INVESTIGATING AGE-RELATED DIFFERENCES IN VISUAL SAMPLING BEHAVIOUR DURING ADAPTIVE LOCOMOTION AND THEIR CONSEQUENCES FOR STEPPING ACCURACY

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List of Abbreviations

LROA	Older adults deemed to be at a low-risk of falling
HROA	Older adults deemed to be at a high-risk of falling
FOF	Fear of falling
EDR	Electro-dermal response
M-L	Medio-lateral
A-P	Anterior-posterior

Abstract

Older adults at a high-risk of falling (HROA) look away prematurely from targets they are stepping on in order to fixate future constraints in their walking path. This gaze behaviour is associated with decreased stepping accuracy. The first aim of this thesis was to investigate a possible causal link between premature redirection of gaze from a target and reduced stepping accuracy. Results showed that when older adults voluntarily delayed gaze transfer from a target, their foot placement showed greater accuracy and consistency. Secondly, we investigated a possible relationship between increased anxiety about upcoming obstacles and early gaze transfers away from an initial target. We found that progressively increasing task complexity resulted in associated increases in anxiety, extent of early gaze transfers and stepping inaccuracies in HROA. Finally, we investigated the extent to which young, low-risk older adults and HROA can perform visually guided online alterations to foot trajectory during the swing phase towards a target. We found that adjustments made by older adults (specifically HROA) were characterised by increased latencies and reduced magnitude. We suggest that age- and fall-risk related differences in strategies governing visual sampling and the allocation of attention during adaptive locomotion contribute to incidences of elderly falls.

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Chapter 1

General Introduction

Elderly falls represent one of the most severe and costly problems to society, as approximately 32% of adults over the age of 75 have been shown to fall annually (Tinetti et al. 1988; Lord et al. 1993; 1994; Campbell et al 1989; Luukinen et al. 1995), at an annual cost of one billion pounds to the UK health services (Scuffham et al. 2003). As a result researchers have placed a large emphasis on identifying factors that contribute to fall-risk, as well as developing new methods of rehabilitation for falls prevention.

1.1 Factors contributing to elderly falls

According to Grabiner and Jahnigen (1992), avoiding a fall requires our central nervous systems to perceive relevant threats to balance, and then select and execute appropriate postural responses. However, the functions that serve these processes are susceptible to age-related decline. Problems associated with musculoskeletal function will primarily impair the execution of movements, whereas deficits associated with sensation are likely to compromise the availability of information to plan, and in some cases guide appropriate responses. Vision is our primary means of gathering prospective information regarding potential hazards, particularly when walking. However, evidence is growing for age-related differences in visual behaviour when walking and negotiating constraints, and these changes have been linked with a decline in the accuracy of stepping actions (Chapman and Hollands, 2007); a trait indicating higher fall-risk in older adults (Lord and Deyhew, 2001). Therefore, alterations in visual sampling may have potentially dangerous consequences in older populations. It is the purpose of this thesis to identify possible relationships between visual strategy and maladaptive walking behaviours, but also to explore potential mechanisms driving alterations in visual behaviour. In order to identify consequences of age-related changes to visual behaviour on stepping ability, it is important to first understand the biomechanical and physiological principles underlying the control of locomotion, and how age-related changes in these functions can predispose individuals to increased fall-risk.

1.1.1 Age-related changes to gait characteristics

Walking involves a complex synergy of actions. When standing in a stationary position, an individual can maintain balance providing their centre of mass remains over the base of support. However, when walking, the centre of mass is projected beyond the base of support (the foot in stance) as the swinging foot is transported to a new location (Jian et al. 1993; Mackinnon and Winter, 1993). As a result, gravitational force causes the body to fall forwards and sideways, and it is suggested that these movement characteristics are predetermined when the foot leaves the ground (Lyon and Day, 1997). In order to prevent a forward fall, the swinging foot then must 'catch' and support the falling body mass. At this time the opposite limb generates a subsequent projection of the centre of mass towards the foot currently in stance. Therefore, measuring postural stability during walking is not a simple task since the act of walking is inherently an unstable movement. Various criteria are used to categorise locomotor function. The measures associated with age-related decline and increased fall-risk are discussed below.

A variety of age-related alterations in gait characteristics have been identified, such as reduced stride length and increased time spent in the double support phase (Menz et al. 2003), the accumulation of which results in reduced gait velocity (Prince et al.

1997). Such behaviours are indicative of a conservative strategy designed to preserve stability. However, these changes in stepping behaviour have also been associated with increased fall-risk (Gunter et al. 2000). Variability within the stepping patterns of older adults has received much attention in the literature, and has been commended as a strong indicator of fall-risk (Hausdorff et al. 2001; Maki, 1997), more so than previously identified indicators such as walking velocity. Other studies have illustrated associations between increased variability in step width (as opposed to step length) and increased fall-risk (Owings and Grabiner, 2004; Grabiner et al. 2001; Maki and McIlroy, 1997). Mechanisms underlying increases in stepping variability are likely to be multi-factoral, driven by decline in somatosensory and visual function (Thies et al. 2005) in addition to broad deficits in motor control associated with increased age. More recent work showed that high-risk older adults demonstrated increased foot placement variability during precision stepping tasks (Chapman and Hollands, 2007), suggesting a reduced ability to execute stepping actions as consistently.

Although age-related changes in gait characteristics appear to reflect deterioration in sensory and motor systems discussed previously, it is not clear to what extent stepping behaviour is altered as a result of physical limitations, or altered gait strategy to preserve postural stability. The following sections shall discuss common age-related physiological and psychological changes previously shown in the literature, in particular those associated with increased likelihood of falling.

1.1.2 Neuromuscular function

The ability to move our limbs in an appropriate fashion relies on the contractile properties of skeletal muscle, and appropriate activation patterns within motoneurones. Maintaining balance often relies on rapid compensatory responses in response to a slip or trip, and such responses are limited by the strength of muscle groups in the lower limbs, such as hip flexors and knee extensors (Maki and McIlroy, 1999). The hip adductors and abductors have also been shown to play a key role in the maintenance of lateral stability (Rogers et al. 2003).

Many studies have shown a relationship between increased age and a reduction in muscle strength (Doherty et al.1993), particularly in the lower limbs (Ostchega et al. 2004). Larsson et al. (1979) found that quadriceps strength decreased between 24-36% between the age of 50 and 70 years. In addition, age-related decline in the number of muscle fibres (40%) (Lexell et al. 1988) and motor units has been demonstrated (Roos et al. 1999) in conjunction with reduced innervation of fast-twitch fibres (Tseng et al. 1995).

A reduction in muscle force has been shown during knee extention (Lord et al. 1994), ankle dorsiflexion (Whipple et al. 1987) and hip flexion (Robbins et al. 1989). Consequences of accelerated muscle atrophy in older adults not only include a reduction in peak torque around the ankle joint, but also the rate of torque production (Thelen et al. 1996). Increased age has been associated with reduced nerve conduction velocities (Falco et al. 1992), a possible consequence of a reduction in the number of myelinated nerve fibres and reductions in nerve fibre diameters (Mittal and Logmani, 1987). Simple reaction time has also been shown to rise 25% between the ages of 20 and 60 years and increasing further in the years that follow (Fozard et al. 1994). Therefore, impairments may not only be in the ability to produce sufficient force, but in the timing of force production.

As age-related musculature decline is associated with reduced gait speed (Ostchega et al. 2004; Hunter et al. 1995; Fiatrone et al. 1990), increased incidence of falls

(Moreland et al. 2004) and morbidity (Tinetti et al. 1995), much work has focussed on developing rehabilitative programs to counteract reduced muscle strength. However, of all the programs designed, the most effective in counteracting age-related muscle atrophy is yet to be established; a consequence of inconsistent findings in the literature. One problem is that training programs often target muscle groups in isolation, and although there is strong evidence for improvements in muscle force (Latham et al. 2003; Fiatarone et al. 1994) this type of training is not specific to the context in which the muscle is used during functional tasks, and can predispose participants to increased risk of injury (Latham et al. 2003). These problems associated with strength training may help to explain some of the inconsistent findings concerning functional mobility. Combinations of strength and balance exercises have produced the most encouraging results (Lord et al. 1996; Shumway-Cook et al. 1997; Campbell et al. 1997; Means et al. 2005), possibly through improvements in the neural component of adaptations within muscles.

A loss of range of motion (ROM) in hip and ankle joints has been associated with normal aging (Tinetti, 1988). Age-related changes such as reduced hip motion (Kerrigan et al. 1998), reduced power generation (Kerrigan et al. 1998; Judge et al. 1996), and reduced range of motion in the ankles (Hageman and Blanke, 1986) have clear consequences on mobility. Indeed, deficits in ROM have been shown to impair performance in daily activities commonly used as assessments of functional mobility (stair climbing and rising from a chair). Therefore, it is not surprising that reduced ROM has been linked with increased fall-risk (Guralnik et al. 1995; Neitz and Choy, 2004; Kemoun et al. 2002). A reduction in ROM in the hip and ankle is likely to impede the capacity to produce adequate foot clearance when stepping over obstacles or walking up stairs. Johnson et al. (2007) demonstrated improvements in passive ankle dorsiflexion after six weeks of training. However, to our knowledge no study has extended these findings to demonstrate improvements in mobility tasks, possibly because the improvements seen may not be functionally significant in isolation. A reduction in hip ROM is commonly linked to arthritis; a condition shown to compromise locomotor function (Arokoski et al. 2004), possibly as a result of increased hip and knee pain (Pandya et al. 2003; Majewski et al. 2005), predisposing older adults to increased fall-risk (Wyke, 1979).

1.1.3 Summary

Age-related decline in muscle strength and joint function compromises the ability of older adults to produce locomotor actions in the same manner as young adults. Exercise and training programs have produced some encouraging results, although few have demonstrated significant effects on mobility scores. Although musculoskeletal deficits have been clearly identified as an important factor indicating fall-risk, the problem extends beyond motor capabilities. Adaptive locomotion demands the ability to extract relevant information from the environment and use it to inform appropriate responses. The following section shall review the literature concerning age-related changes in the capacity to acquire sensory information.

1.2 Changes in the acquisition of sensory information

1.2.1 Somatosensory information

Locomotor actions are a result of the integration of activity from supra-spinal motor commands, but also spinal neuronal circuits and sensory feedback signals. Sensory information plays an important role during walking; contributing to regulation of spinally generated rhythms, triggering corrective reflexes, and providing current information regarding the position of the body, relative to that which is intended.

Somatosensory feedback refers to information relating to cutaneous sensation (touch), proprioception (body position), movement (kinesthesia) and nociception (pain). Proprioceptive input is derived from various organs located in and around the muscles. Golgi tendon organs situated at the tendon-muscle interface provide information regarding muscle tension and muscle spindles inform of contractile velocity and muscle length. Collectively, proprioceptive input allows the CNS to calculate relative joint position. Proprioception is typically measured according to the threshold for detecting movement of a limb in addition to the ability to reproduce a joint angle. A decline in the ability to carry out such tasks has been demonstrated in older adults (Horak et al. 1989; Thelen, 1998) and has been shown to impair locomotor function (Bishop et al. 1997), and has been identified (in the lower limbs) as a risk factor for falls (Lord et al. 1991). These age-related alterations in proprioceptive function may be the product of changes within the muscle spindles (Miwa et al. 1995), such as a reduction in the number of intrafusal fibres (Kararizou et al. 2005).

Information from plantar mechanoreceptors in the feet is an important source of sensory feedback for the maintenance of postural stability (Duysens et al. 1995), giving information about contact pressures under the feet through cutaneous afferents (Perry et al. 2000). Plantar sensation is more accurate during weight-bearing exercises (Bullock-Saxton et al. 2001), and in these conditions exhibits a lower threshold for movement detection than visual or vestibular information (Fitzpatrick and McCloskey, 1994). Plantar sensation has been shown to decline with increased age, and is associated with reduced balance function (Menz et al. 2005).

In terms of associating age-related somatosensory decline with fall-risk, the literature contains conflicting results. Although there is a wealth of evidence to link somatosensory decline with deficits in postural control (Menz et al. 2005; Lord and Fitzpatrick, 2001), numerous studies have found no relationship with increased fall-risk (Wolfson et al. 1995; Grisso et al. 1991). However, information from peripheral neuropathy patients can provide insight into the debilitative affect of somatosensory decline on gait (Son et al. 2009). Individuals with peripheral neuropathy walk slower, with shorter stride lengths, longer stride durations and greater stride widths than healthy subjects (Richardson et al. 2004); behaviours indicative of increased fall-risk and a conservative gait strategy.

Recent studies have provided evidence that specialist insoles can assist proprioceptive input (Perry et al. 2008). Such assistive aids may play an important role in counteracting somatosensory deficits that are not easily addressed through training interventions.

1.2.2 Vestibular function

The vestibular system provides information regarding head position and spatial orientation. The vestibular system is divided in two sections: three semi-circular canals detect angular head rotations, and the otolithic system detects linear head accelerations. Input from these systems project to the neural pathways concerned with the control of balance, head and eye movements. Contributions to postural control are made through vestibulospinal reflexes, generation of corrective movements of the trunk (Pozzo et al. 1990), neck and other areas as required (Highstein, 1996).

Rotations of the head and oscillations of the body are compensated for by the vestibuloocular reflex (VOR) in all three planes, where short latency compensatory eye movements are informed by vestibular information, stabilising the image received on the retina during movements of the body (particularly the head). Other mechanisms are also capable of producing such responses such as the cervico-ocular reflex, a system informed through receptors in the neck. However, these systems are generally only used in people with vestibular loss (Barnes, 1993).

Age-related deficits in vestibular function (Johnsson, 1971; Fife and Baloh, 1993) are likely to be a consequence of deterioration of vestibular apparatus such as a decline in the number of hair cells and nerve fibres in the otolith organs (Rosenhall, 1973; Rosenhall and Rubin, 1975). However, recent studies have shown that vestibular rehabilitation can reduce some of the symptoms associated with vestibular deficits (Cohen and Kimball, 2003; Johansson et al. 2001; Yardley et al. 1998).

People with vestibular loss can appear to function in a normal fashion during daily activities, probably due to compensations in the CNS prioritising the use of proprioceptive and visual systems. However, Deshpande and Patla (2007) showed that in older participants, when applying transmastoidal galvanic vestibular stimulation, deviations in walking direction and trunk tilt occurred regardless of whether clear vision was available or not. In addition, Di Fabio et al. (2001b) demonstrated that older adults with a history of falls were unable to suppress the VOR whilst rising from a chair, whereas the non-faller group were still able to do so. These findings suggest that older adults have a reduced capacity to reweight the ‘gain’ of vestibular input when walking. Unresolved deficits in the fidelity of vestibular input may cause conflicts between vestibular and other sensory information, including a reduced ability to retain a consistent image on the retina during head movements, thus compromising the collective information used to control balance.

1.2.3 Head stabilisation

Oscillations generated from the lower limbs during walking can reduce head stability. As the eyes require a stable platform in order to gather accurate spatial and temporal information regarding the visual scene, if body oscillations are not attenuated the fidelity of images reaching the retina would be compromised. As a result, the management of head accelerations is fundamental to the control of gait (Mazzà et al. 2008). Young adults are able to achieve a high degree of head stability whilst walking (Pozzo et al. 1990; Cromwell et al. 2001b). The primary means by which this is achieved is through compensatory rotations of the head in the sagittal plane (Cromwell et al. 2001a; 2004a), with respect to the degree of transitional motion caused by gait (Pozzo et al. 1990; Mulavara et al. 2002). However, Kavanah et al. (2006) demonstrated that compensations in the trunk play a critical role in attenuating oscillations is all directions, and that rotations in the neck are only required in the direction of walking. Both passive and active mechanisms are used in the attempt to compensate for gait generated oscillations. Ligaments and vertebral discs in the spine serve to passively dampen and absorb fluctuations in trunk acceleration, whereas compensatory contractions in skeletal muscles throughout the trunk and neck are coordinated to further reduce adverse accelerations of the head (Kavanah et al. 2006).

Increased age is associated with a reduced ability to produce head stabilising movements, presumably due to deterioration in the sensory input. Cromwell et al. (2002) showed that older adults whilst simultaneously walking and fixating a target would produce a tighter coupling (reduced range of movement) between the head and trunk compared to young adults. However, this coupling significantly deteriorated under no vision conditions. This suggests that older adults rely more on visual information to coordinate necessary head movements, as they are less able to employ input from the vestibular system.

These problems may be compounded by increases in variable patterns of upper body movements in older adults (Laudani et al. 2006), although this has only been shown during gait initiation. However, older adults generally show reduced pelvis and head accelerations compared to young adults (Menz et al. 2003c). Therefore older adults must employ a compensatory strategy despite a decline vestibular input. One countermeasure shown to reduce upper body accelerations is reduced gait speed (Menz et al. 2003b), a common characteristic of gait in older adults (Prince et al. 1997).

1.2.4 Summary

The CNS is provided with many sources of somatosensory information regarding the position and movement of the body. This information is used to inform important compensatory and voluntary movements concerned with the maintenance of balance and stability of the head. However, increased age is associated with a reduction in sensory acuity (Kenshalo, 1986) and discrepancies between sources of sensory input, if not suppressed may lead to ill-informed responses. In some cases this leads to an increased reliance on visual information to compensate for errors in somatosensory function. The role of visual information and age-related changes in visual function are discussed in the following section.

1.3 Visual Control of walking

1.3.1 Age-related changes to vision

Visual information is utilised by the CNS to create a spatial map of the surrounding environment, allowing us to detect spatial and temporal relationships between objects. The movement of visual field can inform the CNS of self-motion, and is used in the control of balance. This is apparent when a subject stands on compliant foam; as postural sway will increase when they close their eyes (Lord et al. 1991). In addition, Lee and Lishman (1975) showed that postural responses were elicited when subjects perceived self-motion through misleading visual cues. These illusions of self-motion have been used in previous studies to show that older adults tend to rely more on visual input for the control of balance (Tobis et al. 1985; Lord and Webster, 1990). As discussed in the previous section, this is possibly a compensation for sensory loss in other areas such as vestibular input (Over, 1966). However, visual information is not only used to acquire information regarding self-motion; it is the primary means in which spatial information can be gathered regarding specific hazards in our environment that should be avoided. The various forms of visual decline associated with increased age act to deficit the fidelity of information available to distinguish environmental hazards. Therefore, it is not surprising that many of them have been linked with alterations in stepping behaviours and increased fall-risk.

The examination of visual acuity (the ability to distinguish detail in a visual scene) is the most common measure of visual function. Generally visual acuity will remain constant prior to the age of 50 years, but then steadily decline (Pitts, 1982; Grittings and Fozard, 1986). Although older adults have been shown to adopt a more conservative gait strategy when their vision is artificially blurred (Heasley et al. 2004), reductions in visual acuity have been repeatedly associated with an increased risk of falling (Ivers et al. 1998; Lord et al. 1991; 1994). Visual acuity is generally measured according to an individuals' ability to identify characters displayed in high contrast to the background (see Chapter 2). However, a reduced capacity to distinguish characters, or the edges of shapes displayed at low contrast to their background has been identified as a particularly strong indicator of fall-risk (Ivers et al. 1998; Lord et al. 1991; Lord and Dayhew, 2001). Reduced contrast sensitivity impedes the detection of hazards at ground level (such as a curb, or the edge of a pavement), especially at low illumination levels (Lord and Dayhew, 2001). The judgement of distances is also important for accurate perception of spatial relationships, such as calculating the height of a step from the ground (Vale et al. 2008). The relationship between impaired depth perception and increased fall-risk has been demonstrated in many studies (Cummings et al. 1995; Lord and Deyhew, 2001; Nevitt et al. 1989). Furthermore, Felson et al. (1989) showed that older adults with poor vision in one eye and moderate vision in the other eye were more likely to incur a hip fracture than older adults with moderate vision in both eyes.

Peripheral vision can provide the necessary information to plan and guide stepping actions over suddenly appearing obstacles (Marigold et al. 2007). Understandably, older adults with reduced peripheral vision are more likely to rely on central vision for informative cues (Itoh and Fukuda, 2002). However, there are worrying consequences of such decline in the control of standing balance (Manchester et al. 1989) and safe ambulation. Turano et al. (2004) showed that in a sample of 1504 older adults, participants with reduced peripheral vision not only walked slower, but collided more frequently with obstacles in their path. However, when artificially denying peripheral information, a more conservative stepping pattern has been observed, as young participants increase horizontal and vertical toe clearance over an obstacle (Graci et al. 2009). Nevitt et al. (1989) showed no significant association between reduced peripheral vision and increased fall-risk. However, the majority of studies have shown evidence for a relationship between the two (Klein et al. 2003; Ivers et al. 1988; Sekuler and Sekuler, 2000). Although the previous literature contains mixed results regarding the impact of peripheral vision on walking behaviours, it seems likely that the potential adverse effects are more likely to be realised in situations where an unexpected hazard appears, as opposed to when negotiating a stationary obstacle.

1.3.2 Intermittent sampling during locomotion

When walking we generally do not require constant visual information in order to accurately guide our actions. In fact, young adults only choose to sample visual information during 10% of time spent walking in a familiar environment when no stepping constraints are present (Patla et al. 1996). However, when presented with obstacles in the walkway participants increased fixation frequency and independent fixation durations, resulting in a total fixation period of 40% total walk time.

It appears that vision is used to different extents depending on the phase of the gait cycle, as difficulties occur in controlling step length when vision is only available during swing (Laurent and Thomson, 1988). Conversely, vision during stance only proved sufficient to regulate step length. This evidence is supported by results from Hollands and Marple-Horvat, (1996) who demonstrated that when walking along a series of irregularly placed targets visual information obtained during the stance phase prior to foot-off was sufficient to guide the subsequent swing phase. However, when vision was only available during swing participants significantly prolonged their stance phase, suggesting that visual denial during stance results in insufficient information being acquired to plan the following stepping action.

These results show that intermittent visual information is sufficient to guide locomotion, even when precise foot placements are required. However, when controlling a stepping action vision is optimally used before the initiation of the swing phase, suggesting that during locomotion vision is generally used prospectively to plan and guide movements. The following section shall discuss the evidence for this suggestion in more detail.

1.3.3 Feedforward control of locomotion

Our understanding of how vision is used during locomotion is largely based on where and when people look as they walk. This work is based on the assumption that gaze is directed towards environmental features that are perceived to provide the most relevant information according to the task.

Hollands et al. (1995) and Hollands and Marple-Horvat (1996; 2001) showed that when stepping onto a series of irregularly spaced 'stepping stones' young adults consistently made eye movements to each stepping target prior to the initiation of the swing phase intended for the target in question. These findings demonstrate a clear temporal link between the control of eye and stepping movements, whereby visual information is obtained in advance of the movement in order to plan the upcoming action. When approaching a single obstacle in a travel path, young adults have been shown to choose to fixate the obstacle two steps prior to stepping over it (Patla and Vickers, 1997; 2003). Furthermore the authors reported that participants did not fixate the obstacle during the traversing step, suggesting that visual information regarding the obstacle was used in a feed forward manner during the preceding steps to modify the gait pattern and plan the appropriate stepping action over the obstacle. However, when executing stepping actions towards predefined targets young adults generally maintain fixation on each target until foot contact (Chapman and Hollands, 2006; 2007; Hollands et al. 1995; Hollands and Marple-Horvat, 1996; 2001). This indicates that vision can potentially be used in an online manner to guide alterations in foot trajectory mid swing.

1.3.4 Online control of stepping actions

The evidence described above demonstrates the anticipatory control of locomotion, where visual information is sampled in advance in order to plan the most appropriate stepping actions. During daily activities this strategy is not always sufficient, as our environment is prone to unexpected changes, thus demanding swift appropriate responses to avoid losing balance. These responses are informed through sensory information and executed both through automatic (reflexive) and volitional movements. Automatic responses to postural perturbations have been studied extensively (Maki and McIlroy, 1999; McIlroy and Maki, 1996; 1999; Maki et al. 2001; 2003; Zettel et al. 2005; 2007; 2008). However, the short latency of postural responses dictates that gaze cannot be redirected to relevant areas in time to inform responses. Instead, visual information regarding the environment is sampled prior to perturbation and stored as an egocentric spatial map, which is then used to inform steps made in compensation to the perturbation. Results from these studies suggest that although the ability to use stored visuospatial information to guide compensatory steps is preserved with increased age (Zettel et al. 2007; 2008), it is the execution of the steps that are susceptible to decline as older adults are more likely to take multiple steps when recovering balance (Maki and McIlroy, 2003; Luchies et al. 1994; McIlroy and Maki, 1996). As the timing and amplitude of the initial step are similar in both older and younger adults, the deficits associated with recovering balance are likely to result from problems in the guidance of the foot during the initial recovery step (Luchies et al. 1994; McIlroy and Maki, 1996). These problems could be associated with deficits in the acquisition of sensory information regarding limb position as well as decline in the ability to produce rapid adjustments to the foot mid-step.

Whereas compensatory steps are made in response to a loss of balance, often evasive action is required whilst walking in order avoid a hazard. The capacity to produce these voluntary actions enhances the manner in which individuals can safely interact with their environment, yet only recently have the ability of young and older adults to produce such adjustments been investigated.

Visual response times have been shown in the order of 100-135 ms for both upper limb movements (Carlton, 1981; Prablanc and Martin, 1992; Day and Brown, 2001), and stepping actions (Patla et al. 1991; Weerdesteyn et al. 2004). As the stepping foot is simultaneously engaged in maintaining balance as well as fulfilling the demands of the task, the similarity in the latency of responses between the upper and lower limbs are perhaps surprising. However, Reynolds and Day (2005a) showed very similar response latencies in the lower limbs both with and without balance constraints. As these latencies are similar to those seen in the upper limbs, visual responses may therefore be guided by a common mechanism.

Numerous studies have proposed that reaching movements can be separated into two components; an initial ballistic transportation of the limb followed by a 'homing in' phase (Carlton, 1981; Chua and Elliott, 1993; Goodale et al. 1986). Error correction within the latter phase could rely on many factors, such as the distance travelled (providing information of limb heading), vision of the limb relative to target position (including current movement of the limb as well as changing distance between the limb and target). Nevertheless, it appears that visual information is most useful towards the end of the movement as the limb nears the target (Chua and Elliott, 1993), and can be used to alter limb trajectory in response to a moving target (Day and Lyon, 2000; Day and Brown, 2001). Collectively these results provide compelling evidence that young adults are able to use visual information to perform visually guided alterations in foot and hand trajectory. However, very little work has been done to identify the ability of older adults to produce visually guided online alterations to foot trajectory during multiple step walking. Chapman and Hollands, (2006) counted the number of zero crossings in the foot acceleration profile during the swing phase of a series of target directed steps. The authors concluded that neither young nor older adults made additional adjustments to foot trajectory compared to conditions where vision was only available during stance. However, these steps were made to stationary targets, meaning that small visually guided amendments to foot trajectory may have remained undetected. Tseng et al. (2009) recently showed that compared to young, older adults were slower to respond to a target that moved laterally during a step. The authors also showed a reduction and elongation in the ground reaction force of the limb in stance, suggesting that older adults are less able to alter the projection of their centre of mass mid-swing. However, in this study, as with those described by Reynolds and Day (2005a 2005b), online responses were made following a single step made from a stationary position. Furthermore, Tseng et al. (2009) only documented steps made following a lateral target jump, and only included older adults who had not previously fallen. Surprisingly, the ability of young and older adults to redirect their foot towards an alternative stepping location has never been addressed during a walking task, and to our knowledge no study has described the abilities of HROA to produce such corrections, even during a single step.

In summary, visual information can be used both in a feedforward (open loop) or online (closed loop) manner during locomotion. Stepping actions controlled by both mechanisms appear to be adversely affected by increased age, yet no study to date has investigated the potential for young and older adults to use vision in an online manner to redirect the foot when walking. This represents one of the main aims of this thesis. However, we also aim to illustrate associations between alterations in visual behaviour and stepping performance.

1.3.5 Summary

Visual information is generally used in a feedforward manner when walking to prospectively plan future actions appropriate for the environment. During our daily activities there are often incidences where rapid responses are necessary to avoid an unexpected hazard. For example, one might only realise that a curb is covered in ice half way through a step towards it. In these situations, current evidence suggests that we are able to use vision in an online manner to quickly adjust an ongoing step. However, identifying relevant features of our environment involves active visual search relying on eye movements. Therefore, if we are to understand age-related differences in visual control of walking it is essential to know where and when older adults look when approaching and negotiating stepping constraints. This topic shall be discussed in the following section.

1.4 Age-related differences in visual sampling behaviour: implications for falls

Assessing age-related changes in visual behaviour can provide insight regarding possible areas of deterioration. For example, Di Fabio et al. (2003a) showed that when asked to step on to a raised platform older adults made a downward saccade sooner with respect to foot-off compared to young. In a subsequent study Di Fabio et al. (2003b) documented similar behaviours when approaching an obstacle; that older adults would transfer gaze fixation downwards earlier than young adults. More recently Chapman and Hollands, (2006; 2007) also showed that older adults (specifically those deemed to be at a high-risk of falling (HROA)) were more likely to fixate a stepping constraint earlier than young adults during their approach. The authors suggested that altering visual behaviour to increase target fixation duration may represent a strategy designed to compensate for age-related decline in CNS function.

Choosing to fixate a constraint in the travel path earlier may prove to be a successful compensation, but when faced with multiple constraints in a travel path a decision must be made whether to maintain fixation on a current target, or fixate subsequent constraints in advance. Chapman and Hollands (2007) showed that when required to step on to a single target older adults as well as young will choose to fixate a target until foot contact inside it. However, when this target was followed by a second subsequent constraint older adults (particularly HROA) transferred gaze fixation away earlier with respect to heel contact in order to fixate the second constraint. The same participants transferred gaze earlier still when two constraints followed the first. Foot placement results showed increased stepping error and variability in the initial target during conditions when participants transferred gaze fixation earlier. These findings present the possibility that older adults prioritise the acquisition of visual information regarding future constraints over that concerned with an ongoing stepping action, and suggests that a relationship may exist between visual behaviour and stepping accuracy. Age-related differences in visual sampling strategies may be explained by changes in cognitive function and attention. The following section shall review current evidence concerning cognitive influences in posture and gait, and describe how alterations in cognitive function and attention can affect locomotor performance.

1.5 Psychological factors

1.5.1 Cognitive function

Reflex movements used in the maintenance of posture have previously been considered to be automatic. However, recent work suggests that attentional resources play an important role in the maintenance of balance. Much of the evidence is based on studies using dual tasking paradigms. These findings are based on the assumption that cognitive resources are finite, and that an inability to attend to one of two tasks will be manifest as a decline in performance. Indeed, previous studies have shown that when performing a postural task attention is redirected away from a concurrent cognitive task (Andersson et al. 1998; Lajorie et al. 1993; Teasdale et al. 1993). This is particularly evident in elderly fallers who will tend to prioritise the execution of the postural task first, followed by the cognitive task (Brauer et al. 2002). There are three main suggestions for age-related decline in the control of posture under increased cognitive load: 1) attentional capacity may be reduced in older adults, 2) older adults may have increased difficulty switching attention between tasks, 3) older adults may possess similar cognitive abilities to young, but a greater extent of their capacity is absorbed due to a decline in the automatic control of balance. The implications for falls are considerable if postural control is impaired under dual task conditions. Therefore, it is not surprising to find a clear association in the literature between reduced cognitive function and increased fall-risk in older adults (Nevitt et al. 1991; Speechley and Tinetti, 1991; Tinetti, 1988). The functional impact of these suggestions has been demonstrated as older adults will still contact obstacles more frequently when required to step over them under time constraints (Chen et al. 1994), or under conditions of increased cognitive demand (Chen et al. 1996), despite walking slower and with shorter stride lengths.

Older adults with low executive function have been shown to perform worse during obstacle negotiation than healthy older, and younger adults (Di Fabio et al. 2005). However, participants with low executive function were observed to make fewer downward saccades than other groups. This suggests that individuals with reduced cognitive ability may have difficulty identifying features in the environment that are necessary to fixate in order to gain the required visual information for safe ambulation. One common factor that is likely to absorb attentional resources and cognitive capacity during postural control is increased anxiety/fear of falling (see Woolacott and Shumway-Cook, (2002) for review). This area of research is discussed below.

1.5.2 Balance confidence/fear of falling

The phenomenon now known as fear of falling (FOF) was first described as 'post-fall syndrome' by Murphy and Isaacs (1982). Since then much research has investigated the debilitative influence of reduced falls efficacy, and many attempts have been made to define the phenomenon, the most common being an "ongoing concern about falling that ultimately limits the performance of daily activities" (Tinetti and Powell, 1993). An increased FOF and a loss of balance confidence can result from a non-injury related fall (Tinetti et al.1990). Previous studies have shown that between 29 and 92% of older adults who have fallen previously self-report reduced falls efficacy (Howland et al. 1993; Aoyagi et al. 1998). However, these increases in falls related anxiety can also be prevalent in older adults who have not previously fallen (Tinetti and Powell, 1994), as 12 to 65% of older adult non-fallers self-report FOF (Lawrence et al. 1998; Howland et al. 1993; Murphy et al. 2003). Avoiding every day tasks such as walking up stairs and getting in and out of a car can impact on quality of life. A decline in daily physical activity can result in a reduction in muscle strength and ROM, as well as many factors associated with increased fall-risk, thus fuelling cause for increased FOF (see Scheffer et al. (2008) for a detailed review). Therefore, increased falls related anxiety is one potential mediator of reduced activity amongst older adults.

In addition to the influence of increased anxiety on activity avoidance, alterations in postural control have also been demonstrated (McKenzie and Brown, 2004; Brown and Frank, 1997; Carpenter et al. 1999; Adkin et al. 2000; Adkin et al. 2002; Brown et al. 2002; Brown et al. 2002; Gage et al. 2003). For example, reduced falls efficacy is associated with risk factors such as reduced stride length, slower gait speed, increased time spent in double support phase (Maki et al. 1991). When more anxious about maintaining postural control, young adults are characterised by smaller sway amplitudes and increased sway frequencies during quiet standing and 'rise to toe' tasks (Carpenter et al. 1999,2001; Adkin et al. 2002). These behaviours are indicative of a strategy concerned with a tight regulation over the centre of mass, and represents conservative adaptations to balance control (Carpenter, 2001). When walking this strategy would serve to prioritise postural stability and minimise the risk of gross stepping errors, and therefore may prove beneficial in some hazard avoidance situations (Brown et al. 2005). Therefore one possible influence of anxiety may be to redirect a proportion of attention to processes concerned with postural threat. Gage et al. (2003) demonstrated that increased anxiety alters the allocation of attention during gait under dual task conditions, whereby attention was transferred towards the environmental constraint that individual is most anxious about. However, Persad et al.

(1995) found that increased anxiety corresponded to a higher number of errors when stepping over obstacles. The literature appears to reflect a limited beneficial role of increased anxiety, presumably through increased diligence in avoiding hazards. However, the adverse consequences on postural control behaviours are well documented, and are presumably realised through absorbing attention and cognitive resources. One further way in which anxiety may influence postural control and walking, is though deficits in extracting necessary visual information. In this thesis we describe evidence for a link between increased anxiety and alterations in visual behaviour in HROA, which in turn is likely to detriment the accuracy of stepping actions.

1.6 Summary and aims

As many elderly falls are likely to occur following a misplaced voluntary step (Lord and Deyhew, 2001), it is important to understand the mechanisms behind age-related decline in stepping performance. The research described in this chapter provides a brief overview of the functional changes that may contribute to such decline. However, considering the importance of visual information in the control of accurate stepping, it is somewhat surprising that visual sampling strategies have not been studied more extensively.

Recent findings suggest that older adults (specifically HROA) transfer gaze fixation away from a stepping target earlier than their younger counterparts. The first aim of this thesis was to investigate a causal link between the alterations in visual sampling described, and a reduction in stepping accuracy (Chapter 3). The second aim was to examine a possible role of increased anxiety as a 'driving force' behind differences in visual sampling behaviour (Chapter 4). Finally, we aimed to understand why maladaptive visual behaviour causes reductions in stepping accuracy. More specifically, we aimed to test the extent to which young, low-risk older adults (LROA) and HROA can perform visually guided online alterations to foot trajectory during the swing phase towards a stepping target.

Chapter 2

Methods: Additional information

Each of the following experimental chapters contains a methods section specific to experimental design used. However, certain procedures remained constant across all the studies presented in this thesis. These are described in the following sections.

2.1 Test battery used to determine participant characteristics

2.1.1 Criteria used to determine participant fall-risk

The experimental designs used in this thesis are based on categorising older adults according to whether they are deemed to be at a low- or high-risk of falling. Therefore, it is important to assign appropriate criteria when allocating participants into these groups. However, it is also pertinent to identify significant problems that participants may have in the many areas associated with reduced mobility and fall-risk, especially as the visual and stepping behaviours assessed are likely to be influenced by such deficits. As a result, each participant was subject to a battery of visual and psycho-physiological tests. Due to the number of participants involved in each study, values recorded from these test batteries are not necessarily intended to provide insight into the recorded visual and walking behaviours, only to provide assurance that none of the participants had significant deficits in any of the measures taken.

The allocation of participants into fall-risk groups was based on two criteria used in similar previous studies (Chapman and Hollands, 2006; 2007):

1) Whether the participant had experienced a fall in the previous 12 months. This is supported by evidence showing that 57% of older adults who had fallen in the previous year experienced a subsequent fall the following year, with 31% experiencing two or more falls.
2) Scores from the Berg Balance Scale (Berg et al. 1992); a 14 item functional mobility test assessing balance and flexibility. Tasks assessed include: rising from a chair, retrieving an item from the floor, and standing on one leg. The maximum score is 56 (4 points for each item).

Participants were deemed to be LROA if their Berg Balance score was greater than 45/56. However, if participants had experienced a fall in the previous 12 months, then they were only classified as LROA if their Berg Balance score was greater than 48/56. Further measures used in the test battery are described below.

2.2 Psychological measures

2.2.1 Cognitive function

In order to assess possible cognitive impairment we used the Mini-Mental State Evaluation (MMSE) (Folstein et al. 1975). This test samples various functions such as memory, orientation and mental arithmetic, where a total of 30 points are gained through correct responses. It is commonly used to screen for dementia, where a score greater than 27 is considered normal function. Whereas the MMSE provides an indication of cognitive impairment, it does not diagnose where deficits may be most apparent. As all the studies presented in this thesis were designed to assess the way in which visual information is processed, we also tested each participants' performance in the Trail Making B test, as it specifically measures cognitive processing of visual information. The test requires a participant to connect numbers and letters together in an alternating pattern, and to do so in as little time as possible. Therefore, it is important to ensure that the participant clearly understands the task requirements prior to starting. If the participant makes an error, the examiner indicated the mistake and returns the stylus to the most recent correct location. Scores on the Trail Making B test above are a good indicator of cognitive impairment (shorter time to complete the task indicates improved function), although it is especially important to maintain consistent test conditions between participants, as changes in test administration has a considerable influence on results (Fals-Stewart, 1992). Therefore, all participants who took part in the studies described in this thesis were examined by the same individual.

2.2.2 General health and falls efficacy

In the current studies all participants were required to complete a General Health Questionnaire; a method used for identifying minor psychiatric disorders. The most commonly used version is the 28-item scaled version that assesses 4 sub-scales; somatic symptoms, anxiety and insomnia, social dysfunction and depression. Examiners are then able to profile the scores according to specific factors associated with general well-being (Goldberg et al. 1997). However, the GHQ-28 does not provide specific information regarding the participants' opinion of their physical ability to perform daily tasks. We therefore used two further questionnaires to provide this information. The Falls Efficacy Scale (Tinetti et al. 1990) is a 10-item scale assessing an individual's confidence of achieving indoor tasks without losing balance (such as cleaning or getting dressed). This test is particularly useful for distinguishing problems that particularly frail older adults may encounter. However, as our experimental design incorporated both LROA and HROA, a more universal assessment was also required. The Activities-specific Balance Confidence (ABC) scale (Powel and Myers, 1992) is a 16-item questionnaire measuring an individual's confidence that they will not lose their balance during tasks associated with activities outside the home. This measure is therefore more appropriate for use with participants with higher levels of functioning.

2.2.3 Anxiety

In order to assess feelings of general anxiety we used the Spielberger State-Trait anxiety inventory (STAI). Scores on the STAI-Anxiety scale increase in response to physical danger and psychological stress. Although this is the most commonly used assessment of anxiety, we used this particular test as it differentiates between temporary increases in anxiety (state), and long-term general anxiety (trait). The STAI is a 2*20 item inventory that quantifies feelings of apprehension, tension, nervousness, and worry. Each item is given a response of between 1 and 4, providing a final score of between 20 and 80. This measure allowed us to assess increases in self-reported state anxiety during the walking tasks in experimental sessions, but also compare these values to each participant's perception of their general anxiety levels in daily life. This measure is most pertinent for the study described in Chapter 4.

2.3 Visual function

Visual acuity was assessed in each participant using a Snellen chart. Scores are documented in fractions (e.g. 20/40), referring to the ability to identify small letters with high contrast at a distance of 6 meters. The first number presented in the fraction represents the test distance in feet, the second represents the distance that the average eye can distinguish a particular letter. Scores above 20/40 indicate no significant deficits. Contrast sensitivity was assessed using the Pelli-Robson letter sensitivity test (Pelli- Robson contrast sensitivity chart 4K, Metropia Ltd., United Kingdom). Scores are presented as a 'log CS' representing the number of letters read correctly from a list, where the contrast of the characters progressively reduce. Participants' lower visual field was assessed using kinetic perimetry with a Goldman perimeter (V/4e target) on a background luminance of 10cd/m2. The isopter of each eye was averaged over the lower 10 degrees. The mean score from both eyes were then averaged to provide an overall binocular score.

2.4 Gaze tracker set up/calibration

During the experimental sessions described in this thesis, participants were asked to walk along a path and negotiate a series of stepping constraints. During each walking trial gaze behaviour was assessed using a high-speed ASL 500 head-mounted gaze tracker. This technology assesses the direction of gaze fixation by shining infrared light onto the eye, and measuring the distance between two features:

1) The outline of the pupil (position moves according to the direction of gaze fixation)
2) The corneal reflex (CR) (constant reflection of the infrared light from the surface of the eye)

The ASL controller displayed an image of the participant's eye. This image was used to adjust both the strength of the infrared illumination, and the threshold for reflection detection. This adjustment was necessary to compensate for the varying degrees in which the participant's cornea reflected the infrared light. The ASL controller also generated a video that represented the participants' visual scene. This was recorded from a camera mounted on the forehead. The calibration process involved the participant making eye movements between 9 markers placed in 3*3 rows (all visible in the visual scene image). The ASL software calculated the vertical and horizontal distances between the pupil and CR for each marker fixation. The software then used these values to calculate the pupil-CR distances for the rest of the visual scene. Following calibration the ASL controller superimposed a crosshair on the visual scene. This represented the point of gaze fixation, and was recorded onto digital tape. The participant was then asked to make eye movements between all 9 markers again. The accuracy of the calibration was assessed using the visual scene image, by visually comparing the distance between the position of the fixated marker and the crosshair. If this distance appeared to be greater than 5cm (when the participant stood 5m from the fixated marker), the calibration was carried out again. Inevitably, due to the dynamic nature of the walking tasks, the position of the head tracker moved, or was knocked by the participant, thus disturbing the calibration. Therefore, an assessment of the calibration accuracy was carried out every 5 trials. This was achieved through moving a pointer in front of the participant at a distance of ~5m. Again, if the error between the pointer and marker appeared to be greater than 5cm, a further calibration was carried out. Details regarding further analysis of gaze data are documented in each experimental chapter.

2.5 Motion tracking

Kinematic data were recorded using a Vicon MX motion capture system. There were 13 cameras in the system, each with a resolution of 1.3 megapixels (1280*1024) pixels. Calibration was carried out first using a static frame capture (setting the capture volume origin), followed by a dynamic capture. We accepted the calibration if the point accuracy (predicted error in the system) was below 1mm at a distance of 6m.

Therefore, all kinematic data in the following chapters carries a maximum error of 1mm. We were unable to record kinematic data from markers placed above the waist, as infrared light from the motion capture system interfered with gaze tracking data. Therefore, only coordinates were only recorded from a series of reflective markers (10mm diameter) placed on participants' shoes. Marker positions were labelled and exported to text files using Vicon Workstation software v5.2 (Oxford Metrics, England), and were subsequently analysed using Visual Basic (Chapters 3&4) and Matlab programs (Chapter 5). Further details regarding kinematic data analysis are documented in each experimental chapter.

Chapter 3

Can telling older adults where to look reduce falls? Evidence for a causal link between inappropriate visual sampling and suboptimal stepping performace.

3.1 Introduction

Moving safely through our cluttered world requires visual identification of obstacles and safe places to step. Age-related decline in sensory processes associated with the control of adaptive gait, such as visual function, has been well established as an important predictor of increased fall-risk (Lord and Menz, 2000; Lord and Deyhew, 2001). The major contribution that falls make to morbidity and mortality in older adults (Tinetti and Williams, 1997; Prince et al. 1997) emphasises a need not only to identify risk factors, for elderly falls but also to develop effective rehabilitation techniques to improve stepping performance.

It is well-documented that there are strong spatiotemporal relationships between eye and stepping movements during precision walking tasks. Participants invariably fixate a target prior to initiating the step towards it and the time interval between looking and stepping is consistent for a particular walking task (Hollands et al. 1995; Hollands and Marple-Horvat, 1996; Patla and Vickers, 1997). The robust nature of eye-stepping interactions is demonstrated by the fact that coordinated eye and stepping movements are still made even when vision of the stepping targets is temporarily removed (Hollands et al. 2001). These findings suggest not only that vision is used in a feedforward manner to plan future stepping actions but also that the eye and stepping motor control systems are not acting independently but rather the central nervous system (CNS) produces a coordinated pattern of eye and stepping movements. During adaptive locomotion the preferred fixation of a future stepping target occurs in the late stage of stance of the targeting limb (Hollands et al. 1995; Hollands and Marple-Horvat, 1996; Di Fabio et al. 2003).

It has previously been demonstrated that older adults show altered gaze behaviour during locomotor tasks. For example, older adults make a downward saccade towards a stepping constraint earlier than their younger counterparts (Di Fabio et al. 2003; Chapman and Hollands, 2006) and fixate the obstacle or target for longer (Chapman et al. 2006). Age-related changes in gaze strategies adopted during adaptive gait may reflect compensation for age-related changes in visual processing function within the CNS necessitated by the need for additional time to gather spatial information regarding stepping constraints.

Chapman and Hollands, (2006) demonstrated that young adults, when faced with multiple stepping constraints usually maintained gaze on a stepping target until after heel contact inside it. In contrast, older adults (particularly HROA) transferred their gaze away from the target significantly earlier in order to fixate a second target in the travel path, and earlier still when constraints following the initial target grew in complexity. There was a significant correlation between the timing of gaze transfer, foot placement error and variability i.e. the earlier the participants looked away during the swing phase, the worse their stepping performance was. This result raises the possibility that there is a causal link between these two variables and provides support for the idea that older adults make use of vision during swing to adjust limb trajectory or dynamic balance. This notion is supported by a recent study that showed that, in contrast to younger adults, older adult participants suffered a significant loss in stepping accuracy when vision was removed during the swing phase (Chapman and

Hollands, 2006). This finding clearly suggests that older adults can, and do, use vision in an online manner to guide dynamic posture during the swing phase of walking.

The aims of the present experiment were to test the hypothesis that there is a causal link between maladaptive gaze behaviour (early gaze transfer from a target) and stepping inaccuracies in older adults during multiple-obstacle walking tasks. To test this hypothesis we compared stepping performance in a group of older adults both before and after an intervention in which they were instructed to alter their gaze behaviour to more closely resemble the visual sampling characteristics of younger adults.

We predicted that our intervention would have a significant effect on the gaze behaviour of our participants (i.e. would result in later gaze transfer away from a target) and would result in an improvement in the accuracy and precision of stepping movements.

1.2 Method

3.2.1 Participants

Sixteen healthy community-dwelling older adults (age >65) participated in the study (for details see Table 3-1). All participants volunteered and gave informed consent prior to taking part. Other than mild symptoms associated with increased age (such as general aches and pains) participants reported no known musculoskeletal or neurological impairments. Other exclusion criteria included the use of medication for dizziness or anxiety. We also excluded individuals who normally wore corrective lenses for use in daily locomotor activities (distance vision correction) due to logistical problems associated with obtaining reliable eye tracker data from spectacle wearers.

3.2.2 Data collection

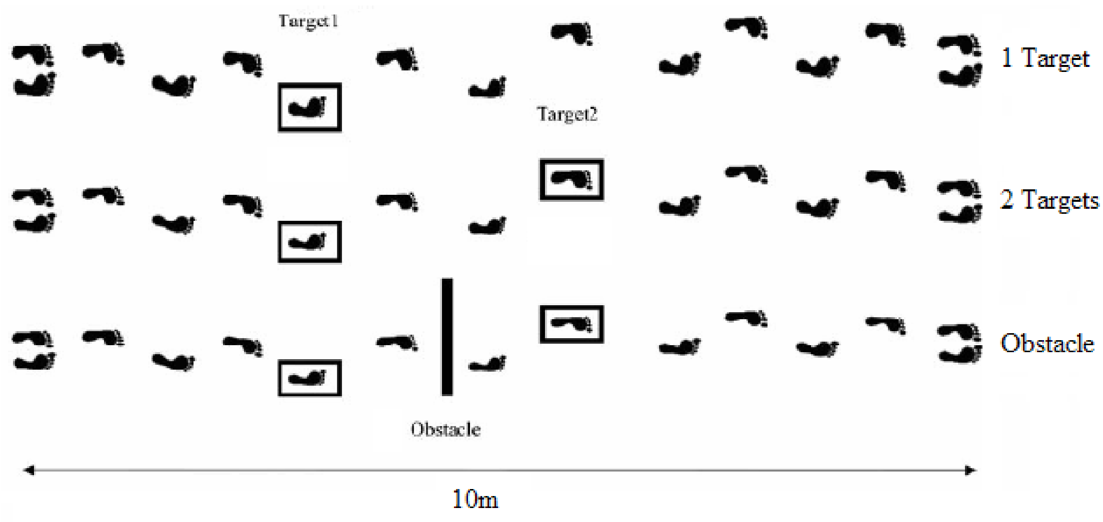
Participants wore flat-soled shoes for the duration of each session. On both feet reflective markers were placed equidistantly between the head of the distal interphalangeal joints of the first and fifth metatarsals (toe marker), between the head of the distal interphalangeal joint and the anterior point of the calcaneus on both medial and lateral sides (mid-foot markers), as well as on the anterior point of the calcaneus (heel marker).

The position of each marker was sampled at 120Hz by a Vicon MX motion analysis system (Oxford Metrics, England). Gaze behaviour was assessed using a high-speed ASL 500 head-mounted gaze tracker. Both horizontal and vertical components of eye position were sampled at 120 Hz, synchronized and recorded with the Vicon video data capture via analogue inputs generated by the ASL controller. These data were used to identify and calculate the timing of saccadic eye movements. The ASL controller also generated a video image of 30 Hz showing the visual scene of each participant, with a superimposed cursor representing gaze location. These data were recorded on digital tape and used to identify the environmental features fixated by the participant throughout each trial.

3.2.3 Protocol

The techniques used have previously been described in Chapman and Hollands (2007). Participants were instructed to walk at their 'own pace' along a 10 m travel path and negotiate one of three conditions: One target, Two target or Obstacle (see Fig 3-1). When the 'One target' condition was presented participants were instructed to place their right foot in Target 1. During the 'Two target' condition participants were instructed to place their right foot in Target 1 and left foot in Target 2. During the 'Obstacle' condition participants were instructed to place their right foot in Target 1, step over the obstacle with their right foot and place their left foot in Target 2. Participants were given the following instruction: "place your foot into the centre of each box, leaving as much space as possible between the outside of your foot and the inside of the target box".

Figure 3-1 Schematic diagram of experimental task



The targets were made from lightweight packaging foam and were not secured to the floor. Both targets were of equal dimensions, with a raised edge and border width (40 mm x 40 mm). Inside each target was a stepping area of 190 mm x 415 mm. The wooden obstacles' height, width and depth measured 210, 670 and 12 mm respectively, and was supported from the posterior side allowing it to fall forwards with respect to the participant should they make contact with it. Each combination of target positions occurred in equal numbers between conditions and was randomised within each session. Each session comprised of 60 trials including 20 trials for each condition. Within each condition the target(s) present appeared in two possible positions separated by 8 cm (medio-laterally). These were intended to discourage task familiarity within participants. There were equal numbers of target position within each condition, the presentation of which was randomised.

Prior to the start of each trial participants were required to stand with their eyes closed. Upon the verbal signal of "Go" participants opened their eyes and began to walk towards and negotiate the constraints in the walkway. This protocol was designed to control for the amount of attention that each participant may have directed towards the walkway constraints prior to the start of each trial.

All participants completed two sessions on separate days. Prior to the start of Session 1 participants were randomly assigned in equal numbers to either a control or intervention (experimental) group. Regardless of which group they were assigned, participants completed a first session under the conditions detailed above (control). At the start of Session 2 all participants watched a video clip (5min) chosen to provide ambiguous references to falls prevention e.g. remembering to leave the lights on around stair cases. All control participants then completed a second session under the same conditions as the first. All intervention participants watched a second video (3min) giving them instructions to maintain their gaze on each target box until they made heel contact inside it. Participants were also shown an example video showing the visual scene from an individual carrying out the experimental task. The video was superimposed with a cursor representing the direction of gaze. Participants were first shown two examples of early gaze transfer with respect to heel contact in the first target, followed by two examples of gaze transfer shortly after heel contact. Video examples were shown in slow motion. Participants were given the opportunity to ask any questions should there be any confusion about the instructions, and then completed a second session. During the second session all participants were reminded after every 10 trials to step as accurately as possible in each target. In addition to this reminder, intervention participants were asked to remember what they were told in the video.

Prior to the start of Session 1 all participants took part in a series of psychophysiological screening measures used to detail any specific deficits or imbalances between groups (see Table 3-1). There were no significant differences between groups in any of the tests completed.

Table 3-1 Characteristics of control and intervention group

Measure: Mean (range)	Control	Intervention
Age *(years)*	75.38 (68-85)	74.75 (68-81)
Height *(cm)*	159.75 (152-169)	163.88 (153-180)
Weight *(Kg)*	66.04 (56.3-87.2)	65.06 (58.1-75.2)
Previous falls [a]	25	37
Mini Mental State	29.37 (27-30)	29.25 (28-30)
Berg Balance Scale *(max = 56)*	49.12 (33-55)	51.37 (45-56)
Visual acuity (Snellen)	All >20/40	
Contrast Sensitivity (Pelli-Robson) *(max = 2)*	1.5 (1.05-1.8)	1.55 (1.05-1.65)
Peripheral vision (lower 10°)	71.16 (64.3-77.3)	71.75 (60.3-81.3)
Falls Efficacy (FES-I) *(max = 100)*	13 (10-22)	12.62 (10-21)
Activities Balance Confidence *(%)*	89.98 (74.3-98)	88.71 (67.5-99.4)
Spielberger State *(max = 80)*	31.87 (21-43)	29.62 (23-41)
General Health Questionnaire (GHQ) *(max = 21)*		
Somatic Symptoms	3.87 (2-7)	2.12 (0-5)
Anxiety/Insomnia	3.75 (0-6)	2.75 (0-6)
Social Function	6.62 (5-8)	6.25 (4-8)
Depression	0.87 (0-5)	0.62 (0-2)

Scores for QHQ-28 were assessed using a Likert scale (0-1-2-3) and the total score for each section was used.

[a] Percentage number of participants within each group experiencing a fall within 12 months prior to the first experimental session.

3.2.4 Data analysis

Kinematic data were passed through a low-pass filter with a cut-off frequency of 5 Hz. Heel contact and toe off events were identified using a procedure adapted from Hreljac and Marshall, (2000). Gaze fixation was evaluated through a frame-by-frame analysis of the digital scene matched with both vertical and horizontal components of the analogue signal. The final frame of each target fixation was identified using the video data. We used the peak velocity profile of the analogue signal to establish the onset and offset of each saccadic eye movement (a saccade onset was defined as a local velocity peak with a threshold of $100^{o}s^{-1}$. Gaze fixations were defined as being a gaze stabilisation on a single environmental feature for 100 ms or longer (Patla and Vickers, 1997). The time difference between saccadic eye movement events (onsets and offsets) and heel contact in each target box was then calculated for each trial (Fig 3-2).

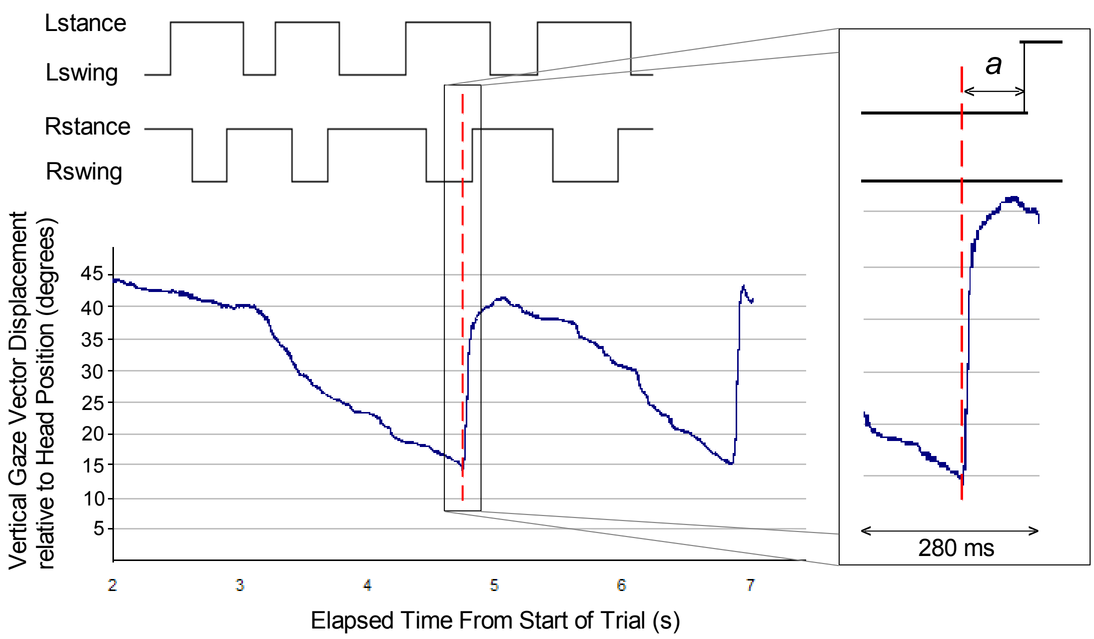


Figure 3-2 The dashed line represents the onset of the saccade away from Target 1. 'Rswing' represents the swing phase and 'Rstance' represents the stance phase of the right foot. Heel contacts and toe offs are demonstrated by the onset of the blocked line changing from Rswing to Rstance (or vice versa).

[a] represents the latency between the saccade onset away from and heel contact of the right foot inside Target 1

Medio-lateral (m/l) and anterior-posterior (a/p) foot position error was defined as the mean coordinate of the centre of the foot relative to the centre of the box i.e. values of foot error took the direction of foot placement relative to the box centre in to account. The centre of the foot was defined as the mid-point between; the heel and toe markers for a/p error, and the mid-foot markers for m/l error. The occurrence of an individuals' foot coming into contact with the box edge, was defined as a 'missed step'. The number of trials in which individual participants missed the target was calculated as a percentage of the total number of trials. The extent of within subject relationships between the time of gaze transfer relative to heel contact and m/l stepping error were calculated for each task condition and within each participant using Pearson's r correlation coefficient. These values were converted to z-scores and analysed using Mixed ANOVA. Walking velocity was calculated from the position and latency between heel contact of the right foot prior to the swing phase into Target 1 and heel contact of the right foot following the step into the final box present in the walkway. The number of adjustments to foot trajectory made during swing was calculated using anterior-posterior displacement data of the toe marker on the right foot. These data were filtered at 10Hz using a dual-pass second order Butterworth filter, prior to calculating an acceleration profile of the swing phase into Target 1. An adjustment in foot trajectory was classified as a reversal in acceleration. However, reversals were only included providing they fulfilled the following criteria used previously by Chapman and Hollands, (2006): (1) reversals must not represent either peak acceleration or deceleration of the moving limb (Brooks, 1974), (2) reversals must not occur within 25ms of each other, (3) each reversal must achieve an amplitude of at least 10% of peak absolute acceleration (Chua and Elliott, 1993; Van Donkelaar and Franks, 1991).

Mixed design analysis of variance (ANOVA) tests were carried out (within participant factors = Session and Obstacle condition, between participant factor = Group) to identify significant differences in mean values between intervention groups for the following dependent variables: Both m/l and a/p foot placement error, duration of fixation on target prior to saccade away, mean latency between gaze transfer from and heel contact within each target box, stance and swing duration of the foot prior to heel contact within each target and walking velocity. Variability measures for each of these dependent variables were assessed by taking the standard deviation (SD) of the mean values within each condition, from each participant. Pearson's Product correlation was used to determine the extent of relationships between gaze transfer latencies and both m/l and a/p stepping errors. All correlation analysis used values representing the mean of all trials within one experimental condition, in one participant. Post hoc analysis was carried out using ANOVA. All confidence levels were set a priori at $p < 0.05$.

3.3 Results

3.3.1 Gaze transfers and fixations

There was a significant interaction effect between session and group ($F_{(1,14)} = 8.31$, $p < 0.05$) in the time interval between gaze transfer from Target 1 and heel contact. Post hoc analysis showed that the groups significantly differed in their gaze transfer times in session 2 only, where intervention participants postponed their gaze transfer from Target 1 until after heel contact (as demonstrated in Fig 3-3). There were no significant between session differences in the control group. Values combining all three experimental conditions for session 1 (s1) and session 2 (s2) for control participants were s1: -128ms ± 164ms and s2: -123ms ± 187ms, and for intervention participants were s1: -102ms ± 214ms and s2: 163 ± 68ms (mean ± SD). There was also a main effect of condition on the timing of gaze transfer away from, and the final fixation period on the target prior to heel contact in Target 1. Participants fixated Target 1 for longer and transferred gaze earlier as the task requirements grew in complexity ($F_{(2,13)} = 9.48$, $p < 0.01$) and ($F_{(2,13)} = 3.45$, $p < 0.05$). Values combining both groups for the timing of gaze transfer from Target 1 for One Target condition (t1), Two Target condition (t2) and Obstacle condition (obs) were t1: -9ms ± 211ms, t2: -57ms ± 211ms, obs: -114ms ± 235ms (mean ± SD).

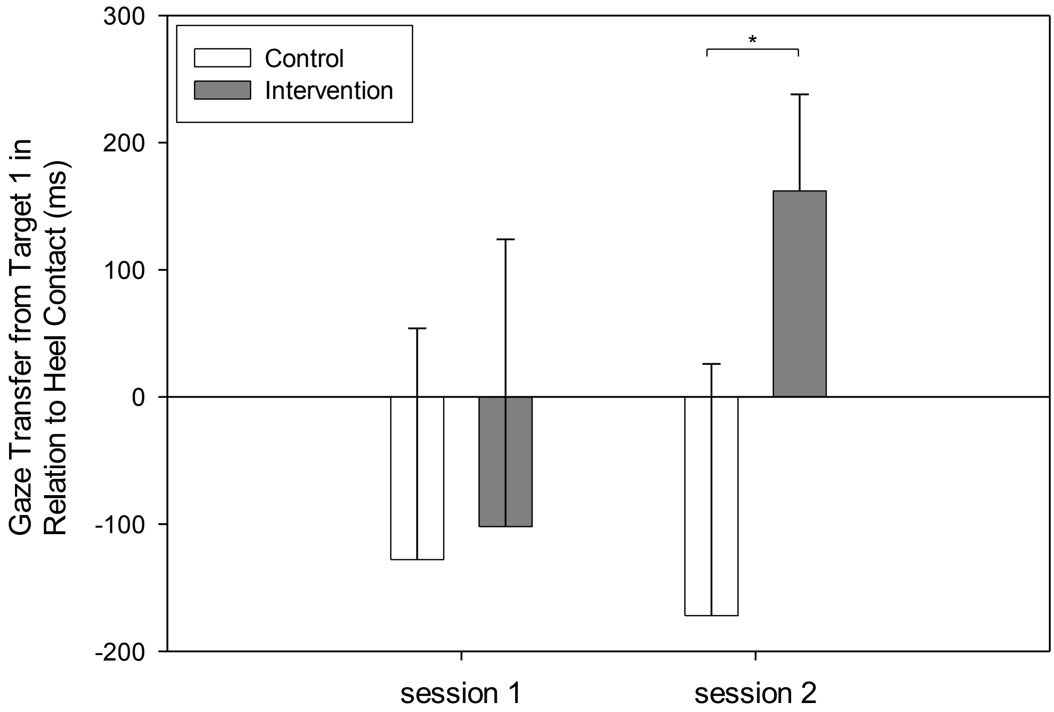


Figure 3-3 Bars represent the timing of gaze transfers relative to heel contact in Target 1. Each bars correspond to data for all 3 experimental conditions. Negative values represent saccades prior to heel contact. Error bars represent standard deviations (SD)

3.3.2 Foot placement error in Target 1

There was a significant interaction between session and group for m/l foot placement error when stepping into Target 1 ($F_{(1,14)} = 10.4$, $p < 0.01$). Post hoc analysis revealed that, on average, the intervention group showed smaller foot placement error in session 2 than control participants (see Fig 3-4a). There were no significant between session differences in the control group. For constant stepping error values combining all experimental conditions for the control group were s1: -6.0mm ± 7.7mm and s2: -

6.6mm ± 9.7mm and for the intervention group were s1: -8mm ± 6.8mm and s2: -0.6mm ± 5.6mm (mean ± SD).

There was a significant interaction effect between session and group in m/l foot placement variability ($F_{(1,14)}$= 8.48, $p < 0.05$). Post hoc analysis showed that between group differences were only significant during session 2, where the intervention group reduced their m/l foot placement variability in Target 1 (see Fig 3-4b). There were no significant between session differences in the control group. Values combining all experimental conditions for the control group were s1: 12.5mm ± 2.3mm and s2: 10.5mm ± 2.1mm and the intervention group were s1: 12.4mm ± 4.3 and s2: 9.4mm ± 3.5mm (mean ± SD).

There was a main effect of session on a/p foot placement error, where foot placement improved in the second session ($F_{(1, 14)}$ = 12.41, $p < 0.01$). However, no significant between group differences were found. Further analysis using Pearson's product moment correlation revealed no significant relationship between session trial number and a/p foot placement error.

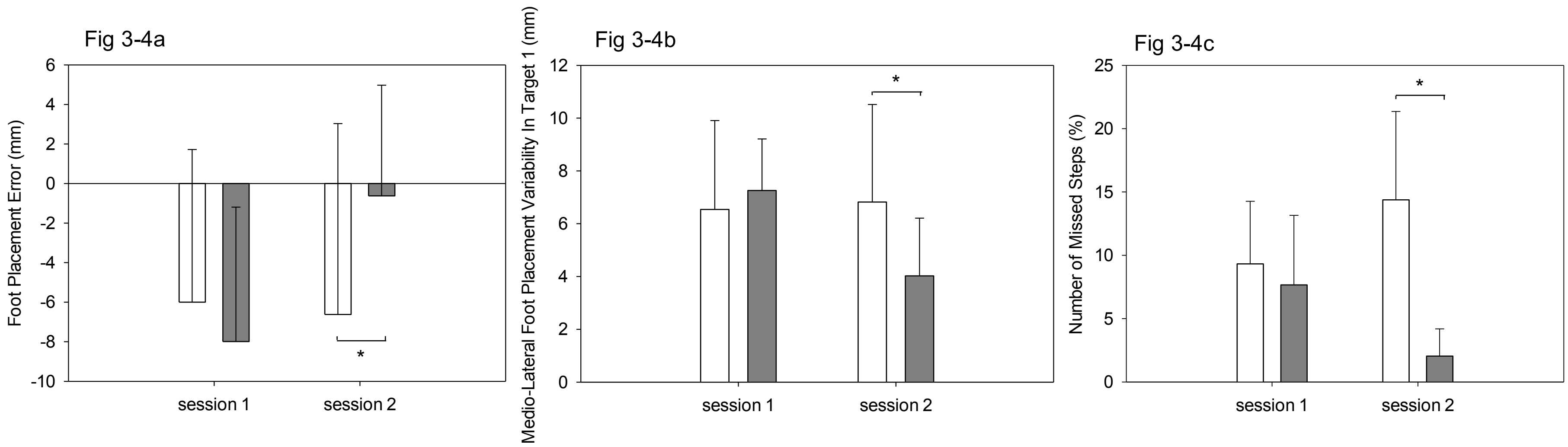


Fig 3-4a Each bar represents medio-lateral foot placement error in Target 1. Each bar corresponds to data from all 3 experimental conditions. Negative values represent foot placement towards the medial (left) side of the target. Error bars represent standard deviations (SD)

Fig 3-4b Bars for each group show the mean variability of medio-lateral foot placement error of each participant over all 3 experimental conditions in Target 1. Error bars represent standard deviations (SD)

Fig 3-4c Bars for each group represent the total number of missed steps (foot contacting the target) in Target 1, as a percentage of the total number of trials within the session. Error bars represent standard deviations (SD)

3.3.3 Missed steps

Figure 3-4c demonstrates a significant interaction of session and group ($F_{(1,14)}$ = 16.37, p = 0.001). Post hoc analysis showed that differences between session and group were only significant in session 2, where the intervention group demonstrated significantly fewer instances in which the participants' foot made contact with the box edges.

3.3.4 Foot placement error in Target 2

There were no significant effects of session or group on foot placement accuracy or variability in Target 2.

3.3.5 Temporal gait characteristics

There were no significant interactions between session and group, nor were there any main effects of session or group for stance or swing durations prior to heel contact in Target 1.

There was a main effect of task complexity on walking velocity ($F_{(2, 13)}$ = 252.93 p < 0.001). However, no between session or group differences were found. In each of the experimental conditions walking velocity in all participants was: Target 1 only: 0.91m/s ± 0.15 m/s, Targets 1 and 2: 0.71m/s ± 0.13 m/s, both targets and obstacle: 0.64 m/s ± 0.14 m/s. Results for stance duration prior to heel contact in Target 2 showed a significant interaction between session and group ($F_{(1,14)}$ = 5.834, p < 0.05). Values combining all three experimental conditions for stance duration prior to Target 2 in the control group were s1: 580ms ± 150ms and s2: 620ms ± 135ms and in the intervention group were s1: 550ms ± 125ms and s2: 584ms ± 150ms. Post hoc analysis showed that in Session 2 the intervention group prolonged stance duration prior to heel contact in Target 2 only.

3.3.6 Relationship between gaze transfer and foot placement error

Analysis using Pearson's Product correlation coefficients show statistically significant linear relationships between earlier gaze transfer from Target 1, and increased m/l foot placement error ($r_{(46)} = -.529$, $p < 0.001$) (see Fig 3-5). Analysis using Pearson's correlation coefficients showed no effects of session trial number on foot placement error in any control session, confirming the absence of any significant affects of task practice or fatigue. However, correlation analysis did reveal a small yet significant increase in m/l stepping error within the intervention group during session 2 ($r_{(6)} = .977$, $p < 0.01$), although it is of note that this reduction in stepping performance was a fraction of the differences described between groups. Correlation analysis between m/l stepping error and the time of gaze transfer relative to heel contact was performed within each experimental condition for every participant. Mixed ANOVA showed no significant effects main effects of participant group or session.

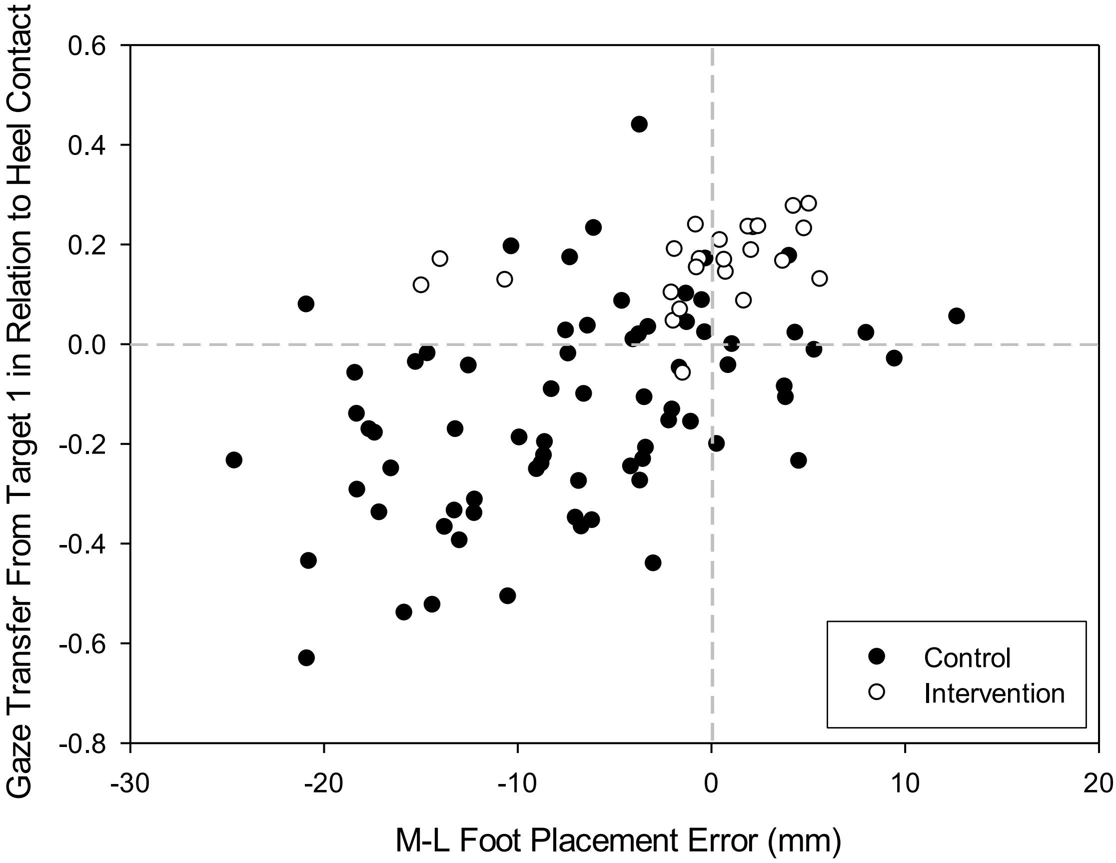


Fig 3-5 Each data point represents the mean value for one participant in one experimental condition. Values shown as control sessions (filled circles) represent the Control group (sessions 1 & 2) and Intervention group (session 1 only). Values shown as Intervention session (unfilled circles) represent the Intervention group (session 2 only). Gray dashed lined represent perfect m/l foot placement (vertical line) and gaze transfer at heel contact (horizontal line).

3.4 Discussion

The aims of the current study were to test the hypothesis that there is a causal link between early gaze transfer from a stepping target and reduced stepping accuracy, and to investigate any benefits of altering gaze behaviour for reducing stepping error. The results demonstrate new and encouraging information regarding achievable improvements in stepping performance in older adults.

Our results clearly show that, on average, our intervention participants were able to follow our instruction to maintain gaze on a target until after their foot had landed (Fig. 3-3). This change in gaze behaviour was accompanied by significant reductions in mean stepping error (Fig. 3-4a), variability (Fig. 3-4b) and task failure (missed steps in Target 1) (Fig. 3-4c). Similar to previous studies there was also a significant correlation between time of gaze transfer from Target 1 and foot placement variability (Chapman and Hollands, 2006; 2007) as well as between time of gaze transfer and medio-lateral foot placement error (Fig. 3-5). There were no significant differences between group and session in walking velocity, stance or swing durations prior to stepping into Target 1 and improvements in stepping performance did not occur at the expense of stepping accuracy in Target 2. Therefore we have demonstrated that older adults are able to intentionally alter their gaze behaviour during adaptive locomotion to more closely resemble gaze behaviour of younger adults (Chapman and Hollands, 2007) and have provided evidence that this change is causally linked to improvements in stepping accuracy and precision.

3.4.1 Improvements due to online corrections in foot trajectory?

Between subjects, the range of the mean timing of gaze transfer from Target 1 relative to heel contact was -370ms – 200ms pre-intervention and 18ms – 250ms post-intervention. To reduce stepping error in Target 1 post-intervention, any extension of the target fixation period would only be useful prior to foot contact in the target. Therefore, following intervention the additional fixation period on Target 1 that could be utilised for improving stepping accuracy was in the range of 0 ms – 370 ms. The clear improvements in stepping accuracy observed in intervention participants appears to suggest that participants may have been making online visually guided alterations to foot position within this extended target fixation period late in swing. It has been previously shown that individuals can make online alterations to lower limb trajectories, during obstacle avoidance with latencies as short as 120ms (Patla et al. 1991; Weerdesteyn et al. 2004). However, these authors proposed that such short latencies were a general avoidance response to an obstacle, and therefore do not represent an adaptive adjustment towards a target. In addition, adjustments to lower limb movements are inherently more complex than reaching actions, as the conservation of postural stability needs to be taken into account. Reynolds and Day (2005) demonstrated the ability of healthy young adults to make online adjustments to their foot trajectory within 300ms after toe-off during a rapid stepping action towards a target. However, Age-related deficits in the ability to perform such visually guided alterations to foot trajectory have recently been shown (Tseng et al. 2009), in addition to deficits in making effective compensatory steps following a perturbation (McIlroy and Maki, 1996). The latter study also showed that the latencies corresponding to the initiation of the first compensatory step are comparable between young and older adults. Therefore, problems associated with reduced stability and foot placement are likely to arise from problems within the swing or landing phases of a compensatory stepping action. Chapman and Hollands (2006) showed that compared to young adults, older adults are less able to use visual information during swing into a target box. Although these findings relate to very different tasks, collectively they suggest that one effect of increased age is to reduce the ability of an individual to accurately guide foot position, as well as use visual information to make online adjustments during swing. Furthermore, we found no differences in the number of adjustments made to foot trajectory during the swing to the target post-intervention. Although this does not discredit suggestions that online corrections might have been incorporated into the swing phase to some extent, it appears unlikely that the improvements seen in stepping accuracy following intervention are solely due to the ability of participants to use the additional target fixation period to make visually guided online alterations to foot placement.

3.4.2 Improvements due to improved movement planning?

In attempting to explain the putative mechanism underlying the post-intervention improvement in stepping accuracy, it is pertinent to consider where and when attentional resources would have been directed prior to gaze transfer i.e. during the planning or early stages of execution of the stepping action towards the target. Electrophysiological studies of monkeys have shown pre-saccadic activity in areas associated with attentional control, such as the parietal cortex (Andersen, 1989) and inferior temporal cortex (Chelazzi et al. 1993). Such activity could be associated with planning the temporal and spatial aspects of the saccade itself. When planning a saccade, the attention allocated towards the currently fixated object is reduced (Kowler et al. 1995). Henderson et al. (1989) proposed that such pre-saccadic attention shifts serve to enhance the perception of the next saccadic target. In the current study, planning for a saccade away from Target 1 would occur prior to, or during swing of the right leg into Target 1 (Hollands et al. 1995; Hollands and Marple-Horvat, 1996). Therefore it is possible that if gaze was transferred too soon away from the target then premature diversion of attentional resources towards future stepping constraints would have disrupted or curtailed the feedforward planning of the step into the target. Participants accuracy may have improved following intervention due to a delay in the shifting of attentional resources away from the planning of the limb transfer to the target.

We have demonstrated that significant reductions in stepping error can be achieved through voluntary alterations in visual strategy. The question arises concerning the sustainability of post intervention behaviours. One would assume that behavioural changes produced in the current study are likely to diminish once the individual ceases to intentionally modify their visual strategy. Therefore, the importance of investigating the underlying causes of the adverse visual strategies described should be emphasized. A previous study (Chapman and Hollands, 2007) has shown that HROA transfer gaze from a stepping target earlier than their 'low-risk' counterparts and that the extent of premature gaze transfer increases with task complexity. Investigations in to the possible influence of state anxiety and FOF on older adults' gaze behaviour during adaptive locomotion are described in Chapter 4.

3.5 Summary and conclusions

In summary, we propose that the improvement in older adults' stepping accuracy resulting from delayed gaze transfer from a stepping target can be explained by; a) improved planning during late stance resulting from a delayed shift of attentional resources away from the stepping target, b) the opportunity to make online adjustments to foot trajectories or body posture during swing, or from a combination of these mechanisms. More experiments are needed to elucidate the mechanisms underlying the relationships between temporal gaze parameters and stepping accuracy.

Chapter 4

Evidence for a relationship between state anxiety, visual sampling behaviour and fall-risk in older adults performing adaptive locomotor tasks.

4.1 Introduction

There are age-dependent changes to the way vision is sampled during adaptive locomotion. For example, older adults tend to look at stepping constraints (e.g. obstacles or stepping targets) earlier than, and for longer than, younger adults prior to stepping on or over them (Di Fabio et al. 2003; Chapman and Hollands, 2006; 2007). There are also differences in when groups of older adults look away from stepping targets. A study of gaze and stepping behaviour of participants in a precision stepping task showed that LROA and young adults usually fixated a stepping target until shortly after the foot landed on it (Chapman and Hollands, 2006). In contrast, on average, HROA transferred gaze away from a stepping target significantly earlier than their low-risk counterparts and young adults, during the ongoing swing phase of the targeting limb. This early gaze transfer, which was associated with a decline in stepping accuracy, was only observed when the initial target was followed by an additional stepping target (Chapman and Hollands, 2006). A separate study designed to investigate the relationship between task complexity and age-related changes in gaze behaviour demonstrated that the extent of early gaze transfer increased in line with the number of stepping constraints following the target and that there was a significant correlation between the extent of early gaze transfer and measures of decline in stepping performance (Chapman and Hollands, 2007). In combination these findings suggest that there may be a causal relationship between early gaze transfer and reduced stepping accuracy in HROA. In order to test this hypothesis, we investigated the effects of instructing older adults to delay gaze transfer away from a stepping target until after the foot has landed on foot placement accuracy and variability. Older adults were able to follow these instructions and this gaze "intervention" resulted in a reduction in stepping error and variability of foot placement thus supporting the notion that there is a causal link between altered gaze behaviour and risk of falling in older adults.

In the above studies, gaze transfer from a stepping target served to fixate a future constraint in the travel path. Therefore premature gaze transfer could be interpreted to be a result of inappropriate prioritisation of sampling of visual cues relating to future constraints over sampling of visual cues relating to the ongoing stepping action. However the question remains as to why HROA adopt this apparently maladaptive visual sampling strategy. One limitation of the aforementioned studies is that there was no analysis of participants' gaze behaviour prior to final fixation and arrival at the obstacle i.e. we have no information about the frequency with which, and the extent to which, participants looked ahead to gain information describing target characteristics. It would be relevant to know, for example, whether older adults who display early gaze away from a target spent less time previewing the target during the approach to it. One aim of the current study is to provide this missing information.

One possible mediator of the altered visual sampling behaviour shown by older adults is anxiety relating to the presence of upcoming obstacles and other environmental features posing a threat to stability. There are many examples of previous studies that suggest there is a relationship between increased anxiety and the control (or regulation) of posture and gait (McKenzie and Brown, 2004; Brown and Frank, 1997; Carpenter et al. 1999; Adkin et al. 2000; Adkin et al. 2002; Brown et al. 2002; Brown et al. 2002; Gage et al. 2003). Increased anxiety has been shown to provoke conservative adaptations to gait such as a tighter regulation of anterior-posterior centre of mass (Carpenter, 2001) and alterations in the magnitude of postural responses (Adkin et al. 2002). It has been hypothesised that these adaptations serve to prioritise postural stability and minimise the risk of gross stepping errors, and therefore may be beneficial in certain situations requiring obstacle avoidance (Brown et al. 2005). However, Gage et al. (2003) provided evidence that increased anxiety alters the allocation of attention during gait under dual task conditions. It would appear that attention is transferred towards the feature of the task that the individual is most anxious about. Therefore, when required to negotiate multiple constraints in a travel path, increased anxiety levels regarding a future walking constraint may drive earlier transfer of gaze towards it.

The aims of the current experiment are to a) quantitatively compare the visual sampling characteristics of HROA and LROA during the approach to stepping targets and determine how these relate to gaze behaviour during target negotiation and b) to determine the extent to which HROA's gaze behaviour and associated decline in stepping accuracy is associated with increased levels of state anxiety. We hypothesize that there are fall-risk-related differences in visual sampling behaviour during both the approach to, and stepping onto, targets and that altered gaze behaviour results from increased anxiety about future stepping constraints in the travel path.

Our prediction based on this hypothesis is that HROA will show progressively higher levels of anxiety as the complexity of the stepping task is increased and that levels of anxiety will correlate with both altered visual sampling during the approach to the target and early gaze transfer away from the target and associated decline in stepping precision.

4.2 Method

4.2.1 Participants

Seventeen healthy community dwelling older adults participated in the study (8 LORA (2 male, 6 female), 9 HROA (1 male, 8 female)). A total of nine of these participants had previously taken part in the study described in Chapter 3 (4 LROA, 5 HROA). All subjects provided written informed consent prior to participation. Participants were excluded from participation if diagnosed with any musculoskeletal or neurological impairment, or if prescribed medication for dizziness or anxiety. Participants requiring the use of corrective lenses for daily locomotor activities were also excluded due to incompatibility with the gaze tracking equipment detailed below. Participants underwent a battery of psychophysiological and visual tests prior to entering the laboratory (see Table 4-1). It is of note that there were significant differences in trait anxiety between participant groups, as measured using Speilberger's trait anxiety inventory (Speilberger, 1971). Individuals who had not experienced a fall in the previous 12 months were deemed to be a LROA if their Berg Balance score was higher than 45/56. However, participants who had fallen in the previous 12 months were deemed to LROA if their Berg Balance Score was higher than 48/56 (Berg et al. 1992).

Table 4-1 Characteristics of LROA and HROA

Measure	Low-Risk	High-Risk
Age *(years)*	72.88 (67 – 82)	75.67 (68 – 83)
Berg Balance Scale *(max = 56)*	54.83 (54 – 56)	45.89 (44 – 48)
Participant's previously fallen *(%)* †	13	78*
Snellen (acuity)	All above 20/40	
Pelli-Robson (contrast sensitivity) *(max = 2)*	1.71 (1.5 – 1.95)	1.58 (1.05 – 1.8)
Trail Making B *(seconds)*	64.25 (57 – 75)	85.38 (70 – 120)*
Goldman (lower 10º peripheral vision)	73.37 (60.3 – 81.3)	73.45 (65.3 – 80)
Falls Efficacy (FES-I) *(max = 100)*	12.5 (10 – 21)	18.67 (10 – 44)
Activities Balance Confidence (ABC) *(%)*	90.84 (69.9 – 98.88)	82.59 (61.65 – 97)
Spielberger State anxiety *(/ 80)*	29 (20 – 37)	33.89 (28 – 42)
Spielberger Trait anxiety *(/ 80)*	28.13 (21 – 38)	28.89 (23 – 41)
General Health Questionnaire (GHQ) *(max = 21)*		
Somatic	0.25 (0.0 – 0.6)	0.46 (0.1 – 0.12)
Anxiety/Insomnia	0.38 (0.0 – 0.7)	0.39 (0.1 – 0.12)
Social	0.6 (0.4 – 0.8)	0.76 (0.3 – 0.12)
Depression	0.25 (0.0 – 0.1)	0.56 (0.0 – 0.1)

† Percentage of subjects that reported falling once or more in the previous 12 months

* Significantly different to LROA

4.2.2 Data Collection

Participants were fitted with reflective markers placed equidistantly between the head of the distal interphalangeal joints of the first and fifth metatarsals (toe marker), between the head of the distal interphalangeal joint and the anterior point of the calcaneus on both medial and lateral sides (mid-foot markers), as well as on the anterior point of the calcaneus (heel marker). Participants were required to wear flat soled shoes for the duration of the experiment.

Each marker was sampled at 120Hz using a Vicon MX motion analysis system (Oxford Metrics, England). Visual behaviour was measured using a high-speed ASL 500 head mounted gaze tracking system, whereby both vertical and horizontal components of eye movements were synchronised and recorded with the Vicon video data at 120Hz via two analogue inputs (vertical and horizontal) produced by the ASL controller. The ASL controller also produced a digital video image (30Hz) displaying the visual scene of each participant, with a superimposed cursor representing the area of gaze fixation. This video was used to assess the environmental features fixated by each participant during each trial. Electrodermal Response (EDR) was measured using a Biopac mp150 and AcqKnowledge 3.8.1 software, with electrodes attached to digits 2 and 3. The Vicon system was used to trigger the acquisition of EDR data from the Biopac mp150. Self-reported anxiety measures were taken using a modified version of the Spielberger state anxiety inventory (Spielberger, 1971). Each questionnaire comprised four task specific questions:-

1) I feel calm when completing the task.
2) I feel tense when stepping into the box.
3) I feel relaxed when stepping into the box.
4) I am worried that I may lose my balance.

Anxiety responses were scaled 1 to 4 (1 = Not at all, 2 = somewhat, 3 = moderately and 4 = very much) participants were instructed to answer with respect to how they felt during their approach and stepping into the target.

4.2.3 Protocol

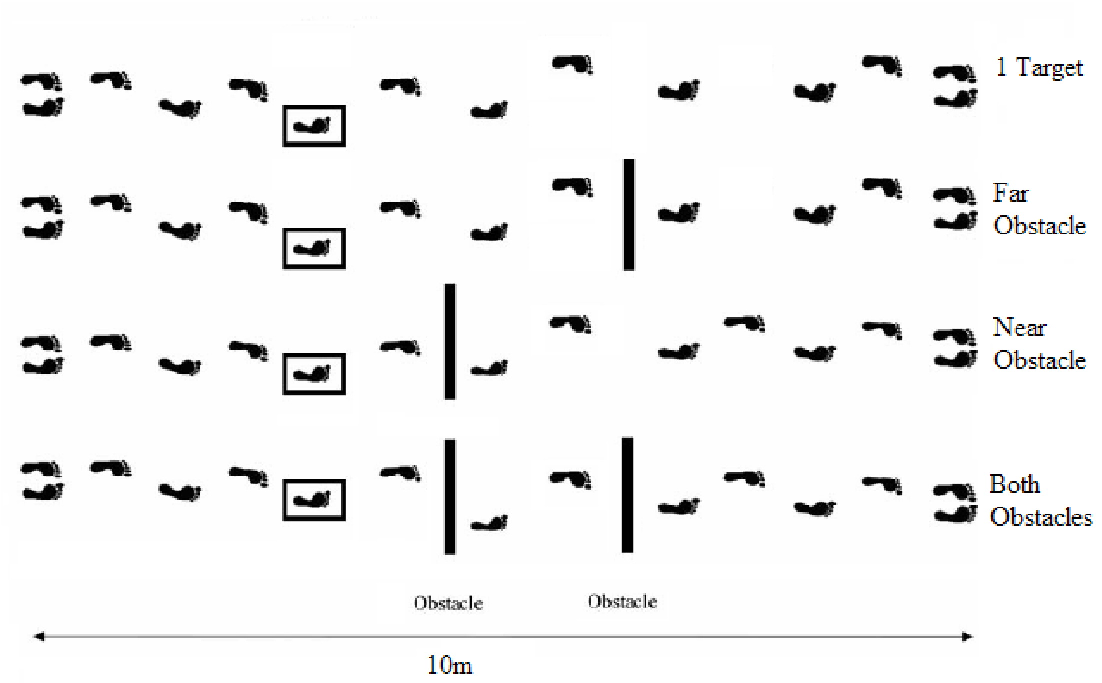
Similar techniques to those described below have been used previously by Chapman and Hollands (2006; 2007). Participants were instructed to walk along a 10m travel path at their 'own pace' and place their right foot into a stepping target. There were four experimental conditions determining the constraints that followed the stepping target: no further constraints (target only), one near obstacle (near obs), one far obstacle (far obs) and both near and far obstacles (both obs). Participants were instructed to step over each obstacle (if present) using their right foot in each instance. There were 10 trials in each condition. Within each condition the stepping target was presented in one of two possible positions separated by 12 cm (medio-lateral) and 8 cm (anterior-posterior). This was intended to reduce the degree of task predictability throughout the session. Equal numbers of trials using each target position were presented within each condition, the order of which was randomised. Participants were required to complete 2 practice trials in each condition prior to start of the first of the randomised trials.

Targets were made from firm lightweight packaging foam and were not secured to the floor. The dimensions of the target box comprised an edge and border (40 mm x 40 mm). Inside each target was a rectangular stepping area measuring 190mm x 415mm. Participants were instructed to place their foot "into the centre of the box, leaving as much space as possible between the outside of the foot and the inside of the target box”. Each obstacle was made from plywood and designed to fall over with ease in the direction of walking should the foot of the subject come in to contact with it. Each obstacle was 22cm high, 100cm wide and 1cm thick. The near and far obstacles (if present) were placed on the walkway 100cm and 180cm following the anterior edge of the most anterior stepping target position.

Three minute rest periods were given after every five trials, where participants were required to sit and rest to allow the EDR signal to return as close as possible to baseline levels. Self-reported anxiety inventories (one for each task condition) were retrospectively completed by each participant at the start of the rest period after 5, 20 and 40 trials. Two baseline EDR measurements were taken during each session: ‘Sat’ and ‘Normal walking’. Sat measures were taken for four separate eight second periods (two measurements prior to the start of the experimental walking conditions, and two after the 40 experimental trials). Each measurement was taken once the subject had been sat quietly for two minutes. In addition, four EDR measures were taken under conditions of ‘normal walking’; two prior to the start, and two following the first and last experimental trial. The mean EDR amplitude was recorded between the initiation of the first step, and nearest heel contact to the position where the stepping target would have been during the experimental trials.

At the start of each trial participants were requested to stand with their eyes closed until given the verbal instruction: “Open eyes”. This was intended to limit the amount of attention directed towards the constraints in the walkway prior to the start of each trial. Participants started walking after receiving the verbal instruction to “Go”.

Figure 4-1 Schematic diagram of experimental task



4.2.4 Data analysis

Kinematic data were low-pass filtered with a cut off frequency set at 5Hz. 'Heel contact' and 'toe off' events were defined using an algorithm adapted from Hreljac and Marshall (2000). Toe off was determined as the minimum in vertical displacement of the toe marker, identified by zero crossings in the vertical velocity profile. Heel contact was determined as the maximum vertical acceleration of the heel marker, identified by zero crossing in the jerk profile (see Sorensen et al. 2002). The area of gaze fixation was assessed using a frame-by-frame analysis of the digital scene video juxtaposed with the vertical and horizontal components of the gaze analogue signal. We used the peak velocity profile of the analogue signal to determine the onset and offset of each saccade (the local velocity peak threshold was set at $100^{o}s^{-1)}$. Gaze fixations were defined as being a gaze stabilisation on a single environmental feature for 100 ms or longer (Patla and Vickers, 1997). We then calculated the respective latencies between eye movements (onsets and offsets) and stepping events ('heel contacts' and 'toe offs').

The EDR response during the experimental conditions was expressed as changes in the signal compared to that of walking at a self-selected pace with no constraints. We took the mean EDR amplitude of four eight second trials, where the subject had sat quietly for three minutes. We also took the mean of four baseline measurements of normal walking with no constraints. For each trial, we took the EDR signal that was recorded between the point of 'toe-off' to initiate gait at the start of each trial and heel contact in the target. The magnitude of this signal was expressed as a percentage of the difference between the two baselines (sat quietly and normal walking). Any percentage changes were plotted against that of walking at a self-selected pace with no constraints, to give a measure of how the signal had changed during the experimental trials, compared to that of normal walking.

A 'missed step' was defined as the foot of the participant contacting the stepping target. For each subject, the number of missed steps was represented as a percentage of the total number of trials. Walking velocity was calculated using the position and latency between the first toe off used to initiate gait and the heel contact of the left foot following the step into stepping target.

A mixed design ANOVA was used classify main effects and interactions of within subject (four experimental conditions) and between subject (two group) factors. The dependent variables assessed were; the timing of gaze transfer from the target in relation to heel contact inside it, temporal component of gaze events (fixation durations, number of fixations on each constraint) between gait initiation and heel contact in the target, percentage number of missed steps, foot placement variability in both medio-lateral and anterior-posterior direction, self-reported anxiety level, and

EDR response. In order to assess the extent to which gaze and stepping behaviour is influenced by anxiety two one-way between-groups ANCOVA were conducted on the following variables: the time of gaze transfer from the target relative to heel contact and the number of missed steps. Measures of self-reported anxiety were included as a covariate. As alterations in anxiety as well as visual and stepping behaviours are likely to be most pronounced during the most complex task, data were only included from the experimental condition containing the target and both obstacles. This was to allow a clearer interpretation of how much the variation in visual and stepping behaviours can be explained by measures of anxiety.

The measurement of foot placement variability was assessed by taking the standard deviation (SD) of foot placement error in the target (centre of foot from centre of box). Our correlation analysis involved using both parametric (Pearson's correlation coefficient) and non parametric (Spearman's rank correlation coefficient) analysis. Non parametric correlations were used when analysing the results from our measure of self-reported anxiety. Parametric analysis was used for all other data sets. Each data point included in correlation analysis represented the mean value for each participant for one experimental condition (the mean of 10 trials). Post hoc analysis was carried out using ANOVA. All confidence levels were set a priori at $p < 0.05$.

4.3 Results

4.3.1 Gaze behaviour

There was a significant interaction between group and condition for the time interval between gaze transfer away from the stepping target and heel contact within it. As demonstrated in Fig 4-2, the results show that compared to LROA, HROA transferred their gaze away from the target earlier with respect to heel contact in the conditions with increased task complexity ($F_{(3,45)}$ = 3.685, p <0.05). Post hoc analysis showed that in every experimental condition HROA transferred their gaze earlier with respect to heel contact than LROA. Post hoc analysis also revealed that LROA transferred gaze away from the target earlier with respect to heel contact in 'both obs' conditions compared to 'target only'. There were no significant differences between conditions for HROA.

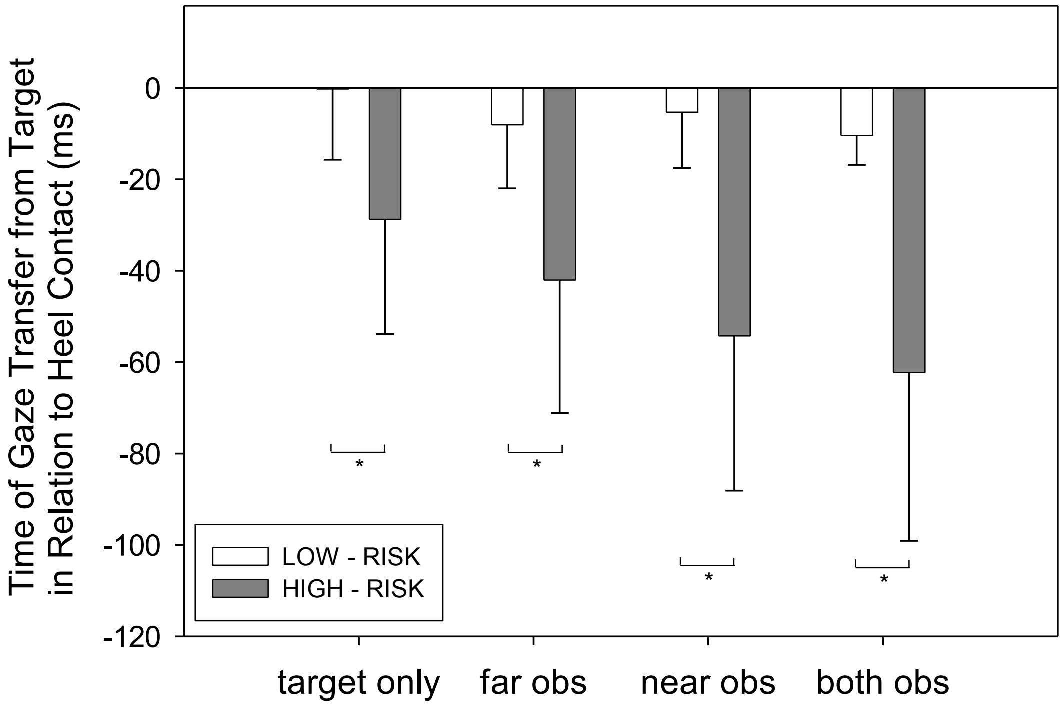


Figure 4-2 Bars represent the timing of the transfer of gaze from the stepping target relative to the heel contact inside it. Negative values represent saccades prior to heel contact. Error bars represent standard deviations (SD)

The final fixation duration on the target was longer in HROA, as shown by a significant main effect of group ($F_{(1,15)}$ = 10.647, p <0.01). Overall values for LROA were: 200.4ms ± 100.7ms, and HROA: 409.1ms ± 173.7ms. A main effect of condition also showed that the final target fixation was significantly extended in conditions where the stepping constraints following the target were more demanding ($F_{(3,45)}$ = 6.061, p <0.001). Values for all participants were 'target only': 430.6ms ± 179ms, 'far obs': 353.2ms ± 191.4ms, 'near obs': 305.7ms ± 175.1ms, 'both obs': 343.7ms ± 212.7ms. Figure 4-3 shows the total target fixation time (the sum of all target fixations) between gait initiation (first toe off at the start of each trial) and heel contact in the target. There was a significant interaction between group and condition ($F_{(3,45)}$ = 4.203, p <0.05). Post hoc analysis revealed significant between-group differences in the 'near obstacle' and 'both obstacles' conditions.

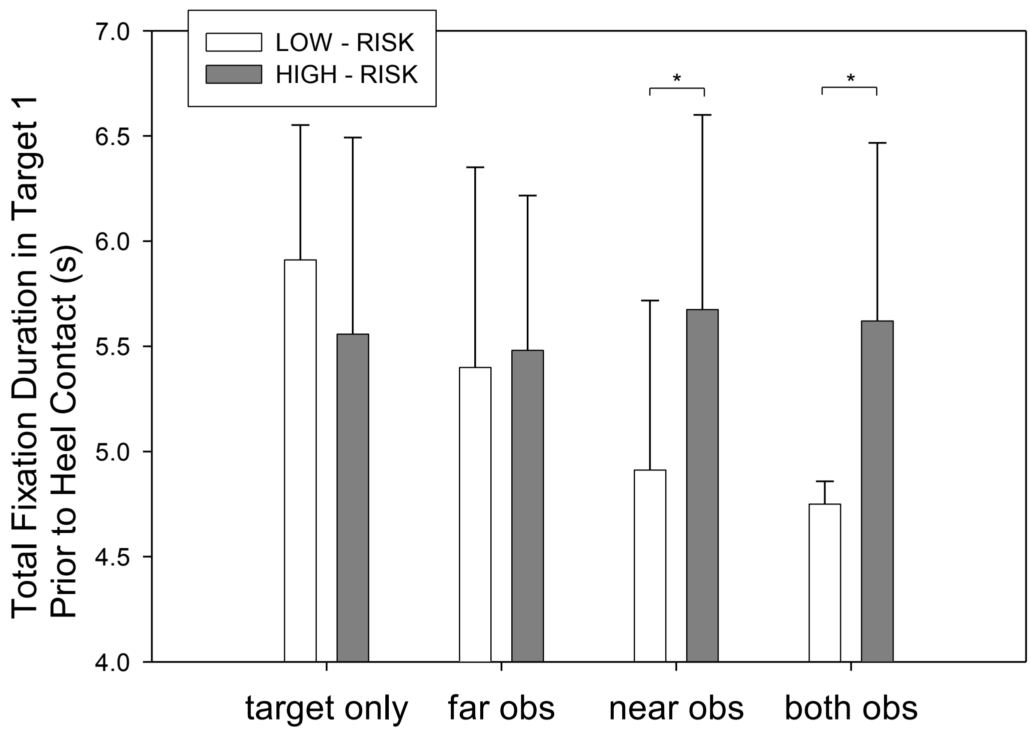


Figure 4-3 Each bar represents the total target fixation time between gait initiation at the start of each trial, and heel contact in the stepping target. Error bars represent standard deviations (SD)

There was a significant interaction between group and condition in the number of fixation transfers between the target and any subsequent obstacle prior to arrival at the target ($F_{(2,30)}$ = 11.675, p <0.001). Post hoc analysis revealed that compared to HROA, LROA made significantly more fixation transfers between the target and any future constraint in the 'near obs' and 'both obs' conditions (Fig 4-4).

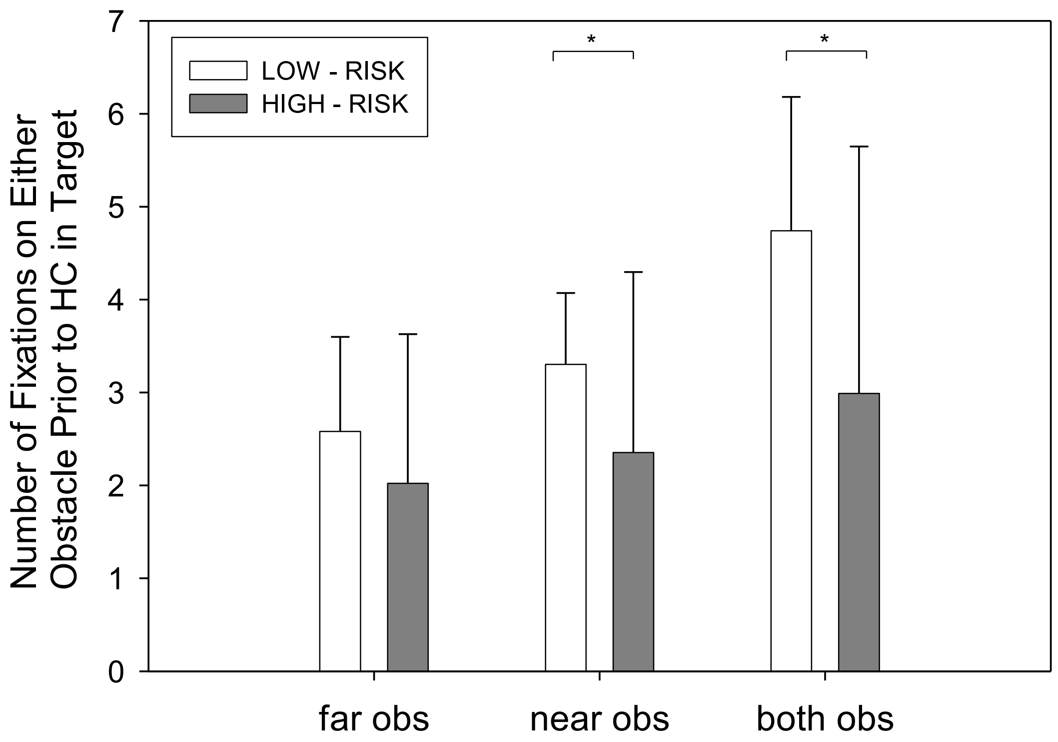


Figure 4-4 Each bar represents the number of fixations between the stepping target and either of the following obstacles between gait initiation and heel contact in the stepping target. Error bars represent standard deviations (SD)

There was a significant interaction between group and condition ($F_{(3,45)}$ = 3.556, p <0.05) where compared to HROA, LROA made a higher number of individual fixations on the target in the time between gait initiation and heel contact in the target.

These fixations were more frequent in LROA in the more complex task conditions. Post hoc analysis revealed no significant differences between groups in the 'target only' condition. However, in all other task conditions compared to HROA, LROA made significantly more frequent target fixations. These results differ from those relating to Fig 4-4 in that on some occasions participants would fixate undefined points of the travel path prior to the target. Therefore, gaze transfers to and from the target box must be segregated as being either between stepping constraints, or otherwise.

Pearson's Product Correlation coefficient analysis showed a significant relationship between duration of the final fixation on the target and the total number of target fixations ($r_{(66)}$ = -.666, p < 0.001), as well as the timing of gaze transfer from the target ($r_{(66)}$ = -.419, p < 0.005). These moderate relationships indicate that when the final target fixation was longer, participants were less likely to fixate the target as frequently prior to heel contact, and also transfer gaze away from the target earlier with respect to heel contact.

4.3.2 Stepping Accuracy

There was a significant interaction between group and condition in the number of missed steps (Fig 4-5) ($F_{(1,15)}$ = 3.122, p <0.05). Post hoc analysis showed that HROA made a higher number of missed steps in all conditions, compared to LROA. HROA also made a higher number of missed steps in all conditions compared to 'target only', whereas LROA showed no significant differences between conditions.

Analysis using Pearson's Product Correlation coefficient showed a significant correlation between earlier gaze transfers from the target in relation to heel contact and increases in the percentage number of missed steps in the stepping target ($r_{(66)} = -.678$, $p < 0.001$).

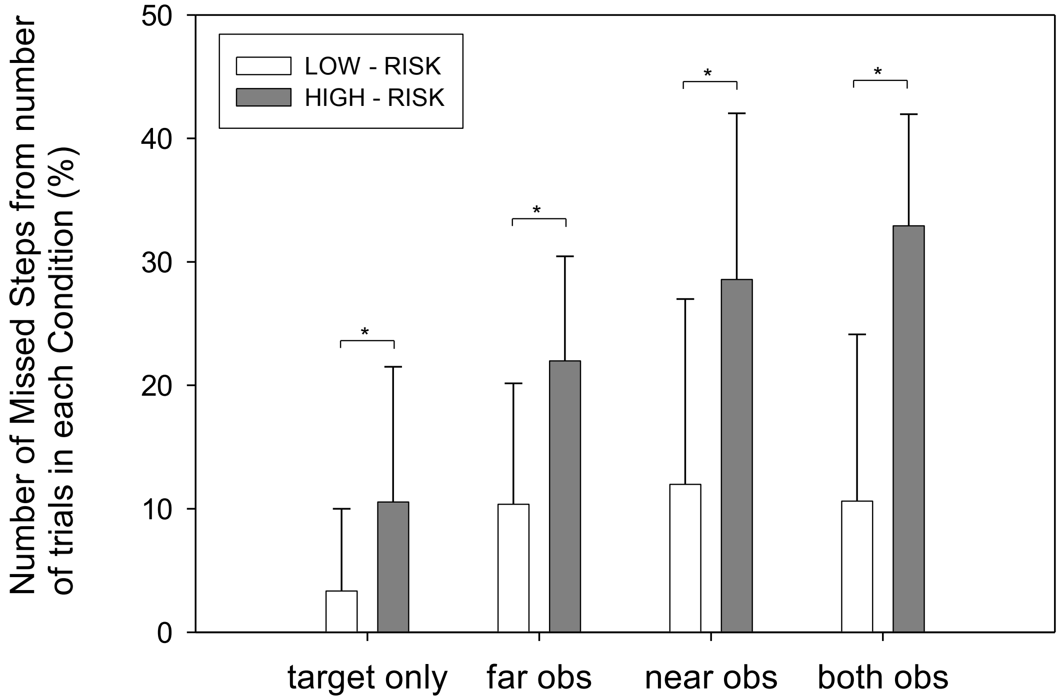


Figure 4-5 Each bar represents the number of missed steps (foot contacting the stepping target) as a percentage of the total number of trials in each condition. Error bars represent standard deviations (SD)

4.3.3 Anxiety measures

The results from the self-reported anxiety inventory showed a significant interaction between group and condition, whereby in comparison to LROA, HROA showed progressively higher anxiety scores in more complex task conditions ($F_{(3,45)} = 7.983$, $p < 0.001$)(for mean scores see Table 4-2). Post hoc analysis revealed that only in the conditions where an obstacle was present following the target did HROA self-report higher anxiety levels compared to LROA. These findings are shown in Fig 4-6. There was a main effect of group ($F_{(1,15)}$ = 12.611, p <0.01) on the magnitude of electrodermal response. HROA showed a 150% increase in EDR response compared to unconstrained walking whereas the EDR of LROA was relatively unaffected by the presence of stepping constraints. Overall values for percentage EDR increase for LROA were: 3.97 ± 108.5 and HROA: 156.74 ± 182.53. Spearman's rank correlation coefficient analysis showed a significant negative correlation between self-reported anxiety levels and timing of transfer gaze away from the target ($r_{(66)}$ = -.770, p < 0.001) i.e. looking away early was associated with greater self-reported anxiety. Increased self-reported anxiety levels also correlated with an increased percentage number of missed steps ($r_{(66)}$ = .710, p < 0.001). After adjusting for self-reported anxiety measures, results using ANCOVA showed no difference between groups for the time of gaze transfer relative to heel contact. However, results using ANCOVA did show a significant difference between groups in the number of missed steps ($F_{(1,14)}$ = 10.918, p <0.01). There was a strong relationship between self-reported anxiety and both the time of gaze transfer from the target and the number of missed steps, as indicated by partial eta squared values of 0.704 and 0.752 respectively.

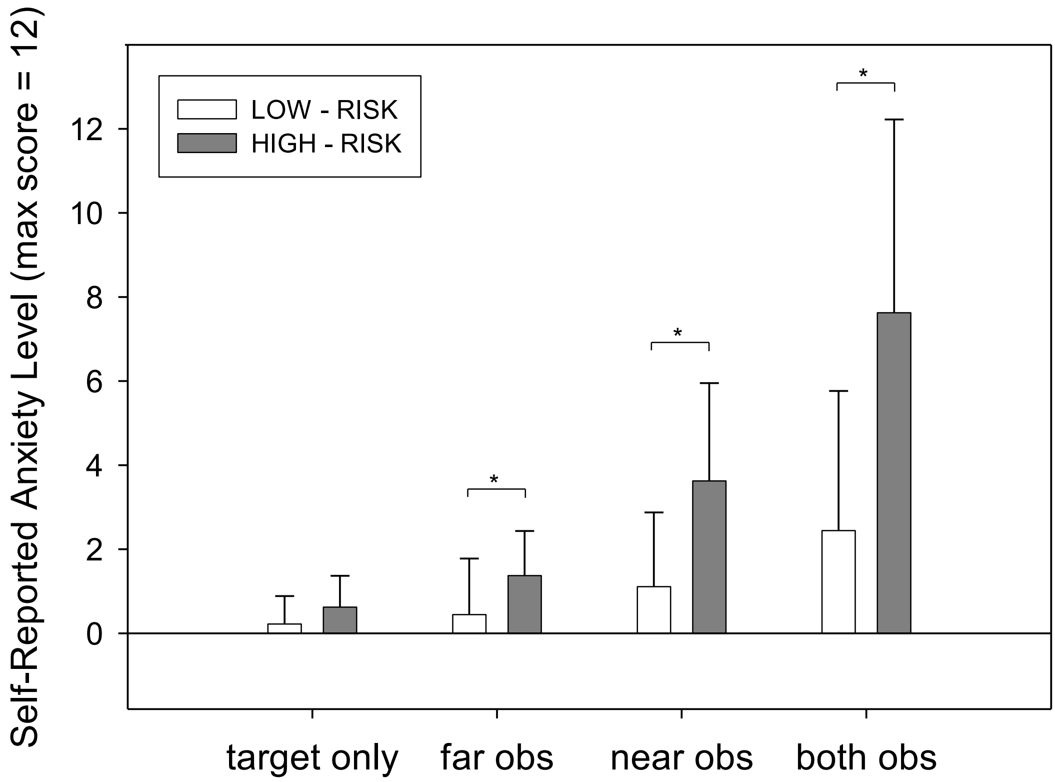


Figure 4-6 Each bar represents anxiety levels self-reported by each participant for each of the experimental conditions. Participants completed the 4-point inventory with respect to how they felt during each trial in the time prior to heel contact in the stepping target. Error bars represent standard deviations (SD)

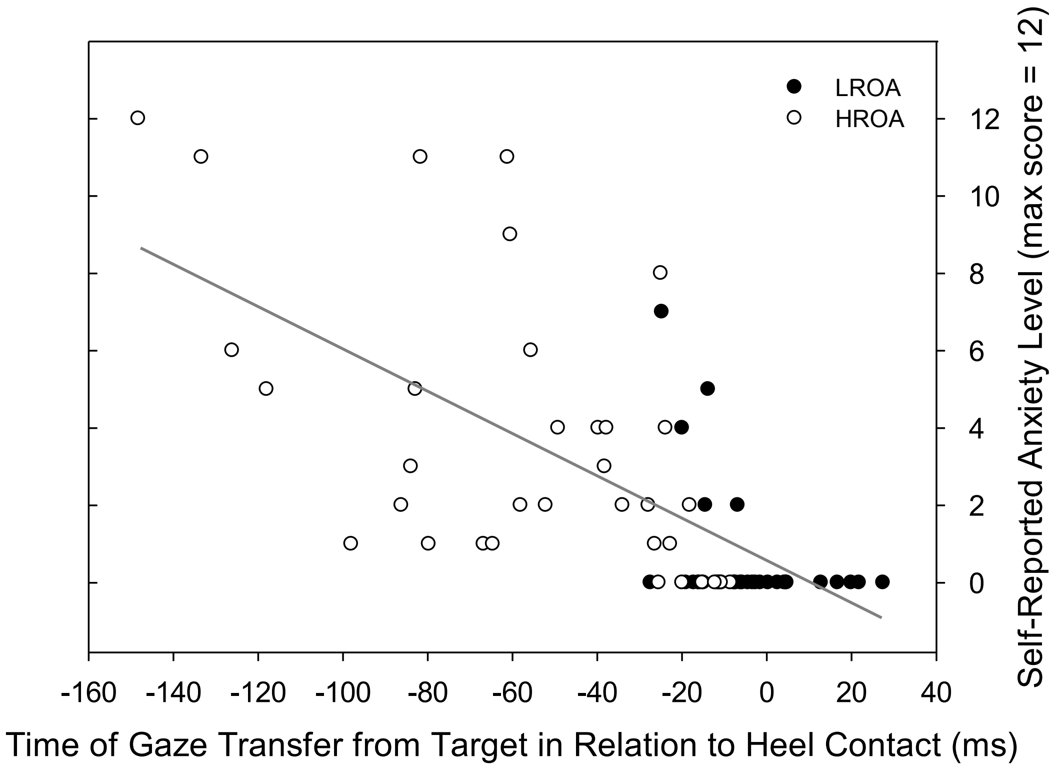


Figure 4-7 Timing of gaze transfer: each data point represents the mean value for one subject in one of the experimental conditions. Self-reported anxiety: Each data point represents the mean of 3 inventories (taken after 5, 20 and 40 trials) for one of the experimental conditions, for one subject.

4.3.4 Gait characteristics

There was a significant main effect of experimental condition on stance ($F_{(3,45)}$ = 4.420, p <0.05) and swing ($F_{(3,45)}$ = 6.260, p <0.01) phase durations prior to heel contact in the target. Stance phase durations increased with task complexity. Values from all participants were 'target only': 857ms ± 114ms, 'far obs': 884ms ± 118ms, 'near obs': 889ms ± 104ms and 'both obs': 897ms ± 102ms. Swing phase duration also increased with task complexity. Values from all participants were 'target only': 776ms ± 112ms, 'far obs': 783ms ± 872ms, 'near obs': 819ms ± 104ms and 'both obs': 822ms ± 103ms.

Table 4-2 Results for gaze characteristics, anxiety measures and missed steps

Dependent Variable	Low-Risk					High-Risk				
	Tonly	Far	Near	Both	Overall	Tonly	Far	Near	Both	Overall
Number of target fix*	3.08 ± 1.62	3.79 ± 1.22	4.18 ± 1.20	4.19 ± 1.13	3.81 ± 1.33	2.30 ± 0.72	2.27 ± 0.86	2.47 ± 0.77	2.33 ± 0.82	2.34 ± 0.76
Number of obs fix *	N/A	2.88 ± 1.71	3.57 ± 1.76	5.25 ± 2.37	3.54 ± 1.56	N/A	1.82 ± 0.93	2.22 ± 0.68	2.73 ± 1.02	2.46 ± 1.06
Anxiety self (score/12)*	0 0	0 0	0.75 ± 1.49	1.75 ± 2.76	2.44 ± 1.77	0.78 ± 0.83	1.67 ± 1.32	3.67 ± 2.18	7.67 ± 4.3	3.31 ± 2.18
Missed steps (%)*	1.25 ± 3.54	6.67 ± 9.72	7.92 ± 9.38	8.19 ± 9.81	9.07 ± 12.04	11.6 ± 13.98	23.98 ± 9.95	30.34 ± 11.7	32.59 ± 8.3	23.51 ± 10.75
* Significant interaction between group and task condition										

4.4 Discussion

The first aim of the current experiment as stated in the introduction was to quantitatively compare the visual sampling characteristics of HROA and LROA during the approach to stepping targets and determine how these relate to gaze behaviour during target negotiation.

Our results clearly show significant differences in visual behaviour between HROA and LROA, when approaching the target. The final fixation on the target, as well as the total time spent fixating the target was longer in HROA (Fig 4-3), particularly during the more complex task conditions. HROA also made fewer fixations of constraints following the target than LROA under conditions of high task complexity (see Fig 4-4). The time at which participants looked away from the stepping target correlated with the number of times, and length of time that participants spent previewing the future stepping constraints. Those participants that looked away early from the stepping target (predominantly HROA) spent less time previewing the future travel path than the participants (predominantly LROA) that looked away later.

On average, the LROA group spent more time previewing future obstacles during the approach to the target as complexity increased. Adopting this strategy would have provided participants with advanced visuospatial information describing upcoming constraints which presumably would have been stored in memory. This strategy allowed participants to fixate stepping target until around heel contact, thereby maximizing detailed visual information available to guide targeting of the limb.

In contrast the HROA group tended not to preview upcoming constraints but instead participants kept attention on target during approach. Apparently as a consequence, these participants looked away from the target sooner than LROA, during swing phase of the targeting limb. The extent of early gaze transfer increased in line with increasing task complexity and was associated with a decline in target stepping accuracy and precision. A question that arises is what are the factors that might be driving these differences in visual sampling behaviour between groups?

One possibility is that HROA fixate future constraints less often as they cannot retain visuospatial information describing the future obstacles long enough to utilize it. Persad et al. (1995) found no relationship between visual spatial memory and locomotor characteristics in an obstacle avoidance task. Sekuler et al. (2005) also demonstrated how the ability to retain an internal spatial map may be preserved in normal ageing. However, in the current study participants encountered numerous constraints in one path; a task more likely to emphasize deficits in visual spatial memory. Therefore differences in visual strategy described in the current study may arise from fall-risk dependent factors relating to visual spatial memory.

We suggest that in the current study HROA may reduce the number of 'preview fixations' and increase target fixation in order to maximise acquisition of visual information regarding the target. Regardless of any deficits in visual spatial memory, this behaviour is likely to reduce the resolution of an 'internal spatial map' regarding future constraints. With respect to heel contact in the target, transferring gaze fixation from the target at an earlier time, in order to fixate the following constraint, may be a way of compensating for deficits in spatial information regarding the future obstacle(s).

Another possible factor driving group-related differences in visual sampling behaviour is participants' level of psychological arousal; specifically their anxiety regarding aspects of the walking task. The second aim of our study was to determine the extent to which HROAs' gaze behaviour and associated decline is stepping accuracy was associated with increased levels of state anxiety.

Our results clearly show that HROA self-reported significantly higher levels of anxiety when negotiating pathways with higher levels of obstacle task complexity (see Fig 4-6). We also found significant and large between-group differences in the percentage increase in EDR magnitude during the experimental trials. The measure of EDR is inherently subject to considerable variability, as it is sensitive to many factors such as ambient temperature and movement of the electrodes, especially during a dynamic task like ours. As physiological arousal is indicative of anxiety (Ashcroft et al. 1991) we suggest that the group differences in physiological response provide a general validation for the group differences shown in the self-reported anxiety results.

Our anxiety measures correlated significantly with timing of gaze transfer from the stepping target (see Fig 4-7). Furthermore, after adjusting for measures of self-reported anxiety, results showed no between-group differences in the time of gaze transfer relative to heel contact. These findings support our hypothesis that the differences in gaze behaviour demonstrated by HROA can be explained, at least in part, by increased anxiety relating to aspects of their future travel path. Our anxiety measures also correlated with the number of "missed steps" indicating a decline in stepping accuracy. However, when adjusting for anxiety scores, we found that a significant proportion of between group differences in stepping inaccuracies were independent of measures of self-reported anxiety, although a strong relationship was found between the two. In combination these results show that the increased anxiety about stepping over obstacles reported by HROA is associated with changes to visual sampling characteristics. In the previous chapter we showed evidence for a causal link between early gaze transfer away from a stepping target and decline in stepping performance. Therefore, we suggest that increased anxiety about stepping constraints in the travel path may be responsible for inappropriate visual sampling, which in turn is associated with a reduction in stepping accuracy in HROA.

The influence of increased anxiety or FOF has been previously shown to promote a tighter control over centre of mass, characterised by smaller amplitude and increased sway frequency during quiet standing and 'rise to toe' tasks (Carpenter et al. 1999,2001; Adkin et al. 2002). Effects of increased anxiety have also been described during obstacle negotiation tasks (Persad et al. 1995) and when walking along a raised platform (Gage et al. 2003). It is suggested that during locomotor tasks, anxiety will redirect the allocation of attention towards the maintenance of postural stability rather than a secondary cognitive task. When required to negotiate multiple constraints in a travel path, attention must be divided between the different constraints, unless the individual prioritises each constraint one at a time. Although compared to the low-risk, HROA would appear to adopt the latter strategy; high-risk participants did make preview saccades to future constraints, and therefore must have divided their attention between the target and following obstacle(s). Heightened anxiety has been shown to inhibit performance in divided attention tasks in older, but not younger adults (Hogan, 2003), and it is suggested that such deficits are the product of a mechanism by which increased anxiety reduces attentional capacity. Therefore, longer fixation periods on the target in HROA may relate to the inhibitory role of anxiety on visual information processing, as well as deficits in CNS function associated with normal age and fall-risk.

It has been suggested that changes in the ability of older adults to process spatial information has consequences on the time that an individual will choose to fixate a constraint in the travel path (Di Fabio et al. 2003). Our results show that HROA transferred their gaze earlier, and self-reported higher anxiety levels in the condition of 'near obstacle' compared to 'far obstacle'. Differences in the perception of threat regarding future obstacles could be associated with ability to process visual spatial information, and future work should aim to investigate this further. However, our findings support the notion that the timing of gaze transfer is modified when perceived threat level increases regarding the position or 'time to contact' of the upcoming obstacle.

There are limitations in the current study that are important to mention. Our self-reported measure of anxiety was completed retrospectively, and is potentially venerable to a degree of bias within participant responses. The comparison between LROA and HROA is an informative way of indicating behaviours associated with an increased likelihood of falling. However, as the current data does not include a young population, we cannot comment on age-related changes to the measures described.

4.5 Summary and conclusions

Our results demonstrate significant relationships between increased anxiety, changes to visual sampling behaviour and associated decline in stepping accuracy in high-risk older adults during adaptive locomotion. Further work is needed to elucidate the mechanisms underlying age-related changes to psychological function, and the coordination of gaze, gait and postural control.

Chapter 5

Can vision be used on-line by young and older adults to alter foot trajectory during locomotion?

5.1 Introduction

In order to successfully move through our cluttered world we must extract relevant visual information from the environment and use it to plan and execute appropriate locomotor actions. When stepping on multiple targets there is a tight temporal coupling between eye and foot movements: individuals generally initiate a saccadic eye movement to fixate a target area just before the targeting limb leaves the ground (Hollands and Marple-Horvat, 2001). Occluding vision during the swing phase of a step towards a target has no detrimental effects on stepping actions in young adults (Hollands and Marple-Horvet, 1996; Patla et al. 1996; Chapman and Hollands, 2006). These findings suggest that young adults are able to use visual information sampled prior to swing in a feedforward manner in order to guide the foot to an intended stepping location and support the notion that motor plans relating to body motion during a step are fixed at foot off and are tailored according to the intended foot placement (Lyon and Day, 2005) i.e. are ballistic in nature. However, during stepping tasks involving obstacle perturbations, visual information has been shown to inform rapid alterations in foot trajectory in the order of ~120ms (Patla et al. 1991; Weerdesteyn et al. 2004). During a single unconstrained step Reynolds and Day (2005a) also documented similar delays in response to a target perturbation. These short latency responses were shown under conditions both with and without balance constraints, and are comparable to those seen in upper limb reaching movements (Day and Lyon, 2000). These results lead to the interpretation that similar pathways are involved in the control of visually guided online responses in both upper and lower limbs. For example, there is evidence to suggest that short latency responses to visual perturbations in upper limb actions are generated sub-cortically (Day and Brown, 2001). Therefore, comparable response latencies described by Reynolds and Day (2005a) during lower limb stepping actions are perhaps evidence for sub-cortical online control of foot trajectory.

Reynolds and Day (2005b) described how vision of the foot and target during swing is beneficial to ongoing swing accuracy. In accordance with theories proposing that during reaching movements there is an initial ballistic phase propelling the limb towards the intended goal, followed by a visually guided error correction phase (Carlton, 1981; Chua and Elliott, 1993; Goodale et al. 1986) Reynolds and Day (2005b) suggested that visual information of the target (perturbed at foot off) was only used in the latter half of swing, and occurred only when the foot was in close vicinity to the target. Therefore, compelling evidence exists for the ability of younger adults to produce visually guided alterations in foot trajectory in a similar manner to that of the upper limbs.

Surprisingly, little previous work has assessed whether the ability of younger adults to produce visually guided online corrections to stepping actions is preserved with increased age. Chapman and Hollands (2006) showed that in older adults the occlusion of vision during swing resulted in significant reductions in stepping accuracy. This finding is evidence that older adults may have a reduced ability to use visual information in a feedforward manner when planning stepping actions. In order to produce an accurate step, some level of online adjustment is therefore necessary to inform corrections to foot trajectory. Tseng et al. (2009) showed that older adults take longer to elicit a response when a stepping target is moved during swing. Older adults also reduced the magnitude of lateral ground reaction force produced in the stance leg. However, no significant differences in final stepping error were found compared to young adults. Collectively this provides evidence that older adults are able to produce online corrections to swing, although deficits in sensorimotor function and/or musculoskeletal properties may be responsible for delays and reductions in the response. However, these findings only provide a comparison between young and older adults who have not fallen in the previous 12 months and only relate to targets moved to a lateral position. In order to evade an unanticipated hazard during a step, adjustments have to be made in the direction appropriate for the situation. Reynolds and Day (2005a) showed that final stepping error was higher following medial, compared to lateral target jumps in young adults. The current study aims to investigate alterations to foot trajectory following anterior target perturbations (requiring an extension of the swing phase), in addition to both medial and lateral target perturbations. Also, previous findings (Reynolds and Day, 2005a; 2005b; Tseng et al. 2009) only reflect alterations in trajectory of a single step made from a static standing position. Therefore, questions remain regarding the ability of young and older adults (particularly HROA) to produce such online corrections to foot trajectory when walking; a task very different to a single step due to contrasts such as dynamic balance requirements.

The notion that there are age-related differences in visual or visuomotor processing ability is supported by the finding that older adults generally fixate stepping targets earlier and for longer than younger adults (Chapman and Hollands, 2007; Young and Hollands, Chapter 3&4). Recent studies have also shown that when approaching multiple stepping targets, HROA transferred gaze fixation from a target before completion of the step onto it in order to fixate a subsequent stepping constraint

(Chapman and Hollands, 2007; Young and Hollands, Chapter 4). In contrast, younger adults and LROA, on average, maintained fixation on a target until after the foot had landed. The early gaze transfer shown by HROA was associated with increased stepping error and a higher incidence of task failure. When participants were instructed to maintain gaze fixation on the first target until after completing the step onto it, all measures of stepping accuracy and consistency showed significant improvement. The authors suggested two likely mechanisms behind the improvements shown: (1) voluntarily delaying gaze transfer allowed a more comprehensive planning of the movement earlier in stance/swing, (2) the older adult participants were able to use the additional fixation period on the target to make online corrections to foot trajectory during the swing phase.

The aim of the current study is to assess if age- and fall-risk related differences exist in the amount of time that individuals need to make stepping adjustments to unpredictable target locations when walking. Our hypothesis is that older adults (particularly HROA) will show a reduced ability to make online corrections to their foot trajectory, due to delays in visuomotor processing. Therefore, we predict that LROA and HROA will take longer to respond to unexpected alterations in target position and make fewer adjustments to foot trajectory during late target perturbations, collectively resulting in reduced stepping accuracy.

5.2 Method

5.2.1 Participants

Eight healthy young adults and sixteen healthy community-dwelling older adults and participated in the study. The older adult participants were divided into two equal groups depending on whether they were deemed to be at a low, or high-risk of falling. Individuals who had not experienced a fall in the previous 12 months were deemed to be a LROA if their Berg Balance score was higher than 45/56. However, participants who had fallen in the previous 12 months were deemed to HROA if their Berg Balance Score was below 48/56 (Berg et al. 1992). All participants provided written and informed consent prior to the start of the study. Ethical approval was received from The University of Birmingham Ethics Committee.

The criteria for exclusion from the study were as follows: (1) Diagnosis of any musculoskeletal or neurological impairment. (2) Prescription of medication for anxiety or dizziness. (3) The required use of corrective lenses for daily locomotor activities. This final criterion was imposed due to the incompatibility of corrective lenses with the gaze tracking equipment used (detailed below). Participants also underwent a battery of visual and psychophysiological tests (detailed in Table 5-1).

Table 5-1 Participant characteristics

Measure: Mean (range)	Young	Low-Risk	High-Risk
Age *(years)*	24.125 (21-30)	73 (68-76)	74.75 (68-83)
Height *(cm)*	160.1 (151-174)	161.6 (151-180)	159.4 (155-173)
Weight *(Kg)*	70.3 (55.3-81.6)	65.1 (58.1-75.2)	68.2 (56.3-85.3)
Previous falls *(%)* †	0	12.5	87.5 *
Mini Mental State (/30)	30 (30-30)	29.5 (28-30)	29 (26-30)
Berg Balance Scale (/56)	56 (56-56)**	54.8 (52-56)	47 (43-49)*
Visual acuity (Snellen)	All > 20/40		
Contrast Sensitivity (Pelli-Robson) *(max = 2)*	1.83 (1.7-1.95)	1.69 (1.5-1.95)	1.66 (1.5-1.95)
Peripheral vision (lower 10°)	78.6 (72.4-84.2)	75.5 (65.6-81.3)	74.19 (66-80)
Falls Efficacy (FES-I) *(/100)*	10 (10-10)	11.5 (10-16)	16.75 (10-44)
Activities Balance Confidence *(%)*	100 (100-100)	94.9 (79.4-98.9)	89.5 (61.7-98.8)
General Health Questionnaire (GHQ) *(/ 21)*			
Somatic Symptoms	0.75 (0-2)**	1.63 (0-3)	2.86 (0-9)*
Anxiety/Insomnia	0.75 (0-2)	3.0 (0-6)	2.63 (0-6)
Social Function	1.5 (0-3)	5.75 (4-7)	6.88 (3-12)
Depression	0	0.5 (0-2)	0.25 (0-1)

† Percentage of subjects that reported falling once or more in the previous 12 months

* Significantly different to LROA

** Significantly different to older adults

5.2.2 Data Collection

Participants were fitted with reflective markers placed equidistantly between the head of the distal interphalangeal joints of the first and fifth metatarsals (toe marker) and on the anterior point of the calcaneus (heel marker) on both feet. On the right foot an additional marker was placed on the head of the 3rd metatarsal. Coordinates of each marker was sampled at 240Hz using a Vicon MX motion analysis system (Oxford Metrics, England). Spatial and temporal components of visual behaviour were measured using a high-speed ASL head mounted gaze tracker. The ASL controller produced a digital video image of the visual scene (sampled at 30Hz). A cursor (representing the point of gaze fixation) was superimposed on the visual image and was used to identify the features of the environment fixated by the participant during each trial. Two analogue channels corresponding to the vertical and horizontal components of visual behaviour (sampled at 120Hz and outputted from the ASL controller) were recorded in synchrony with the Vicon video data and used to assess the timing of each saccade.

5.2.3 Protocol

Participants walked at their own pace along a 5.5m path. Positioned 1.5 meters prior to the walkway end were a set of four LEDs mounted beneath a transparent acrylic sheet mounted flush with the rest of the floor. The LEDs were positioned in a triangular formation, with a fourth central LED in the centre of posterior edge, as shown in Figure 5-1. The medial and lateral targets were positioned 14cm from the central target. The forward target position was situated 10% of each participant's normal swing distance (during normal walking) anterior of the central target (~14cm).

A starting position was placed approximately four meters from the central LED. However, this was adjusted to match each participants natural stride length, so that after initiating gait with the left leg, the completion of the 3rd gait cycle naturally carried the right foot in close proximity to the central LED position at foot contact.

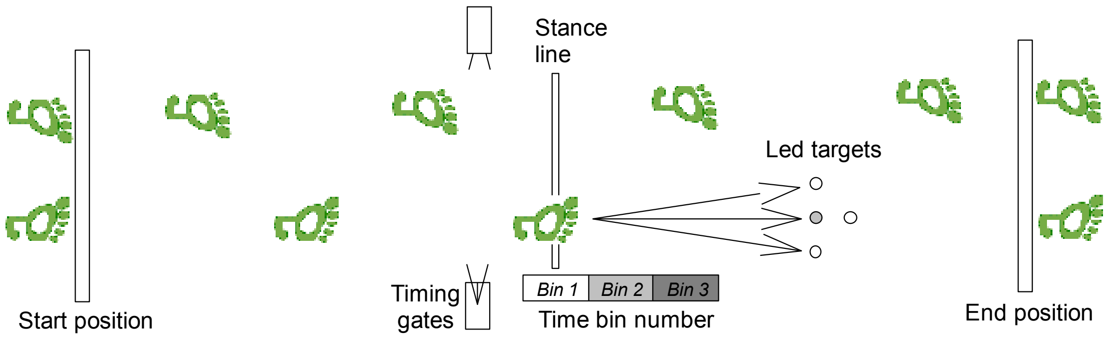
Prior to the experimental trials participants were requested to walk the length of the path seven times with no stepping constraints. Mean stride length was calculated for the latter five trials. A white line was placed on the floor a natural stride length from the central LED. Participants were instructed to place their right foot on the line whilst walking along the path. All participants achieved this with ease as it was situated at the natural footfall position. Optoelectric timing gates (metrodyne, Taiwan) stood 30cm prior to the white line. A pressure sensor was attached to the sole of the right foot (under the third metatarsal head) and covered with thin rubber tape. The timing gates and pressure sensor were connected to a separate computer, where a LabView program was used to manipulate the illumination of the LEDs at various stages of the participants step towards them.

During the participant's approach to the targets the central LED was always illuminated. During baseline trials this central LED would remain illuminated throughout the trial. However, during the experimental trials the position of the illuminated LED would jump to one of the other three LED positions. In all trials participants were instructed to place the 3rd metatarsal marker (positioned on their right foot) on to the illuminated LED target and to keep walking maintaining a consistent cadence until reaching the end of the walkway.

During the experimental trials the LED jump was programmed to occur once the pressure sensor under the participant's foot made contact with the floor (having broken the infrared beam between timing gates) with a delay of 0ms, 100ms or

200ms. All trials were randomised and a total of 60 trials were completed by each participant, constituting 5 trials in each condition (3 LED time delay conditions, 4 possible target locations). Control trials were repeated not only as baseline measures, but to encourage participants to maintain consistent cadence and to minimise the risk of participants guessing the direction of the LED change.

Figure 5-1 Schematic of experimental paradigm



5.2.4 Data analysis

Kinematic data were passed through a low pass FIR digital filter cut off at 5 Hz. Heel contact and toe-off events were defined using an algorithm adapted from Hreljac and Marshall (2000). 'Heel contact' was determined as the maximum vertical acceleration of the heel marker, identified by zero crossing in the jerk profile. 'Toe off' was determined as the minimum in vertical displacement of the toe marker, identified by zero crossings in the vertical velocity profile.

For each participant mean swing duration was calculated, and trials were grouped into 'time bins' according to when the LED jumped in relation to swing duration. There were three time bins specifying that the LED position was perturbed within: (1) 'Late stance' (defined as a period of 25% of swing duration, prior to foot off). (2) 'Early swing' (the first 25% of swing duration). (3) 'Mid swing' (the second 25% of swing duration). Trials containing LED jumps outside of these time bins were discarded, as the number of remaining trials was insufficient for statistical analysis. ANOVA showed no significant main effects of participant group on the time between LED jump and foot contact on the target in any target jumps directions. Mean time delays between LED change and foot contact are shown in Figure 5-2.

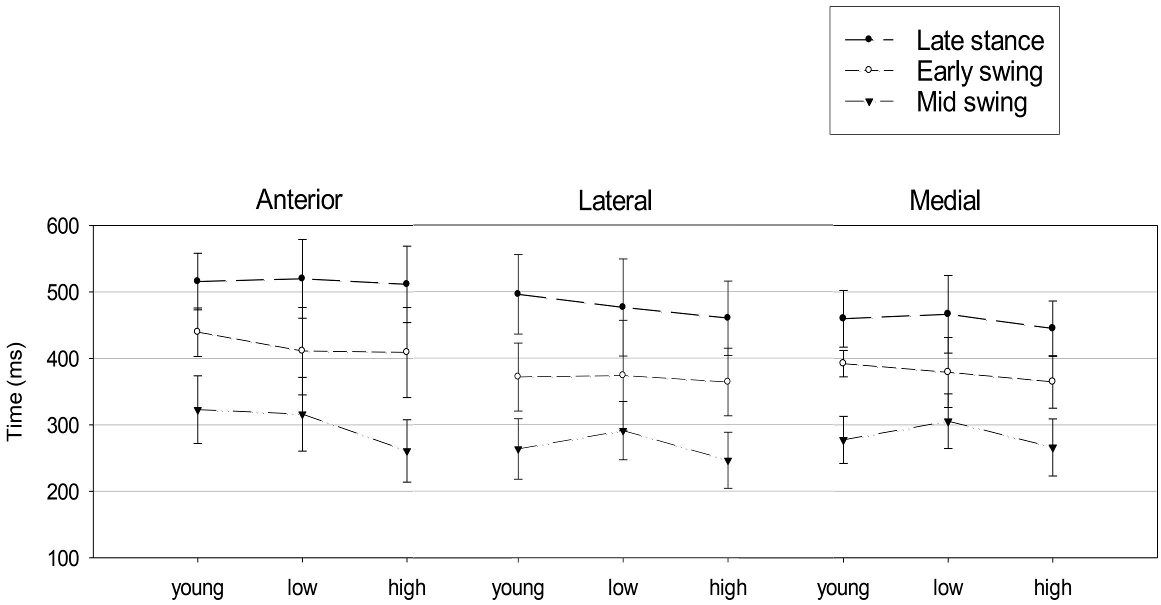


Figure 5-2 Plots represent the mean delay between the time the target jumped from its central position and foot contact on the target area. Error bars represent standard deviations (SD)

Coordinates of the Rmid marker were subtracted from the position of the central target. We used m/l displacement coordinates for analysis of trials consisting of medial or lateral target jumps, and coordinates of a/p displacement for anterior target jumps. A mean trajectory was calculated by synchronising trials according to the time of swing onset. Data from control trials were also processed in the same manner and plotted against experimental trajectories. Within subject standard deviations were calculated for control trial trajectories and multiplied by 2 (2SD). Each 2SD value was both subtracted and added to values from control trajectories (creating 'lower' and 'upper' standard deviation boundaries). A significant alteration in foot trajectory during experimental trials was quantified as an instance when foot position deviated outside the 2SD boundary.

Terminal foot error was assessed by taking the mean relative distance between the Rmid marker on the right foot (at foot contact) and target. In this way the direction of stepping error was taken in to account. During medial or lateral target jumps, foot placement error was calculated using medio-lateral coordinates. During anterior target jumps, anterior-posterior coordinates were used. The number of trajectory corrections executed during the swing phase toward the target was assessed using anterior-posterior displacement data of the additional marker placed on the head of the 3rd metatarsal on the right foot. These data were filtered at 10Hz using a dual-pass second order Butterworth filter, before calculating acceleration profiles. Corrections in foot trajectory were classified as a reversal in the acceleration of the right foot marker. However, reversals had to meet the following criteria previously used by Chapman and Hollands, (2006) and in data analysis described in Chapter 3: (1) reversals must not represent either peak acceleration or deceleration of the moving limb, (2) subsequent reversals must not occur within 25ms, (3) each reversal must achieve an amplitude of at least 10% of peak absolute acceleration (Chua and Elliott, 1993; Van Donkelaar and Franks, 1991).

The following variables were analysed using repeated measures ANOVA with a 3*3 design (age group*time bin): (1) Mean stance duration prior to swing towards the target. (2) Mean swing duration to target. (3) Foot placement relative to target position (foot placement error). (4) Foot placement variability (the mean of within subject standard deviation in foot placement error). (5) The percentage number of trials in which participants' foot trajectory surpassed the 2SD boundary. (6) Number of reversals in acceleration profile. (7) Saccadic reaction time to target jump. Post hoc analysis was carried out using one way ANOVA. Values representing the time between LED perturbation and divergence of foot trajectory outside 2SD of control trials were only analysed for trials when the target was perturbed following swing onset, due to the confound that no trajectory adjustment could be made whilst the foot was still in contact with the floor.

5.3 Results

5.3.1 Gait characteristics

During trials containing anterior and medial target perturbations a main effect of timing of LED perturbation showed that participants reduced swing duration in trials containing later target jumps ($F_{(2,42)} = 4.981$, $p < 0.01$) and ($F_{(2,42)} = 5.613$, $p < 0.05$). There was no significant effect of the time of LED perturbation on swing duration during lateral jump trials. There were no differences between participant groups in any of the experimental conditions.

There were no differences between participant groups in mean stance duration prior to the target directed swing in any target jump conditions. However, a main effect of timing of LED perturbation showed that during anterior target jumps stance was prolonged during later target perturbations ($F_{(2,42)} = 6.573$, $p < 0.005$). However, there were no effects of timing of LED perturbation on stance duration in either medial or lateral target jump conditions. Swing duration values are shown in Table 5-2.

Table 5-2 Swing durations during step towards target

Time Bin	Young	Low-Risk	High-Risk
Anterior target jump			
Late stance	480 ± 34	496 ± 35	465 ± 38
Early swing	519 ± 37	502 ± 54	475 ± 65
Late swing	498 ± 52	491 ± 49	431 ± 53
Medial target jump			
Late stance	457 ± 55	453 ± 57	430 ± 48
Early swing	448 ± 49	452 ± 69	423 ± 43
Late swing	440 ± 46	452 ± 49	414 ± 42
Lateral target jump			
Late stance	428 ± 34	441 ± 38	410 ± 33
Early swing	459 ± 35	458 ± 33	424 ± 42
Late swing	455 ± 39	464 ± 55	424 ± 43

Values represent swing duration (ms)

5.3.2 Foot placement error

5.3.2.1 Anterior target perturbations

Results for terminal a/p foot position relative to the end target position showed a significant interaction between participant group and timing of LED perturbation for anterior target perturbations ($F_{(4,42)} = 4.456$, $p < 0.005$). Both LROA and HROA were less accurate than young participants, but only during trials in which the target jump occurred following swing onset. Results for a/p foot placement error during anterior perturbations are shown in Figure 5-3.

5.3.2.2 Medial target perturbations

Results for relative foot placement error following medial target jumps showed a significant interaction between participant group and timing of LED perturbation ($F_{(4,42)} = 2.744$, $p < 0.05$). Both LROA and HROA demonstrated higher stepping error compared to young during trials where the target was perturbed in late stance and early swing, yet during mid swing target perturbations, only HROA demonstrated higher stepping error compared to young. These results are shown in Figure 5-4.

5.3.2.3 Lateral target perturbations

During lateral target perturbations main effects of timing of LED perturbation ($F_{(2,42)} = 38.185$, $p < 0.001$) and participant group ($F_{(2,21)} = 4.788$, $p < 0.05$) showed that m/l stepping error was higher in older adults, and also higher when the target perturbation occurred later in swing. These results are shown in Figure 5-4.

5.3.3 Variability of foot placement error

There were no significant effects of participant group or timing of LED perturbation on the variability of foot placement error during both anterior and medial target jumps. However, results during lateral target jumps showed significant main effects of participant group ($F_{(2,21)} = 4.498$, $p < 0.05$) and timing of LED perturbation ($F_{(2,42)} = 4.332$, $p < 0.05$), whereby variable error was higher in older adult groups, and increased following later target jumps.

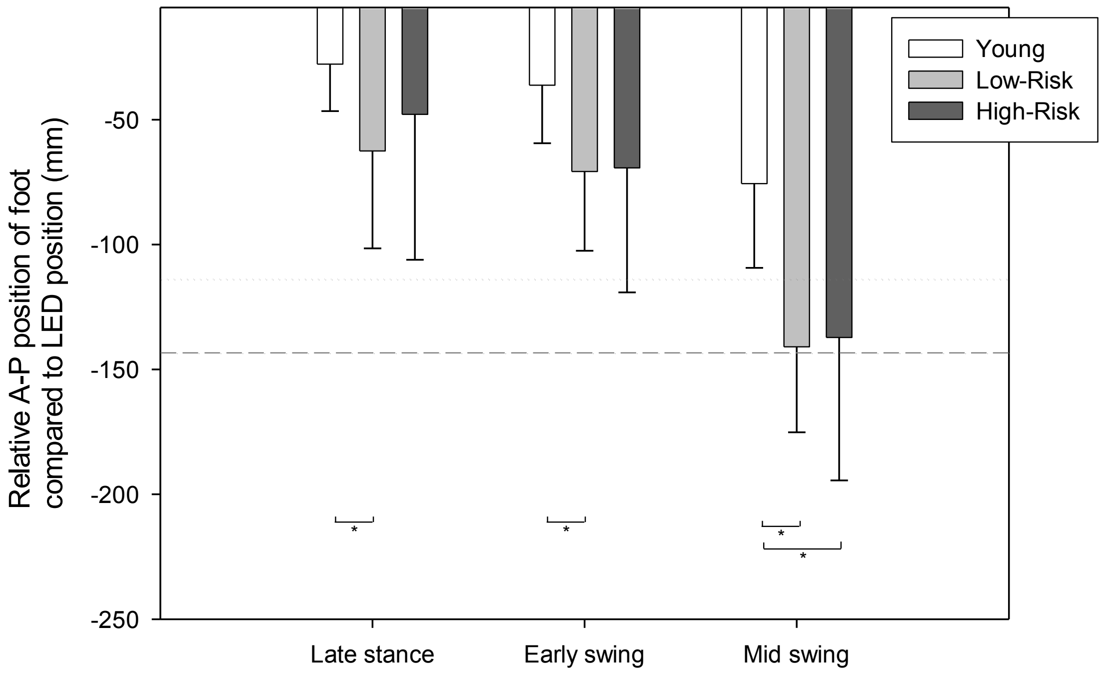


Figure 5-3 Bar plots represent relative anterior-posterior foot placement error with respect to the anterior target position. Negative values indicate that the foot was posterior to the target at foot contact. Error bars represent standard deviations. The anterior target was placed 10% of mean swing distance anterior of the central target. Gray lines represent the minimum (dots) and maximum (dashed) distance between anterior and central target.

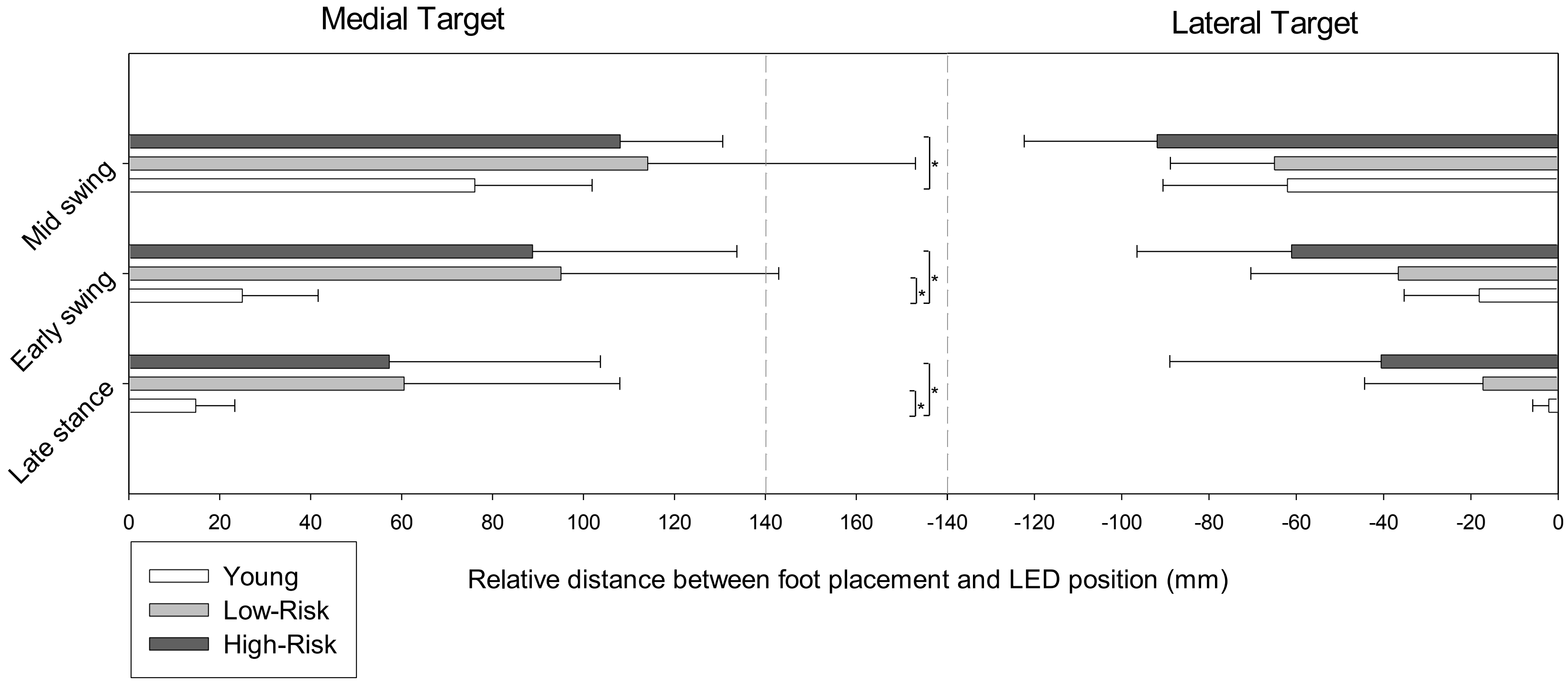


Figure 5-4 Bar plots represent the relative medio-lateral foot placement error with respect to the medial (left plots) and lateral (right plots) target position. For both plots, positive values indicate that the foot was positioned laterally to the target at foot contact. Error bars represent standard deviations. Gray lines represent the position of the central target relative to the medial (left line) and lateral (right line) targets.

5.3.4 Deviations in trajectory

A/P trajectory analysis (Figure 5-5) show that when LED perturbation occurred prior to swing onset, only young and LROA demonstrated significant deviations outside the 2SD boundary. However, when the target was perturbed following swing onset, no group produced significant deviations in a/p foot trajectory. M/L trajectory analysis (Figure 5-6) clearly demonstrates a progressive inability of older adults (particularly HROA) to produce alterations in foot trajectory during later target jumps, especially towards the medial target. Calculations of the time delay between target perturbation and deviation outside the 2SD boundary showed a significant main effects of participant group for both medial ($F_{(2,16)}$ = 3.796, p <0.05) and lateral ($F_{(2,21)}$ = 9.255, p <0.01) target perturbations. As shown in Figure 5-7, this result demonstrates that young adults made significant adjustments to foot trajectory with reduced latency compared to older participants. There was a significant effect of both participant group and the time of LED perturbation on the percentage number of trials where participants produced alterations in foot trajectory beyond the 2SD boundary following medial target jumps ($F_{(2,21)}$ = 5.402, p <0.05) and ($F_{(2,42)}$ = 8.872, p <0.05). This was also the case following lateral target jumps ($F_{(2,21)}$ = 3.680, p <0.05) and ($F_{(2,42)}$ = 14.851, p <0.001), showing that older adults were less able to produce significant alterations in trajectory as often as young participants in both m/l target jump directions (Fig 5-7).

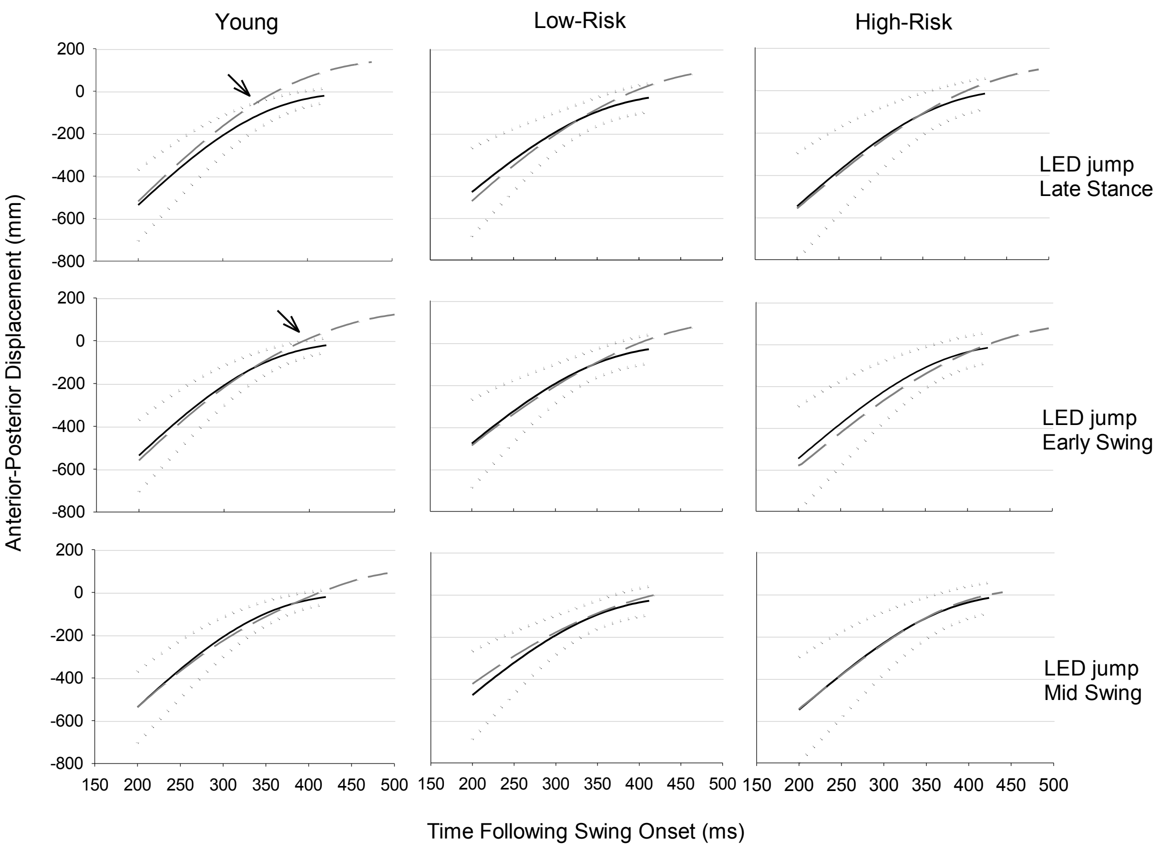


Figure 5-5 A/P displacement of the right foot during swing following anterior target jumps. Data at '0' ms on x-axis represents the point of swing onset. The black solid line represents the mean control trajectory. Black dotted lines indicate 'upper' and 'lower' 2SD boundaries, and the gray dashed line represents the trajectory during anterior target perturbations. Arrows indicate the point in which a/p displacement surpasses 2SD boundary.

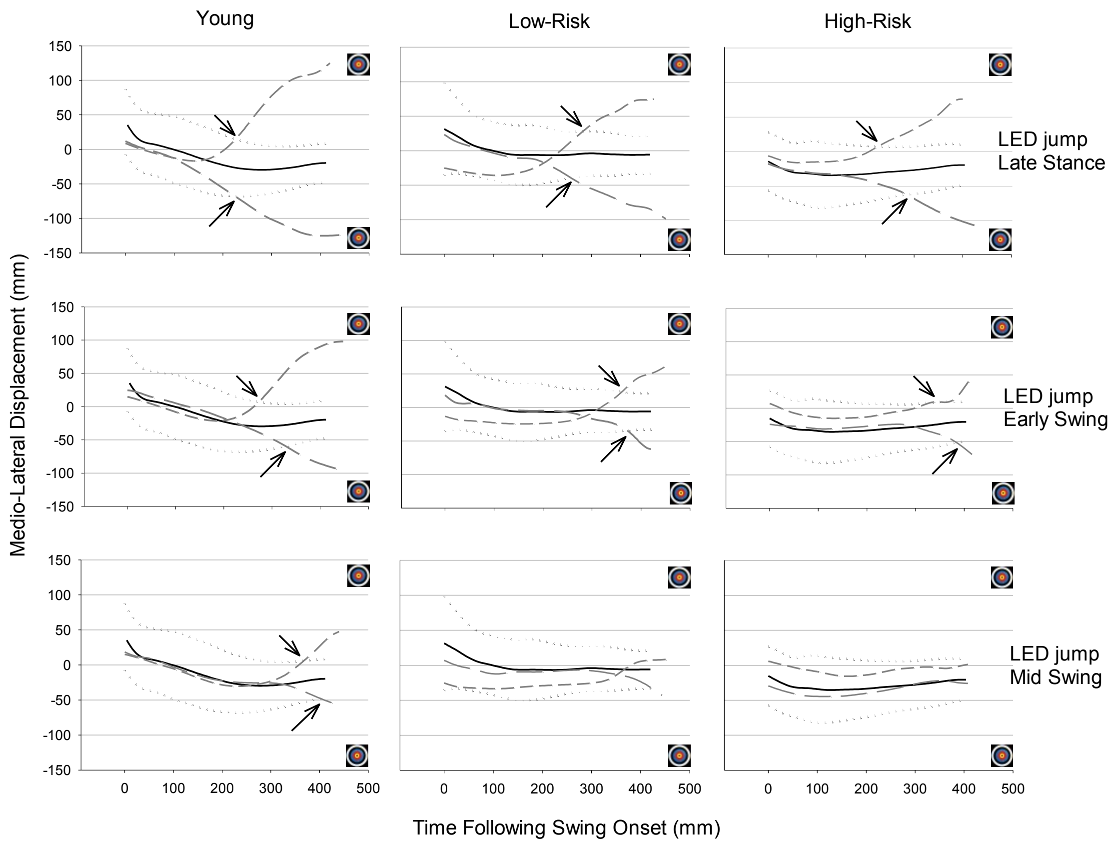


Figure 5-6 m/l displacement of the right foot during swing following m/l target jumps. Data at '0' ms on x-axis represents the point of swing onset, and '0' on the y-axis represents the position of the central LED. The black solid line represents the mean control trajectory. Black dotted lines indicate 'upper' and 'lower' 2SD boundaries, and the gray dashed line represents the trajectory during medio-lateral target perturbations. Traces plotted on the positive axis represent swing displacement during medial target jumps, and traces plotted on the negative axis represent swing displacement during lateral target jump. Target positions on the upper and lower right corners represent the m/l position of the medial and lateral target. Arrows indicate the point in which m/l displacement surpasses 2SD boundary.

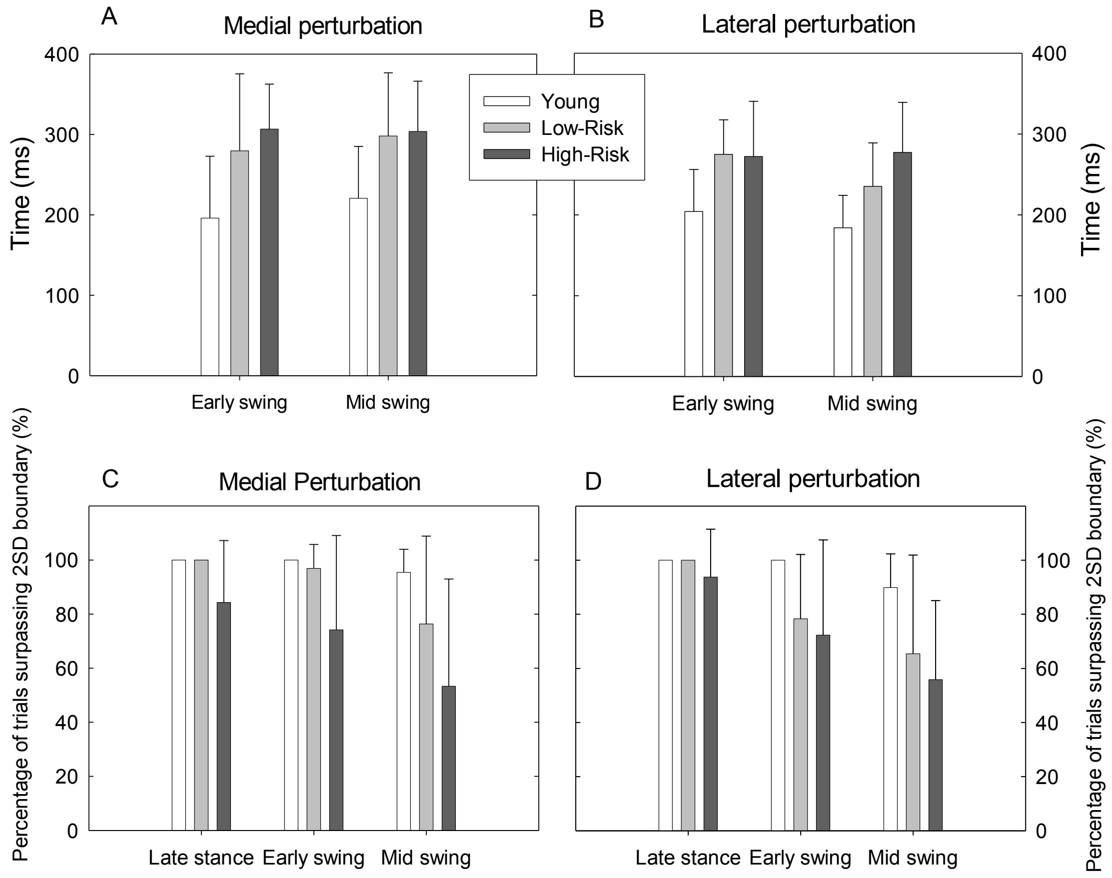


Figure 5-7 Bar plots represent the delay between LED perturbation and medio-lateral foot displacement deviating outside that of the 2SD boundary during medial (A) and lateral (B) target jumps. If foot displacement failed to surpass the 2SD boundary no value was assigned to that trial. Bar plots in figures C and D represent the total number of trials where participants adjusted foot trajectory beyond the 2SD boundary as a percentage of the total number of trials analysed in each condition. Error bars represent standard deviations.

5.3.5 Number of adjustments

5.3.5.1 Anterior target perturbation

Our results showed a significant interaction between participant group and timing of LED perturbation in the number of anterior-posterior acceleration reversals during anterior target jumps ($F_{(4,42)}$ = 2.655, p <0.05). HROA demonstrated a fewer number of adjustments compared to young adults when the target was perturbed following swing onset. HROA also made fewer adjustments compared to LROA during mid swing target perturbations (see Table 5-3).

5.3.5.2 Medial target perturbation

Counting the total number of reversals in medio-lateral foot acceleration during swing revealed a significant interaction between participant group and timing of LED perturbation during medial target jumps ($F_{(4,42)}$ = 2.745, p <0.05). LROA produced fewer medio-lateral adjustments compared to young when the target was perturbed prior to swing onset, and HROA made fewer adjustments compared to young during target perturbations during early swing (see Table 5-3).

5.3.5.3 Lateral target perturbation

There were no significant main effects of participant group or timing of LED perturbation on the number of acceleration reversals during lateral target jumps.

Table 5-3 Number of adjustments to foot trajectory during step towards target

Time Bin	Young	Low-Risk	High-Risk
Anterior target jump			
Late stance	2.29 ± 0.79	1.77 ± 0.52	2.16 ± 0.54
Early swing	2.93 ± 0.6	2.20 ± 0.61*	1.95 ± 0.83*
Late swing	2.35 ± 0.61	1.91±0.76	1.25±0.28* **
Medial target jump			
Late stance	2.37 ± 0.52	3.03 ± 0.84*	3.04 ± 0.83
Early swing	2.81 ± 0.88	3.68 ± 0.59	2.69 ± 1.01*
Late swing	3.73 ± 0.60	3.75 ± 0.85	3.27 ± 0.39
Lateral target jump			
Late stance	3.54 ± 0.75	3.36 ± 0.95	2.81 ± 0.42
Early swing	3.61 ± 0.96	3.20 ± 0.48	2.71 ± 0.42
Late swing	3.50 ± 0.92	3.50 ± 0.80	3.01 ± 0.50

* Significant difference to young adults

** Significant difference to Low-Risk participants

Table 5-3 Values represent the number of acceleration reversals of the foot during swing in the (1) A/P plane during anterior target jumps, (2) M/L plane during medial target jumps. Acceleration reversals were discounted if representing peak acceleration or decelerations, was within 25ms of a separate reversal, or was below 10% of peak acceleration.

5.3.6 Saccadic response time

Results showed significant main effects of group in the time between target perturbation onset and the following responsive saccade towards the new target position. Compared to young, older adults (particularly HROA) exhibited significantly longer saccadic response times during anterior ($F_{(1,21)}$ =5.156, $p < 0.05$), medial ($F_{(1,21)}$ =4.137, $p < 0.05$) and lateral ($F_{(1,21)}$ =3.749, $p < 0.05$) target jumps (see Figure 5-8). Following target perturbations in all directions saccadic latency in HROA was approximately twice that of young participants.

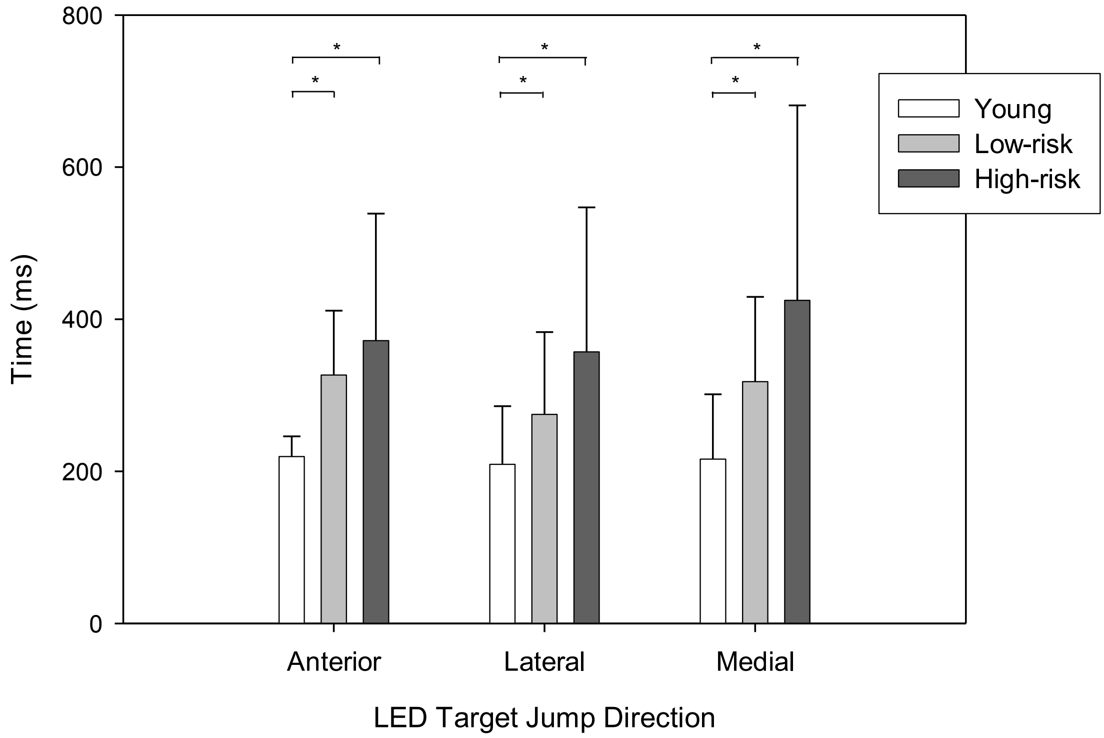


Figure 5-8 Bar plots represent the time between target jump and the following saccadic eye movement towards the target. Each bar represents pooled data for all target jump directions. Error bars represent standard deviations.

5.4 Discussion

The aim of the current study was to test the hypothesis that differences exist between young and older adults in the ability to produce visually guided online correction to foot trajectory in response to an unexpected target perturbation. Our result show age-and fall-risk related differences in the ability to make online stepping adjustments during the swing phase characterized by a reduction in the number and magnitude of adjustments to foot trajectory made during swing resulting in lower stepping accuracy.

5.4.1 Medio-lateral target perturbations

On average, both LROA and HROA produced m/l stepping errors of 110mm, compared to errors of 70mm in young participants following mid-swing medial target jumps (Fig 5-4). These significant differences between young and older adult groups were more apparent during trials when the target moved earlier in swing and late in stance, where stepping errors in older adults were three times that of young. These results extend to lateral perturbations, although stepping errors in LROA are more comparable to young participants when the target was perturbed early in swing. Within LROA the apparent improvement in stepping performance during lateral target jumps is supported by the similar number of m/l adjustments made compared to young participants. A reduced capacity for generating medial adjustments, mainly shown in older adults is probably due to the additional postural demands associated with rapidly reducing the base of support, and placing one foot in front of the other, increasing the risk of the legs colliding (Maki et al. 2000; Maki and McIlroy, 2001). Nevertheless, HROA were able to produce significant alterations in foot trajectory in 60% of trials during both medial and lateral jumps occurring in mid swing (Fig 5-7c&d). This suggests that older adults are able to use vision as late as mid swing to inform changes in trajectory. However, the clear discrepancy in final stepping error illustrates the clear age-and fall-risk related differences in response magnitude.

5.4.2 Anterior target perturbations

None of the participant groups produced significant deviations in a/p displacement when anterior target perturbations occurred after swing onset (Fig 5-5). However, young participants significantly prolonged swing duration and demonstrated a superior ability to produce an accurate step onto the anterior target, as a/p errors were approximately half that of older adults (Fig 5-3). Indeed, foot placement error demonstrated by HROA following mid-swing target jumps would suggest that no adjustments were made. These findings are supported by the greater number of a/p adjustments in foot trajectory in young adults (as shown by the number of reversals in acceleration). Increases in stride length are usually generated through two key mechanisms. Firstly, increased activity in the rectus femoris (hip flexor) and tibialis anterior (ankle flexor) maintains leg flexion for a longer period, meaning the foot contacts the floor later, and therefore further. Secondly, additional forces are generated within the biceps femoris (hip extensor) and soleus (ankle extensor) in the ipsilateral leg, providing increased anterior propulsion of the centre of mass (Varraine et al. 2000). In addition, when the target was perturbed during late stance further propulsion of the centre of mass may have been generated in the soleus of the right leg prior to swing onset. Therefore, visually guided online adjustments to anterior target jumps appear to have been incorporated in to the stepping action through a synergy of adjustments propelling the centre of mass towards the new target position. As a result we are reluctant to assign criteria to assess when adjustments occurred in response to anterior target jumps. Nevertheless, the differences in stepping error in conjunction with the number of adjustments made indicate that older adults are less able to produce the supplementary propulsion of the centre of mass along with other postural adjustments necessary to increase swing amplitude.

5.4.3 Peripheral vision used to inform adjustments

During precision stepping tasks visual information is most useful during the preceding stance phase of each step (Hollands et al. 1995; Hollands and Marple-Horvat, 1996; 2001; Chapman and Hollands, 2006). Therefore, in the earliest time bin conditions, the period following target perturbation and swing onset may have been particularly useful in affecting necessary alterations in movements planning and anticipatory adjustments. However, following a target jump the delay prior to swing onset is likely to have been too short to be of significant use. Certainly the saccadic response latencies were too long (even in young adults) to provide time fixating the new target position during stance (Fig 5-8). Our results show that latencies in saccadic response are similar to the delay between target perturbation and significant deviation of foot trajectory in all groups (Fig 5-7a&b). Interestingly, as deviations of the foot were only detected once the trajectory surpassed 2SD boundary, the start of the divergence must have occurred prior to this point. Taking in to account a minimal neural lag of ~120ms, peripheral vision must have been used in an online manner to inform initial deviations in trajectory, even in HROA. Whereas previous findings have shown that older adults are able to produce reactive stepping responses in the absence of a redirection of visual fixation (Zettel et al. 2005; 2008), our findings suggest that both young and older adults are able to perform voluntary adjustments to a step prior to gaze fixation on a new target position. This finding supports previous work demonstrating that peripheral vision is sufficient to detect and guide an appropriate step over an obstacle (Marigold et al. 2007), although this is the first instance where peripheral vision has been shown to guide alterations in a step made to a precise location.

Reynolds and Day (2005b) suggested that vision of both the target and the foot can be used during the latter half of swing to improve stepping accuracy. It was proposed that vision was used to inform error corrections based on an assessment of either the relative error between the foot and target, or the current heading error once the foot has travelled a certain distance. Our findings suggest that finite online corrections such as these are not evident in older adults, due to their reduced number of adjustments in foot trajectory. Although our findings suggest that LROA and HROA can use vision in an online manner to produce significant medio-lateral corrections to the foot during swing, the scale and consistency with which the alterations occur appear to define the differences between the groups. This is shown in the clear differences in final stepping error where HROA appear not to make any notable deviation from the central target when the LED was jumped mid-swing.

5.4.4 Saccadic response time

Our results show an increased delay between medio-lateral target perturbations and trajectory adjustments in HROA compared to young participants (Fig 5-7a&b). Therefore visually guided corrections to foot trajectory in HROA are characterised not only by reduced response magnitude (Fig 5-4&6), but also by increased response latency. One possible explanation for this is the remarkable contrast in saccadic response times, where HROA take twice as long to initiate a saccade towards the target following perturbation compared to young (Fig 5-8). These response times are consistent between the conditions dictating target direction, justifying our argument for age- and fall-risk related differences in this measure. In order to fixate a new target position following perturbation, participants had to make a pro-saccadic response, a behaviour shown repeatedly to be preserved with increased age (Pratt et al. 2006; Gotlob et al. 2007). However, there is evidence for decline in visual tasks requiring greater cognitive control such as saccadic response inhibition (Davidson and Knox, 2002; Rogers and Monsell, 1995), multiple object tracking (Moschner and Baloh, 1994; Sekuler et al. 2008) and visual search function (Madden and Whiting, 2004). Values for our young group are comparable to those previously shown (Pratt et al. 2006). Therefore the relative increase in response latency in older adults is likely to be linked to high demands on postural control within the task. Deficits in older adults have been shown in visual attention (Madden, 2007) and attention switching capacity during postural tasks (Maki et al. 2001). Furthermore, older adults rely more on cognitive resources (Brown et al. 1999; Brauer et al. 2002; Chen et al. 1996; Shumway-Cook and Woolacott, 2000) and visual information to control posture. Therefore, as postural control and other task requirements compete for attention, areas associated with rapid visual responses to task constraints are not prioritised. However, a reallocation of attention is unlikely to be the sole cause of the comparative inability of LROA and HROA to generate online changes to foot trajectory.

5.4.5 Decline in locomotor function

Age-related decline in physiological function is a potential mediator of the capacity to produce prompt corrections to limb position during swing. However, Luchies et al. (1994) showed that musculoskeletal function (flexion/extension torques and ROM) of lower limbs in older adults were adequate to withstand rapid compensatory steps. Guiding the foot to an intended foot-fall location places demands on sensory and motor functions. Age-related somatosensory decline reported in older adults (Skinner et al. 1984; Horak et al. 1989; Robbins et al. 1985) acts to reduce the proprioceptive information required to calculate limb position. In addition to limitations in sensory feedback reduced muscle strength within the hip flexors/abductors and knee extensors is often inadequate to generate sufficient force required for rapid movements of lower limbs (Maki and McIlroy, 1999). The hip aductors and abductors play an important role in the maintenance of lateral stability (Rogers et al. 2003), and when producing medio-lateral adjustments of the lower limbs, such as those required in the current study. During postural perturbation studies deficits in such areas result in the necessity to take multiple steps to recover balance (Maki and McIlroy, 2003; Luchies et al. 1994; McIlroy and Maki, 1996) or the failure to recover balance (Pavol et al. 2002). However, during their first compensatory step in response to perturbation older participants demonstrate similar response timing and stepping amplitudes compared to young (Luchies et al. 1994; McIlroy and Maki, 1996). Due to the additional number of subsequent steps required, older adults appear to be less able to control the centre of mass as well as the swing and landing phase of the foot. Although these previous results show that older adults are able to generate stepping responses with similar latencies compared to young adults, it also leads to the suggestion that older adults may be reluctant to produce rapid corrections to foot trajectory during a step as they are less able to provide adequate steps for recovery. After all, older adults are known to adopt a conservative gait strategy (keeping the centre of gravity within the base of support) and prioritise the conservation of balance (Shumway-Cook et al. 1997; Brown et al. 2002) when in situations containing postural threat.

This suggestion is further supported by the reduced rate of force produced by older adult 'non-fallers' in their supporting limb in response to a lateral target jump (Tseng et al. 2009). It is likely that this behaviour would be even more apparent in HROA and therefore may represent a major factor contributing to the ability to make online adjustments to foot trajectory. However, Tseng et al. (2009) showed no differences in terminal foot placement between young and older adults. Our results show that stepping errors were more comparable between young and LROA following target jumps to the lateral side, compared to the medial and anterior direction. While this suggests that both LROA and HROA have greater difficulty producing medial and anterior adjustments, it also poses an interesting question: why did LROA show significantly higher stepping error in the current study? Tseng et al. (2009) found that older adults, whilst producing a reduced rate of lateral force in the supporting leg, the force exerted was prolonged compared to young, as was the entire swing duration. Therefore, older adults may have improved the accuracy of their terminal foot position through an extended moderate adjustment in trajectory. Whilst this may have been possible during a single step, we found no significant differences in swing duration during m/l target jumps, suggesting that the momentum generated through walking prevented extensions to swing duration seen by Tseng et al. (2009), resulting in a decline in foot placement accuracy in older adult participants.

5.5 Summary and conclusions

The current study demonstrates clear differences between young LROA and HROA in their abilities to produce online corrections to unexpected target jumps. The causes for differences between participant groups are likely to be associated with task prioritisation, sensory-motor deficits and visual function. To our knowledge this is the first occasion where increased saccadic response latencies have been described in older adults during adaptive locomotion. During daily locomotor activities, delays in redirecting visual fixation towards environmental constraints would be expected to jeopardise the ability to make appropriate responses in sufficient time, increasing the likelihood of falling. Reynolds and Day (2005a) showed that rapid alterations in foot trajectory can occur with or without balance constraints in young adults. Future work should investigate the limitations imposed by postural constraints of locomotion on the capacity of older adults to produce online corrections to foot trajectory.

Chapter 6

General Discussion

The rationale for the work described in this thesis was based on previous findings describing altered visual sampling behaviour in older adults (particularly HROA), whereby gaze fixation is redirected towards subsequent stepping constraints prior to completion of a step into an initial target box. A relationship was observed in older adults whereby earlier gaze transfers from the target correlated with increased medio-lateral stepping error (Chapman and Hollands, 2007). However, the authors were unable to provide clear evidence for a causal relationship between the visual behaviour described and a reduction in stepping performance. It was therefore our intention to investigate this relationship further in our first study (Chapter 3).

6.1 Improvements in stepping performance

Our findings clearly showed that when older adults voluntarily prolonged fixation of the initial target, stepping performance was comprehensively improved by means of a reduction in: 1) medio-lateral stepping error, 2) medio-lateral stepping variability, 3) number of functional errors (foot contacting the target edges) (Fig. 3-4a,b&c) These improvements occurred in the absence of any alterations in preceding stance, or swing phase durations, suggesting that improvements described were not a consequence of participants slowing down, or altering stride parameters. Additionally, improvements in stepping occurred in the absence of differences in the number of alterations in foot trajectory during swing. This suggests that improved stepping was not primarily due to corrections in foot heading error towards the end of swing. We suggest that voluntarily prolonging visual fixation on the target postponed the redirection of attention towards future constraints, and therefore allowed a more comprehensive planning of the entire swing towards the target. These findings indicate that transferring gaze from an intended stepping location has direct adverse consequences on final stepping error. This presents a clear need to investigate possible factors that may drive premature redirection of visual fixation and attention towards future constraints in older adults when walking.

6.2 Anxiety and visual strategy

We investigated a possible relationship between increased state anxiety and visual sampling behaviour (Chapter 4). We assessed anxiety/FOF through a self-reported anxiety questionnaire, where participants were asked to respond according to how they felt when stepping into the target box. We also measured EDR, as an indication of physiological arousal. Our results showed that self-reported anxiety increased dramatically as task complexity grew, but only in HROA (Fig 4-6). In addition, we found no significant differences between HROA and LROA in scores of Spielberger's trait anxiety inventory (Table 4-1), assessed prior to the experimental session. This suggests that the heightened anxiety reported by HROA was a consequence of the demands of the locomotor tasks, rather than imbalances in trait anxiety between groups. When negotiating constraints in the travel path HROA also showed a 150% increase in physiological arousal compared to LROA. While this measure perhaps lacked the sensitivity required to detect physiological changes between task conditions, we suggest that this be considered a general validation of the increased anxiety self-reported by HROA compared to LROA. Furthermore, we showed that gaze transfers occurred earlier in participants reporting higher anxiety levels (correlation: $r=-0.77$) (Fig 4-7), and that when adjusting for anxiety scores no significant differences existed between HROA and LROA groups in the time of gaze transfers in the most complex task condition. Although we cannot conclude a causal link between the two, this relationship leads to a number of suggestions concerning how increased anxiety may drive changes in visual sampling behaviour.

Saccades are only made in the direction that attention is oriented (Hoffman and Subramaniam, 1995), and heightened anxiety has been shown to alter the allocation of attention during locomotor tasks (Gage et al. 2003). As HROA self-reported higher anxiety levels when the constraints following the target presented greater postural threat, we suggest that attention was transferred towards the future constraints earlier, driving the premature saccades from the stepping target in order to maximise the time available for the CNS to process visual information regarding the imminent obstacles in their path. The allocation of attention may also be affected by a reduction in available cognitive resources; a factor shown to be affected by increased anxiety (see Woolacott and Shumway-Cook, (2002) for review).

6.3 Visual sampling during approach

As an extension of our investigation in to the mechanisms underlying early gaze transfers, we conducted an analysis describing the duration and frequency of fixations to each of the stepping constraints during the participants' approach to the target. Previous studies have shown that prior to negotiation, the final fixation period on an initial target is longer in HROA (Chapman and Hollands, 2006; 2007). However, earlier gaze transfers from the initial target suggest that older adults prioritise future targets in their path. Our results show that during their approach, HROA reduce the frequency of saccades made to constraints following the initial target, and increase the total fixation period on the initial target prior negotiation (Fig 4-3&4). Therefore, our findings add to the previous literature showing that compared to LROA, HROA prioritise visual information regarding the first constraint requiring negotiation during their entire approach. Furthermore, HROA only appear to prioritise the acquisition of visual information regarding subsequent constraints when executing the final step into the initial target.

An increased tendency for HROA to transfer gaze fixation earlier during target negotiation may be a direct consequence of the reduced visual information acquired regarding future constraints during the approach. This potential link may be exacerbated by other factors described above, such as increased anxiety and deficits in visual information processing within the CNS. There are a number of factors that may influence, and provide an explanation for the differences in visual strategy adopted by LROA and HROA during their approach to the target. Presumably LROA 'preview' future constraints in their path as a means of gathering visuospatial information used to plan appropriate stepping actions in a feed forward manner. Zettel et al. (2005; 2007) showed that compared to young, older adults made more frequent downward saccades to gather visual information regarding surrounding environmental features prior to a postural perturbation. It was suggested that this behaviour improved stepping accuracy, and may serve to compensate for deficits in visual spatial memory. However, during a compensatory step older adults can use previously acquired visuospatial information to inform rapidly induced compensatory steps (Zettel et al. 2008), although it was not shown for how long such information can be retained prior to perturbation. Furthermore, these findings relate to an internal spatial map formed from a stationary position. During walking rhythmic oscillations of the body coupled with optic flow variables may impede the retention of spatial information in older adults. As a result, HROA may be unable to effectively store and retrieve prospective visual information (regarding multiple constraints) to the same extent as LROA during locomotion. Therefore, 'Preview' fixations of future constraints may be ineffective in HROA, and removed from the visual strategy as a result. Although age-related decline in working spatial memory has been shown previously (Lustig et al. 2001), we are unable to illustrate such differences between participant groups. Therefore, a clear need remains for further investigation into the consequences of altering visual information acquired during the approach to stepping hazards, especially with reference to the behaviours of young adults.

Another possible reason for reduced frequency of ‘preview’ fixations may be the prioritisation of visual/head stabilisation. The avoidance of head and eye movements may transmit several advantages associated with reducing postural instability (Hunter and Hoffman, 2001), providing a steady platform for the acquisition of vestibular and visual information (Paquette et al. 2006; Keshner and Chen, 1996), thus improving the fidelity of information derived concerning self-motion (Brandt et al. 1973). HROA may adopt a strategy such as this to minimise the need to update visuospatial working memory, that would likely develop following changes is head position and/or gaze fixation (Admiraal et al. 2004).

6.4 Corrections to foot trajectory late in swing

The improvements shown following intervention in Chapter 3 may be due to additional time fixating the target late in swing, as opposed to control conditions where gaze was redirected away earlier. Extra time fixating the target may have provided useful information for the guidance of supplementary corrections in foot trajectory, resulting in a more accurate step. However, when comparing control and post-intervention swing trajectories, we found no differences in the number of adjustments made during swing, suggesting that stepping may have benefited through improved planning. During a very similar task Chapman and Hollands (2006) showed no differences in the number of adjustments made during swing under conditions of visual occlusion during stance, compared to swing. This was shown in both young and older adults. The authors suggested that vision was not used in an online manner to inform alterations in foot trajectory in any of the participant groups. Reynolds and Day (2005a; 2005b) had previously shown evidence for online corrections to foot trajectory following a change in target position in young adults. However, little was known regarding possible age-related decline in this area, particularly not during walking tasks. The study described in Chapter 5 was designed to address these issues.

During medial and lateral target jumps, we found that older adults were able to make a surprisingly high percentage of significant alterations in foot trajectory during swing, even when the target moved mid-swing (significant deviations in 60% of trials) (Fig 5-7c&d). However, it is the magnitude of the deviations in trajectory that describe the clearest age-related differences, shown by the final foot placement errors (Fig 5-3&4). When the target had moved late in stance or early in swing, in all directions older adults' (particularly HROA) final stepping error was approximately double that of young participants. Furthermore, when the target moved mid-swing, young participants were able to make adjustments so that, on average, the foot landed approximately equidistant between the central and new target position. In contrast, with the exception of lateral target jump, older adults mean foot placement error indicated that almost no deviation had been made from the central target position. Therefore, the results for foot placement error suggest that our criteria used to quantify a significant deviation in trajectory were too lenient, and the magnitude of the corrections made may not be substantial enough to be of functional significance.

Our results support the findings of Reynolds and Day (2005a; 2005b) as young adults are clearly able to use visual information to amend foot trajectory in response to an altered target position. Reynolds and Day (2005b) also suggested that vision was only used to inform corrections in the latter half of swing. Our results and those shown by Tseng et al. (2009)

support this suggestion, but also add to the previous literature showing that the magnitude of these corrections is contingent on the time in which visual information (regarding the new target position) is made available during the stepping action.

Many factors are likely to contribute to age- and fall-risk related decline in the ability to produce online correction to foot trajectory. We have shown that peripheral vision was used to inform initial corrections in all participant groups. However, in older adults the clear delays shown in saccadic latency would impose limitations on the accuracy of visual information obtained regarding the new target position (Fig 5-8). Older adults choose to fixate a stepping constraint sooner in their approach, compared to young adults (Di Fabio et al. 2003b; Chapman and Hollands, 2007). It is suggested that this behaviour is a compensation for deficits in processing of visual information in the CNS. It is possible that the differences in saccadic latency shown between young, LROA and HROA in Chapter 5 may be a product of slowed visual information processing. This seems unlikely, as pro-saccadic 'express' eye movement responses are comparable in older compared to younger adults (Pratt et al. 2006; Gotlob et al. 2007; Yang et al. 2005). Increased saccadic latency may therefore represent a certain degree of saccadic inhibition, possibly to preserve visual stability (Admiraal et al. 2004), in a similar manner to that discussed during the approach to the target in Chapter 4. However, the inhibition of a saccade places a demand on cognitive function, which is likely to be allocated elsewhere considering the demands of the task (Brauer et al. 2002). Therefore, increased latencies in saccade production may be due to older adults not attending to the movement of the target to the same extent as young participants. This proposal can be explained, in part, by the 'oculomotor readiness hypothesis' (Klein et al. 1980; Rizzolatti et al. 1987). The hypothesis postulates that saccadic latencies are reduced when attention is allocated towards the new saccadic location. Other previous work supports this finding, but has also shown reduced saccadic latencies when participants were expecting the target to appear in a different location (Shepherd et al. 1986). Collectively this suggests that if younger adults attended to all the possible locations where the target may move and older participants prioritised the allocation of attention towards postural control, saccadic response time is likely to be considerably shorter in young participants following the target jump.

Increased saccadic latency and the likely associated delays in retrieving precise information regarding the new target location may help to explain the increased delay between the target jump and a significant deviation in foot trajectory in older adults. However, it is unlikely to justify differences in the magnitude of final foot placement error. Although Tseng et al. (2009) showed no differences between young and older adults in stepping error following lateral jumps; they demonstrated a clear reduction in the magnitude of lateral force produced from the supporting leg in older adults. There are various age-related deficits in musculo-skeletal function that could potentially influence the magnitude of alterations made during stepping actions. However, in response to postural perturbations, older adults have been shown to produce compensatory steps with similar latencies and scaling as their younger counterparts (Luchies et al. 1994; McIlroy and Maki, 1996), thus indicating that older adults are able to execute rapid movements in the lower limbs. It is the subsequent finding that older adults are more likely to take additional steps following a perturbation evoked compensatory step (Maki and McIlroy, 2003; Luchies et al. 1994; McIlroy and Maki, 1996). Therefore, we propose that the failure of older adults to accomplish adequate online adjustments in Chapter 5 can be explained by a reduced capacity to regain balance, rather than an inability to make rapid adjustments to the lower limbs. In short, older adults prioritised postural stability over the requirements of the task; a common finding in aging research using dual-task paradigms (Brauer et al. 2002). This presents a clear opportunity for future work; to identify the relative contribution of balance constraints to online corrections in the lower limbs in older adults. Whereas Reynolds and Day (2005a) showed that response latencies in young adults were comparable both with and without balance constraints during a single step, our results suggest that this finding is unlikely to extend to older adult populations, particularly during walking tasks.

6.5 Limitations and directions of future research

As discussed previously, our assessment of significant deviations in foot trajectory in Chapter 5 was perhaps too lenient, as 60% of HROA were deemed to successfully adjust their swing trajectory (Fig 5-7c&d). Although this method has been used in a similar experiment (Tseng et al. 2009), deviations in foot trajectory would likely take a variable amount of time to reach the 2SD boundary. Therefore, we suggest that using these values as a means of determining the time of deviation is not ideal. An important aspect of the study was to investigate online adjustments to swing whilst walking, as opposed to taking a single step. Therefore, the position of the stance foot prior to swing towards the target was inevitably variable. We decided that this limitation would impose too many errors on an assessment of when deviations started. Furthermore, this measure was not directly related to our hypothesis. Future work should be directed towards assessing the latency of online responses in young and older adults whilst walking, using measures such as the electro-myography recordings used by Reynolds and Day (2005a).

The recent publication by Tseng et al. (2009) demonstrated age-related differences in online adjustments to a target perturbed laterally. Our findings provide novel information regarding adjustments made to targets moved in various directions, visual response times, comparisons between LROA and HROA, all during walking compared to a single step. However, Tseng et al. (2009) elegantly demonstrated differences in the ground reaction forces in the supporting limb during the step onto the target. Using a measure such as this would have benefited our study, providing information regarding the role of the supporting limb particularly following anterior target jumps.

Due to limitations imposed by interference between the motion tracking system and head-mounted gaze tracker, the kinematic data presented in this thesis only represent foot position. A full kinematic analysis including centre of mass measures would have benefited the work, particularly in Chapters 3 and 5. Also, differences in head movements both pre- and post-intervention (Chapter 3) and during the approach to the target (Chapter 4) would have provided further insight in to behaviours relating to head stabilisation and alteration in head angle. If head angle is coupled to the early transfer of gaze from a stepping target (participants lift their head as they redirect gaze), there are further implications for the control of posture, particularly for individuals using multifocal spectacles (Johnson et al. 2009). Future work should examine a possible relationship between head angle and maladaptive visual behaviours, but also look to include older adults who require the use of spectacles when walking. We were unable to include spectacle wearers due to the errors that were imposed in the gaze tracking measure. Future work could include this demographic if the timing of saccades were assessed through other means, such as electrooculography. Although this measure does not provide an accurate spatial resolution regarding gaze fixation, it would be an important progression to examine whether differences in visual strategy exist between LROA and HROA in a wider population, and whether these differences relate to stepping performance in a similar manner to that shown in this thesis.

Our results showed significantly longer saccadic response latencies in older adults (particularly HROA) (Fig. 5-8). The reasons underlying these differences are unclear, as saccadic response times have been shown to be preserved in older age (Pratt et al. 2006; Gotlob et al. 2007). We suggest that increases in saccadic response latency are related to the relatively high postural demands of the task, as eye movement latencies have been shown to increase when they involve cognitive organisation (Davidson and Knox, 2002; Rogers and Monsell, 1995). We showed that participants of all ages were able to initiate online alterations in trajectory by detecting target jumps using peripheral vision. However, an inability to quickly fixate an unexpected feature in the environment is likely to detriment the capacity to initiate and guide appropriate responses, particularly during locomotion. These findings highlight a need for future work to investigate the reason for increased saccade latencies in older adults. An appropriate way of investigating the influence of attention on saccadic latency would be to increase cognitive load using a dual-task paradigm during a similar locomotor task. The relative contribution of the postural demands of the task could also be assessed by removing balance constraints and assessing possible alterations in saccadic latency.

Due to the time taken to analyse the temporal and spatial aspects of visual behaviour, we were unable to include a young participant group in Chapter 4. Information regarding anxiety and arousal levels in young participants would have provided a useful comparison. However, we suggest that the comparison between LROA and HROA presents a more informative description of the attributes associated with early gaze transfers. The assessment of anxiety presents many challenges, as physiological measures are susceptible to environmental factors such as room temperature. However, by controlling room temperature and imposing compulsory rest periods every five trials, we attempted to minimise these inevitable limitations, and most importantly, ensured that conditions remained consistent between participants. However, our self-reported measures may be vulnerable to subjective bias within a participants' response, particularly as the inventory was completed retrospectively during rest periods between trials. In addition, we presented trials in a randomised order in an attempt to reduce task predictability. A more accurate reflection of state anxiety may have been achieved if participants made responses following a blocked set of trials containing the same constraints. This may also have contributed to improved stability of the EDR signal. Although we have shown evidence for a relationship between increased anxiety and maladaptive visual behaviour, we cannot suggest a causal link between the two. This presents an interesting prospect for future work. We suggest that an intuitive method of testing this might be to induce stress in young and older participants, and record their concurrent visual and stepping behaviours. Previous studies have induced posture related anxiety by placing participants on a raised platform (Carpenter et al. 1999; 2001; Gage et al. 2003). However, using these methods presents a number of potential confounds, as visual strategy is likely to be driven by anxiety regarding specific constraints in the travel path, rather than a generic increase in FOF.

Future studies may look to develop strategies for training older adults to maintain gaze fixation on an intended stepping location, similar to the behaviour shown following intervention (Chapter 2). However, we suggest that attempting to address longer term alterations visual strategy is best achieved through designing appropriate rehabilitative techniques aimed at the original causes. For example, changes in visual behaviour may be realised through programs aimed at reducing anxiety/FOF, whereby the redirection of attention away from a current stepping action might be postponed as a consequence of lowered anxiety regarding future constraints. Clear reductions in FOF have been shown in older adult populations following Tai Chi training (Sattin et al. 2005), and cognitive behavioural therapy (Tennstedt et al. 1998). Future work should investigate possible changes in visual and stepping behaviours prior to, and following training of this nature. However, prospective studies would need to control for other physiological and psychological adaptations that would result from training.

6.6 Summary and conclusions

The work described in this thesis has provided new evidence that stepping performance can be improved in older adults following a simple gaze behaviour intervention. The improvements shown in Chapter 3 occurred in the absence of any differences in the number of adjustments to foot trajectory during swing both pre- and post-intervention. Furthermore, we have shown clear evidence for age-related decline in the ability to use vision in an online manner during swing to inform corrections to foot trajectory. Although these findings cannot completely discount the possibility that visually guided corrections were made during swing, it strongly encourages suggestions that other factors are primarily responsible for the improvements shown. As the attention allocated towards a currently fixated object is reduced when planning a saccade away from it (Kowler et al. 1995), we suggest that the redirection of attentional resources were postponed as a consequence of voluntarily delaying gaze transfer from the target. Therefore, stepping performance benefited primarily from a more comprehensive planning. As increased anxiety has been shown to alter the allocation of attention when walking (Gage et al. 2003), these findings provide an exciting opportunity for rehabilitation, such as further investigation into a possible causal link between increased anxiety and adverse visual sampling strategy.

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