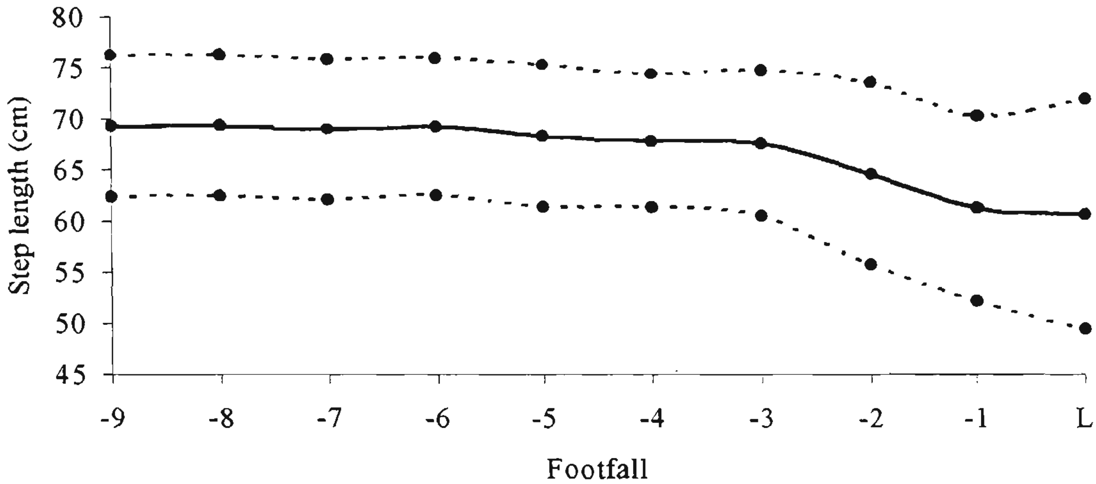


Figure K-1 Mean plot (± SD) of elderly step length in the CWV condition for all trials.

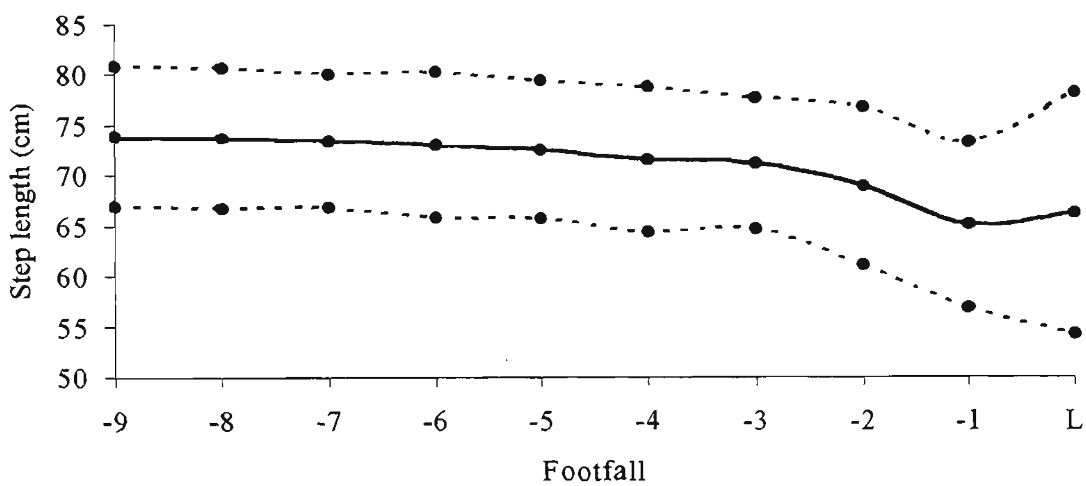


Figure K-2 Mean plot (± SD) of elderly step length in the FWV condition for all trials.

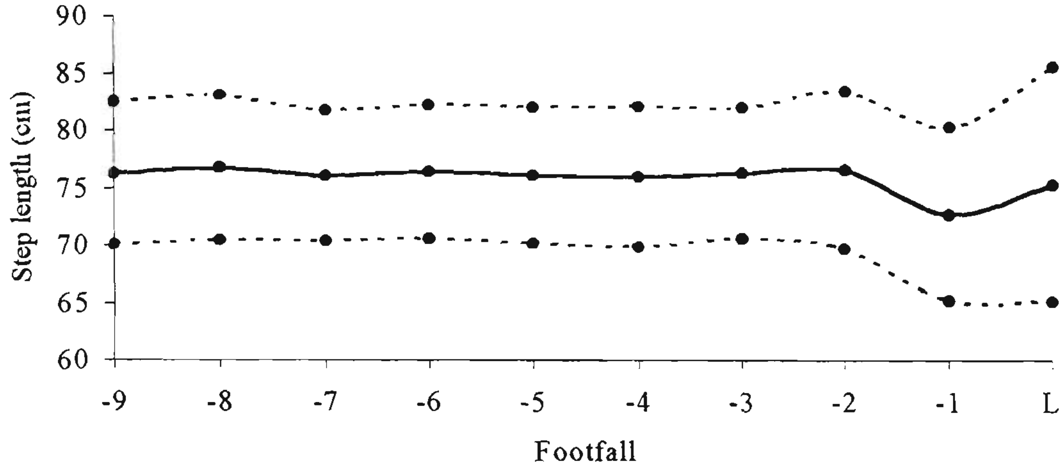


Figure K-3 Mean plot (± SD) of young step length in the CWV condition for all trials.

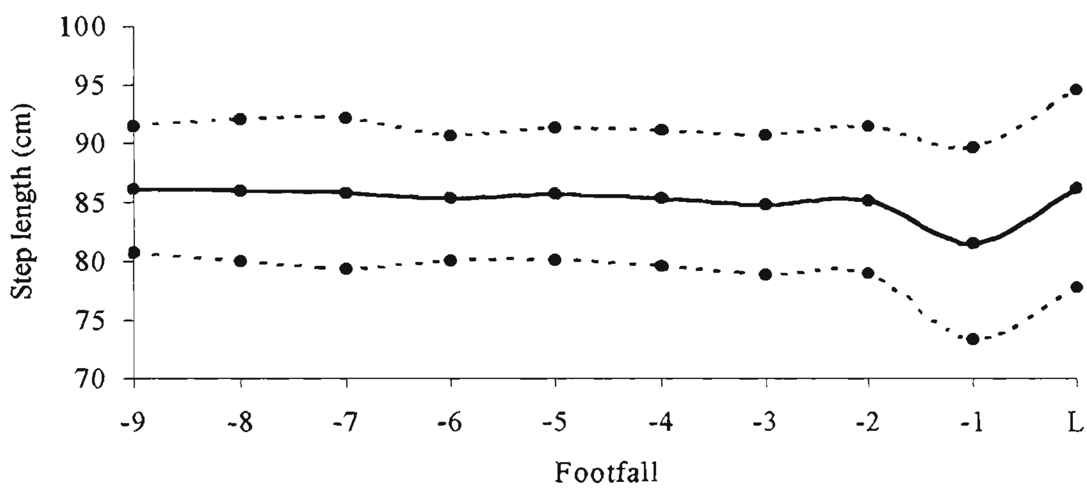


Figure K-4 Mean plot (± SD) of young step length in the FWV condition for all trials.

Appendix L

Mean plots of step lengths (1st trial) in the descent condition

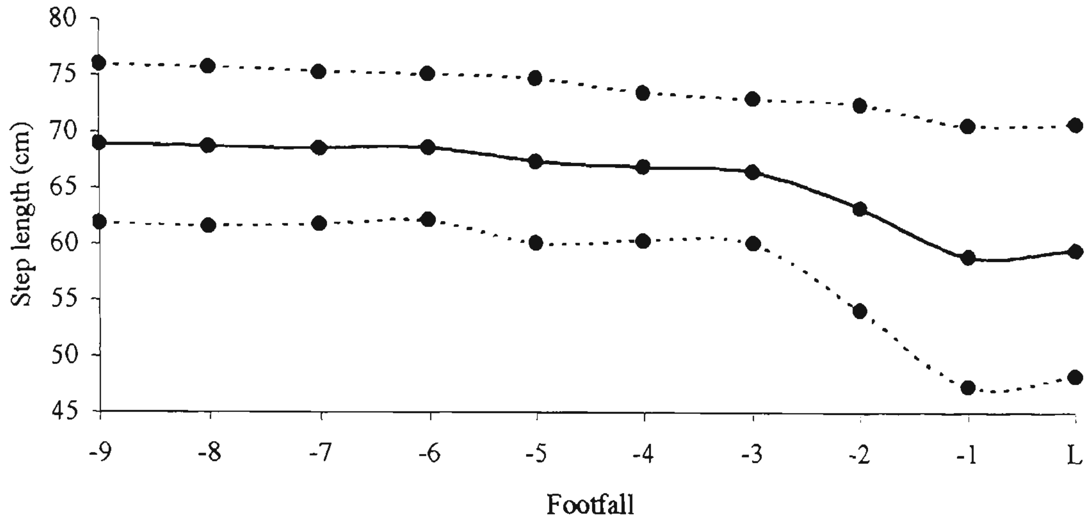


Figure L-1 Mean plot (± SD) of elderly step length in the CWV condition for the first trial.

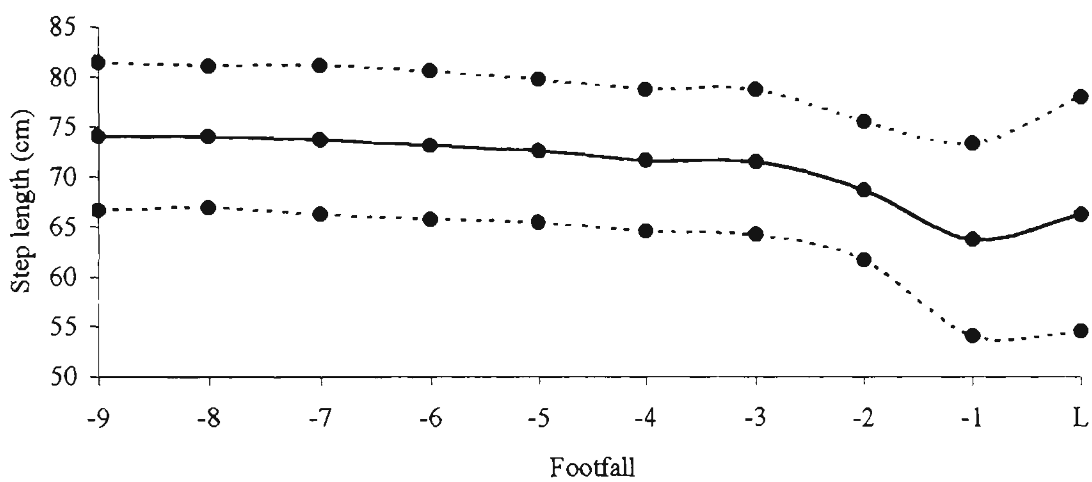


Figure L-2 Mean plot (± SD) of elderly step length in the FWV condition for the first trial.

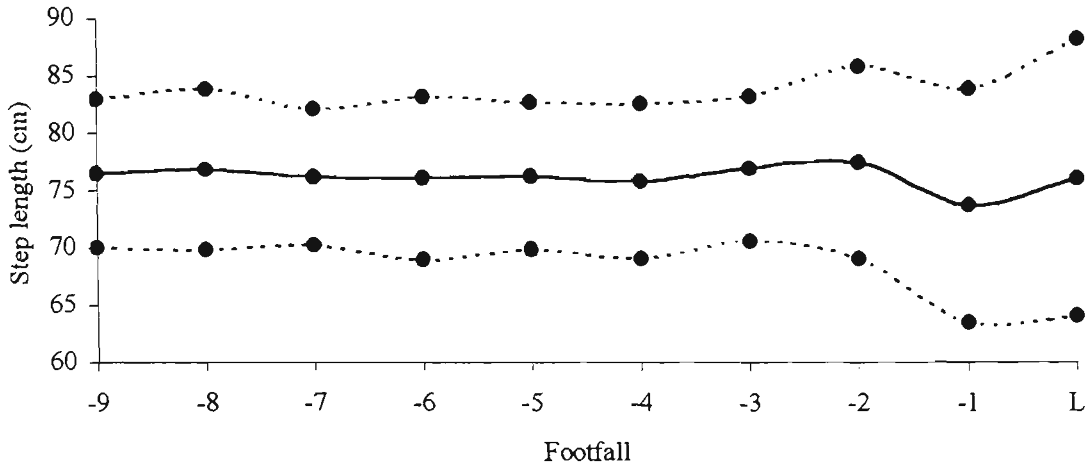


Figure L-3 Mean plot (± SD) of young step length in the CWV condition for the first trial.

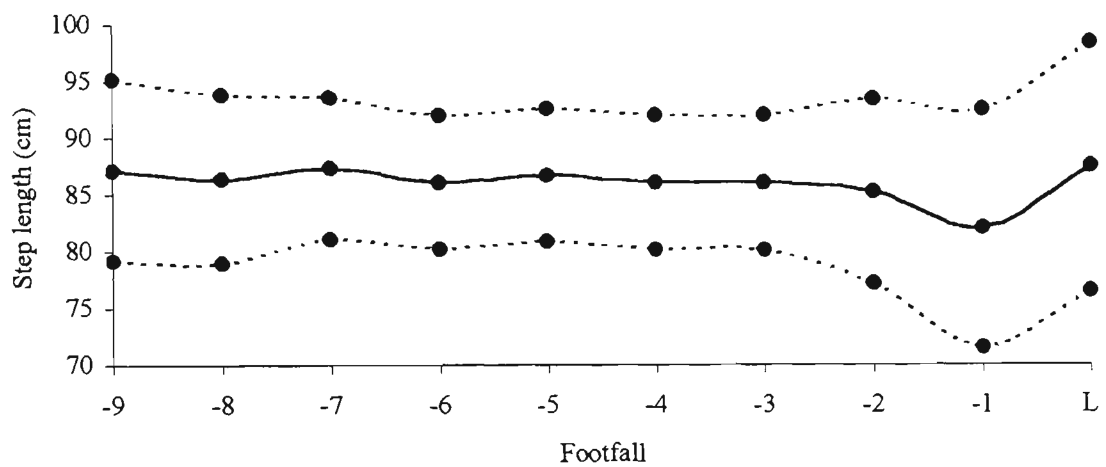


Figure L-4 Mean plot (± SD) of young step length in the FWV condition for the first trial.

Appendix M

Mean plots of step times (1st trial) in the descent condition

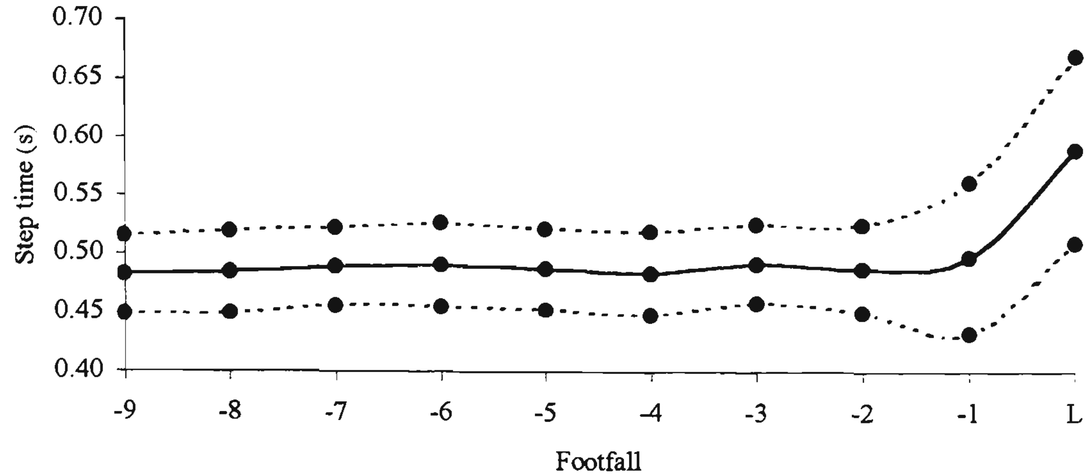


Figure M-1 Mean plot (± SD) of elderly step time in the CWV condition for first trial.

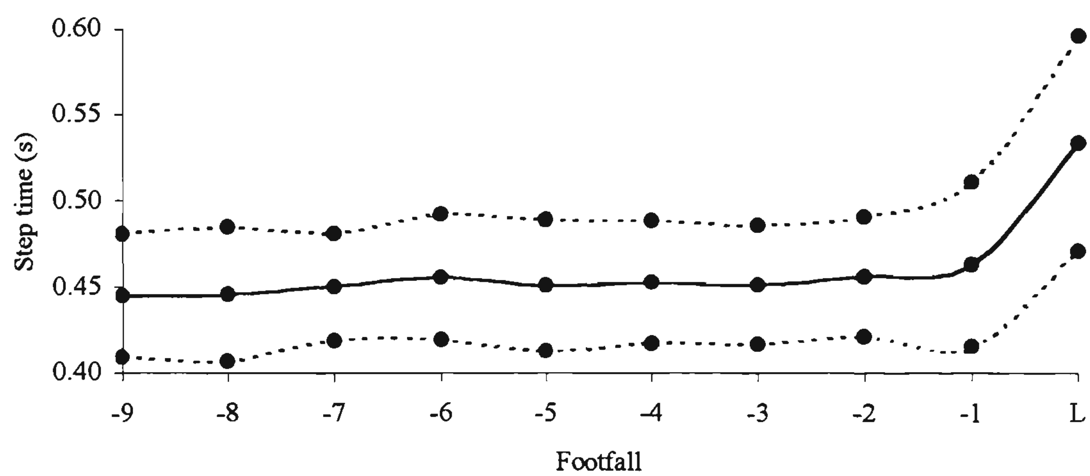


Figure M-2 Mean plot (± SD) of elderly step time in the FWV condition for first trial.

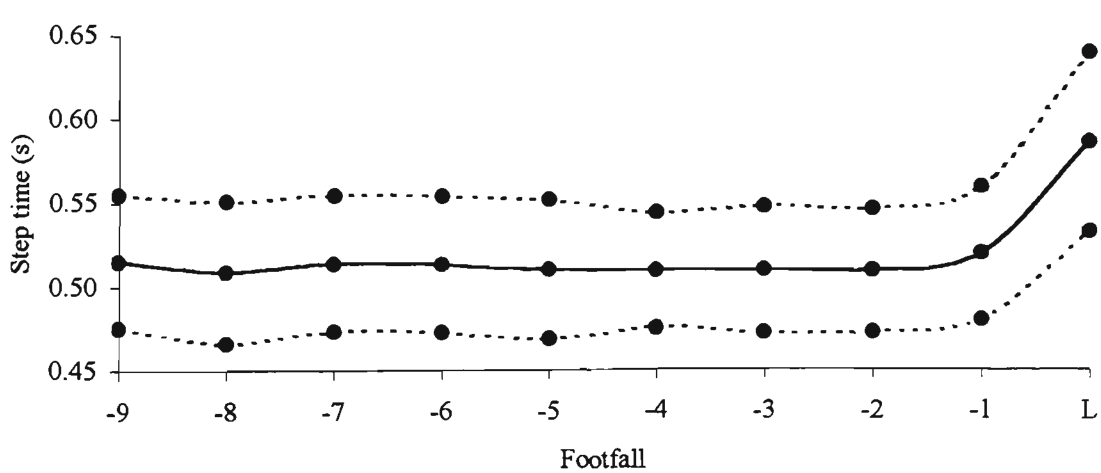


Figure M-3 Mean plot (± SD) of young step time in the CWV condition for first trial.

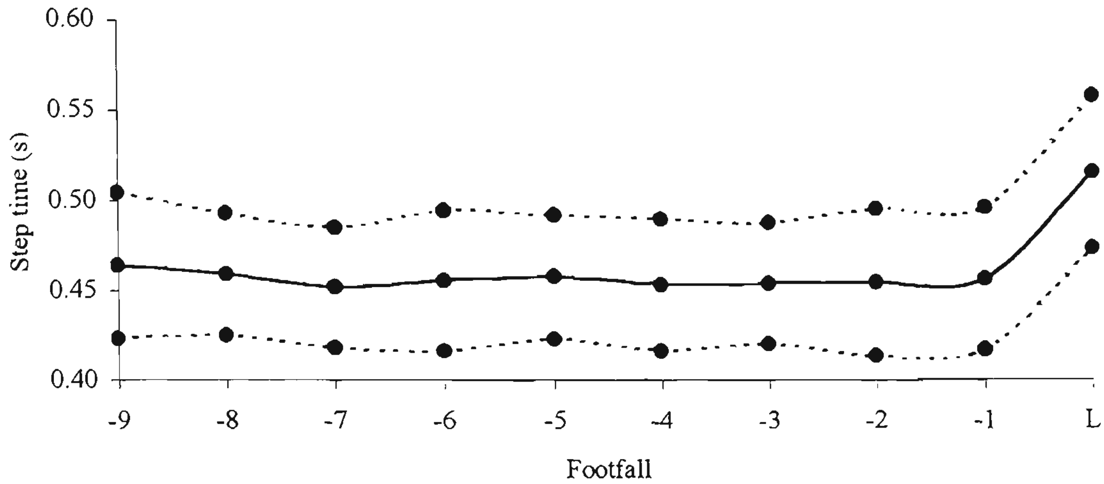


Figure M-4 Mean plot (± SD) of young step time in the FWV condition for first trial.

Appendix N

Correlations found for ascent condition (CWV)

Table N-1 Correlations found among variables

		ART	CSL	CST	DFST	HCD	HCV	HLD	LCA	LFM	LHC	LHD	LLA	LLV	LTC	TCA	TD	THC	TRKCA	TTC
ART	Pearson Correlation	1.00	0.50	-0.23	-0.55	0.93	0.71	0.71	0.57	-0.13	-0.28	-0.33	0.26	0.02	0.44	0.29	-0.72	-0.27	0.18	-0.03
	Sig. (2-tailed)	.	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.25	0.01	0.00	0.01	0.88	0.00	0.00	0.00	0.01	0.09	0.80
CSL	Pearson Correlation	0.50	1.00	0.20	-0.50	0.42	0.56	0.78	0.26	-0.26	0.15	0.34	0.74	-0.03	0.55	-0.19	-0.45	0.20	-0.07	0.07
	Sig. (2-tailed)	0.00	.	0.05	0.00	0.00	0.00	0.00	0.01	0.02	0.17	0.00	0.00	0.78	0.00	0.07	0.00	0.05	0.49	0.48
CST	Pearson Correlation	-0.23	0.20	1.00	0.11	-0.17	-0.33	0.14	-0.04	-0.21	0.35	0.21	0.00	-0.48	0.33	-0.09	0.03	0.06	-0.17	0.04
	Sig. (2-tailed)	0.02	0.05	.	0.30	0.11	0.00	0.17	0.68	0.06	0.00	0.04	0.98	0.00	0.00	0.37	0.76	0.54	0.10	0.69
DFST	Pearson Correlation	-0.55	-0.50	0.11	1.00	-0.43	-0.58	-0.75	-0.09	0.26	-0.29	-0.21	-0.26	0.22	-0.40	0.19	0.23	-0.18	0.10	-0.26
	Sig. (2-tailed)	0.00	0.00	0.30	.	0.00	0.00	0.00	0.38	0.02	0.01	0.04	0.01	0.03	0.00	0.06	0.02	0.08	0.35	0.01
HCD	Pearson Correlation	0.93	0.42	-0.17	-0.43	1.00	0.54	0.63	0.64	-0.13	-0.37	-0.44	0.17	0.01	0.44	0.39	-0.77	-0.37	0.09	-0.11
	Sig. (2-tailed)	0.00	0.00	0.11	0.00	.	0.00	0.00	0.00	0.25	0.00	0.00	0.10	0.89	0.00	0.00	0.00	0.00	0.39	0.28
HCV	Pearson Correlation	0.71	0.56	-0.33	-0.58	0.54	1.00	0.70	0.31	-0.06	-0.13	-0.01	0.42	0.13	0.28	0.03	-0.44	0.00	0.24	0.16
	Sig. (2-tailed)	0.00	0.00	0.00	0.00	0.00	.	0.00	0.00	0.58	0.26	0.91	0.00	0.21	0.01	0.80	0.00	0.96	0.02	0.13
HLD	Pearson Correlation	0.71	0.78	0.14	-0.75	0.63	0.70	1.00	0.23	-0.29	0.26	0.22	0.42	-0.24	0.54	-0.17	-0.42	0.15	0.08	0.18
	Sig. (2-tailed)	0.00	0.00	0.17	0.00	0.00	0.00	.	0.02	0.01	0.02	0.03	0.00	0.02	0.00	0.10	0.00	0.14	0.44	0.09
LCA	Pearson Correlation	0.57	0.26	-0.04	-0.09	0.64	0.31	0.23	1.00	-0.32	-0.68	-0.73	0.14	-0.23	0.58	0.76	-0.90	-0.73	-0.05	-0.38
	Sig. (2-tailed)	0.00	0.01	0.68	0.38	0.00	0.00	0.02	.	0.00	0.00	0.00	0.16	0.02	0.00	0.00	0.00	0.00	0.65	0.00
LFM	Pearson Correlation	-0.13	-0.26	-0.21	0.26	-0.13	-0.06	-0.29	-0.32	1.00	-0.13	0.18	0.04	0.63	-0.56	-0.13	0.34	0.12	0.23	-0.05
	Sig. (2-tailed)	0.25	0.02	0.06	0.02	0.25	0.58	0.01	0.00	.	0.26	0.10	0.72	0.00	0.00	0.25	0.00	0.28	0.04	0.65
LHC	Pearson Correlation	-0.28	0.15	0.35	-0.29	-0.37	-0.13	0.26	-0.68	-0.13	1.00	0.83	0.00	-0.26	0.06	-0.75	0.62	0.76	-0.08	0.47
	Sig. (2-tailed)	0.01	0.17	0.00	0.01	0.00	0.26	0.02	0.00	0.26	.	0.00	0.97	0.02	0.58	0.00	0.00	0.00	0.45	0.00
LHD	Pearson Correlation	-0.33	0.34	0.21	-0.21	-0.44	-0.01	0.22	-0.73	0.18	0.83	1.00	0.40	0.15	-0.18	-0.88	0.67	0.83	-0.01	0.38
	Sig. (2-tailed)	0.00	0.00	0.04	0.04	0.00	0.91	0.03	0.00	0.10	0.00	.	0.00	0.14	0.08	0.00	0.00	0.00	0.90	0.00
LLA	Pearson Correlation	0.26	0.74	0.00	-0.26	0.17	0.42	0.42	0.14	0.04	0.00	0.40	1.00	0.29	0.26	-0.25	-0.19	0.25	-0.01	0.04
	Sig. (2-tailed)	0.01	0.00	0.98	0.01	0.10	0.00	0.00	0.16	0.72	0.97	0.00	.	0.00	0.01	0.01	0.07	0.01	0.96	0.68
LLV	Pearson Correlation	0.02	-0.03	-0.48	0.22	0.01	0.13	-0.24	-0.23	0.63	-0.26	0.15	0.29	1.00	-0.48	-0.18	0.17	0.18	0.11	0.01
	Sig. (2-tailed)	0.88	0.78	0.00	0.03	0.89	0.21	0.02	0.02	0.00	0.02	0.14	0.00	.	0.00	0.08	0.10	0.08	0.31	0.92
LTC	Pearson Correlation	0.44	0.55	0.33	-0.40	0.44	0.28	0.54	0.58	-0.56	0.06	-0.18	0.26	-0.48	1.00	0.24	-0.61	-0.19	-0.19	0.08
	Sig. (2-tailed)	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.58	0.08	0.01	0.00	.	0.02	0.00	0.07	0.06	0.45
TCA	Pearson Correlation	0.29	-0.19	-0.09	0.19	0.39	0.03	-0.17	0.76	-0.13	-0.75	-0.88	-0.25	-0.18	0.24	1.00	-0.69	-0.91	0.04	-0.53
	Sig. (2-tailed)	0.00	0.07	0.37	0.06	0.00	0.80	0.10	0.00	0.25	0.00	0.00	0.01	0.08	0.02	.	0.00	0.00	0.70	0.00
TD	Pearson Correlation	-0.72	-0.45	0.03	0.23	-0.77	-0.44	-0.42	-0.90	0.34	0.62	0.67	-0.19	0.17	-0.61	-0.69	1.00	0.65	0.06	0.30
	Sig. (2-tailed)	0.00	0.00	0.76	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.10	0.00	0.00	.	0.00	0.58	0.00
THC	Pearson Correlation	-0.27	0.20	0.06	-0.18	-0.37	0.00	0.15	-0.73	0.12	0.76	0.83	0.25	0.18	-0.19	-0.91	0.65	1.00	-0.02	0.64
	Sig. (2-tailed)	0.01	0.05	0.54	0.08	0.00	0.96	0.14	0.00	0.28	0.00	0.00	0.01	0.08	0.07	0.00	0.00	.	0.85	0.00
TRKCA	Pearson Correlation	0.18	-0.07	-0.17	0.10	0.09	0.24	0.08	-0.05	0.23	-0.08	-0.01	-0.01	0.11	-0.19	0.04	0.06	-0.02	1.00	-0.01
	Sig. (2-tailed)	0.09	0.49	0.10	0.35	0.39	0.02	0.44	0.65	0.04	0.45	0.90	0.96	0.31	0.06	0.70	0.58	0.85	.	0.89
TTC	Pearson Correlation	-0.03	0.07	0.04	-0.26	-0.11	0.16	0.18	-0.38	-0.05	0.47	0.38	0.04	0.01	0.08	-0.53	0.30	0.64	-0.01	1.00
	Sig. (2-tailed)	0.80	0.48	0.69	0.01	0.28	0.13	0.09	0.00	0.65	0.00	0.00	0.68	0.92	0.45	0.00	0.00	0.00	0.89	.

Appendix O

Correlations found for the ascent condition (FWV)

Table O-1 Correlations among variables

		ART	CSL	CST	DFST	HCD	HCV	HLD	LCA	LFM	LHC	LHD	LLA	LLV	LTC	TCA	TD	THC	TRKCA	TTC
ART	Pearson Correlation	1.00	0.57	-0.25	-0.43	0.93	0.77	0.73	0.48	0.04	-0.24	-0.20	0.37	0.32	0.27	0.18	-0.64	-0.18	0.30	-0.20
	Sig. (2-tailed)	.	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.69	0.03	0.05	0.00	0.00	0.01	0.07	0.00	0.08	0.00	0.05
CSL	Pearson Correlation	0.57	1.00	0.17	-0.41	0.56	0.55	0.78	0.33	-0.05	0.01	0.26	0.77	0.16	0.47	-0.13	-0.62	0.16	-0.06	0.04
	Sig. (2-tailed)	0.00	.	0.10	0.00	0.00	0.00	0.00	0.00	0.65	0.91	0.01	0.00	0.12	0.00	0.19	0.00	0.11	0.55	0.67
CST	Pearson Correlation	-0.25	0.17	1.00	0.22	-0.07	-0.45	0.12	0.00	-0.27	0.29	0.13	0.05	-0.46	0.27	-0.04	-0.05	0.02	-0.16	-0.01
	Sig. (2-tailed)	0.02	0.10	.	0.03	0.49	0.00	0.25	0.99	0.01	0.01	0.20	0.63	0.00	0.01	0.68	0.65	0.84	0.11	0.90
DFST	Pearson Correlation	-0.43	-0.41	0.22	1.00	-0.32	-0.51	-0.65	-0.02	0.22	-0.21	-0.22	-0.22	0.21	-0.28	0.28	0.14	-0.23	0.05	-0.17
	Sig. (2-tailed)	0.00	0.00	0.03	.	0.00	0.00	0.00	0.82	0.04	0.05	0.03	0.03	0.04	0.01	0.01	0.19	0.03	0.65	0.09
HCD	Pearson Correlation	0.93	0.56	-0.07	-0.32	1.00	0.61	0.72	0.52	-0.01	-0.27	-0.25	0.33	0.25	0.34	0.24	-0.68	-0.22	0.26	-0.25
	Sig. (2-tailed)	0.00	0.00	0.49	0.00	.	0.00	0.00	0.00	0.93	0.01	0.01	0.00	0.01	0.00	0.02	0.00	0.03	0.01	0.01
HCV	Pearson Correlation	0.77	0.55	-0.45	-0.51	0.61	1.00	0.64	0.27	0.08	-0.13	0.00	0.41	0.38	0.14	-0.03	-0.44	0.04	0.30	0.05
	Sig. (2-tailed)	0.00	0.00	0.00	0.00	0.00	.	0.00	0.01	0.45	0.23	0.99	0.00	0.00	0.16	0.75	0.00	0.73	0.00	0.61
HLD	Pearson Correlation	0.73	0.78	0.12	-0.65	0.72	0.64	1.00	0.24	-0.13	0.13	0.22	0.51	-0.04	0.39	-0.19	-0.47	0.17	0.16	0.02
	Sig. (2-tailed)	0.00	0.00	0.25	0.00	0.00	0.00	.	0.02	0.23	0.24	0.04	0.00	0.73	0.00	0.06	0.00	0.10	0.12	0.84
LCA	Pearson Correlation	0.48	0.33	0.00	-0.02	0.52	0.27	0.24	1.00	-0.27	-0.57	-0.71	0.18	-0.05	0.58	0.77	-0.89	-0.71	-0.02	-0.50
	Sig. (2-tailed)	0.00	0.00	0.99	0.82	0.00	0.01	0.02	.	0.01	0.00	0.00	0.07	0.60	0.00	0.00	0.00	0.00	0.83	0.00
LFM	Pearson Correlation	0.04	-0.05	-0.27	0.22	-0.01	0.08	-0.13	-0.27	1.00	-0.25	0.20	0.18	0.63	-0.57	-0.21	0.19	0.18	0.15	0.06
	Sig. (2-tailed)	0.69	0.65	0.01	0.04	0.93	0.45	0.23	0.01	.	0.02	0.07	0.10	0.00	0.00	0.06	0.08	0.10	0.17	0.59
LHC	Pearson Correlation	-0.24	0.01	0.29	-0.21	-0.27	-0.13	0.13	-0.57	-0.25	1.00	0.63	-0.03	-0.36	0.06	-0.59	0.49	0.50	-0.14	0.46
	Sig. (2-tailed)	0.03	0.91	0.01	0.05	0.01	0.23	0.24	0.00	0.02	.	0.00	0.79	0.00	0.60	0.00	0.00	0.00	0.19	0.00
LHD	Pearson Correlation	-0.20	0.26	0.13	-0.22	-0.25	0.00	0.22	-0.71	0.20	0.63	1.00	0.37	0.05	-0.19	-0.89	0.57	0.84	-0.03	0.60
	Sig. (2-tailed)	0.05	0.01	0.20	0.03	0.01	0.99	0.04	0.00	0.07	0.00	.	0.00	0.64	0.07	0.00	0.00	0.00	0.80	0.00
LLA	Pearson Correlation	0.37	0.77	0.05	-0.22	0.33	0.41	0.51	0.18	0.18	-0.03	0.37	1.00	0.34	0.36	-0.26	-0.32	0.30	0.02	0.09
	Sig. (2-tailed)	0.00	0.00	0.63	0.03	0.00	0.00	0.00	0.07	0.10	0.79	0.00	.	0.00	0.00	0.01	0.00	0.00	0.84	0.36
LLV	Pearson Correlation	0.32	0.16	-0.46	0.21	0.25	0.38	-0.04	-0.05	0.63	-0.36	0.05	0.34	1.00	-0.35	-0.10	-0.07	0.13	0.20	0.04
	Sig. (2-tailed)	0.00	0.12	0.00	0.04	0.01	0.00	0.73	0.60	0.00	0.00	0.64	0.00	.	0.00	0.34	0.51	0.20	0.05	0.69
LTC	Pearson Correlation	0.27	0.47	0.27	-0.28	0.34	0.14	0.39	0.58	-0.57	0.06	-0.19	0.36	-0.35	1.00	0.28	-0.56	-0.19	-0.22	-0.10
	Sig. (2-tailed)	0.01	0.00	0.01	0.01	0.00	0.16	0.00	0.00	0.00	0.60	0.07	0.00	0.00	.	0.01	0.00	0.07	0.03	0.35
TCA	Pearson Correlation	0.18	-0.13	-0.04	0.28	0.24	-0.03	-0.19	0.77	-0.21	-0.59	-0.89	-0.26	-0.10	0.28	1.00	-0.63	-0.90	0.01	-0.64
	Sig. (2-tailed)	0.07	0.19	0.68	0.01	0.02	0.75	0.06	0.00	0.06	0.00	0.00	0.01	0.34	0.01	.	0.00	0.00	0.96	0.00
TD	Pearson Correlation	-0.64	-0.62	-0.05	0.14	-0.68	-0.44	-0.47	-0.89	0.19	0.49	0.57	-0.32	-0.07	-0.56	-0.63	1.00	0.57	0.03	0.43
	Sig. (2-tailed)	0.00	0.00	0.65	0.19	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.51	0.00	0.00	.	0.00	0.77	0.00
THC	Pearson Correlation	-0.18	0.16	0.02	-0.23	-0.22	0.04	0.17	-0.71	0.18	0.50	0.84	0.30	0.13	-0.19	-0.90	0.57	1.00	-0.01	0.69
	Sig. (2-tailed)	0.08	0.11	0.84	0.03	0.03	0.73	0.10	0.00	0.10	0.00	0.00	0.00	0.20	0.07	0.00	0.00	.	0.94	0.00
TRKCA	Pearson Correlation	0.30	-0.06	-0.16	0.05	0.26	0.30	0.16	-0.02	0.15	-0.14	-0.03	0.02	0.20	-0.22	0.01	0.03	-0.01	1.00	-0.08
	Sig. (2-tailed)	0.00	0.55	0.11	0.65	0.01	0.00	0.12	0.83	0.17	0.19	0.80	0.84	0.05	0.03	0.96	0.77	0.94	.	0.42
TTC	Pearson Correlation	-0.20	0.04	-0.01	-0.17	-0.25	0.05	0.02	-0.50	0.06	0.46	0.60	0.09	0.04	-0.10	-0.64	0.43	0.69	-0.08	1.00
	Sig. (2-tailed)	0.05	0.67	0.90	0.09	0.01	0.61	0.84	0.00	0.59	0.00	0.00	0.36	0.69	0.35	0.00	0.00	0.00	0.42	.

Appendix P

Ensemble average plots of lead foot orientation (crossing step) in the ascent condition (1^{st} trial)

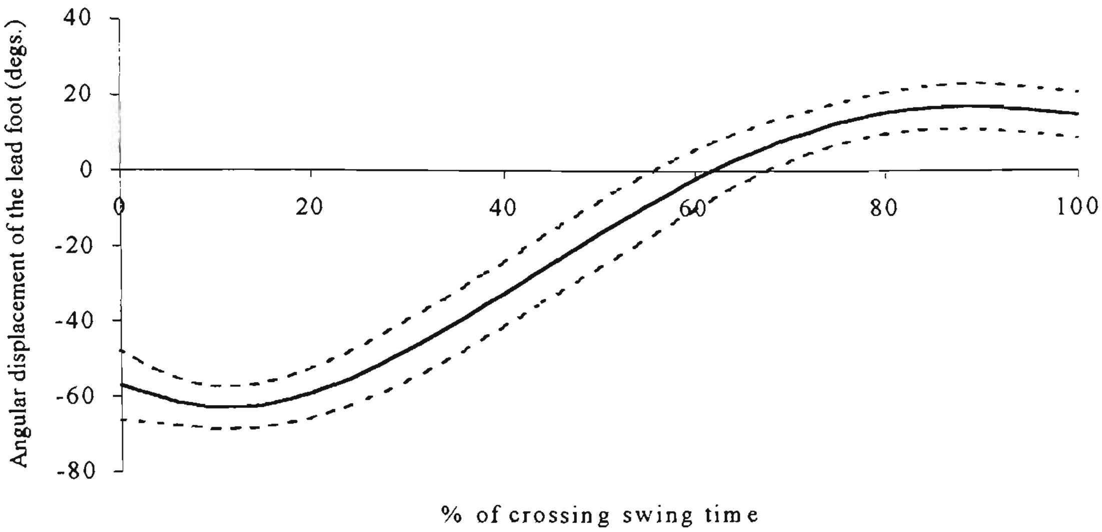


Figure P-1 Ensemble average plot (± SD) for the elderly participants who adopted a heel landing strategy in the CWV condition.

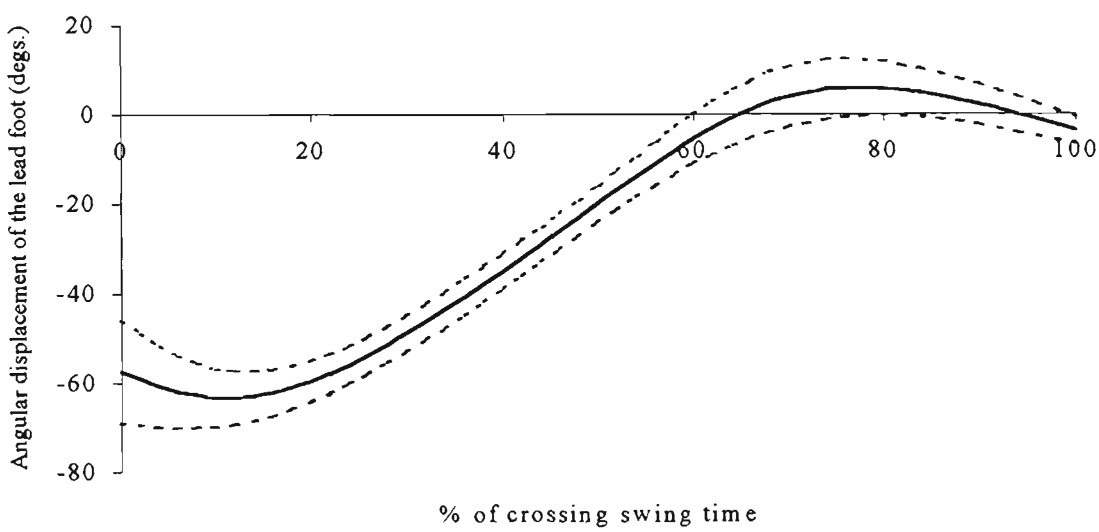


Figure P-2 Ensemble average plot (± SD) for the elderly participants who adopted a forefoot landing strategy in the CWV condition.

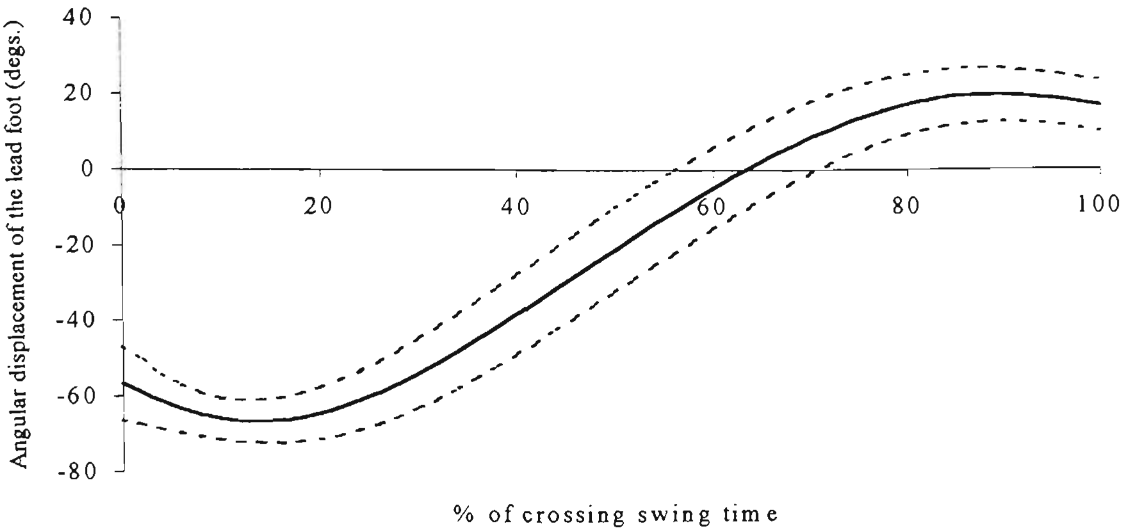


Figure P-3 Ensemble average plot (± SD) for the elderly participants who adopted a heel landing strategy in the FWV condition.

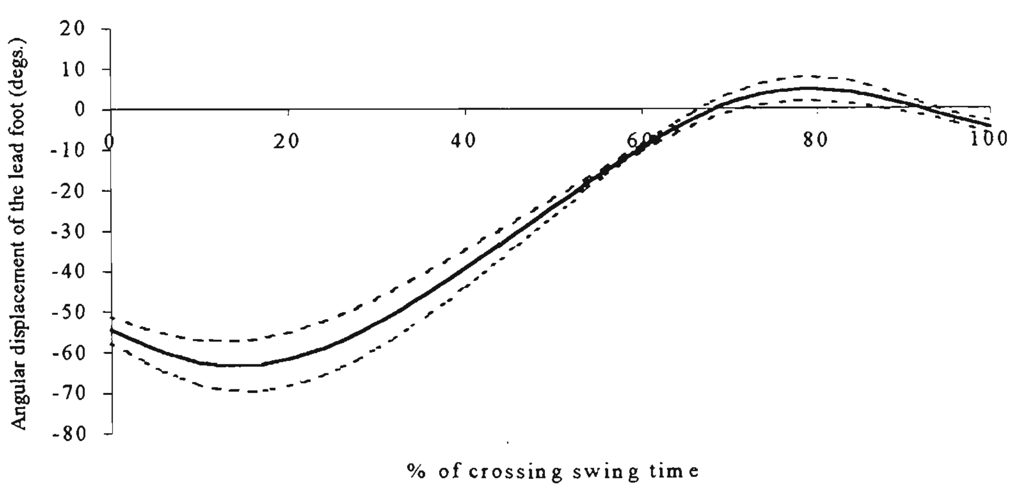


Figure P-4 Ensemble average plot (± SD) for the elderly participants who adopted a forefoot landing strategy in the FWV condition.

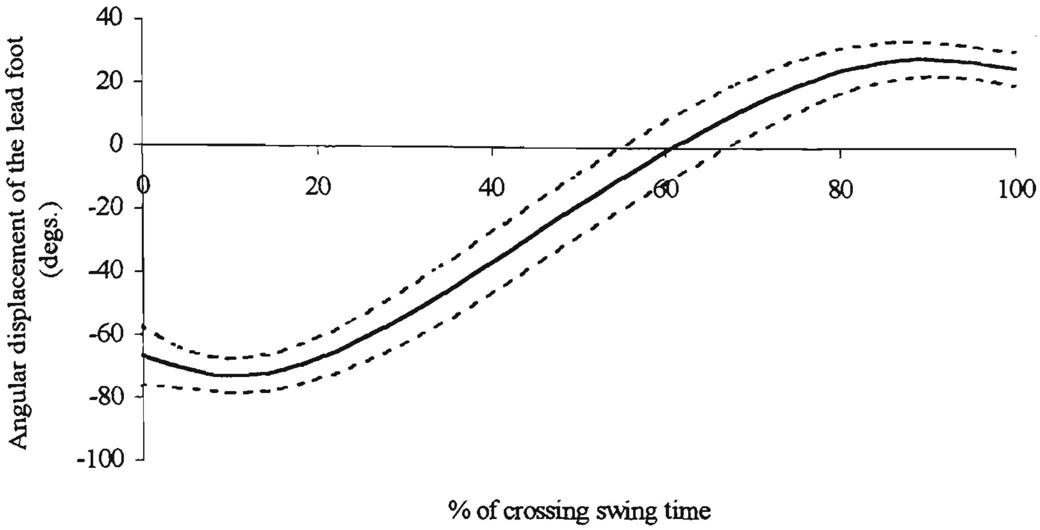


Figure P-5 Ensemble average plot (± SD) for the young participants who adopted a heel landing strategy in the CWV condition.

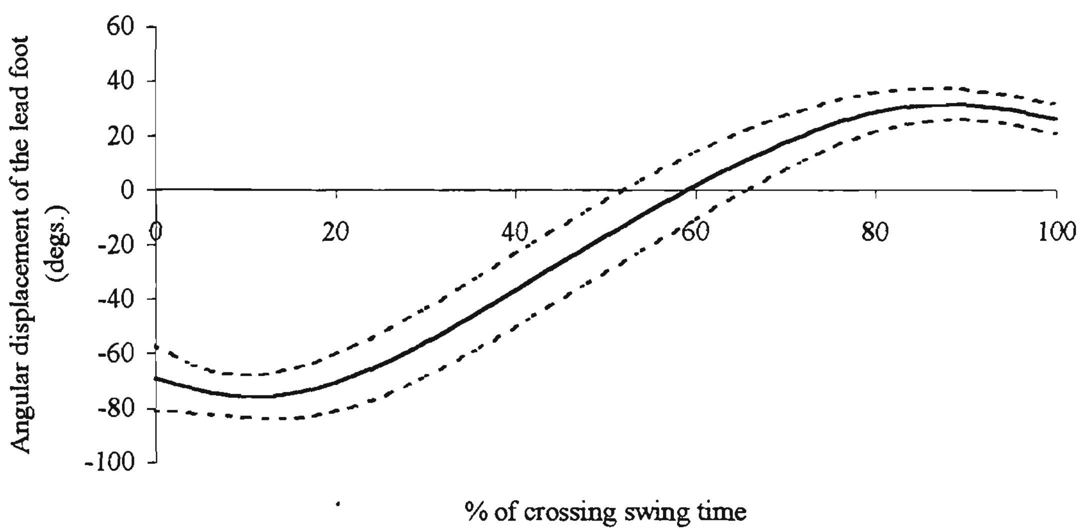


Figure P-6 Ensemble average plot (± SD) for the young participants who adopted a heel landing strategy in the FWV condition.

Appendix Q

Ensemble average plots of vertical displacement of lead toe marker (crossing step) in the ascent condition (1st trial)

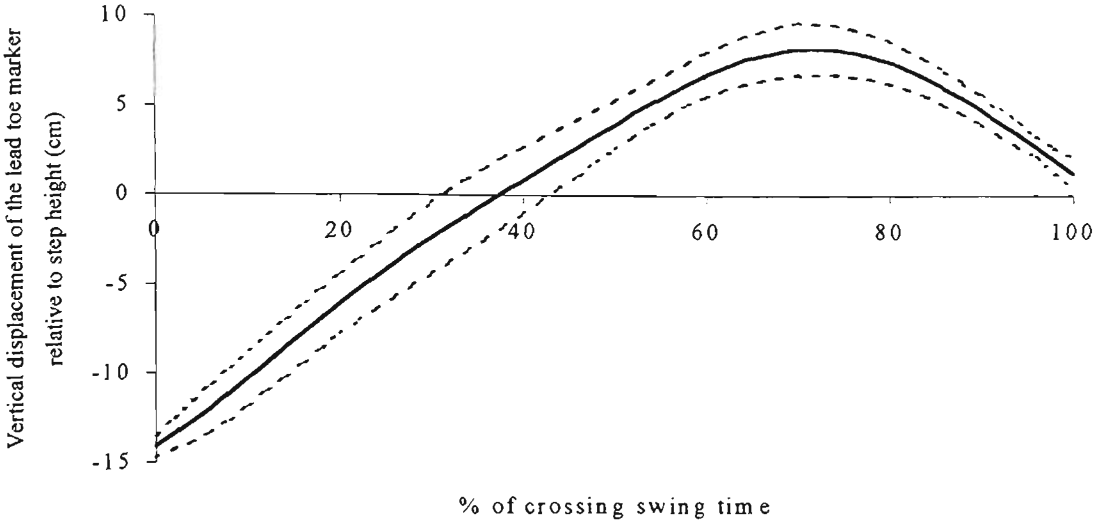


Figure Q-1 Ensemble average plot (± SD) of the vertical displacement of the lead toe marker (relative to step height) for the elderly participants who adopted a forefoot landing strategy in the CWV condition.

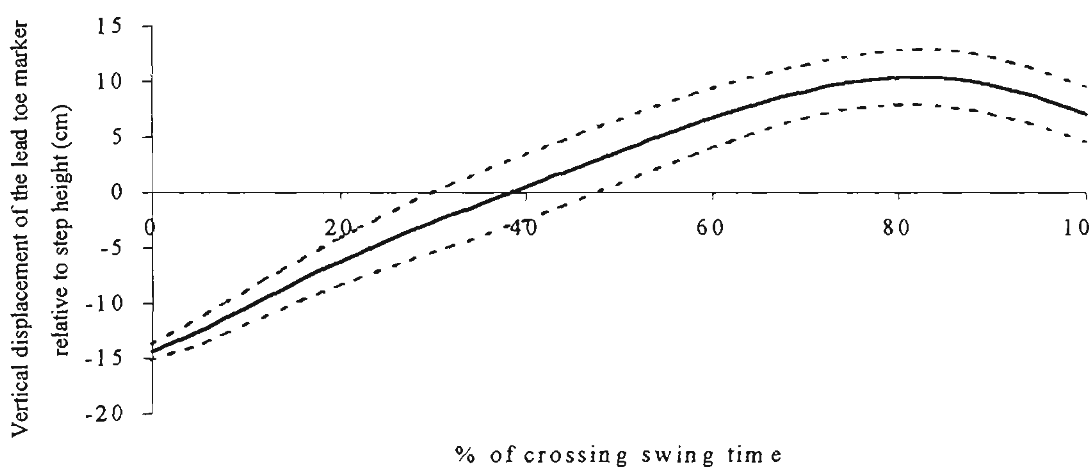


Figure Q-2 Ensemble average plot (± SD) of the vertical displacement of the lead toe marker (relative to step height) for the elderly participants who adopted a heel landing strategy in the CWV condition.

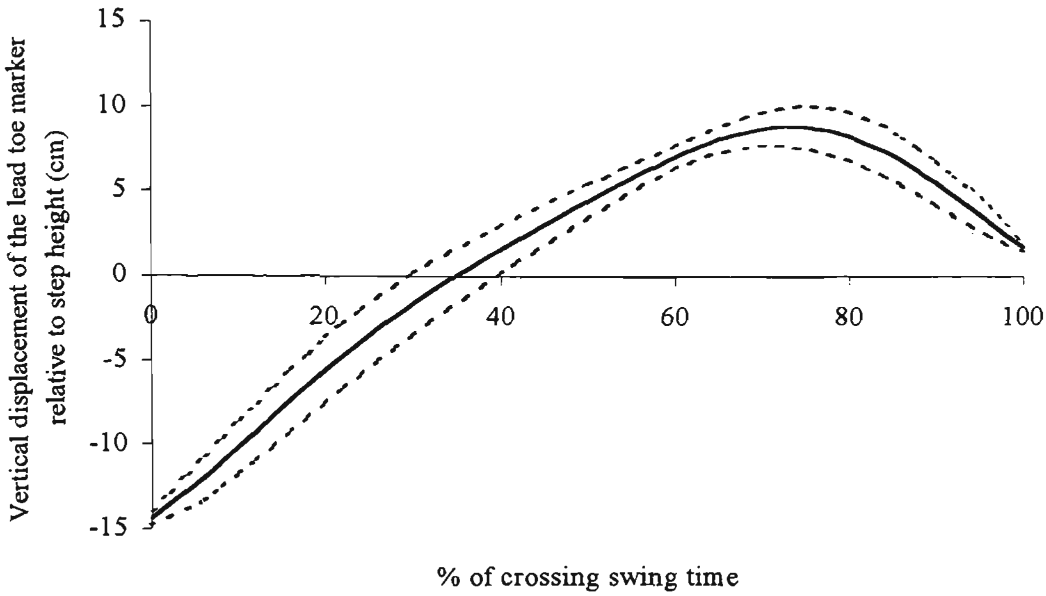


Figure Q-3 Ensemble average plot (± SD) of the vertical displacement of the lead toe marker (relative to step height) for the elderly participants who adopted a forefoot landing strategy in the FWV condition.

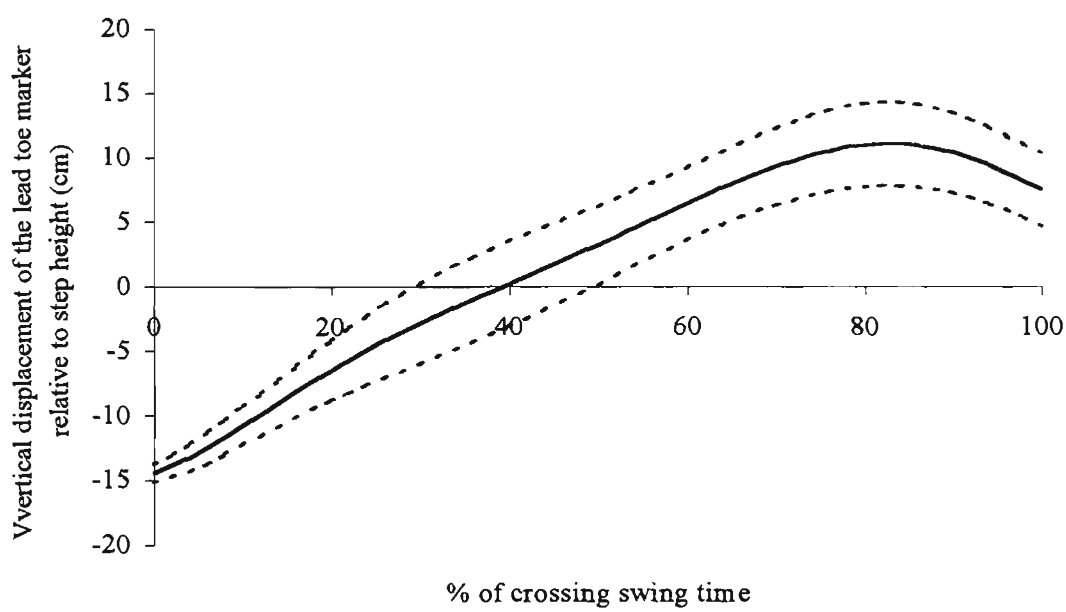


Figure Q-4 Ensemble average plot (± SD) of the vertical displacement of the lead toe marker (relative to step height) for the elderly participants who adopted a heel landing strategy in the FWV condition.

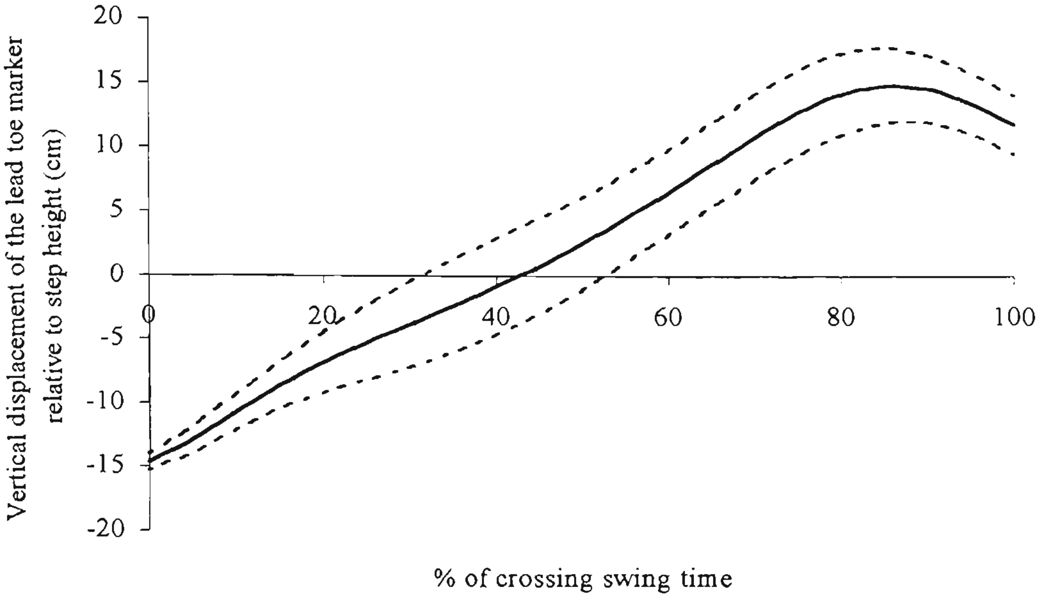


Figure Q-5 Ensemble average plot (± SD) of the vertical displacement of the lead toe marker (relative to step height) for the young participants who adopted a heel landing strategy in the CWV condition.

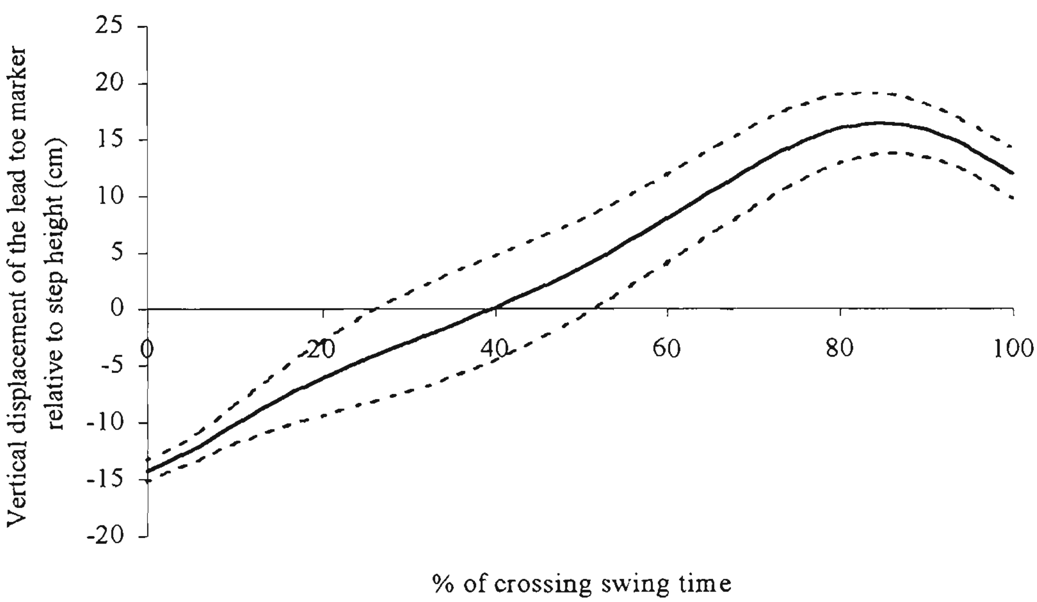


Figure Q-6 Ensemble average plot (± SD) of the vertical displacement of the lead toe marker (relative to step height) for the young participants who adopted a heel landing strategy in the FWV condition.

Appendix R

Plots of footfall variability (approach and crossing phases) in the ascent condition (1st trial)

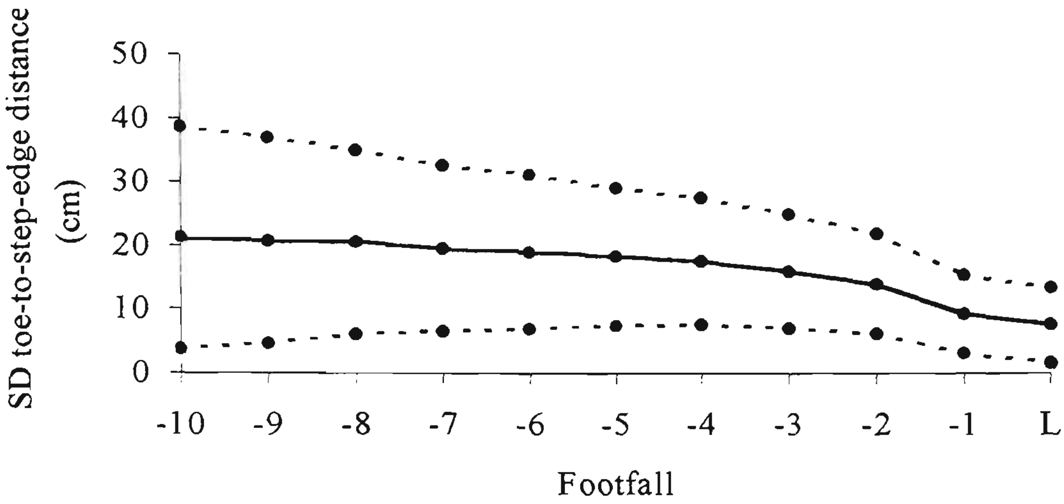


Figure R-1 Mean plot (± SD) of footfall variability for the elderly in the CWV condition.

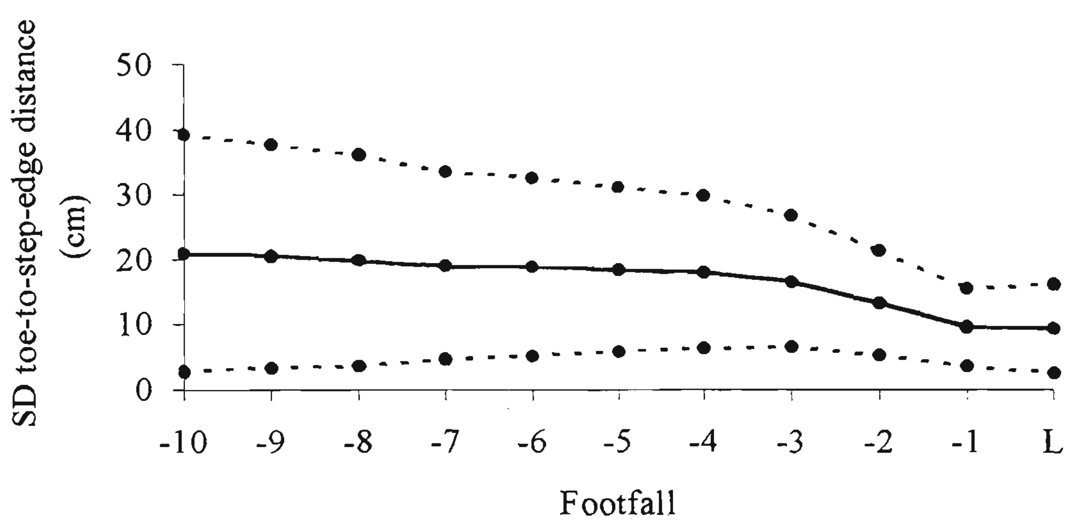


Figure R-2 Mean plot (± SD) of footfall variability for the elderly in the FWV condition.

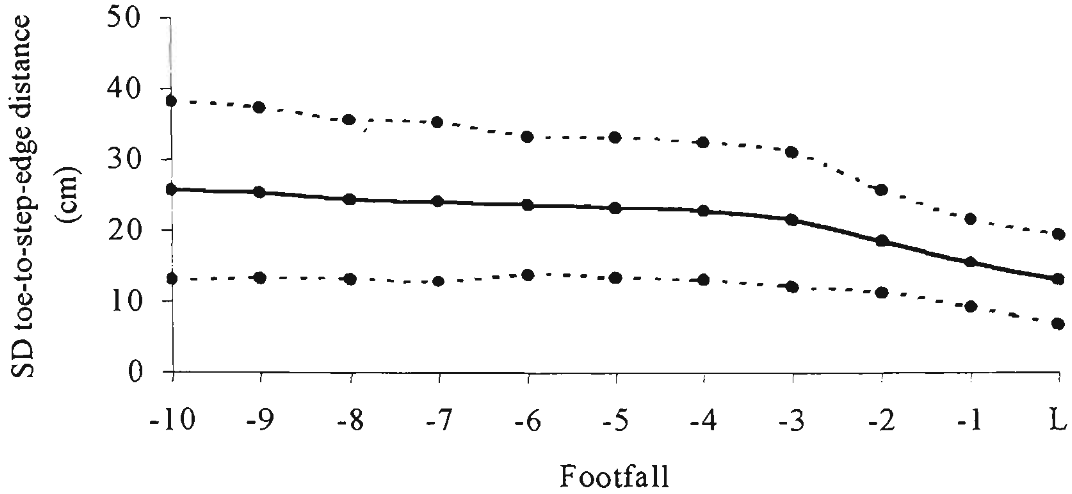


Figure R-3 Mean plot (± SD) of footfall variability for the young in the CWV condition.

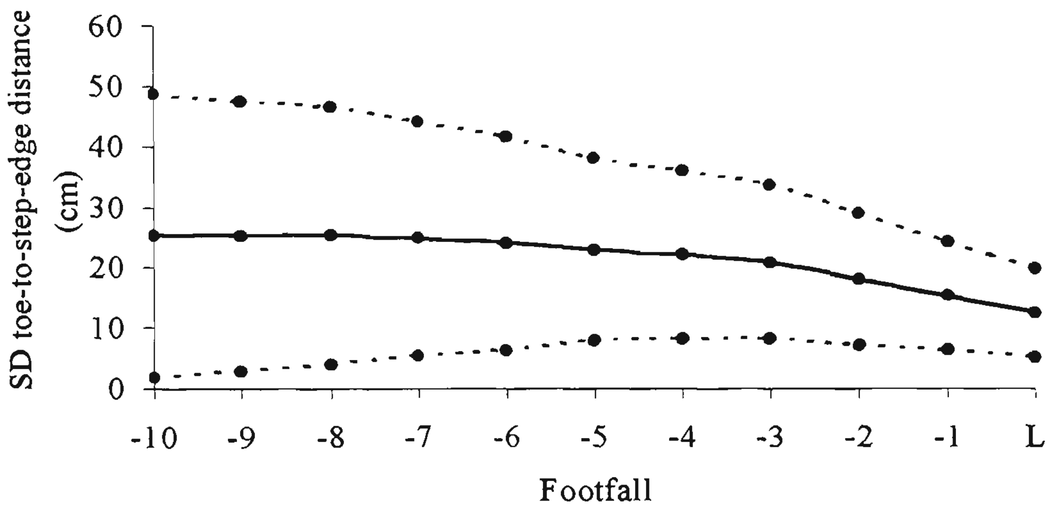


Figure R-4 Mean plot (± SD) of footfall variability for the young in the fast velocity condition.

Appendix S

Mean plots of step lengths (all trials) in the ascent condition

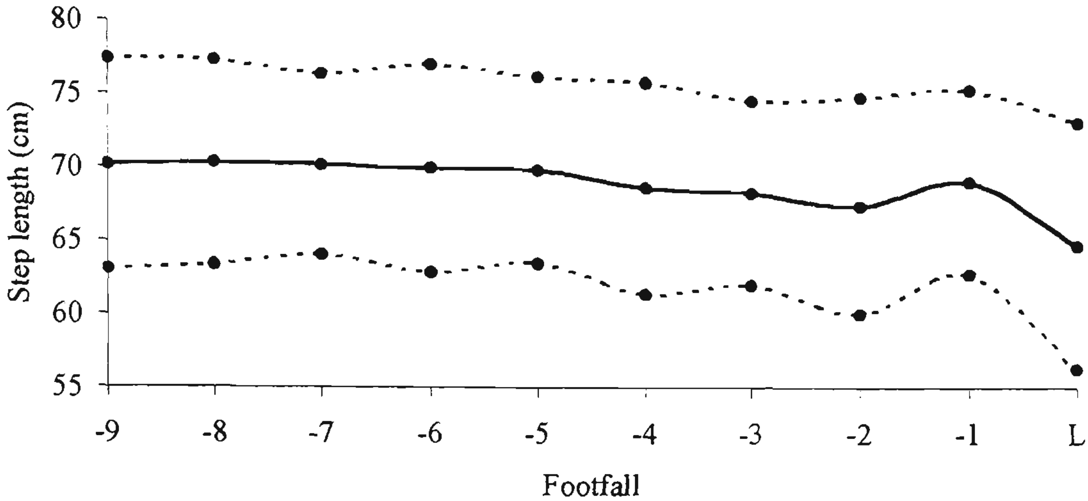


Figure S-1 Mean plot (± SD) of elderly step length in the CWV condition for all trials.

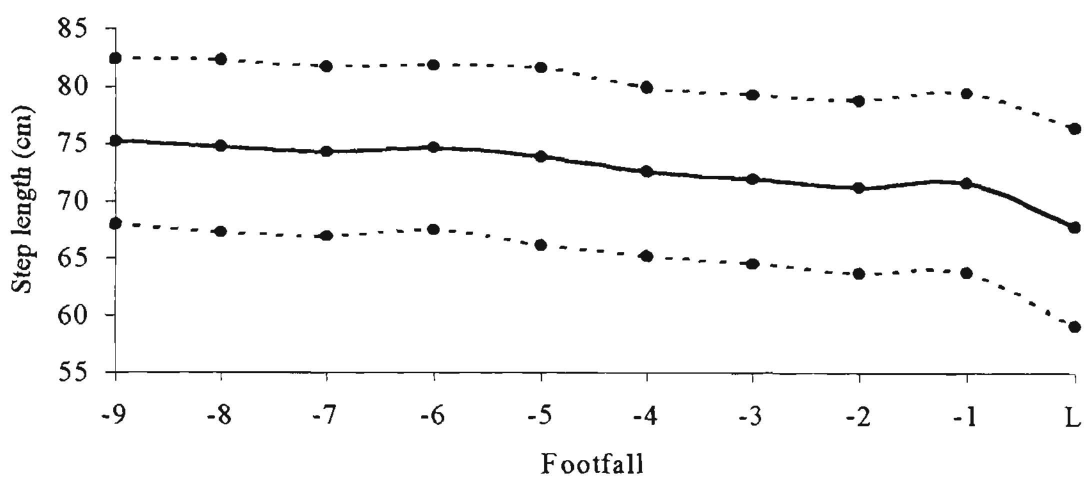


Figure S-2 Mean plot (± SD) of elderly step length in the FWV condition for all trials.

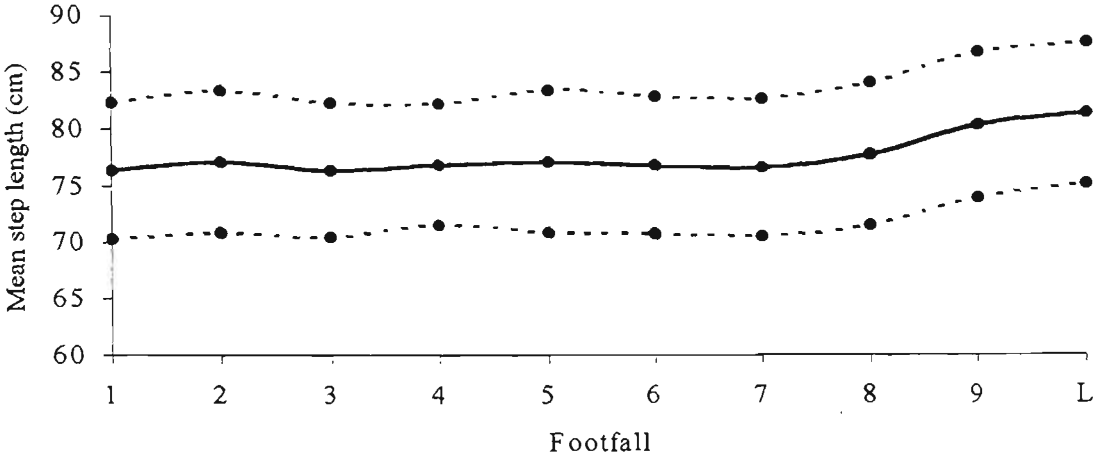


Figure S-3 Mean plot (± SD) of young step length in the CWV condition for all trials.

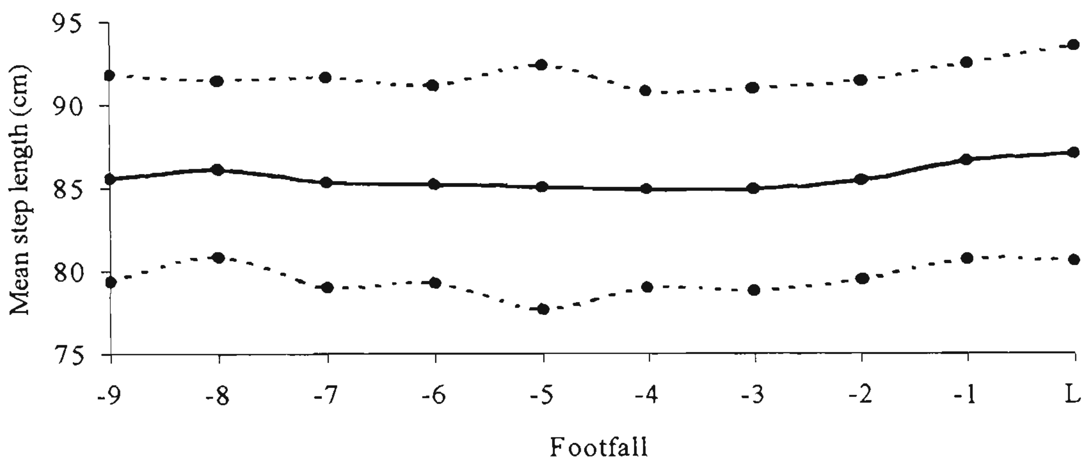


Figure S-4 Mean plot (± SD) of young step length in the FWV condition for all trials.

Appendix T

Mean plots of step lengths (1st trial) in the ascent condition

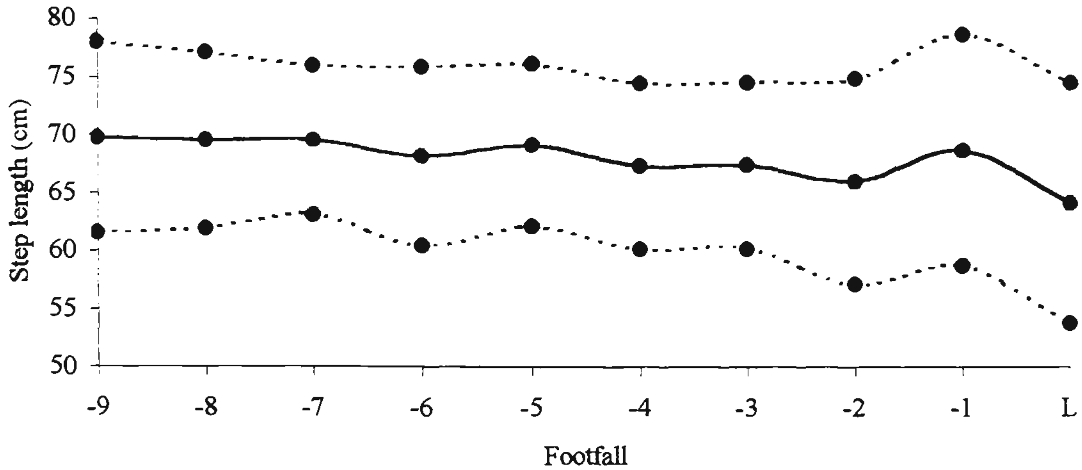


Figure T-1 Mean plot (± SD) of elderly step length in the CWV condition for the first trial.

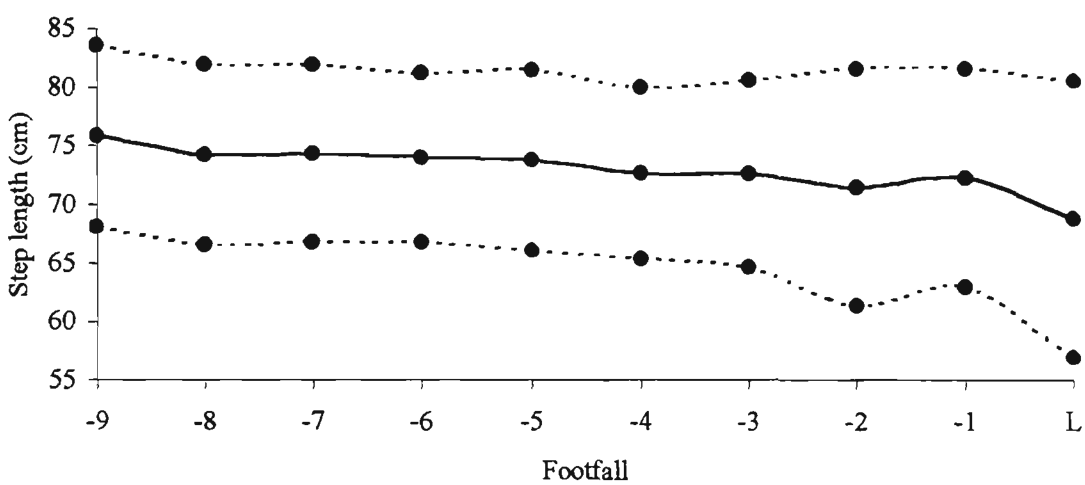


Figure T-2 Mean plot (± SD) of elderly step length in the FWV condition for the first trial.

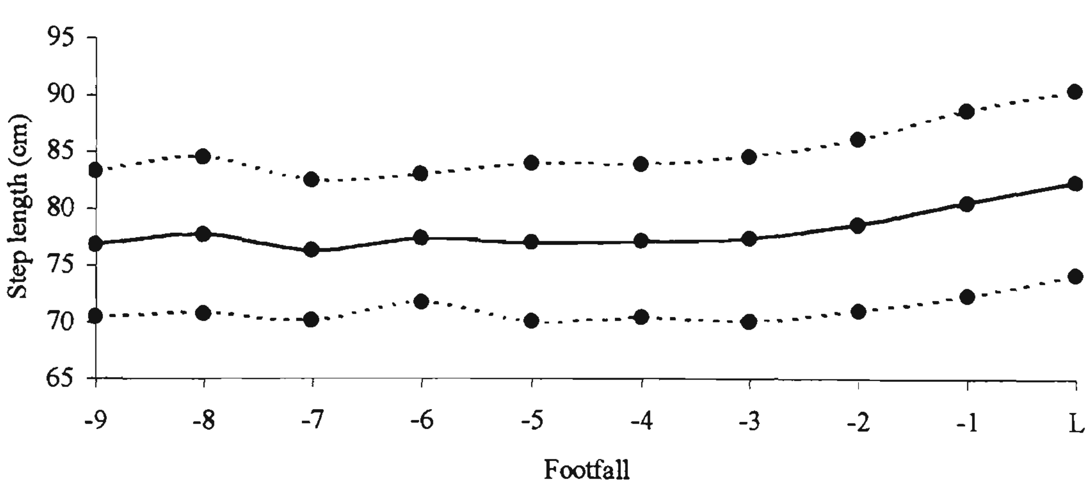


Figure T-3 Mean plot (± SD) of young step length in the CWV condition for the first trial.

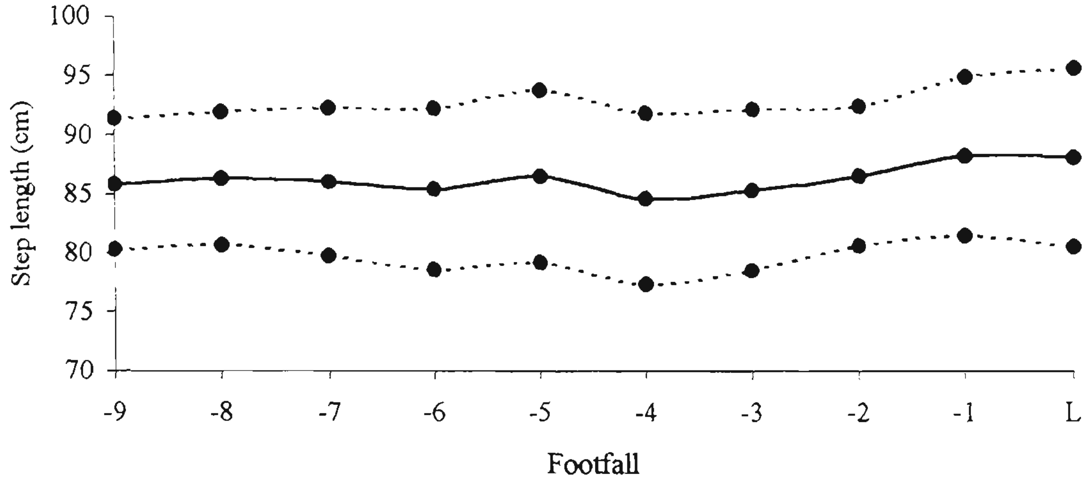


Figure T-4 Mean plot (± SD) of young step length in the FWV condition for the first trial.

Appendix U

Mean plots of step times (1st trial) in the ascent condition

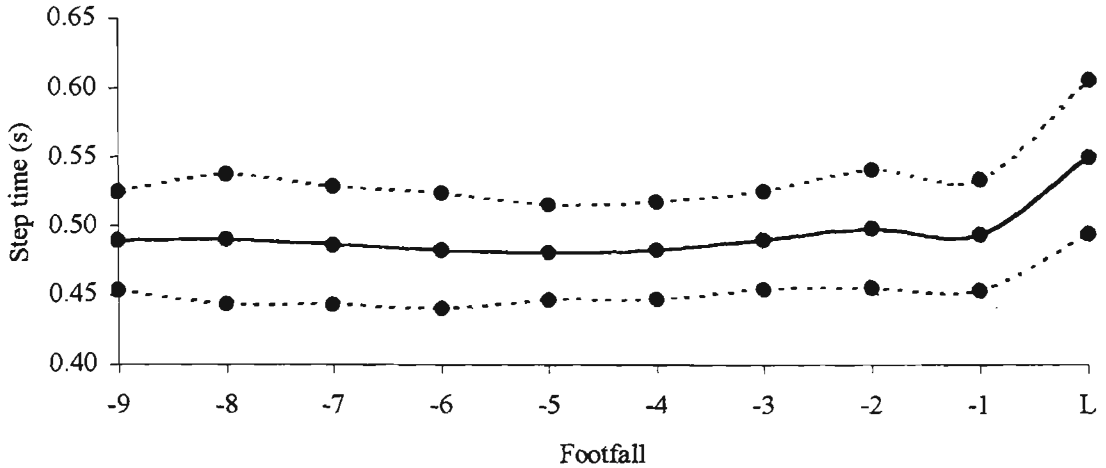


Figure U-1 Mean plot (± SD) of elderly step time in the CWV condition for the first trial.

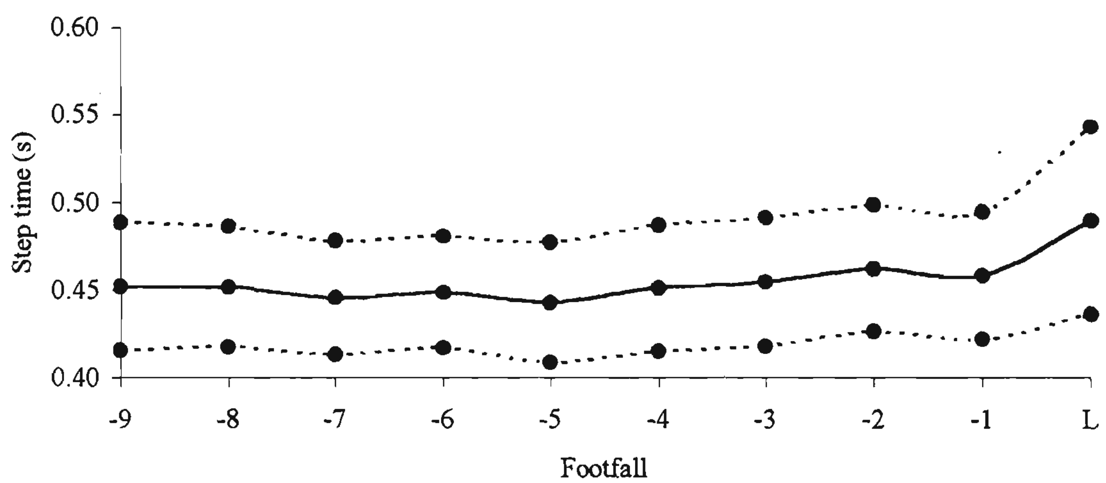


Figure U-2 Mean plot (± SD) of elderly step time in the FWV condition for the first trial.

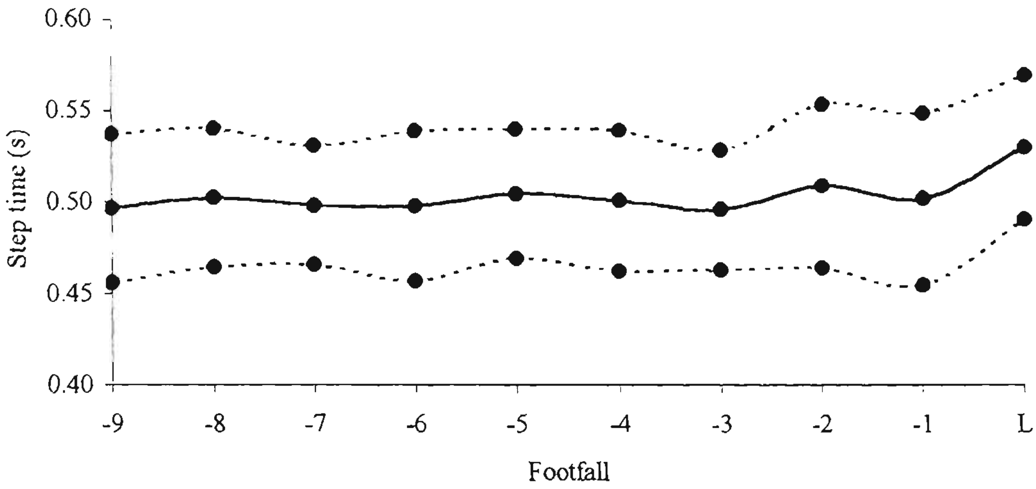


Figure U-3 Mean plot (± SD) of young step time in the CWV condition for the first trial.

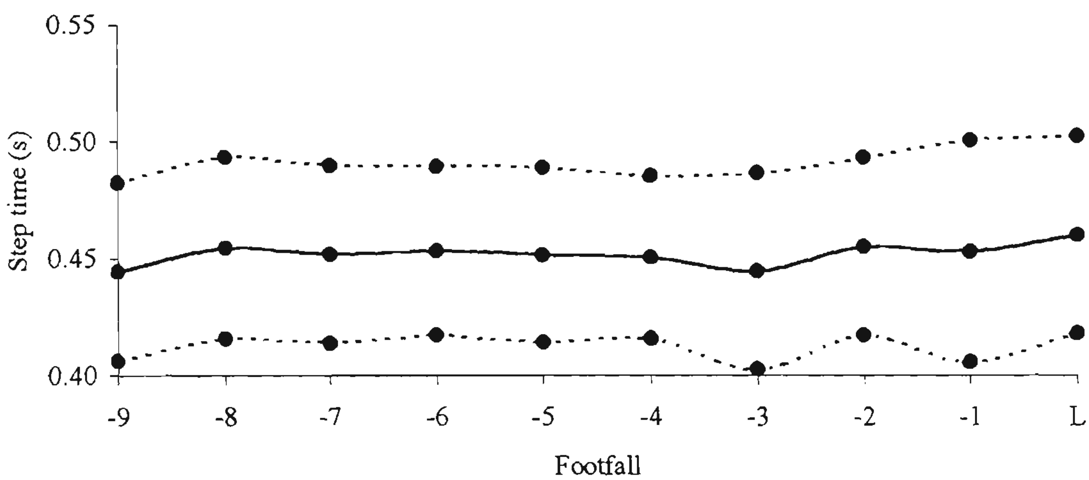


Figure U-4 Mean plot (± SD) of elderly step time in the FWV condition for the first trial.