

**EFFECT OF AGING ON GAZE, STEPPING
BEHAVIOUR, BALANCE CONTROL AND HEAD
POSTURE DURING STAIR NEGOTIATION**

by

Doerte Zietz

A Thesis submitted to
The University of Birmingham
for the degree of
DOCTOR OF PHILOSOPHY

School of Sport and Exercise Sciences
The University of Birmingham
March 2011

UNIVERSITY OF
BIRMINGHAM

University of Birmingham Research Archive

e-theses repository

This unpublished thesis/dissertation is copyright of the author and/or third parties. The intellectual property rights of the author or third parties in respect of this work are as defined by The Copyright Designs and Patents Act 1988 or as modified by any successor legislation.

Any use made of information contained in this thesis/dissertation must be in accordance with that legislation and must be properly acknowledged. Further distribution or reproduction in any format is prohibited without the permission of the copyright holder.

Abstract

Factors contributing towards falls in older age during overground walking have been widely studied. Stepping behaviour, balance and head posture control during stair negotiation in young adults (YA) and older adults with either lower (LROA) or higher (HROA) risk of falling during midstair negotiation have not been investigated. The aims of the thesis were threefold. Firstly, age-related changes in gaze behaviour were investigated. The main finding was that older adults fixate stair edges for longer than YA. Secondly, the effect of manipulating visual information on stepping parameters and balance control was compared between YA, LROA and HROA. For stair ascent, stepping and balance control was preserved in LROA and HROA and highlighted stair edges led to increased foot clearance in all groups. For stair descent, HROA demonstrated smaller foot clearance than LROA and highlighted stair edges improved balance in LROA and HROA. Thirdly, head posture was studied in YA, LROA and HROA. Compared to walking, LROA and HROA demonstrated more variable head posture than YA. Overall the findings suggest that adults use visual and probably proprioceptive information about stair edge locations to negotiate stairs and HROA benefited from highlighted stair edges. HROA should be included in future stair negotiation studies.

Acknowledgements

I would like to thank my supervisors Mark and Martin for their guidance, support and input. Thank you for giving me this opportunity to develop my research skills. Mark, thank you for presenting my poster at the conference in Bologna on my behalf. Martin, thank you for listening to my concerns and giving general advice.

I wish to acknowledge Leif Johannsen for writing MATLAB routines for data preparation and analysis for the studies presented in Chapters 4, 5 and 6. A big thank you for your invaluable help and support.

I thank all the participants in my studies. I appreciate the time you spent trotting up and down the stairs for me. For their help in the lab I wish to thank Will and Jon. Will, thank you for patiently helping out with data collection and Jon, thank you for your technical support, very often as “last minute rescue”.

Thank you, Julie, for giving invaluable advice and for allowing me to sit in a quiet office to finally finish this thesis. I thank Mareen for reading drafts of thesis chapters. I appreciate the time you gave and your very helpful comments and suggestions.

I thank my best friend Ruth for supplying me with tea and chocolate and for sending many encouraging postcards- even from as far away as Australia. Thank you for listening to my complaints, keeping me sane and believing in me that I will finish my PhD in the end.

Last but not least I wish to thank my little girl for just being there. Sometimes it was hard to prioritise the work on this thesis, but looking after you was a good distraction and a lot of fun, which made this PhD an even more challenging and truly unforgettable experience.

List of contents

Acknowledgements	iii
List of contents	iv
List of tables	ix
List of figures	x
List of abbreviations	xi

CHAPTER 1

General Introduction	1
1.1 Body structures and their function contributing to increased risk of falling	2
1.1.1 Neuromuscular system	2
1.1.2 Vision	5
1.1.3 Proprioception	10
1.1.4 Vestibular system	13
1.1.5 Head posture and stabilisation	14
1.1.6 Changes in balance and gait characteristics	16
1.1.7 Fear of falling	18
1.1.8 Summary	20
1.2 Environmental factors contributing to increased fall risk	20
1.3 Visual guidance during walking and stepping	21
1.3.1 Visual guidance during walking with predefined foot placement	21
1.3.2 Visual guidance during single step and stair negotiation	22
1.3.3 Summary	25
1.4 Biomechanics of stair ascent	26
1.4.1 Temporal characteristics	26
1.4.2 Kinematics and kinetics	26
1.4.3 Muscle activity	28
1.4.4 Foot placement and clearance	28
1.4.5 Age-related changes and adaptation to functional loss	28
1.4.6 Handrail use	30
1.5 Biomechanics of stair descent	30

1.5.1	Temporal characteristics	31
1.5.2	Kinematics and kinetics	31
1.5.3	Muscle activity	32
1.5.4	Foot placement and clearance	32
1.5.5	Age-related changes and adaptation to functional loss	33
1.5.6	Handrail use	34
1.6	Summary and aim of thesis	34

CHAPTER 2

Gaze behaviour of young and older adults during stair negotiation	36
2.1 Introduction	36
2.2 Methods	38
2.2.1 Participants	38
2.2.2 Stairs and apparatus	39
2.2.3 Experimental procedure	41
2.2.4 Data preparation and analysis	41
2.3 Results	46
2.3.1 Gait characteristics	46
2.3.2 Characteristics of gaze behaviour	47
2.3.3 Relationship between gaze fixation and stepping	49
2.4 Discussion	50
2.4.1 Where do individuals look during stair negotiation?	51
2.4.2 Differences between gaze characteristics during stair ascent and descent	52
2.4.3 Age-related differences in gaze behaviour during stair negotiation	52
2.4.4 Role of vision in maintaining balance during stair negotiation	53
2.4.5 Limitations	54
2.5 Summary and conclusion	55

CHAPTER 3

General methods	57
3.1 Participants	57
3.2 Tests and assessments	58

3.3 Participant's characteristic and assignment of OA to fall risk groups	59
3.4 Details about technical equipment and experimental conditions	60
3.5 Experimental design and protocol	64
3.6 Data processing and analysis	65

CHAPTER 4

Stepping characteristics and Centre of Mass control during stair ascent:

effects of age, fall risk and visual factors	67
4.1 Introduction	68
4.2 Methods and data analysis	70
4.3 Results	73
4.3.1 Effect of walking speed	73
4.3.2 Group differences in stepping characteristics and COM control	73
4.3.3 Effect of altering ambient light levels	76
4.3.4 Effect of stair edge contrast	77
4.3.5 Additional analysis of the effect of handrail use on COM acceleration	78
4.4 Discussion	80
4.4.1 Differences between age groups in stepping behaviour and COM control	80
4.4.2 Fall risk-related differences in stepping behaviour and balance control	81
4.4.3 Effect of manipulating ambient light levels	82
4.4.4 Effect of manipulating stair edge contrast	83
4.4.5 Effect of handrail use on COM control	84
4.5 Conclusion	85

CHAPTER 5

Stepping characteristics and Centre of Mass control during stair descent:

effects of age, fall risk and visual factors	86
5.1 Introduction	86
5.2 Methods and data analysis	88
5.3 Results	90

5.3.1	Effect of walking speed	90
5.3.2	Group differences in stepping characteristics and COM control	90
5.3.3	Effect of altering ambient light levels	93
5.3.4	Effect of stair edge contrast	93
5.3.5	Additional analysis of foot position relative to the stair edge and the effect of handrail use on COM	96
5.4	Discussion	98
5.4.1	Differences between age groups in stepping behaviour and COM control	98
5.4.2	Fall risk-related differences in stepping behaviour	99
5.4.3	Effect of manipulating ambient light levels	100
5.4.4	Effect of manipulating stair edge contrast	100
5.4.5	Effect of handrail use on COM control in HROA	101
5.5	Conclusion	102

CHAPTER 6

Head posture during stair ascent and descent and the effect of age, fall risk and visual factors	103
6.1 Introduction	104
6.2 Method and data analysis	107
6.3 Results	108
6.3.1 Effect of walking speed	110
6.3.2 Effect of age groups and fall risk	110
6.3.3 Effect of ambient illumination and stair edge contrast	112
6.4 Discussion	114
6.4.1 Effect of age group and fall risk	114
6.4.2 Effect of ambient illumination and stair edge contrast	117
6.5 Summary and conclusion	118

CHAPTER 7

General discussion	119
7.1 Summary of findings of the experimental chapters	119

7.2	Similarities and differences between stair ascent and descent on gaze behaviour, stepping characteristics, balance and head posture control	121
7.2.1	Age-related changes in gaze behaviour and head posture control	121
7.2.2	Differences between participant groups in stepping behaviour and balance control	123
7.2.3	Differences between OA with lower or higher risk of falling	125
7.2.4	Effect of manipulating ambient illumination on stepping parameters, balance and head posture control	126
7.2.5	Effect of manipulating stair edge contrast on stepping parameters, balance and head posture control	127
7.2.6	Effect of handrail use on balance control in HROA	129
7.3	Limitations	129
7.4	Directions for further research	132
7.5	Conclusion	134
	Glossary	136
	Appendix A: School-internal General Health Questionnaire	138
	Appendix B: Berg Balance Scale	142
	Appendix C: Modified Falls Efficacy Questionnaire	145
	Appendix D: Stair Self-Efficacy Questionnaire	147
	Bibliography	150

List of tables

Table 2.1	Mean (SD) for gait data and gaze behaviour for YA and OA	47
Table 3.1	Participants' characteristics	60
Table 4.1	Mean (SD) and intra-subject variability for spatial stepping characteristics and COM acceleration (stair ascent)	75
Table 4.2	Result of stepping characteristics and COM acceleration for all visual conditions (stair ascent)	79
Table 5.1	Mean (SD) and intra-subject variability for spatial stepping characteristics and COM acceleration (stair descent)	92
Table 5.2	Result of stepping characteristics and COM acceleration for all visual conditions (stair descent)	97
Table 6.1	Results of head posture data (stair ascent) for YA, LROA and HROA	109
Table 6.2	Results of head posture data (stair descent) for YA, LROA and HROA	109
Table 6.3	Results of head posture data (stair ascent) for all visual conditions	113
Table 6.4	Results of head posture data (stair descent) for all visual conditions	113

List of figures

Figure 2.1	OA with mobile eye-tracker and attached LED lights	40
Figure 2.2	Definition of middle eight stair section	42
Figure 2.3	Picture from the eye-tracker's video camera during stair descent	43
Figure 2.4	Raw data of one YA and one OA for stair ascent and descent	45
Figure 2.5	Number of gaze fixations	49
Figure 2.6	Temporal relationship between gaze behaviour and stepping behaviour	50
Figure 3.1	Camera placement in the lab	62
Figure 3.2	Experimental set-up: YA with markers and indication of stairs used for data analysis	63
Figure 4.1	Definition of vertical and horizontal foot clearance for stair ascent	72
Figure 4.2	COM location with respect to the leading leg (stair ascent)	77
Figure 4.3	Results for vertical and horizontal foot clearance (stair ascent)	78
Figure 5.1	Definition of vertical and horizontal foot clearance for stair descent	90
Figure 5.2	Results for vertical and horizontal foot clearance (stair descent)	94
Figure 5.3	Results per group for COM variability in vertical direction	95
Figure 5.4	COM location with respect to the leading leg (stair descent)	96
Figure 6.1	Calculation of the head pitch angle	108
Figure 6.2	Mean head angles during one gait cycle for stair ascent and descent	111
Figure 6.3	Head velocity profile of one gait cycle for stair ascent and descent	112

List of abbreviations

ADLs	Activities of daily life
a-p	anterior-posterior
BBS	Berg Balance Scale
CNS	Central nervous system
COM	Centre of Mass
COP	Centre of Pressure
GRF	Ground reaction force
LROA	Older adults with a lower risk of falling
m-l	medio-lateral
MFES	Modified Falls Efficacy Scale
HROA	Older adults with a higher risk of falling
OA	Older adults (without specification about fall risk)
SSEQ	Stair Self-Efficacy Questionnaire
YA	Young adults

CHAPTER 1

General introduction

Older age is accompanied by increased difficulty in executing activities of daily life (Baltes, et al., 1999) and falls are common in the older age group. Stair negotiation is a challenging task for older adults (OA) (Hamel & Cavanagh, 2004), and falls on stairs mainly result from balance difficulties. The main injuries resulting from falls are head injuries and lower limb fractures (Svanström, 1974). It is necessary to understand the mechanisms underlying stair falls before exploring possible preventative measures.

Age-related factors adversely influencing overground walking ability, resulting in increased risk of falling, have been studied in much detail (Menz, et al., 2007; Hill et al., 1999; Lord et al., 1996). In addition, there have been intervention studies aimed at improving balance of OA with a view to reducing fall risk (Pijnappels et al., 2008; Thompson et al., 2003; Ferri et al., 2003). However, there has been little research investigating the contributing factors to imbalance during stair negotiation which is the focus of this thesis. Identifying OA who are at increased risk of falling, but have not yet experienced a fall is important because tailored activity or exercise programs, correction of impaired vision and changes in the living environment may help to prevent falls on stairs.

1.1 Body structures and their function contributing to increased risk of falling

Falls are a common problem in the older age group- it is known that one third of OA 65 years of age and over experiences at least one fall within a year (Campbell et al., 1981). The likelihood of a fall increases with increasing age (Campbell et al., 1981; Sattin et al., 1990) and the admission rate to hospital after a fall on stairs at home increases sharply after the age of 60 years (Gunatilaka et al., 2004). Resulting impairments from a fall in an older individual result in high costs for health service providers (Scuffham, et al., 2003), have a big impact on the affected person and can even lead to the end of independent living and in extreme cases, death (Gunatilaka et al., 2004). There are personal and environmental factors contributing to increased risk of falling, such as reduced lower limb muscle strength and slippery or uneven ground. This chapter discusses factors contributing to increased fall risk in OA.

The human body declines with increasing age, affecting not only the function of specific structures, but also limiting the capacity of an OA resulting in an increased risk of falling. The following sections describe the age-related changes that take place in the neuromuscular, visual and vestibular systems, their relation to increased fall risk and possible compensatory strategies that are adopted by the older individual. Age-related changes to balance ability, changes in gait pattern and fear of falling in the elderly are also discussed.

1.1.1 Neuromuscular system

There is a strong relationship between muscle strength and balance (Wolfson et al., 1995), but a loss in skeletal muscle mass with increasing age is inevitable and known as sarcopenia (Evans, 1995). On the structural level, factors contributing to sarcopenia are the loss of alpha motor neurons in the spinal cord (Tomlinson & Irving, 1977), the

loss of muscle fibres (Lexell et al., 1983) and the replacement of muscle tissue with fat and fibrous tissue (Lexell et al., 1988). These structural changes affect the contractibility of the muscle as characterised by a reduction in muscle contraction speed, muscle strength (Kubo et al., 2007; Perry et al., 2007) and muscle power (Ferri et al., 2003). For example, the knee extensor strength decreases by between 24% and 30% in OA within 12 years between 65 and 77 years of age (Frontera et al., 2000) which, in addition to decreased hip abductor strength, is associated with a reduction in comfortable and maximum walking speed (Bohannon, 1997). Likewise, ankle dorsiflexion strength decreases with increasing age (Scott et al., 2007) which can negatively affect toe clearance during overground walking and stair negotiation.

Age-related muscle weakness contributes to increased fall risk (for review see Moreland et al., 2004). Hip and knee extensors as well as ankle plantarflexors are the antigravity muscles in the lower limbs, which means that these muscles are important for holding the body upright against gravity during standing, walking and stair negotiation and prevent the body from collapsing. Unstable OA have not only weaker hip and knee extensors and plantarflexors, but also reduced muscle strength in hip flexors and ankle dorsiflexors compared to stable OA (Lin & Woollacott, 2005). This finding is supported by other studies which found weaker dorsiflexors in elderly fallers compared to OA without previous falls (Skelton et al., 2002; Perry et al., 2007). Furthermore, older fallers are more variable in the production of eccentric muscle force in their knee extensors compared to older non-fallers who show similar force production ability as young adults (YA) (Carville et al., 2007). Knowing that reduced muscle strength is associated with increased imbalance and fall risk, is it possible to identify fallers by investigating muscle strength? Pijnappels et al. (2008) induced falls in OA under safe laboratory conditions and showed that reduced leg press performance, which involved hip and knee extension in a non weight-bearing position, correlated with falls. However, the correlation between weak muscle strength and falls result may not

be transferrable to falls in daily life when environmental factors contributing to falls are also present.

OA can compensate for reduced muscle strength in the lower limbs by using a device, such as a walking stick or a handrail to reduce the load on weak legs. However, muscle strength and power in knee extensors and ankle plantarflexors can be increased even in OA by physical activity such as resistance training (Ferri et al., 2003). Improved muscle strength after resistance training has been shown to improve balance recovery after a trip (Pijnappels et al., 2008) and may therefore reduce the likelihood of a fall.

Not only muscle strength is important, but also appropriate range of motion in the lower leg joints is necessary for safe walking and stair negotiation. However there is conflicting evidence whether passive range of motion at the ankle is affected by age. Reeves et al. (2008b) did not find age-related differences, but Scott et al. (2007) found smaller range of ankle motion in OA than in YA. In addition, these authors found reduced passive range of motion in the 1st metatarsophalangeal joint in OA compared to YA, which may negatively affect the push-off phase during walking and may be associated with compensatory movements at knee and hip level during walking. For example, OA use ankle plantarflexors and knee extensors less and hip extensors more than YA, resulting in a torque and power redistribution from ankle and knee joints to the hip joint during walking (DeVita & Hortobagyi, 2000a). Redistributing torques and power generation within the lower limbs may therefore be a compensation for the loss of full range of motion and could also contribute to increased risk of falling.

There are also age-related changes in the peripheral nervous system in addition to the above mentioned structural decline in the central nervous system (CNS) related to sarcopenia. The nerve conduction velocity reduces (Lauretani et al., 2006), which negatively affects the timing of muscle contraction and the muscle contraction speed. Furthermore, a decline in peripheral nerve function in the lower limbs is

associated with reduced strength in the lower limbs (Strotmeyer et al., 2009). Therefore, age-related changes in the peripheral nervous system contribute to increased fall risk when appropriate reactive muscle activation after a threat to balance is delayed or resulting power generation to recover balance is insufficient.

In summary, OA experience a loss of muscle mass, strength and power which is accompanied by slower nerve conduction velocities and probably by reduced range of motion in the lower limb joints. Every single aspect could contribute to increased fall risk in the older population and affects each other. For example, reduced muscle mass and slower nerve conduction velocity lead to inadequate and delayed muscle contraction and force production within a reduced range of motion. These changes adversely affect an individual's ability to recover from a threat to balance when quick reactive and appropriate muscle activation is necessary.

1.1.2 Vision

Vision is a very important sense in humans for planning and controlling movements and provides information about the location and movement of objects in space as well as self-motion. Vision can be divided into central and peripheral vision and this is best explained by the anatomical structure of the retina which is the light-sensitive cell layer of the inner surface of the eye. The photoreceptor cells in the retina are the colour-sensitive cone cells and light-sensitive rod cells (Trepel, 2004). The fovea is the area with the highest number of cone cells (Curcio et al., 1990; Cubbidge, 2005), the sharpest visual acuity and slow visual sampling frequency. Foveal vision is also called central vision and is used for exploring the environment by fixating details in this environment. In contrast to the fovea, the area around the fovea is characterised by a lower number of photoreceptor cells and these are predominantly rod cells (Curcio et al., 1990). These cells work best when the light is dimmed, in twilight or in partial

darkness. Visual perception from this area is called peripheral vision and is used for movement perception due to the higher sampling frequency and reduced stimulus resolution compared to central vision. The visual field of an individual is the area in which objects can be seen (Cubbridge, 2005) and has been shown to be symmetrical between eyes of an individual (Brenton et al., 1986). The monocular visual field ranges between 60° nasally and 100° temporally and between 60° superiorly and 75° inferiorly (Spector, 1990; Cubbigde, 2005). Partial or complete loss of the visual field indicates impairments originating from either the anatomical structures of the eye, such as scotoma following retinal detachment, or from the central nervous system, such as hemianopia following a stroke (Trepel, 2004; Cubbridge, 2005).

Eye movements include saccades, microsaccades, smooth pursuit, vergence movements as well as reflexes such as the vestibulo-ocular reflex and the optokinetic reflex (Kandel et al., 2000). Saccades are extremely fast eye movements of both eyes in the same direction for the purpose of fixating a detail in the environment. Reported values of peak eye velocity are approximately 500° / second for 20° eye rotation (Bahill et al., 1981, Yee et al., 1985). Microsaccades are described as small, involuntary eye movements with an amplitude of less than 1 degree which usually occur during longer periods of fixation (Barlow, 1952, Ditchburn & Ginsborg, 1953). Smooth pursuit movements of the eyes keep a moving object on the fovea (Robinson, 1965). Vergence movements occur when the eyes fixate an object nearby or further away, resulting in the eyes rotating toward or away from each other depending on the distance to the object (Kandel et al., 2000). The vestibulo-ocular reflex stabilises the image of an object on the retina in the event of head rotation by producing an equally sized eye rotation in the opposite direction to the head. Like the vestibulo-ocular reflex, the optokinetic reflex contributes to a stable eye position in space during head rotation by focussing on a moving object until the eyes reach their maximum movement excursion.

A saccade follows to bring the eyes back to the contralateral side for fixating a new target in the visual field (Trepel, 2004).

Eye movements can be extremely fast and therefore, eye movements cannot be easily observed without technical equipment. Modern methods used for tracking and recording eye movements include an eye tracker, a search coil or electrooculography (Yee et al., 1985). The eye tracker measures the movement and position of the eye non-invasively by creating a pupil and corneal reflexion with infrared or near-infrared light (Wagner & Galiana, 1992). A change in the separation between the pupil and the corneal reflexion characterises the change of eye position and this can be either videotaped as a crosshair in the visual scene or further processed as analog data. The search coil is a contact lens with a coil and is inserted in either one or both eyes (Robinson, 1963). An electrical current is induced through electromagnetic induction caused by a magnetic field around the eye. The position of the eye is determined from the change in the direction and magnitude of this electrical current. Electrooculography measures the potential difference between two electrodes placed either above and below or left and right of the eye (Brown et al., 2006). Because there is a constant voltage difference between the cornea and the backside of the eye ball, movement of the eye will cause a change in the potential difference which is then recorded and interpreted as eye movement. It has been shown that recording eye movements with a search coil gives the most accurate results (Yee et al., 1985, van der Geest & Frens, 2002).

The contribution of visual information to balance has been shown in various studies comparing balance under normal and altered vision. For example, exclusion of vision during standing results in increased body sway to the extent that some OA may lose their balance (Woollacott et al., 1986). Manipulation of visual information during walking results in a variable gait pattern, particularly when walking with visual impairments in low light conditions (Helbostad et al., 2009). During locomotion, the

visual field of a person moves and provides information about movement direction and speed of objects in the environment and self-motion which is known as optic flow. It has been shown that walking is guided by optic flow generated by central vision and optic flow information is used to control steering behaviour (for review see Angelaki & Hess, 2005) as well as foot clearance during walking (Graci et al., 2009) and obstacle crossing (Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006). There is contradicting evidence whether the use of optic flow information is affected by increasing age. OA were found to be unable to adjust their heading direction accordingly to changes in optic flow information (Berard et al., 2009), but other studies found that OA were equally able to extract optic flow information about walking speed and walking direction as YA (Chou et al., 2009). The discrepancy in the findings may be explained by the inclusion of relatively young participants in the older age group in Chou's et al. study where the age ranged between 46 to 73 years. Participants younger than 65 years may have masked true age-related differences in this study.

Visual acuity, the ability to detect objects of different sizes, and contrast sensitivity, the ability to distinguish between object and background, are common visual assessments. Visual acuity (Gittings & Fozard, 1986; Pitts, 1982) and contrast sensitivity (Puell et al., 2004; Maentyaervi & Laitinen, 2001) have been shown to deteriorate with increasing age. This decline may contribute to imbalance in OA and it was suggested that OA increasingly rely on visual input rather than other sensory information such as proprioception (Pyykkoe et al., 1990) or vestibular input (Deshpande & Patla, 2007). This finding is supported by another study which included the normal older population within a specified area and correlated the best achievable corrected visual acuity of less than 6/20 to increased fall risk (Kuang et al., 2008). Not only is the quality of visual information compromised in older age, but there are also differences in the time period between acquiring visual information and executing a movement. For example, it has been shown that the time between the downward

saccade to a step and initiation of the foot lift is significantly prolonged in OA stepping up one level compared to YA (Di Fabio et al., 2003).

There are various adaptation mechanisms of the eye to respond to changes in the ambient illumination from light to darkness. Firstly, when the ambient illumination is reduced, the pupil dilates to increase the amount of light that reaches the retina. Secondly, the sensitivity of the cone and rod cells increases by neural mechanisms. This process takes approximately 30 minutes before the rod cells reach their maximum sensitivity (Dieterle & Gordon, 1956) and is usually investigated from pre-exposure with bright white light to total darkness (McMurdo & Gaskell, 1991; Dieterle & Gordon, 1956). Age-related decline in adaptation to darkness includes a smaller pupil size under dimmed light conditions (Winn et al., 1994), reduced sensitivity of rod cells (Pulos, 1989) and fovea (Coile & Baker, 1992). It has been shown that contrast sensitivity declines with increasing age and low illumination (Puell et al., 2004). Elderly fallers with comparable visual acuity present with impaired dark adaptation compared to non-fallers (McMurdo & Gaskell, 1991).

The effect of manipulating vision on balance has been extensively studied. It has been shown that experimentally blurring of vision, thereby reducing visual acuity, affects walking behaviour and leads to specific compensatory mechanisms: When vision is blurred, stepping time increases (Buckley et al., 2005b; Heasley et al., 2005) and medio-lateral (m-l) postural stability during single stance phase reduces (Buckley et al., 2005a) when stepping up or down a single stair. Furthermore, weight-bearing of the trailing leg is prolonged (Buckley et al., 2005b) and horizontal and vertical foot clearances are increased (Heasley et al., 2004; Heasley et al., 2005) when vision is blurred. Impaired balance due to reduced vision may contribute to increased fall risk and it seems sensible to suggest appropriate treatment of impaired visual acuity to reduce this risk. However, there is also evidence of increased risk of falling when vision is corrected. Cumming et al. (2007) found that assessment of visual function and

appropriate treatment in OA increases the number of falls and fractures resulting from these falls. The authors found that falls occur most often within the first months after prescribing new glasses. They argue that individuals need time to adapt to the new glasses and mainly fall during this adaptation period. In addition, not every type of glasses appears to be beneficial. For example, it has been shown that multifocal glasses impair the depth perception within an area close to the feet, resulting in a lack of accurate visual information about the environment and subsequently increases the risk of falling, particularly during stair negotiation (Lord et al., 2002). Furthermore, the use of multifocal glasses has been shown to increase the variability in foot clearance which also increases the likelihood for trips (Johnson et al., 2007).

How vision is used to guide walking with predefined foot placement and single step and stair negotiation is discussed in detail in section 1.3.

In summary, the acquisition of visual information about the environment is important to regulate balance, particularly in OA. The age-related decline of visual function leads to compensatory strategies during locomotion and stepping, negatively affecting balance.

1.1.3 Proprioception

Proprioception is defined as stationary limb position sense and sense of limb movement without visual control (Kandel et al., 2000). Receptors conveying information about movement excursion, speed and direction include muscle spindle receptors, joint receptors and cutaneous mechanoreceptors. Studies investigating the contribution of proprioceptive information to balance control and walking use vibration of either the muscle tendon or muscle belly. Vibrating a tendon or muscle induces discharges of action potentials in the Ia afferent fibres of the muscle spindle receptors and is interpreted by the CNS as an increase in muscle length (Burke et al., 1976). The

illusion of muscle lengthening results in increased muscle contraction of the vibrated muscle and therefore changes to the position of a limb or even the whole body. Depending on the body part of the application of vibration, different changes in the walking pattern and Centre of Mass (COM) control occur. For example, vibrations applied to neck and trunk muscles on the left side of the body result in deviation of the walking trajectory to the right side (Courtine et al., 2006) and vibrations applied symmetrically to the neck muscles lead to an increase in walking speed (Ivanenko et al., 2000). Vibrations applied to the Achilles tendon during the swing phase result in increased ankle plantarflexion during swing (Verschuere et al., 2002). Vibrations applied to the Achilles tendon during the stance phase lead to reduced lateral COM acceleration and a-p distance between COM and Centre of Pressure (COP) (Sorensen et al., 2002). These examples show that manipulating proprioceptive input leads to specific changes during walking and imply that accurate proprioceptive input and processing of this information is important and necessary for normal walking pattern and balance control. Although there are currently no published studies which investigate muscle vibration-induced changes to walking pattern during stair negotiation or investigate proprioception during locomotion in the older population, there is some evidence for age-related decline in proprioception.

Results from studies investigating age-related changes to proprioception during isolated joint movements suggest that the perception of angular limb displacement declines with increasing age more distally than proximally. Actively moving the leg to a remembered target angle in hip abduction in non-weight-bearing (Pickard et al., 2003) and knee flexion in weight-bearing (Bullock-Saxton et al., 2001) reveal no differences in the accuracy of the remembered angles between YA and OA. However, OA are less accurate in reproducing the targeted knee flexion angle when partially weight-bearing (Bullock-Saxton et al., 2001) or non weight-bearing (Hurley et al., 1998). There are larger differences between the young and older age group at the ankle. OA were less

accurate and more variable in matching foot positions than YA (Meeuwsen et al., 1993) and OA detected the movement onset at the ankle significantly later than YA (Thelen et al., 1998). However, training appears to improve proprioception at the ankle (Meeuwsen et al., 1993) and knee joint (Thompson et al., 2003).

It appears that the ankle joints are an important source of proprioceptive information when a threat to balance occurs during standing. The reactive activation of the lower leg muscles is known as the ankle strategy (Shumway-Cook & Woollacott, 2001). Inaccurate proprioceptive information about ankle position, delayed detection of movement onset at the ankle and increased variability of the perceived ankle position may contribute to increased risk of falling because inaccurate proprioceptive information leads to inappropriate muscle activation. In addition, wearing shoes can even further reduce the sense of ankle position (Robbins et al., 1995). During walking and stair negotiation, increased variability in the perceived ankle position during the swing phase of the gait cycle may contribute to foot clearance problems, adding to increased risk of trips and falls in OA. There are currently no published studies that have investigated the direct relationship between age-related decline in the perception of the ankle position and movement and foot clearance behaviour during walking or stair negotiation.

In summary, age-related decline in proprioception appears to occur more distally than proximally and can explain the incorrect perception of joint position, delayed perception of movement onset and increased variability of joint position sense at the ankle. In OA, this may contribute to delayed and inappropriate muscle activation when balance needs to be recovered and may alter the foot trajectory during locomotion resulting in decreased and variable foot clearance.

1.1.4 Vestibular system

The vestibular system is bilaterally located in the inner ear and is involved in postural control, gaze stabilisation and spatial orientation. The vestibulum detects angular head acceleration by three semicircular canals and by detecting linear head acceleration by the otolith organs. Signals from the vestibular system are sent via the nucleus vestibularis in the brainstem to other brain areas concerned with balance control, gaze stabilisation and spatial orientation. Postural control and adaptation is generally achieved by the vestibulospinal reflex which activates extensor (= antigravity) muscles and inhibits flexor muscles. As mentioned before, the vestibulo-ocular reflex stabilises an image on the retina in the event of head rotation by producing an equally sized eye rotation in the opposite direction to the head. Awareness of spatial body orientation is achieved by projections via the thalamus to the cerebrum.

Age-related decline of the vestibular system is characterised by a decrease in hair cell and nerve fibre numbers (Rauch et al., 2001) leading to inaccurate and delayed signals conveyed to the CNS. The loss of otolith function with increasing age has been shown to result in increased m-l sway, particularly in older women (Serrador et al., 2009) which adds to the difficulty to control lateral movements by appropriate muscle activation and which in turn is associated with increased fall risk.

Given the central nervous connections with visual and proprioceptive pathways in the brain, slowly developing vestibular impairments can be compensated for by these other two senses. Therefore, individuals with vestibular dysfunction may be able to live their normal daily lives.

1.1.5 Head posture and stabilisation

Stabilising the head during locomotion is essential to reduce oscillatory movements resulting from the lower limbs in order to provide a stable reference frame for the eyes, vestibular system and to control balance (Mazza et al., 2008).

The normal human gait pattern itself supports a stable trunk and head posture. For example, specific phases and movements within the gait cycle contribute to minimise vertical trunk and head movements, such as the drop of the contralateral side of the pelvis during the loading response phase at the knee (Perry, 1992). During walking, trunk and neck segments attenuate the accelerations from the lower limbs and pelvis resulting in decreased head acceleration, particularly in the sagittal plane (Kavanagh et al., 2004). Head stabilisation movements during walking is linked to gait cycle events (Mulavara et al., 2002; Kavanagh et al., 2004) and the head posture is stabilised by counteracting vertical head shifting movements with head movements around the m-l axis (Pozzo et al., 1990).

Compared to overground walking, stair negotiation requires larger ranges of lower limb movements (Livingston et al., 1991; Andriacchi et al., 1980; Reeves et al., 2008a) and trunk movements (Krebs et al., 1992). These larger movements may be more challenging to be attenuated by the trunk than those during overground walking in order to achieve a stable head posture. Indeed, it has been shown that head posture in YA was less stable during stair ascent and even less stable during stair descent compared to walking (Cromwell & Wellmon, 2001). The authors argue that the more forward tilted head posture and increased range of head motion in the sagittal plane causes the COM of the head to be positioned more anteriorly with respect to the movement axis, presenting a challenge to muscle activation to control head position. However, to date there are no studies investigating head stabilisation in OA ascending and descending stairs.

A stable head posture during locomotion contributes to dynamic balance (Pozzo et al., 1990) and is crucial for maintaining a stable image of the environment on the retina. Gaze stabilization is achieved by the vestibulo-ocular reflex and contributes to normal visual acuity (Crane & Demer, 1997). Visual acuity is dependent on the image motion across the retina (Demer & Amjadi, 1993) and starts to decline when the velocity with which images move across the retina exceeds 4 °/s (Grossman et al., 1989; Crane & Demer, 1997). During walking and running, visual acuity has been shown to decrease compared to standing, but the vestibulo-ocular reflex is mainly preserved (Grossman et al., 1989). However, head posture control is not only important for providing a stable reference frame for the visual system, but also for providing non-visual sensory information which is used by the CNS to align the body segments and to organise body movement in space. The head is stabilised by the neck muscles and proprioceptive input from these muscles provides the CNS with information about head posture in relation to the trunk and the rest of the body. Indeed, manipulating proprioceptive input to neck muscles has been shown to affect the perceived postural relationship between head and trunk, leading to adaptations to body orientation and steering behaviour during quiet standing, stepping on the spot and walking. For example, symmetrically applied neck muscle vibration has been shown to generate the illusion of a backward trunk lean which results in a forward body sway while standing, stepping forward when stepping on the spot and increased walking speed while walking (Ivanenko et al., 2000). During walking without visual input, unilaterally applied neck muscle vibration resulted in a deviated walking path towards the non-vibrated side (Bove et al., 2002; Courtine et al., 2006; Bove et al., 2001). All these findings suggest that visual, vestibular and proprioceptive information is integrated leading to task-specific adaptations of body orientation and actions which serve to keep the COM within the safe limits of the base of support.

Maintaining a stable head posture during overground walking appears to be more challenging in OA than in YA. For example, although peak angular head velocity in OA was smaller than in YA, indicating better head stabilisation than YA, OA improved their lower leg and trunk stability by reducing the walking speed and cadence (Cromwell et al., 2002). In addition, OA were shown to adopt different strategies in a-p trunk and head accelerations compared to YA, aiming to further improve balance particularly during the balance-challenging single stance phases of the gait cycle (Kavanagh et al., 2004). Other age-related differences include that OA rely on visual input to stabilise the head (Cromwell et al., 2002) and that they angle the head further down than YA (Hirasaki et al., 1993). There are currently no published studies directly linking head stabilisation ability to fall risk, although OA with previous falls and reported fear of falling were included in previous studies (Cromwell et al., 2002; Cromwell et al., 2001).

1.1.6 Changes in balance and gait characteristics

Balance can be defined as the ability of an individual to maintain an upright posture during sitting, standing and locomotion. Input from visual, vestibular and proprioceptive systems provide information about posture and movement of the body in space and result in appropriate muscle activation to keep the COM within the base of support which is defined by foot placement during standing and walking. As previously discussed, age-related decline in the sensory systems contributes to impaired balance and it is therefore not surprising that increased age is associated with increased imbalance (Lin & Woollacott, 2005). One early indication of balance decline may be the reaction of OA to a lateral balance threat while standing or walking on a movable platform (Maki et al., 2000). The authors point out that OA tended to take multiple steps, made more extra steps and demonstrated more reactive arm movements to

recover balance and to avoid a fall than YA. OA were also more likely to hit the stance leg with the swing leg during the attempt to recover balance than YA, requiring further balance recovery strategies such as more arm movements and grasping a handrail. These findings support other evidence that the control of m-l body movement during walking is impaired in OA compared to YA (Dean et al., 2007). Previous research has shown that OA walk with wider step width and increased step width variability than YA and that a reduction in these measures can be achieved by external lateral support at hip level (Dean et al., 2007). Hip abductors stabilise the pelvis throughout the gait cycle and their strength (or weakness) affects the extent of pelvic obliquity and lateral foot placement. Furthermore, walking speed in OA has been shown to correlate with hip abductor strength (Bohannon, 1997). In addition, OA demonstrate smaller lateral stepping actions when stepping onto laterally shifted targets on the floor is required (Chapman & Hollands, 2010) which might be due to an underestimation of the distance between current foot position and target location or due to an age-related reduction in hip abductor strength. In summary these findings suggest that stepping movements and the gait pattern in the coronal plane are more difficult to control in older age.

Generally, OA walk more slowly than YA (Menz et al., 2003b; Mazza et al., 2008) with reduced cadence and stride length (Lord et al., 1996) and with greater movement variability in parameters such as step length and trunk movements in the sagittal and transverse planes (Kang & Dingwell, 2008). However, there is also evidence that movement variability may not be an indicator of stability during walking and that variability and stability are dependent on walking speed (Li et al., 2005). OA with fear of falling or with increased fall risk walk slower (Deshpande et al., 2008a; Reelick et al., 2009), reduce their stride length and show reduced pelvic stability (Menz et al., 2007) in comparison to OA without fear of falling. However, Maki (1997) argues that decreased walking speed, stride length and prolonged double support phases may be adaptations of older individuals with a fear of falling to improve balance and may not

necessarily be fall risk factors, although he also observed that older individuals with a fear of falling are more likely to experience a fall within the next year. Prolonged double support phase and gait asymmetry (Hill et al., 1999) as well as reduced and variable cadence (Lord et al., 1996) were found to be predictors for future falls. In addition, increased minimum toe clearance variability adds to increased risk of falling in the older population (Mills et al., 2008).

Although not strictly a personal factor, the choice of shoe design influences the balance of an older individual as well. Flat heeled hard shoes were shown to be more beneficial for balance than shoes with 4.5 cm high heel or shoes with soft sole (Menant et al., 2008).

A common compensation for impaired balance during walking includes the use of a walking aid such as a walking stick or walking frame because contact with an external support has been shown to improve balance (Dickstein & Laufer, 2004). However, the design of a walking frame should allow the user to make lateral recovery steps without colliding with the frame (Maki et al., 2008).

1.1.7 Fear of falling

Previous research has identified many factors contributing to increased fall risk in OA and many OA seem to be aware that normal age-related decline in body structure and function increases their chances to experience a fall. Fear of falling is subjectively perceived and can be present in OA who have previously fallen (Murphy & Isaacs, 1982), but also in OA who have not. The percentage of OA who reported fear of falling ranges between 22% (Wijlhuizen et al., 2007) and 63% (Deshpande et al., 2008b) and includes healthy and impaired OA of the general population. Fear of falling often results in a limitation of outdoor activities to prevent a fall (Deshpande et al., 2008b; Wijlhuizen et al., 2007; Fletcher & Hirdes, 2004; Zijlstra et al., 2007). Reducing activity may result

in a vicious circle consisting of fear of falling, reduction in activity and subsequent reduction in muscle strength and balance, which in turn contributes to an increased fear (Wijlhuizen et al., 2007) and even increased risk of falling. OA with a fear of falling may not only reduce activities, but also present with changes in walking pattern which was described in more detail in paragraph 1.1.6.

It is no surprise that OA with a fear of falling try to reduce their fall risk by using devices to improve balance, such as the handrail during stair ascent and descent (Tiedemann et al., 2007; Hamel & Cavanagh, 2004) or other support for standing and walking, particularly after a previous fall (Murphy & Isaacs, 1982).

Studies investigating fear of falling, its relation to other fall risk factors and its effect on behaviour in OA, need to quantify and measure this fear. Before a standardised measurement was available, fear of falling was self-reported (Murphy & Isaacs, 1982). The first attempt to quantify fear of falling was the development of the Falls Efficacy Scale (Tinetti et al., 1990) which mainly focussed on the confidence to master a task without falling during indoor activities which contribute to independent living. A few years later, this scale was further developed into the Modified Falls Efficacy Scale (Hill et al., 1996) which was extended to include outdoor activities such as crossing a road and using public transport. Knowing that balance plays a very important role in fear of falling, Powell and Myers (1995) developed the Activities-specific Balance Confidence (ABC) scale, which is also used in fall-related studies (Herman et al., 2009). However, previous studies assessing fear of falling also used a questionnaire such as the survey of activities and fear of falling in the elderly (Lachman et al., 1998; Deshpande et al., 2008a) or a single question with rated answers (Tiedemann et al., 2007; Wijlhuizen et al., 2007; Menz et al., 2007; Zijlstra et al., 2007).

1.1.8 Summary

Falls are caused by many factors. Age-related changes in muscle architecture and central and peripheral nervous systems contribute to increased fall risk in the OA by altering the gait pattern and the ability to recover balance efficiently. OA can even be at higher risk of falling in the absence of objective falls-related factors, just because of the subjectively perceived fear of falling. Compensation strategies for age-related decline include altered movement strategies such as reduced walking speed and the use of devices to improve function and balance such as glasses and walking frames.

1.2 Environmental factors contributing to increased fall risk

The nature of the complex environment we live and work in contributes towards increased risk of falling, particularly in OA. This environment is likely to present with various hazards resulting in threats to balance. During overground walking, environmental factors contributing to falls have been identified as objects in the travel path, uneven ground and low lighting (Hill et al., 1999).

Building regulations for public buildings are intended to facilitate the safe access and use of these places with all facilities for all users (Document M, Department for Communities and Local Government, 2006). For staircases these regulations also provide very detailed information about their design and surrounding areas. For example, stairs in public places must be accompanied by non-slippery, good visible handrails with a minimum diameter of 4 cm and minimum distance to the wall of 6 cm. The building regulations specifically refer to individuals with impairments who need to be considered when building staircases, such as “people who wear callipers or who have stiffness in hip or knee joints” or “people with weakness on one side or with a sight impairment” (Department for Communities and Local Government, 2006; p.22, paragraph 1.31).

It has been shown that the layout of a staircase affects the number of accidents. Single flight stairs without landings have a higher number of stair fall incidents than “u”-shaped staircases with landing (Templer, 1994; Svanström, 1974). However, it appears that the number of steps within a flight of stairs is also important as 70% of falls occur at the bottom and top three steps (Templer, 1994). Other environmental factors facilitating trips and falls include poor ambient illumination, loose objects on stairs, slippery surface or round stair edges and poorly visible stair edges (Templer, 1994).

1.3 Visual guidance during walking and stepping

Vision is used to sample spatial information about the environment and it has been shown that gaze is normally directed to interesting or important points in the scene (Masciocchi et al., 2009). There are few studies investigating gaze behaviour or availability of visual information about the environment during overground walking and its link to increased fall-risk in the older population. The following sections discuss the role of central and peripheral vision during walking with predefined foot placement, during single step negotiation and stair negotiation.

1.3.1 Visual guidance during walking with predefined foot placement

Accurate information about suitable and safe foot placement sites is important when walking around in an environment presenting with challenges such as kerbs, uneven ground or obstacles in the pathway. Previous studies investigating visual guidance of walking under safe conditions in the laboratory included walking with predefined foot placement (Patla & Vickers, 2003; Hollands & Marple-Horvat, 1996; Hollands & Marple-Horvat, 2001), walking with changes in walking direction (Hollands et al., 2002), stepping over obstacles in the pathway (Patla & Greig, 2006) and stepping into multiple targets (Young & Hollands, 2010; Chapman & Hollands, 2007; Chapman & Hollands,

2006). Few studies explored gaze behaviour in natural and more complex environments such as walking in a public building (Vivekananda- Schmidt et al., 2004) and crossing an intersection (Geruschat et al., 2003). These studies show that visual information is generally used in a feed-forward manner for either accurate foot placement or obstacle avoidance. However, the extent to which individuals look ahead is variable and dependent on the task. For example, when YA are required to place their feet onto targets in the walking path, they look on average two steps ahead (Patla & Vickers, 2003). When stepping over an obstacle in the travel path, YA fixate the hazardous object to plan the swing phase over the obstacle within a few steps before the obstacle (Patla & Vickers, 1997). A reduction or even denial of visual information about the obstacle increases the variability in foot clearance and the number of trips (Patla & Greig, 2006; Rhea & Rietdyk, 2007).

Older age is associated with changes in the visual system (see section 1.1.2) contributing to changes in gaze behaviour. When OA are asked to step accurately into a target in the pathway, they turn their gaze sooner towards the target and fixate it for significantly longer than YA but they are less precise and more variable in their foot placement than YA (Chapman & Hollands, 2006). These findings suggest that OA need longer to process visual information and to plan and execute leg and foot movements accordingly. When OA are allocated to either a lower or higher fall risk group, OA with higher risk of falling tended to look away earlier from a stepping target on the floor when presented with multiple stepping targets than OA with a lower risk of falling which reduces stepping accuracy (Chapman & Hollands, 2007).

1.3.2 Visual guidance during single step and stair negotiation

It is known from overground walking studies that visual information is sampled prior to movement execution and inaccurate or even absent visual information alters the

normal stepping pattern and increases the chances of trips or foot placement errors. Controlling the amount of visual information that an individual can collect is achieved in two ways: firstly by manipulating the visual input by reducing the visual field, blurring the vision or occlusion of vision, or secondly by manipulating the environment, such as the reduction of ambient light levels. Although there are few studies investigating the effect of ageing and vision on stepping behaviour, these studies compare either the performance of YA and OA or the performance of OA under normal and manipulated vision.

When stepping up to a new level, OA take more time than YA. For example, YA and OA produce a downward saccade prior to foot lift, but OA need then longer to lift and move the foot than YA (Di Fabio et al., 2003). Furthermore, when vision is blurred, which impairs visual acuity, OA increase vertical and horizontal foot clearance and need longer to complete the task than under normal vision (Heasley et al., 2004). Impaired vision also affects balance, particularly in the m-l direction. It was previously shown that balance in the coronal plane is negatively affected when vision was blurred (Buckley et al., 2005a).

During stepping down, vision is probably used to estimate the height of a step and to prepare foot position for landing. When investigating midstair descent, occlusion of vision results in stiffer or less cushioned landings with a lack of anticipatory muscle activation in the ankle plantarflexors (Craig et al., 1982) and delay in the weight transfer from the trailing to the leading leg when vision was denied compared to normal vision (Buckley et al., 2007). However, blurring vision appears to be sufficient for affecting stepping actions. For example, the time used for stepping down increases, the trailing leg supports the body weight for longer (Buckley et al., 2005b), foot clearance increases and foot placement is more variable (Simoneau et al., 1991) when vision is blurred, but not completely denied. In OA, m-l balance and limb stability during the single stance phase deteriorate when vision is blurred compared to normal vision,

which also suggest that vision plays an important role for balance during stepping down (Buckley et al., 2005a). When changing the environment, such as reducing the ambient light in the laboratory, OA show no changes in foot clearance, but clearance variability increases (Hamel et al., 2005).

Not only central vision, but also manipulating peripheral visual information appears to affect stepping behaviour. When occluding visual information from the lower visual field during descending a single step, knee and ankle angular velocity at initial contact have been shown to be reduced compared to full vision (Timmis et al., 2009). This finding suggests a cautious landing strategy, particularly when the height of the step is not known. Landing control, measured as angular velocity of the ankle and vertical COM velocity, has been shown to improve by using single vision distance glasses in comparison to bifocal glasses, which blur the lower visual field (Timmis et al., 2010).

Before an individual ascends a staircase, it is likely that some estimation about the “climbability” of the staircase takes place. Climbability means whether a person perceives the riser height of a stair as being ascendable in a step-over-step manner, moving the COM forward and up onto the next stair. It was previously shown that the judgement about the climbability of a staircase depends on the individual’s leg length, range of hip and knee flexion and stair riser height (Warren, 1984). The author showed that the ratio of riser height/ leg length should not exceed 0.88 for YA. This constant has been shown to be valid for all individuals independent of their height, suggesting that the visual perception of the environment is closely linked to biomechanical limits of an individual. In a further study it has been shown that not only leg length and joint flexibility needs to be taken into account when judging stairs on their climbability, but also the peak plantarflexion moment (Konczak et al., 1992). The authors pointed out that OA were more accurate in their assessment of the climbability of stairs. In 61% of OA the perception and physical ability to ascent stairs matched, whereas only 30% of

YA were so accurate in their estimation. However, 21% of the OA overestimated their abilities whereas 62% of the YA underestimated their maximum stair climbing capability. Taken these findings together, they suggest that individuals estimate the climbability of a staircase on the basis of their biomechanical constraints.

Stair negotiation is characterised by the need to make alternating foot placements on pre-defined stepping targets. In addition, stair ascent is in essence an obstacle crossing or avoidance task as both feet usually clear the stair edges in a step-over-step manner. Although there is some literature describing where and when people look during overground walking, in 2006, when this PhD started, there were no published data on where and when individuals look while ascending and descending stairs. It is clinically important to understand the relation between sampling visual information and motor behaviour during stair negotiation as falls on stairs occur frequently, particularly in the older population (Gunatilaka et al., 2004).

1.3.3 Summary

Previous studies, recording gaze behaviour during overground walking, found that individuals use vision in a feed-forward manner to guide their stepping actions in a laboratory setting and to navigate in real life. Dependent on the task, YA and OA fixate objects in the environment within a few steps before stepping onto predefined targets or avoiding contact with an obstacle in the pathway. Previous research focussed on the effect of manipulated visual input on stepping errors and changes in kinematic and temporo-spatial parameters as well as balance during single step and stair negotiation. To date there is no study directly measuring gaze behaviour during mid stair negotiation in YA and OA.

1.4 Biomechanics of stair ascent

Stair ascent is characterised by moving the body against gravity up to the next stair during mid stance, labelled as “vertical thrust” by Zachazewski et al. (1993). The following sections describe normal stair ascent in young and healthy adults and changes to stair ascent in OA. Temporal parameters, specific gait cycle characteristics, range of motion in the lower limb joints, kinetics, muscle activation and age-related changes are discussed in more detail below.

1.4.1 Temporal characteristics

Self selected mean stair walking speed in YA is between 0.49 m/s (Protopapadaki et al., 2007) and 0.70 m/s (Livingston et al., 1991) and is therefore slower than overground walking speed which is around 1.4 m/s (Stacoff et al., 2005; Bohannon, 1997). Self selected cadence during stair ascent ranges between 110 steps/ min (Livingston et al., 1991) and 120 steps/min (Larsen et al., 2008) and is therefore similar to overground walking (Winter, 1991).

Compared to overground walking, the stance phase during stair ascent is slightly prolonged, ranging from 61% (Protopapadaki et al., 2007) to 65% (Zachazewski et al., 1993) of the gait cycle. The swing phase is shortened accordingly.

1.4.2 Kinematics and kinetics

The required range of motion in hip, knee and ankle joints in the sagittal plane depends on body height of an individual (Livingston et al., 1991) and stair height. Therefore, differences between the presented maximum flexion values may not only reflect the normal range in the young population but also differences in stair height and body height of study participants. For step heights between 18 cm (Protopapadaki et al., 2007) and 21cm (Andriacchi et al., 1980), reported values in the literature include mean

peak hip flexion range from 41° (Andriacchi et al., 1980) to 56° (Livingston et al., 1991) and mean peak knee flexion range from 73° (Andriacchi et al., 1980) to 102° (Livingston et al., 1991). Peak hip and knee flexion occur during swing. Maximum ankle dorsiflexion occurs during loading response and the mean peak ranges between 13° (Andriacchi et al., 1980) and 24° (Livingston et al., 1991). Peak ankle plantarflexion occurs in initial swing and reported means range from 24° (Livingston et al., 1991) to 31° (Protopapadaki et al., 2007).

The vertical ground reaction force (GRF) curve during stair ascent has a similar “M” shape compared to the vertical GRF curve during over ground walking (Stacoff et al., 2005). The difference to walking is a more pronounced second peak during stair ascent, relating to push-off at the end of the stance phase (Stacoff et al., 2005; Protopapadaki et al., 2007).

Peak internal hip and knee extension moments occur during loading response and beginning of mid stance, whereas the peak internal plantarflexion moment occurs in preswing (Protopapadaki et al., 2007; Novak & Brouwer, 2010; Andriacchi et al., 1980; McFadyen & Winter, 1988). Protopapadaki et al. (2007) note that knee and ankle joint moments reported in the literature are fairly consistent, but reported hip moments vary at the beginning and end of the stance phase, probably due to a variable trunk position. A more forward leaning or upright trunk results in a GRF vector either anterior or posterior of the hip joint affecting the hip joint moment.

Zachazewski et al. (1993) identified a “vertical thrust” during mid stance, when the body is lifted up to the next stair. This is realised by increased ankle push-off power of the trailing leg in mid and late stance (Rietdyk, 2006). It is thought that the trailing leg pushes the body up to the next level more than the leading leg pulling the body up onto the next stair. A critical point occurs at initial contact of the contralateral leg when the body weight is transferred to the leading leg. The lateral COM displacement reaches a

maximum (Zachazewski et al., 1993) and hip, knee and ankle joints are in flexion which presents a challenge to balance (McFadyen & Winter, 1988).

1.4.3 Muscle activity

During stair ascent, the body is lifted up to the next stair. This is mainly realised by concentric muscle activity of the hip and knee extensors and ankle plantarflexors (Protopapadaki et al., 2007) from initial contact to toe-off (Andriacchi et al., 1980). The biceps femoris muscle becomes active prior to toe-off until peak knee flexion during mid swing to realise knee flexion and therefore to help with foot clearance. The tibialis anterior muscle is activated prior to toe-off until mid swing to dorsiflex the ankle and to help with foot clearance (Andriacchi et al., 1980).

1.4.4 Foot placement and clearance

Foot placement on the stair during stair ascent describes the a-p distance between toe-cap and stair edge, which indicates whether the whole or only a part of the foot is placed on the stair. There are no studies investigating foot placement or foot clearance on the stair during midstair ascent. However, there are data available from single step studies. During single step ascent, minimum foot clearance is calculated as the minimum vertical and horizontal distance between toe and stair edge in the sagittal plane (Heasley et al., 2004) (see also Figure 4.1). In YA, previous studies reported mean vertical foot clearance of 4.7 cm and horizontal clearance of 6.4 cm (Heasley et al., 2005).

1.4.5 Age related changes and adaptation to functional loss

Physical factors affecting stair negotiation performance in OA include the decline in visual acuity, muscle weakness in ankle dorsiflexors as well as knee extensors and

flexors contributing to reduced walking speed (Tiedemann et al., 2007). Not only walking speed is reduced in OA in comparison to YA (Lee & Chou, 2007), but also cadence (Larsen et al., 2008), ranging between 92 steps/min (Reeves et al., 2008a) and 108 steps/min (Mian et al., 2007a).

OA demonstrate greater hip flexion and adduction throughout stance than YA followed by moment redistribution between hip and knee joint (Karamanidis & Arampatzis, 2009). There are few age-related changes in the GRF and moment distribution during stair ascent. The mean GRF and the 1st peak- relating to loading of the leading leg- is smaller in OA than in YA (Larsen et al., 2008; Reeves et al., 2009). OA demonstrated reduced COM-COP separation in the coronal plane to improve balance during stair ascent (Reeves et al., 2009). When walking at self selected speed, OA demonstrate increased muscular co-activation throughout stance with greater EMG activation in knee flexors and extensors and ankle plantarflexors and dorsiflexors than YA (Larsen et al., 2008). There is evidence that OA pull themselves up to the next stair by extending the leading leg rather than pushing themselves up with the plantarflexors of the trailing leg (Rietdyk, 2006), particularly when using handrails (Reeves et al., 2008a).

It appears that foot clearance is affected by age, at least in single-step studies. It was found that mean vertical foot clearance was 4.7 cm in YA and slightly reduced to 4.3 cm in OA when stepping up to a new level (Heasley et al., 2005). Horizontal clearance was measured as 6.4 cm in YA and ranged between 6.7 cm (Heasley et al., 2005) and 7.9 cm (Heasley et al., 2004) in OA under normal visual conditions. One could argue that stepping over obstacles while walking requires similar foot clearance of the leading leg as stepping up one stair. In line with the results from the single-step studies, foot clearance in object crossing studies has been shown to be unaffected by older age, when the height of the object was fixed and not scaled to a proportion of the individual's leg (Chen et al., 1991; Harley et al., 2009; Lowrey et al., 2007).

Individuals use handrails during stair negotiation for both reassurance and balance control or for unloading the lower limbs because of pain or muscle weakness. OA using the handrail are more likely to present with reduced vision, strength, balance, more fear of falling (Tiedemann et al., 2007) and less confidence to ascent stairs than OA not using the handrail (Hamel & Cavanagh, 2004). However, it is likely that handrails are of limited use to OA in the event of a fall as they are able to only produce half of the necessary force to avoid a fall by grasping the handrail (Maki et al., 1998).

1.4.6 Handrail use

In public buildings, handrails on a flight of stairs are stipulated (Department for Communities and Local Government, 2006) and the use of this external support during stair ascent has been related to less confidence of an older person to ascend stairs (Hamel & Cavanagh, 2004). Previous studies have shown that light touch at the handrails led to a redistribution of joint moments. For example, OA using the handrail demonstrated decreased peak plantarflexion moment of the trailing leg and increased peak knee extension moment of the leading leg, although redistributing the joint moments did not improve balance in the sagittal or coronal planes (Reeves et al., 2008a).

1.5 Biomechanics of stair descent

Stair descent is characterised by the controlled lowering of the body down to the next stair during mid to terminal stance (Zachazewski et al., 1993). The following sections describe normal stair descent in YA and changes in performance in OA. Specific gait cycle characteristics, temporal parameters, range of motion in hip, knee and ankle joints, kinetics, muscle activation, age-related changes and handrail use are discussed in more detail below.

1.5.1 Temporal characteristics

YA were reported to descend stairs with a mean walking speed of 0.56 m/s (Protopapadaki et al., 2007). Preferred cadence in YA has been documented as being between 124 (Mian et al., 2007a) and 135 steps/min (Larsen et al., 2008), which is slightly higher than over ground walking. Cadence and walking speed during stair descent is also dependent on body height. Livingston et al. (1991) have shown that shorter individuals descend stairs with higher cadence and velocity than taller individuals.

The relative stance and swing phase duration during stair descent is similar to overground walking, but the stance phase ranges from 60% of the gait cycle (Protopapadaki et al., 2007) to 68% (Zachazewski et al., 1993). Similar to stair ascent, there are two critical points for balance during the stance phase. The maximum m-l COM displacement occurs in mid stance and the lowering of the COM occurs during single stance (Zachazewski et al., 1993). These authors also argued that stair descent is a more challenging task for balance because the double support phase is shorter and the COM-COP separation in the coronal and sagittal planes is larger compared to stair ascent.

1.5.2 Kinematics and kinetics

Similar to stair ascent, the range of motion in hip, knee and ankle joints in the sagittal plane depends on the body height of an individual and stair height (Livingston et al., 1991). Peak hip and knee flexion occur during initial swing. Mean peak hip flexion ranges between 23° (Protopapadaki et al., 2007; Andriacchi et al., 1980) and 45° (Livingston et al., 1991) and mean peak knee flexion ranges from 82° (Andriacchi et al., 1980; Protopapadaki et al., 2007) to 107° (Livingston et al., 1991). Peak dorsiflexion occurs during pre-swing and is between 21° (Protopapadaki et al., 2007) and 36°

(Livingston et al., 1991). Ankle plantarflexion is largest during terminal swing when prepositioning the foot for initial contact and the range is reported between 26° (Andriacchi et al., 1980) and 40° (Protopapadaki et al., 2007).

The vertical GRF curve during the stance phase during stair descent is “M”-shaped with a pronounced first peak at around loading response and a significantly reduced or even absent second peak compared to overground walking (Stacoff et al., 2005; Hamel et al., 2005). There are two peaks for the internal hip extension moment and the internal plantarflexion moment at the ankle. The first peak occurs at loading response and a second peak is present during terminal stance (Novak & Brouwer, 2010; Protopapadaki et al., 2007; Reeves, Spanjaard et al., 2008b). The peak internal knee extension moment occurs in terminal stance (Novak & Brouwer, 2010; Protopapadaki et al., 2007).

1.5.3 Muscle activity

As described in the kinematic analysis, the body has to be lowered down to the next stair. This is mainly achieved by eccentric muscle activity of the antigravity muscles such as the quadriceps (McFadyen & Winter, 1988) and triceps surae which is pre-activated to absorb the impact of the body weight during stepping down (Craig et al., 1982).

1.5.4 Foot placement and clearance

For stair descent there are no data available for step width or step length, neither for YA nor OA. In contrast to stair ascent, minimum foot clearance during stair descent was previously calculated as overall minimum distance in the sagittal plane between heel and stair edge during the swing phase (Simoneau et al., 1991, Hamel et al., 2005). In YA, minimum foot clearance ranges from 1.8 to 3.8 cm and it appears that

this value is dependent on the place of measurement: foot clearance is greater during the transition phases from upper landing to stair and from stair to lower landing compared to midstair clearance (Hamel et al., 2005).

1.5.5 Age-related changes and adaptation to functional loss

During stair descent, OA walk slower (Lee & Chou, 2007), with reduced cadence (Reeves et al., 2008a; Mian et al., 2007a) and increased stride time (Mian et al., 2007b) than YA. Kinematic comparison between YA and OA revealed reduced peak knee flexion during swing and increased pelvis and hip movements in the coronal and transverse planes in OA (Mian et al., 2007b). Although ankle and knee joint kinematics are seemingly unaffected by age, OA descend stairs with higher knee joint moments relative to their maximum capacity and reduced ankle joint moments compared to YA (Reeves et al., 2008b). This finding indicates a redistribution of joint moments from the ankle to the knee in order to descend stairs safely. In addition, OA increase the stiffness of their legs by co-activating thigh and calf muscles during the stance phase (Larsen et al., 2008) and OA rely more on their skeletal rather than muscular system (DeVita & Hortobagyi, 2000). This finding is further supported by EMG studies. In comparison to YA, OA demonstrate generally increased EMG activity, including increased muscle co-activation at the thigh during loading of the leading leg and during stance (Larsen et al., 2008). All these strategies may help OA to lower the body safely down to the next stair.

Minimum foot clearance is slightly reduced in OA and ranges between 1.5 cm (Hamel et al., 2005) and 2.8 cm (Simoneau et al., 1991). Nevertheless age-related changes in foot clearance only include increased variability in OA which may contribute to increased fall risk (Hamel et al., 2005). Foot placement on the stair, namely the extent that the toes overlap the stair edge, has previously been studied in older

women. Simoneau et al. (1991) found that the toe overlaps the stair edge by 0.6 to 1 cm, meaning that the toe-cap is not placed on the run. Interestingly, foot placement remains unchanged when visual input is impaired by blurring the visual field.

1.5.6 Handrail use

The most obvious change in stair descent performance between YA and OA may be the use of a handrail. Indeed, the less confident an older person feels about walking down a staircase the more likely it is that this person will use this external support (Hamel & Cavanagh, 2004). Previous studies have shown that light touch at the handrails led to a redistribution of joint moments. For example, when OA use the handrail, the peak plantarflexion moment increases and the peak knee flexion moment decreases due to an earlier heel rise compared to unaided stair descent (Reeves et al., 2008a). Although OA already use a higher proportion of their capacity of ankle joint moments than YA (Reeves et al., 2008b) and an even higher plantarflexion moment occurs when using handrails, this strategy improves balance by increasing the base of support with additional contact points at the handrail (Reeves et al., 2008a).

1.6 Summary and aims of thesis

The human body declines in older age and these physical and functional changes, such as a reduction in muscle mass, inaccurate and delayed perception of visual, proprioceptive and vestibular information and variable and inaccurate movement execution, are related to increased risk of falling. In addition, environmental factors such as uneven ground or insufficient illumination add to the likelihood of falls.

Previous research focussed on contributing factors to increased fall risk in OA during walking, such as age-related changes in walking parameters and gaze behaviour. However, there is no published data regarding where individuals look while

they ascend or descend stairs. Although it is likely, it is still unknown if older individuals' gaze behaviour during stair negotiation shows similar changes to those observed during overground walking. Therefore, one aim of the present thesis is to describe gaze behaviour during stair negotiation and age-related changes during midstair walking. This study is presented in Chapter 2.

Stair edges may serve as point of interest in the visual scene and although many studies have highlighted changes in stepping behaviour in fit OA when vision is experimentally reduced, it remains unknown how the stepping pattern and balance control is affected in OA with a higher risk of falling during midstair negotiation in comparison to OA with lower risk of falling and YA. Therefore, the second aim of the present thesis is to investigate the effect of manipulating stair edge visibility on stepping behaviour and balance control as well as age-related changes in these measures, which are likely to contribute to a higher risk of falling in some OA. In addition, the relative effects of experimentally manipulating ambient illumination and stair edge contrast on stepping and balance control is described in YA, OA with lower risk of falling (LROA) and OA with higher risk of falling (HROA). Chapters 4 and 5 present the studies for stair ascent and descent respectively.

Head stabilisation has been shown to be challenged in OA and to decrease in YA during stair ascent and descent compared to overground walking. However, OA demonstrate improved head stabilisation when required to fixate a point straight ahead during walking. A third aim of the present thesis is to investigate age and fall risk-related changes as well as the effect of enhanced stair edge visibility on head posture and head posture control. The study is presented in Chapter 6.

A general discussion of results and a discussion about differences between stair ascent and descent are presented in Chapter 7.

CHAPTER 2

Gaze behaviour of young and older adults during stair negotiation

2.1 Introduction¹

Visual information is important for effective and safe walking on stairs, as evidenced by the fact that experimentally impairing vision has a detrimental effect on motor performance during single step and stair negotiation. For example, exclusion or blurring of sight results in changes to the normal stepping pattern such as increased step execution time, increased proportion of body weight borne by the stance limb (Craig et al., 1982; Buckley et al., 2005b), increased imbalance during stepping down (Buckley et al., 2005a) and changes in foot placement (Simoneau et al., 1991) and foot clearance (Hamel et al., 2005). Also, the use of optical aids such as multifocal glasses, that impair depth perception within an area close to the feet, has been shown to clearly increase the risk of falling during stair negotiation (Lord et al., 2002).

Visual guidance of walking has previously been investigated in experimental settings such as walking with predefined stepping positions (Patla & Vickers, 2003; Hollands & Marple-Horvat, 1996; Hollands & Marple-Horvat, 2001), walking with direction change (Hollands et al., 2002) or stepping into multiple targets (Chapman & Hollands, 2006b; Chapman & Hollands, 2007), and also in natural environments such as walking in a public building (Vivekananda-Schmidt et al., 2004) or crossing an

¹ The data in this chapter have been published in the *Journal of Motor Behaviour* (2009); 41 (4): 357-365.

intersection (Geruschat et al., 2003). A common finding from these studies was that visual information is generally used in a feed-forward manner for movement planning and execution. For example, during level walking with prescribed stepping targets in the walking path, YA looked on average two steps ahead (Patla & Vickers, 2003). There is large variability in the extent to which individuals look ahead which can range from the next step (e.g. Hollands et al., 1995; Hollands & Marple-Horvat, 2001) to several steps in advance (e.g. Chapman & Hollands, 2006b; Chapman & Hollands, 2007) depending on the task constraints. However, there is currently no published study describing where and when people look during the daily activity of stair negotiation. Understanding the visuomotor control mechanisms underpinning stair negotiation is clinically important since falls on stairs occur frequently, particularly in OA, often with severe consequences such as impairments needing expensive treatment and long term care (Scuffham et al., 2003). If we are to understand the mechanisms underlying stair falls in OA then there is a clear need to know where and when individuals look as they negotiate stairs and whether there are age-related changes in this behaviour.

The experimental approach of monitoring gaze behaviour during walking has been used to good effect in previous studies of OA which have demonstrated age-related changes in visual sampling characteristics during precision stepping tasks. For example, OA have been shown to look sooner to stepping targets in the travel path and to fixate these targets for longer than YA, suggesting that older individuals might need more time to plan accurate stepping movements (Chapman & Hollands, 2006b). Other studies have demonstrated that OA categorized as being at a high-risk of falling showed a tendency to look away from a stepping target prematurely and that this apparently mal-adaptive behaviour was associated with a reduction in the accuracy and precision of stepping movements (Chapman & Hollands, 2006b; Chapman & Hollands, 2007). Although there is some evidence that OA show altered visual

behaviour during stepping over obstacles (Di Fabio et al., 2003a) or onto a raised platform (Di Fabio et al., 2003b), there is no published study describing the temporospatial relationships between gaze and gait or how the ageing process affects visuomotor control during stair negotiation, involving multiple steps. It is still unknown if older individuals' gaze behaviour during stair negotiation shows similar changes to those observed during overground walking.

The aims of this study were to quantitatively describe where and when individuals look during stair negotiation and to determine whether there are any age-related differences in these measures that might contribute to our understanding of the increased incidence of stair falls in older adult populations. It was hypothesised that 1) both groups of participants would spend the majority of time looking at future stepping locations on the stairs, but that 2) OA would look to these locations sooner and fixate them for longer than YA.

2.2 Methods

2.2.1 Participants

Ten YA (5 females, 5 males, mean age 21.4 years \pm 2.2) and 10 OA (6 females, 4 males, mean age 70.7 years \pm 3.1) were recruited from the School of Sport and Exercise Sciences and the local community. All participants lived independently in the community and were included if they were able to ascend and descend stairs in a step-over step manner. All participants were screened for general health by a school-internal General Health Questionnaire and by self-report by the participant. Participants reported their confidence in stair negotiation under various conditions by the Stair Self-Efficacy Questionnaire (SSEQ) (Hamel & Cavanagh, 2004). The Berg Balance Scale (BBS) (Berg et al., 1989) and the Timed-up-and-go test (TUG test) (Podsiadlo & Richardson, 1991) were performed to assess balance ability and walking performance.

These assessments are described in more detail in paragraph 3.2. Visual function assessment included visual acuity (Snellen eye chart) and contrast sensitivity (Pelli-Robson contrast sensitivity chart 4K, Metropia Ltd., United Kingdom), both tested at 6 m. Exclusion criteria for this study were musculoskeletal, neurological or vestibular impairments which affect stair negotiation ability or gaze behaviour, acute or untreated heart conditions, use of walking devices, a BBS score less than 54 and more than 10 s needed for the TUG test. Due to technical problems associated with obtaining gaze data of acceptable quality from participants wearing eye glasses, individuals who reported that they normally wore glasses during walking were also excluded, however, there was one person in each age group who wore contact lenses.

Age groups were comparable in their confidence in stair walking (SSEQ score for YA= 143 ± 19.1 , for OA= 139 ± 27.2 ; $F_{(1,18)} = 0.124$, $p = .729$) and balance abilities (BBS score for YA= 56 ± 0 , for OA= 56 ± 0.5 ; $F_{(1,18)} = 3.857$, $p = .065$), but OA completed the TUG test significantly slower ($7.4s \pm 0.8$) than YA ($5.8s \pm 0.8$); $F_{(1,18)} = 19.200$, $p < .001$). Visual acuity was 6/12 or better for both YA and OA, contrast sensitivity was significantly better for the YA ($F_{(1,18)} = 16.200$, $p = .001$).

The study was approved by the School's Safety and Ethics Subcommittee. All participants gave informed written consent prior to participation.

2.2.2 Stairs and apparatus

The 12-step staircase used for data collection was located in a quiet area of the school's building; the stairway had large windows without shutters. The stair size was 16.1 cm x 27.3 cm (rise x run), resulting in a stair angle of 30.5°. The stairs were covered with dark grey vinyl floor tiles and 5 cm plastic edge strips of light grey colour. Handrails were mounted on both sides at a height of 90 cm.

A head mounted eye tracking system (Model 501, Applied Science Laboratory, USA) (weight 480g) was used for recording the eye movements (Figure 2.1). A digital video recorder recorded gaze data and data from a scene camera, attached to the eye tracker, at a sample rate of 30 Hz. Essential technical equipment was stored in a backpack (weight 4.1 kg) and carried by the participant. One Force Sensing Resistor™ device (4.5 x 4.5 cm, Interlink Electronics Europe) was attached to each sole of the footwear in the area of the metatarsal heads II to IV and connected to a LED light. The lights were laterally attached to the lower thighs and switched on for the duration of stance phase of either the left or right leg. A second digital camera (Sony Handycam DCR-H30) with a sample rate of 30 Hz recorded the stepping characteristics of the lower limbs in addition to the LED lights.



Figure 2.1: OA with mobile eye-tracker and attached LED light to detect foot contact on the stair

2.2.3 Experimental procedure

The eye tracker was optimally calibrated for the area two to four steps in front of the participant and after preparing the backpack, all participants were allowed to walk around to familiarise themselves with the additional weight.

Each participant completed three trials in each walking direction, starting with stair ascent. The starting position was 1m in front of the stairs. Participants started each trial with eyes closed to prevent any early visual exploration of the staircase environment. When hearing the start signal “go!”, participants opened their eyes and either ascended or descended the stairs. All participants were asked to walk at their preferred speed and always to start with the preferred leg. Light handrail use was allowed, but not encouraged. The participants were told to use the handrail as guide only and not for “pulling themselves up”. During the trial, the experimenter walked next to the participant to aid stability in the event the participant needed additional support.

2.2.4 Data preparation and analysis

Gait and gaze data were only analysed for travel over the middle section of the staircase (Figure 2.2) as non-specific areas of the visual scene (e.g. areas of the floor or wall) were not amenable to quantitative analysis in the transition phases from landing to stair and from stair to landing.

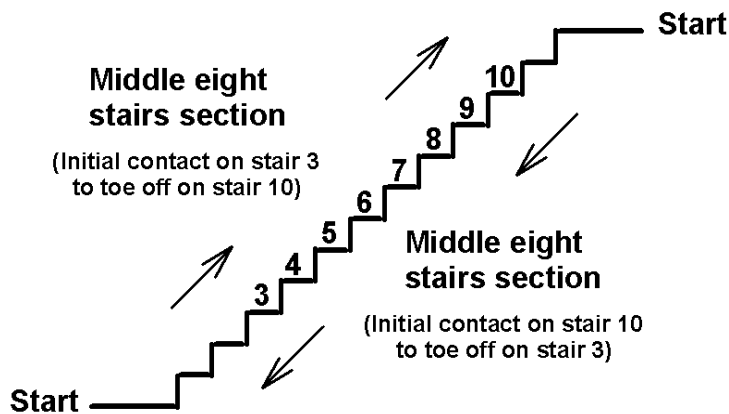


Figure 2.2: Definition of the middle eight stairs section used for data analysis

Walking speed was calculated from the time interval between initial contact with stair 3 and toe off on stair 10 for ascent and initial contact with stair 10 and toe off on stair 3 for descent. Cadence (number of steps per minute) was also calculated over this distance. All gait data were averaged over three trials for each walking direction. The video data from the eye tracker and video camera were synchronised for each trial by recording three LED flashes, using the LED light on the right thigh of the participant. These flashes were simultaneously recorded by the eye tracker and the external digital video recorder and used post-hoc to align the video data time codes. Every trial was analysed frame by frame. Trials with more than 30% data loss of eye tracker data were excluded from further analysis. Loss of data occurred when the eye tracker failed to maintain a picture of the eye when the participant fixated locations outside the field of the eye tracker's scene camera or the illumination in the stairway changed due to sudden sunshine. At least two trials were analysed for each walking direction for each participant.

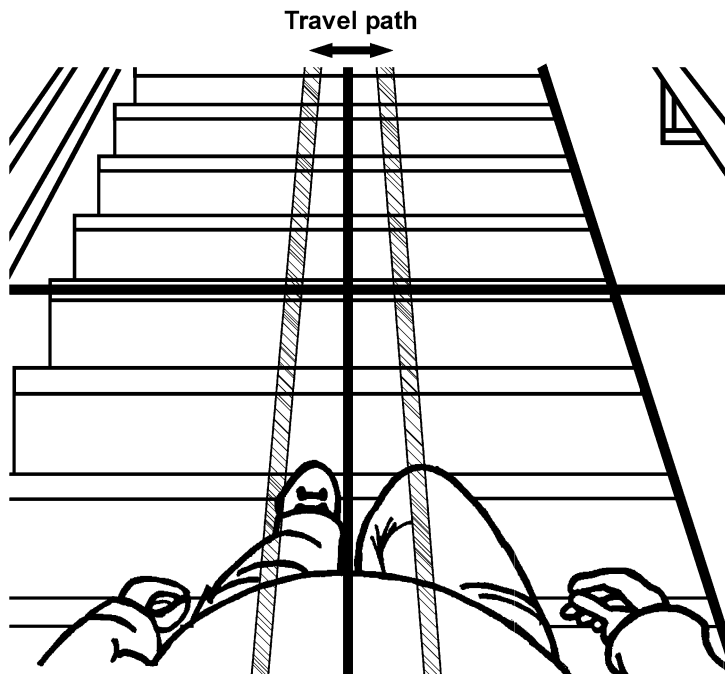


Figure 2.3: Stair descent: Picture from the eye tracker's video camera. The cross-hair indicates that the person is fixating the contrast coloured edge of the stair within the travel path.

The following dependent gaze variables were analysed and further explained below: (1) total duration for which gaze was directed at the travel path, (2) number of stairs the participants looked ahead, (3) within-subject variability of number of stairs the participants looked ahead, (4) time interval between onset of last gaze fixation on a stair and initial foot contact on that stair, (5) time interval between looking away from a stair and initial foot contact on that stair and, (6) duration of last gaze fixation of a stair before stepping onto that stair.

The total duration for which gaze was directed at the travel path was expressed as a percentage of the time taken to travel the eight stairs under investigation. The travel path was defined as the area of the staircase within the boundaries represented by trajectories of the lateral edges of the two feet (Figure 2.3). The number of stairs the participants looked ahead is presented as frequency analysis. The within-subject variability of number of stairs the participants looked ahead was calculated as the

average standard deviation of number of stairs looked ahead during each trial and for each walking direction. Gaze fixation was defined as continuance of gaze at one location in the scenery for at least 66 ms (two video frames) following precedents from Tatler et al. (2006), Terao et al. (2002) and Geruschat et al. (2003). Very few fixations of 66 ms (9.6% of all fixations) were found. Participants were considered to look one stair ahead when they fixated a stair prior to the start of the swing phase towards that stair (Patla & Vickers, 2003). Gaze fixations starting during the swing phase towards a fixated stair were considered as fixations of zero stairs ahead. For example, a person standing on stair 2 while looking to stair 7 would need to complete four steps from stair 2 to the stairs 4, 5, 6 and 7 resulting in a gaze fixation four stairs ahead, without counting the ongoing swing phase towards stair 3 as a complete step (Figure 2.4).

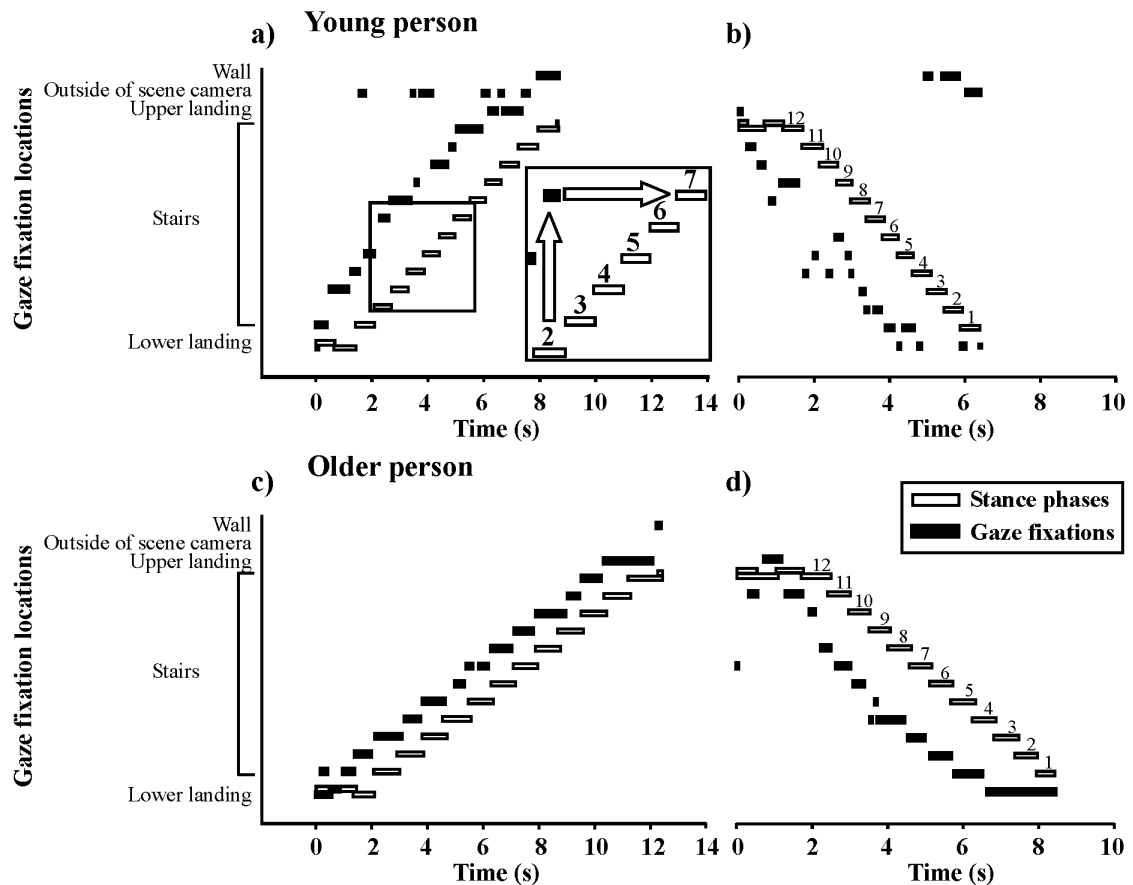


Figure 2.4: Raw data from one typical trial of one young and one older adult during stair ascent (a,c) and descent (b,d). Gaze fixation locations are shown in relation to the stance phases on the stairs. The magnified section shows the person standing on stair 2 while looking to stair 7, resulting in looking four stairs ahead. Different slopes correspond to different walking speeds.

SPSS 15.0 for Windows was used for statistical analysis. Gait and gaze data were analysed using a mixed 2 (age group: YA and OA) x 2 (walking direction: stair ascent and stair descent) ANOVA. A correlation was performed to assess the relationship between gaze behaviour and walking speed. An ANCOVA with walking speed as covariate was calculated when walking speed has been shown to be correlated with gaze behaviour. A level of $\alpha=.05$ was considered to be significant, and only significant results are reported.

2.3 Results

A total of 29 trials for OA and 27 trials for YA were analysed for both walking directions. Figure 2.4 presents the raw data from one trial of one young and one older adult during stair ascent and descent. Gaze fixation locations are shown in relation to the stance phases on the stairs. During stair ascent, one trip occurred in an OA; one YA and four OA used the handrail occasionally. During stair descent, no trips occurred; one YA and five OA used the handrail occasionally. The light use of handrails did not produce any significant differences in walking or gaze behaviour; therefore data from handrail users and non-users in each group were analysed together.

2.3.1 Gait characteristics

The results of the ANOVA indicated that OA walked significantly slower during both ascent and descent and with a significantly lower cadence than YA. All participants walked faster with higher cadence during stair descent. Single stance phases were prolonged in the OA in both walking directions, whereas no differences between age groups were found for the double support phase. Mean values and the results of statistical analyses for the gait data are shown in Table 2.1.

Table 2.1: Mean (SD) for gait data and gaze behaviour for YA and OA during stair ascent and descent

	Stair ascent		Stair descent	
	Young	Old	Young	Old
Walking speed (m/s)	0.59 (0.05)**	0.47 (0.07)	0.67 (0.08)**	0.50 (0.07)
Cadence (steps per min)	112 (10)**	90 (14)	127 (15)**	96 (14)
Single stance phase (s)	0.45 (0.06)**	0.56 (0.10)	0.38 (0.04)**	0.54 (0.09)
Double stance phase (s)	0.08 (0.02)	0.11 (0.02)	0.09 (0.03)	0.09 (0.03)
Gaze directed at travel path (% of walking time)	75.4 (14.9)	90.7 (7.9)	86.2 (10.3)	91.3 (10.7)
Looks ahead (number of stairs)	3.5 (0.8)	3 (0.7)	4 (1.2)	3.4 (1.7)
Within-subject variability (number of stairs participants looked ahead)	0.92 (0.24)**	0.58 (0.14)	1.68 (0.56)	1.25 (0.79)
Time between last gaze fixation and initial contact on the stair (s)	1.81 (0.40)	2.17 (0.55)	1.40 (0.35)	1.79 (0.68)
Time between looking away from and initial contact on the stair (s)	1.55 (0.43)	1.72 (0.54)	1.18 (0.35)	1.48 (0.72)
Duration of last gaze fixation (s)	0.30 (0.05)*	0.49 (0.10)+	0.25 (0.04)**	0.35 (0.08)

* $p < .05$, ** $p < .01$ for differences between age groups within one walking direction

+ $p < .05$, for influence of walking speed

2.3.2 Characteristics of gaze behaviour

There was a main effect of age group on the amount of time participants' gaze was directed toward the travel path, showing that older participants spent significantly more time looking within this region than YA ($F_{(1,18)} = 6.012$, $p = .025$, $\eta^2 = .250$). OA directed their gaze toward the travel path for 90% of walking time in both walking directions,

whereas YA spent 75% (stair ascent) and 86% (stair descent) of their walking time looking at features lying along their future travel path (Table 2.1). Gaze was directed most commonly toward the high-contrast strip on the edges of the stairs (Figure 2.3).

Figure 2.5 depicts the frequency distribution of the number of stairs participants looked ahead during stair ascent and descent. All participants looked most frequently three stairs ahead during stair ascent and descent. All participants looked most frequently three stairs ahead (YA: 29%, OA: 44%) during ascent. OA rarely looked more than four stairs ahead, whereas the frequency of gaze fixation locations is more widely distributed in the young group. During stair descent the distribution of the number of stairs the participants looked ahead was even in all participants, indicating similar gaze behaviour in both age groups. YA fixated most frequently four (21%) and two (17%) stairs ahead, whereas OA looked most frequently two (22%) and four (17%) stairs ahead. There was a significant correlation between walking speed and extent of looking ahead for the YA during stair ascent ($r_{(9)} = 0.650$, $p < .05$, $R^2 = .422$), but no significant correlation was found for descent or for the OA in either walking directions.

There was significantly less within-subject variability in the extent to which older participants looked ahead compared to YA ($F_{(1,18)} = 5.665$, $p = .029$, $\eta^2 = .239$). The extent of looks ahead varied between 0.58 stairs (stair ascent) and 1.25 stairs (stair descent) in OA and between 0.92 (stair ascent) and 1.68 (stair descent) in YA (see Table 2.1). Both age groups were more variable in their gaze pattern during stair descent ($F_{(1,18)} = 20.835$, $p < .001$, $\eta^2 = .536$) than ascent. There was no significant correlation between walking speed and variability in the extent to which the participants looked ahead.

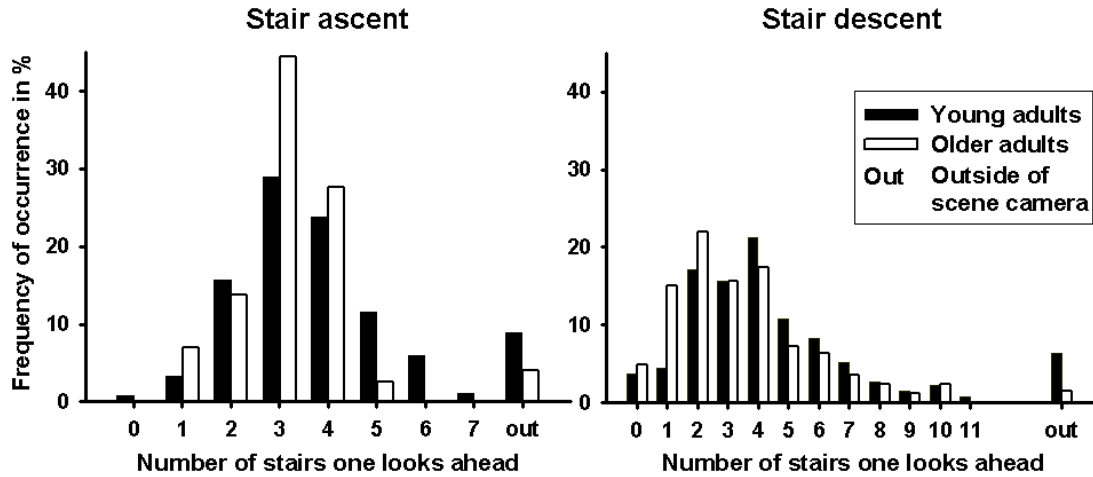


Figure 2.5: Number of gaze fixations in % for the middle eight stairs section during stair ascent and descent for young and older participants.

2.3.3 Relationship between gaze fixation and stepping

There were significant main effects of walking direction on the time interval between last gaze fixation of and initial foot contact with a stair ($F_{(1,18)} = 16.461$, $p = .001$, $\eta^2 = .478$) and on the time interval between looking away from a stair and foot landing on that stair ($F_{(1,18)} = 8.289$, $p = .01$, $\eta^2 = .316$). This indicates that all participants looked later towards stairs during stair descent than during ascent, and that all participants looked away earlier from the stairs during stair ascent (Figure 2.6). OA did not look significantly sooner at the stairs than YA.

There were significant main effects of age ($F_{(1,18)} = 29.673$, $p < .001$, $\eta^2 = .622$) and walking direction ($F_{(1,18)} = 22.020$, $p < .001$, $\eta^2 = .550$) on the duration of last gaze fixation on a stair before stepping onto that stair, showing that OA fixated the stairs longer than YA and both age groups fixated the stairs for a shorter time during stair descent (Figure 2.6). A significant correlation between walking speed and the duration of the last gaze fixation was found for OA during stair ascent ($r_{(9)} = -0.772$, $p < .01$, $R^2 = .579$), but not during stair descent nor for the YA irrespective of walking direction. Although walking speed influenced the duration of the last gaze fixation ($F_{(1,18)} = 14.971$, $p = .001$,

$\eta^2=.468$), age remained a significant factor ($F_{(1,18)}= 5.684$, $p=.029$, $\eta^2=.251$) using ANCOVA with walking speed as a covariate.

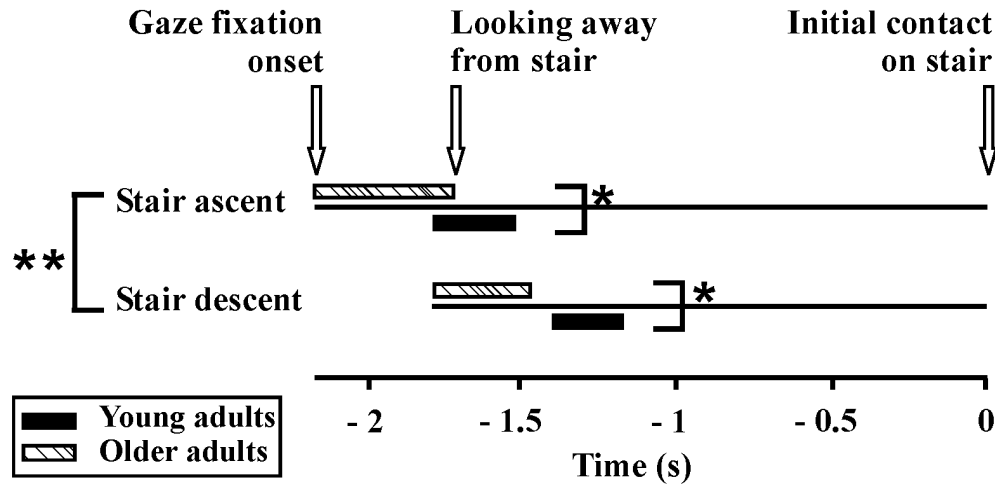


Figure 2.6: Temporal relationships between gaze and stepping behaviour in young and OA. Only the gaze fixation duration is significantly different between age groups and walking directions, * $p < .05$, ** $p < .01$

2.4 Discussion

This is the first study to directly measure gaze behaviour during stair negotiation in a natural environment on a real multiple-stair staircase. The study provides novel information about which environmental features individuals look at during stair negotiation and when individuals look at these features with respect to the timing of stepping movements. The study provides further novel information by comparing data obtained from YA and OA. The information provided is crucial to the understanding of how vision is used to control stair negotiation and adds to the understanding of age-related changes in this control which may contribute to stair falls in OA.

2.4.1 Where do individuals look during stair walking?

The main finding of this study is that all participants spent the majority of their walking time visually fixating aspects of the stairs which represent future stepping locations (around 90% during stair descent and around 75 – 90% for stair ascent; see Table 2.1). This result confirms the first hypothesis and is consistent with the results of previous studies suggesting that visual information of the stair properties are crucial for safe stair negotiation (Craig et al., 1982; Lord et al., 2002; Simoneau et al., 1991; Hamel et al., 2005). Even if individuals are able to negotiate the stairs by using an internalized representation of their dimensions based on experience or by reliance on somatosensory input, vision nevertheless is clearly preferred during stair negotiation. This is easily demonstrated by carrying an empty box up and down stairs. The loss of one's lower visual field during stair negotiation is unnerving and usually results in altered walking behaviour (e.g. turning sideways to restore vision of the stairs).

In the present study, on average, all participants looked three stairs ahead during stair ascent and either two or four stairs ahead during stair descent (OA and YA respectively). Walking speed only correlated with the extent to which YA looked ahead during stair ascent; the higher the walking speed the further they looked ahead. These results are consistent with the notion that central vision is used in a feed-forward manner to guide stair walking and similar to the strategy used for walking on stepping targets over flat terrain (Hollands et al. 1995, Patla & Vickers 2003). Analysis of video data also indicated that all participants spent most of the time looking at points on the stairs lying along their future travel path represented by a projected area within the trajectories of the lateral edges of the feet (see Figure 2.3). A strategy whereby participants made clear alternating left and right saccades to future foot landing positions was only occasionally seen. Two older participants used this strategy in a total of five trials during ascent and two trials during descent. Two young participants

showed these saccades in a total of two trials during descent. Furthermore, in both walking directions participants' gaze was directed towards the contrast strips on the edges of the stairs. In combination these results suggest that participants were collecting visual information about the anterior-posterior (a-p) location of step edges rather than identifying m-l position on the steps for future foot placement. This is perhaps not surprising since stair negotiation places far more restraints on foot placements in the a-p direction (stair run) than in m-l direction (stair width).

2.4.2 Differences between gaze characteristics during stair ascent and descent

During stair descent, all adults fixated a stair later and looked away from it later prior to stepping onto it than during stair ascent (see Table 2.1). This suggests that, during stair descent, more up-to-date visual information about stair properties is needed to guide stepping movements and is consistent with the notion that stair descent poses a greater challenge to dynamic postural stability than stair ascent (Mian et al., 2007b). This increased challenge presumably explains why falls occur more frequently during stair descent (Svanström, 1974).

2.4.3 Age-related differences in gaze behaviour during stair negotiation

It was previously shown that OA fixated a stepping target sooner (Chapman & Hollands, 2006b; Di Fabio et al., 2003a) and for longer than YA during walking (Chapman & Hollands, 2006b). The present results showed that similar trends are observable during stair negotiation although only the longer gaze fixation time reached statistical significance. Walking speed can only partially explain the longer fixation time in OA during stair ascent. Although OA walked slower and therefore had more time to look around than YA, they did not use this additional time to fixate other environmental

features such as the handrail. In contrast to stair ascent, walking speed had no effect on gaze fixation time during stair descent in either age group. This suggests that OA need more time fixating the stairs in order to process visual information describing stair locations in order to generate an accurate stepping movement. It is noteworthy that the duration of final fixation on a target prior to movement initiation has been demonstrated to be an important predictor of movement accuracy in many different sporting contexts ranging from golf swings, to basketball free throws (Vickers, 2007). The term “quiet eye” was coined by Vickers (1996) to describe this phenomenon, and the concept has been used effectively in coaching scenarios to successfully improve sporting achievement (Vickers, 2007). The “quiet eye” literature suggests that the gaze strategy adopted by OA during our task may be appropriate for optimizing stepping accuracy.

Although it is conceivable that biomechanical differences between the groups of participants could influence head posture (e.g. neck flexibility which determines head range of motion) during stair negotiation, it is hard to see how this would constrain gaze behaviour. If OA did have reduced range of head motion, then they could still independently move their eyes to fixate the stairs (the eyes have a vertical range over $\pm 45^\circ$). Even, if participants were unable or unwilling to move their eyes independently from their head during stair negotiation then reduced neck flexibility would make it more difficult for OA to look down. When walking down stairs the OA looked down by the same extent as YA and during ascent they looked down to a greater extent. Therefore, it is proposed that the age-related differences in gaze behaviour represent differences in visual control rather than biomechanical constraints.

2.4.4 Role of vision in maintaining balance during stair negotiation

Individuals looked ahead by a fairly consistent extent during stair negotiation, as demonstrated by the small within subject variability in this measure. The strategy of

maintaining a constant gaze angle with respect to the support surface has previously been described in human participants walking on stepping targets (Patla & Vickers, 2003) and over obstacles (Patla & Vickers, 1997) and also in cats walking down a cluttered alley (Fowler & Sherk, 2003). However it is important to note that these papers describe behaviour in which participants do not continually fixate environmental features at a relatively constant distance ahead but rather “park” their eyes in orbit so that gaze is shifted by the forward progression of walking. This gaze strategy was never observed in the current study; participants were always fixating environmental features (predominantly the stair edges). Nevertheless, maintaining a relatively constant angle between gaze and staircase may be advantageous to participants by simplifying the extraction of pertinent information from retinal flow fields for maintaining heading and guiding posture. For example, looking a consistent distance ahead in the direction of travel will serve to minimize the extent of rotary and linear components of optic flow arising from compensatory eye movements. Interestingly, OA showed significantly less variability than the YA in the extent to which they looked ahead. It is possible that OA were more reliant on visual information to guide balance during stair negotiation and therefore direct their gaze in a way that better facilitates the extraction of optic flow from the visual scene.

2.4.5 Limitations

Although this study has provided important novel information pertaining to visual sampling strategies used during stair negotiation, it has some obvious limitations. The study investigated how vision is used to guide stair negotiation in fit and healthy YA and OA in a natural environment outside of laboratory-controlled conditions. Studies of more frail OA would likely show greater age differences in gaze and stepping behaviour in line with those documented in previous walking studies (Chapman & Hollands,

2006a; Chapman & Hollands, 2007). However, frail OA can only be investigated in a controlled lab-based environment where appropriate safety precautions can be implemented. The aim was to analyse gaze data collected in a natural environment in order to gain insight into the visual cues that are normally sampled from the real world during stair negotiation and this has been clearly achieved. Another limitation of the study is the temporal resolution of the measurements of gaze behaviour. The mobile eye tracking system only has a sampling frequency of 30 Hz which limits the analysis of eye movement characteristics to duration of gaze fixations with a resolution of 33 ms. A higher resolution system would be required to detect saccade onsets more precisely and to reveal more subtle age-related changes to oculomotor characteristics, such as saccade excursions. Finally, the eye tracking equipment including the backpack represented an additional weight that may have changed the stepping behaviour even in fit and healthy OA. Walking speed and cadence were slightly lower in this group, whereas gait data in the young group were comparable with those from other studies (Mian et al., 2007a; Lee & Chou, 2007; Larsen et al., 2008).

2.5 Summary and conclusion

The findings clearly show that central visual information describing stair locations is an important source of information for both YA and OA walking up and down stairs. Both age groups fixated future stepping locations within the travel path on average three stairs ahead in both walking directions. Therefore it is important that vision within this area is as good as possible to minimise the risk of a trip or fall, particularly for OA. In both walking directions, OA fixated the stairs for longer than YA. Furthermore, OA were less variable in the extent they looked ahead during ascent. These findings lend support to the suggestion that OA require more time to process visual information describing a step and transform it into an appropriate stepping movement. Given the

finding that stair edges are predominantly fixated, the following study will investigate the differences in gaze behaviour between YA and OA with lower or higher risk of falling and the effect of stair edge visibility on stepping parameters and balance control.

CHAPTER 3

General methods

This chapter summarises the general methods used in the following three experimental chapters.

3.1 Participants

Eight YA (7 females, mean age 26.0 years \pm 4.0), seven OA with lower risk of falling (LROA) (6 females, mean age 72.1 years \pm 3.8) and eight OA with higher risk of falling (HROA) (7 females, mean age 79.3 years \pm 6.4) were included in the studies. All participants were living independently in the community at the time the study was conducted. YA were recruited within the university and OA were recruited using either an existing in-house database of participants or through visits to local community groups. The general inclusion criterion was that all participants were able to ascend and descend stairs in a step-over step manner, resulting in one foot contact per stair. General exclusion criteria for the studies were musculoskeletal, neurological or vestibular impairments, acute or untreated heart conditions and the use of walking devices during stair negotiation. YA were selected to match for gender and height distribution (\pm 4 cm) in the older participants.

The studies were approved by the School's Safety and Ethics Subcommittee and all participants gave informed written consent prior to participation.

3.2 Tests and assessments

All participants underwent a screening for exclusion criteria, vision, balance ability, fear of falling and confidence in stair negotiation prior to data collection. The falls history included falls in the previous 12 months.

Musculoskeletal, neurological and vestibular impairments were assessed by a school-internal General Health Questionnaire (Appendix A) and by self-report by the participant.

Visual function assessment included visual acuity (Snellen eye chart) and contrast sensitivity (Pelli- Robson contrast sensitivity chart 4K, Metropia Ltd., United Kingdom). Participants were included for data collection when their visual acuity of normal or corrected to normal vision was 6/12 or better.

Balance was assessed by the Berg Balance Scale (BBS) (Berg et al., 1989) (Appendix B). This scale is a 14-item assessment with active balance tasks such as standing with eyes closed, turning around and standing on one leg. Possible scores are 0 to 56 and the maximum score of 56 signifies no balance impairment. The BBS has been shown to be highly sensitive and specific to identify community-dwelling OA at higher risk of falling (Shumway-Cook et al., 1997).

Fear of falling was assessed by the Modified Falls Efficacy Scale (MFES) (Hill et al., 1996) (Appendix C). This scale is a 14-item assessment on how confident participants feel to do activities without falling such as getting dressed, walking inside the house or crossing roads. Possible scores are 0 to 140 and the maximum score of 140 indicates full confidence in doing the task in question without falling.

Confidence in stair negotiation was assessed by the Stair Self-Efficacy Questionnaire (SSEQ) (Hamel & Cavanagh, 2004) (Appendix D). The questionnaire is an 8-item assessment on how confident participants feel to negotiate stairs without losing balance under different circumstances such as using stairs without handrail or

using stairs outside their home. The answers are divided into walking up and walking down stairs. Possible scores are 0 to 160 and the maximum score of 160 indicates full confidence. The reliability of this questionnaire has been reported to be good (Hamel & Cavanagh, 2004).

3.3 Participants' characteristic and assignment of OA to fall risk groups

Details of the participants' characteristics are presented in Table 3.1 and group differences were calculated by using an ANOVA for age, height, weight, MFES and SSEQ scores and contrast sensitivity. The Kruskal-Wallis test was used for calculating group differences in the BBS score and a post-hoc Mann-Whitney test with Bonferroni corrected α - level ($p \leq .017$) was used to calculate the difference between the LROA and HROA group. There were no significant differences in height and weight between groups, but LROA were younger than HROA ($p=.032$). Reported falls were none in the YA, one in the LROA and two in the HROA group. HROA demonstrated reduced balance abilities, indicated by lower BBS scores than LROA ($p=.010$) and YA ($p=.001$). HROA reported less confidence in stair negotiation than LROA ($p=.008$) and YA ($p=.002$) as indicated by the SSEQ score. Vision was corrected with glasses in one YA, two LROA and two HROA. Three YA wore contact lenses during data collection. Contrast sensitivity was comparable in all groups, ranging from 1.65 to 1.95 log contrast in both OA groups and from 1.95 to 2.1 log contrast in the YA.

OA were assigned to the fall risk group on the basis of their combined assessment scores in BBS, MFES, SSEQ. The scores from each assessment were ranked and the individual's sum of all ranks was used to separate the older participants into two groups with the lowest and highest combined scores from these assessments. Since impaired balance and subjectively perceived fear of falling contribute to a

restriction of activities (Zijlstra et al., 2007; Deshpande et al., 2008a), lead to a decline in lower limb function (Deshpande et al., 2008b) and are associated with increased fall risk (Lin & Woollacott, 2005) it is believed that grouping participants in this manner resulted in two groups representing older individuals with a comparatively higher and lower risk of falling.

Table 3.1: Participants' characteristics in mean (SD)

	YA	LROA	HROA
Age (years)	26.0 (4.0) *+	72.1 (3.8) §	79.3 (6.4)
Height (m)	1.63 (0.08)	1.62 (0.09)	1.60 (0.10)
Weight (kg)	60.4 (8.9)	56.6 (8.0)	63.4 (17.2)
Stair self-efficacy score (max. 160)	151 (8) +	145 (4) §	98 (39)
Modified falls efficacy score (max. 140)	139.4 (1.8)	138.8 (2.3)	119.3 (23.2)
Berg Balance Scale score (max. 56)	56.0 (0) +	55.6 (0.5) §	52.7 (2.2)
Contrast sensitivity (log contrast)	1.99 (0.07)	1.88 (0.14)	1.84 (0.14)

* sig. difference ($p < .05$) between YA and LROA, + sig. difference ($p < .05$) between YA and HROA, § sig. difference ($p < .05$) between LROA and HROA

3.4 Details about technical equipment and experimental conditions

The 5-step wooden staircase used in studies presented in Chapters 4, 5 and 6 was 80 cm wide with a stair size of 17 cm x 27 cm (rise x run), resulting in a stair angle of 32°. The chosen stair dimensions conform to the UK Building Regulations for institutional and assembly stairs (Document K, Department for Communities and Local Government, 2006). The upper landing was 1.50 m long. Handrails were mounted on

both sides at the height of 85 cm. To change the contrast between tread and edge of the stair, the stair edges could be covered with a 3 cm wide smooth aluminium edge strip of black colour. The location of the stair edges in space was identified by attaching markers to the aluminium edge strip and marker positions were captured prior to data collection for each participant.

A 13 camera 3D motion capture system (Vicon MX; consisting of eight MX3 cameras with a resolution of 0.3 megapixels and five MX40 cameras with a resolution of 4 megapixels) recorded movement data at a sample rate of 250 Hz. A schematic of camera placement is shown in Figure 3.1. The camera volume covered a volume of approximately 6.00 x 1.50 x 2.85 m (length x width x height) to ensure that all markers were seen at all times and was consistent between participants. The camera system was calibrated statically by using the Static calibration frame and dynamically by using the 3-marker calibration wand. The calibration for each data collection resulted in camera residuals of <1 mm for each camera, suggesting a very high accuracy of the camera system and marker reconstruction.

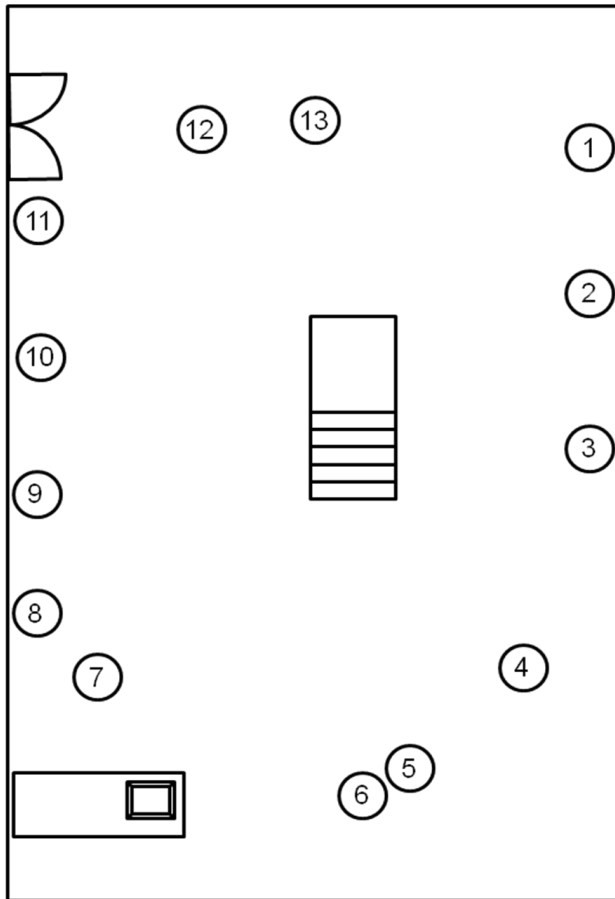


Figure 3.1: A schematic of the placement of all 13 cameras in the laboratory with respect to the stair case. The desk with the collection computer was located in the left lower corner. The door to the laboratory is seen in the left upper corner.

A complete PlugInGait marker set (Oxford Metrics, Ltd.) of markers with 14 mm diameter was attached to the participant's head, trunk, legs, feet, arms and wrists and was extended by four additional markers on the shoes (area of metatarsal heads I and V) (Figure 3.2). The toe marker was attached to the top of the shoe which will result in an overestimation of the foot clearance for the toe during stair ascent and for the heel during stair descent, since both markers need to be placed at the same height. This effect was taken into account when interpreting the data. To reduce movement artefacts, the markers were placed directly onto the skin where possible (wrists, arms, C7, clavícula) or onto tight fitting clothes or shoes (leg and foot markers) or onto the shirt fixated to the skin with doublesided tape (T12, pelvis). Head markers were fixated

onto a cap (Figure 3.2). Participants wore their usual foot wear, including trainers in young participants, casual shoes in male participants and boat shoes in female participants. Marker placement and attachment should not adversely affect positional outcome measures such as foot clearance and foot placement on the stair, but may affect the accuracy of the COM acceleration as some markers were not directly attached to the skin, introducing movement artefacts due to movement of the clothes.

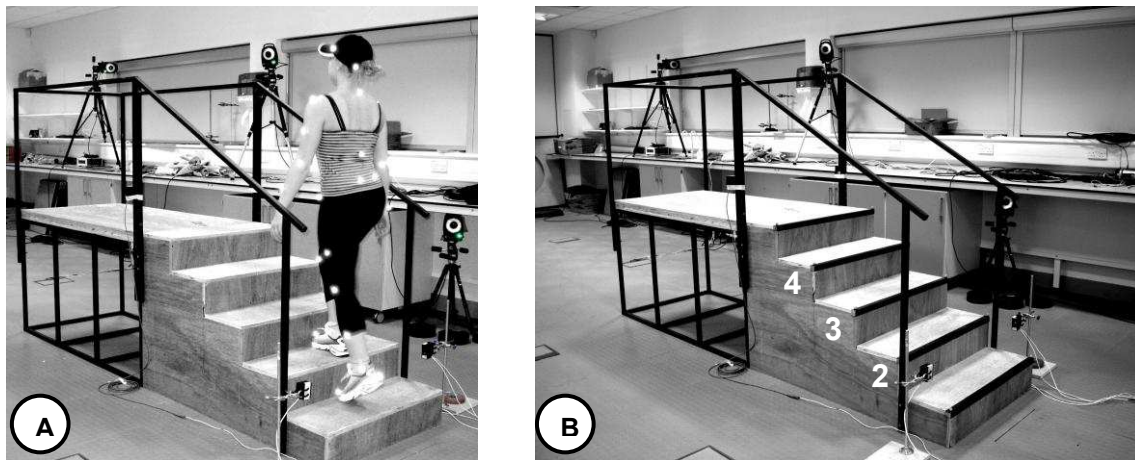


Figure 3.2: (A) Experimental set-up with lights switched on and low stair edge contrast. A young adult with reflective markers ascending stairs is shown. (B) Experimental set-up with high stair edge contrast. Data were analysed on stairs 3 and 4 for stair ascent and on stairs 3 and 2 for stair descent as these stairs did not interfere with the transition between landings and stair in either walking direction.

Ambient illumination in the laboratory was calculated by measuring the mean reflected light from four calibrated grey papers (corresponding to 3%, 18%, 45% and 90% reflectance) placed at the upper landing of the staircase. The luminance meter (Konica Minolta LS-100) measured the reflected light from these papers under “lights on” and “lights dimmed” conditions. The ambient illumination was then calculated using the equation: $\text{ambient illumination} = \text{reflected light} / \text{reflectance of the calibrated grey paper}$ and resulted in 200 lux for the “lights on” and 1 lux for the “lights dimmed” condition. The objective contrast between staircase and contrast strips could not be

measured because the experimental equipment (staircase and light shield) had been recycled. It is noted that ambient illumination levels would affect the perceived contrast between stair run and stair edge. With lights on, the contrast would be perceived as higher and may therefore present a clearer visual cue for the participant about the stair edge location than with lights dimmed. In addition, contrast sensitivity and visual acuity in participants would deteriorate as shown in previous studies, particularly in the older participants (Jackson & Owsley., 2000; Haegerstrom-Portnoy et al., 1997, Pitts, 1982).

3.5 Experimental design and protocol

All participants ascended and descended the stairs 20 times at their preferred walking speed. Participants rested for five minutes after every ten trials (5 trials ascending stairs, 5 trials descending stairs) to exclude fatigue effects. Two visual conditions were manipulated simultaneously 1) ambient illumination in the laboratory (“lights dimmed”: 1 lux and “lights on”: 220 lux) and 2) contrast of the stair edges (low contrast: without edge strip, high contrast: with black edge strip) (Figure 3.2). The trials were grouped in blocks of five accordingly to the illumination condition. Before data collection started, participants were given approximately three minutes for adapting to the new illumination condition in the laboratory. The order of blocks and the contrast conditions within blocks were randomised between participants by using the randomisation function in Excel. Each participant completed five trials in each condition and each walking direction. For both walking directions, starting position was two steps in front of the stairs, starting with the left leg. The instructions given to participants for the stair ascent trials were: “Please walk up the stairs and stop at the end of the upper landing. Start walking with the left leg.”. The instructions given to the participant for the stair descent trials were: “Please walk down the stairs and keep walking until you hear me say ‘stop’. Start walking with the left leg.”. The experimenter said “stop” after the

participant went unknowingly past a small marker on the floor which was approximately 3 steps after stepping down from the staircase. Furthermore, the participant was told that light touch on the handrail was allowed but he or she should not use the handrail to pull himself or herself up or lean onto the handrail while descending the stairs. During the trial the experimenter walked next to the staircase to provide stability in the event the participant needed additional support.

3.6 Data processing and analysis

After data collection, all markers in all trials were labelled manually and the 3D positional data (x, y and z coordinates) of each marker were exported from Vicon Workstation (version 4.6) to .csv files. The full body PlugInGait model was used for the COM calculation in Vicon Workstation, which bases the COM calculation on the inertial properties of body segments reported by Winter (1990). The 3D positional COM data were exported to .csv files. The head pitch angles were also calculated in Vicon Workstation and also exported to .csv files. All raw data were imported to Matlab R2007a Student version (Simulink) for further processing with the help of custom-made Matlab codes. All raw kinematic data were filtered with a dual pass 4th order Butterworth filter with a low-pass cut-off frequency of 10 Hz as this filter maximally reduces the frequency response gain in the pass-band below the cut-off frequency (Butterworth, 1930). The filter was applied in Matlab as a standard method for noise reduction in the kinematic data. The selection of 10 Hz as cut-off frequency was based on the rationale that any motor performance based on long-latency processes greater than 100 ms would be unaffected by the filter. Furthermore, this cut-off frequency resulted in the most accurate detection of the point in time (± 1 frame, resulting in an accuracy of events within ± 0.004 s) for vertical and horizontal foot clearance as well as initial contact of the foot on the stairs as validated by playing back all stair walking trials

for one older participant in Vicon Workstation. Gait events such as initial contact, vertical and horizontal foot clearance were detected in Matlab and the x, y and z coordinates were extracted and copied into Excel before calculating the outcome measures (see Chapters 4, 5 and 6). Walking speed in both walking directions was calculated with the help of the T12 marker travelling between the stair edge of stair 2 and the stair edge of stair 4. The marker therefore travelled 2 stair runs in the horizontal direction (stairs 2 and 3) and 2 stair rises in the vertical direction (stairs 3 and 4). The resulting travelled distance was therefore calculated with the equation $\text{distance travelled} = \sqrt{((2 \times \text{stair run})^2 + (2 \times \text{stair rise})^2)}$ and equalled ~63.8 cm. The time the T12 marker needed between crossing stair edge 2 and stair edge 4 was calculated with the help of the number of frames the T12 marker needed to move this distance and the 250 Hz sampling frequency of the Vicon system. The equation $\text{speed} = \text{distance} / \text{time}$ was then used to calculate the walking speed.

SPSS 15.0 for Windows was used for statistical analysis. A level of $\alpha=.05$ was considered to be statistically significant. A mixed 3 (group: YA, LROA, HROA) x 2 (light: lights dimmed, lights on) x 2 (contrast: low contrast, high contrast) ANCOVA was calculated for the dependent variables described in each chapter and included average stair walking speed as the covariate. Pairwise comparisons between groups and post hoc calculated paired t-tests for interactions were calculated. The reported p- values for the paired t-tests are Bonferroni corrected probabilities ($p \leq .017$). Each walking direction was analysed separately because biomechanics are different between stair ascent and descent (see paragraphs 1.4 and 1.5).

Unless indicated otherwise, all data are presented as mean \pm SD.

CHAPTER 4

Stepping characteristics and Centre of Mass control during stair ascent: effects of age, fall risk and visual factors

One important finding from the Chapter 2 was that YA and OA do not randomly fixate parts of the staircase while ascending and descending stairs, but predominantly direct their gaze towards the stair edge. One possible interpretation of this behaviour is that central vision is used to collect spatial information about the stairs which is used to aid planning of foot placement and maintenance of balance. Another finding was that OA tend to fixate a stair for longer than YA before stepping onto it which may indicate that OA need more time to process visual information about stair properties during stair negotiation. Although the stair edge appears to be an important visual cue during stair negotiation, the effect of stair edge visibility on walking behaviour remains unknown, particularly in OA with higher risk of falling. The studies presented in Chapters 4 and 5 investigate age-related changes to foot placement, posture and balance during stair ascent and descent that are likely to contribute to a higher risk of falling in some OA and how these effects are modulated by ambient illumination levels and stair edge contrast characteristics. Because stair ascent and stair descent are biomechanically two different tasks, data collected during stair ascent and descent are analysed and discussed separately. A general discussion about similarities and differences between the two walking tasks follows in Chapter 7.

4.1 Introduction

Although the majority of falls on stairs happen during stair descent one quarter of all stair falls occur during stair ascent (Svanström, 1974). Loss of balance during stair ascent primarily occurs due to individuals catching their toes on the stair edge and positioning their foot inaccurately on the stairs (Templer, 1994). The author also reported that injuries following from forward falls mostly affect the upper limbs, probably because of the reflexive arm use to avoid head contact with the stair. Therefore it is likely that visual detection of stair edges and locations for safe foot placement is essential for safe stair ascent.

Given the finding that catching the foot on the stair is a major cause of falls during stair ascent (Templer, 1994), it is surprising that there have not been previous studies investigating toe-clearance during this task. However, stair ascent can be regarded as an obstacle crossing or avoidance task as both feet typically clear the stair edges in a step-over-step manner and there have been several studies investigating the effect of age on toe clearance of the leading foot while crossing objects placed in the travel path. However, the results depended on the height of objects used in these studies. For example, when object height was scaled to a specific proportion of the individual's leg length, OA demonstrated more leading toe clearance than YA (Lu et al., 2006; Yen et al., 2009). In contrast, when object height was fixed for everybody, no age-related differences were found (Chen et al., 1991; Harley et al., 2009; Lowrey et al., 2007). When stepping onto raised surfaces, OA cleared the edge with the leading leg with less distance than YA (Lythgo et al., 2007; McFadyen & Prince, 2002), but during stepping up a single step, OA cleared the stair edge horizontally and vertically with the same distance as YA (Heasley et al., 2005).

Balance control during obstacle crossing, when the height of the object was scaled to a proportion of the individual's leg length, was found to be different in OA

compared to YA. In the direction of travel, COM range of motion and COM-COP separation were decreased in OA compared to YA, suggesting that OA located their COM further back and loaded the trailing leg more than YA (Hahn & Chou, 2004). For stair ascent, the evidence is equivocal: While Lee and Chou (2007) did not find differences in dynamic balance between YA and OA in the coronal plane during stair ascent, Reeves et al. (2009) found that OA demonstrated a smaller m-l COM-COP separation than YA suggesting that OA use a more cautious strategy for maintaining lateral balance. The different results might be explained by the calculation of different parameters describing balance, such as the m-l COM-COP inclination angle and m-l COM-COP separation (Reeves et al., 2009).

Altering the availability of visual information describing the object height has an effect on walking and stepping behaviour during object crossing tasks. For example, in YA occlusion of the lower visual field led to increased vertical leading foot clearance (Rietdyk & Rhea, 2006; Patla, Davies & Niechwiej, 2004) and increased variability in this measure compared to normal vision (Rhea & Rietdyk, 2007). During a single step up, blurring the vision of OA resulted in longer stepping time, increased vertical and horizontal toe clearance and reduced m-l excursion of the COP (Heasley et al., 2004; Heasley et al., 2005).

There is little evidence about the effect of manipulating ambient light levels or highlighting features of objects in the travel path on stepping patterns. One study investigating multiple object avoidance tasks, including walking around an object, stepping over and ducking under an object, did not analyse foot clearance, but did show that step length while crossing the object decreased when ambient illumination was dimmed and that step velocity decreased when the contrast between obstacle and floor was high (Lowrey et al., 2007).

Previous studies have investigated age-related differences between YA and OA in stepping behaviour during obstacle crossing tasks and single stair ascent. It remains

unknown how the stepping pattern is affected by older age during multiple stair ascent. In addition, there is equivocal evidence for age-related deterioration of m-l balance control during stair ascent (Lee & Chou, 2007, Reeves et al., 2009) and OA with increased risk of falling have not been included in previous studies. Therefore, the main aims of the present study were: 1) to characterise age-related changes to stepping behaviour and balance control during stair ascent and 2) to identify differences in stepping behaviour and balance control between LROA and HROA. A secondary aim was to investigate the relative effects of experimentally manipulating ambient illumination and stair edge contrast on stepping and balance control in YA, LROA and HROA. Previous obstacle crossing studies (Chen et al., 1991; Harley et al., 2009) and the single stair ascent study (Heasley et al., 2005) found no differences in foot clearance between YA and OA. Lowrey et al. (2007) studied older participants similar to the age of the HROA in the present study and also found no differences in foot clearance. Based on these findings it is hypothesised that LROA and HROA ascending stairs will show no differences in foot clearances. Because of the increased step width variability in OA during walking (Dean et al., 2007) and m-l foot placement errors when accurate foot placement is required (Chapman & Hollands, 2010), it is hypothesised that LROA and HROA will show more variability in step width than YA, which may be more pronounced when vision is manipulated by reduced ambient illumination levels and low stair edge contrast.

4.2 Methods and data analysis

Participant selection and inclusion, stairs, equipment and experimental protocol were described in detail in Chapter 3.

Measures of spatial parameters for stepping behaviour included: (1) vertical and (2) horizontal foot clearances, (3) step width and (4) step length. Foot clearances were calculated as the vertical and the horizontal distance between toe marker and stair edge in the sagittal plane during the swing phase (Heasley et al., 2004) (Figure 4.1). Step width was calculated as the m-l distance between left and right ankle markers at initial contact on the stairs. Step length was calculated as the a-p distance between left and right ankle markers.

Balance during overground walking is typically described by the spatial relationship between COM and COP at any given point in the gait cycle (Winter, 1995) and has also previously been used in stair negotiation studies (Mian et al., 2007a; Reeves et al., 2008a). However, COP data for one gait cycle can only be collected with two independently working force plates embedded into the staircase. Because this technical equipment was not available, COM acceleration was chosen as gross indication of balance control. COM position mainly depends on trunk posture as this is the largest and heaviest single segment of the human body (Winter, 2005) and the control of COM position during locomotion is realised by appropriate intermuscular coordination of agonistic and antagonistic muscles of the trunk, pelvis and hips. Measurements of balance control included (4) a-p distance between COM position and ankle marker position of the leading leg and (5) a-p, m-l and vertical COM acceleration at initial contact on the stairs.

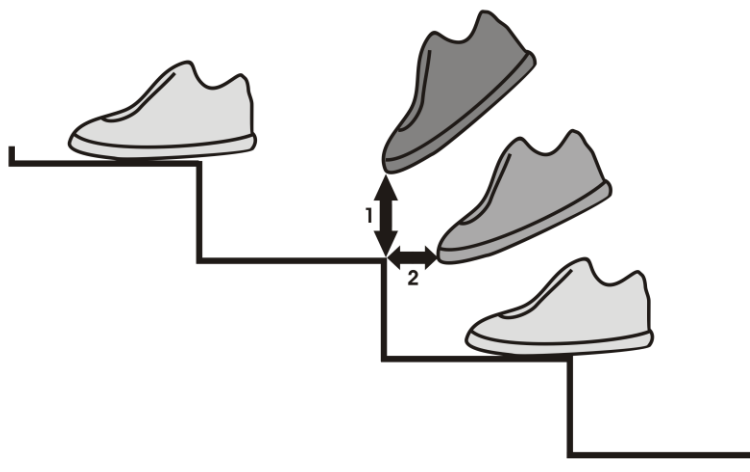


Figure 4.1: Definition of vertical (1) and horizontal (2) foot clearance during the swing phase for stair ascent

Mean values and intra-subject variability of the dependent variables were used to analyse mean and variability differences between groups. One standard deviation calculated from 5 trials in each condition for each participant was used as the measure for variability. It is acknowledged that there are other variability measures obtainable such as between subject variability within one group. However, the idea was to look at how variable the dependent variables in each participant are and whether there are differences in the within-subject variability between groups. It was thought that calculating the within-subject variability is important because a very variable movement pattern suggests underlying difficulties in the sensorimotor control of movement and is likely to contribute to an increased likelihood to trip and fall (e.g. vertical and horizontal foot clearance) or loss of balance (e.g. COM acceleration measures).

Because stepping movements and balance control differ between midstair walking and transition phases from lower landing to stair and stair to upper landing (Lee & Chou, 2007), stairs 3 and 4 were used for data analysis for stair ascent (Figure 3.1, B).

Since four out of eight HROA occasionally used the handrail and handrail use was previously shown to improve balance (Reeves et al., 2008a; Dickstein & Laufer, 2004), the COM data were further explored for differences between handrail users and non-users in the HROA group. COM data were averaged across visual conditions and analysed by a multivariate ANOVA.

4.3 Results

There was no significant difference in the preferred walking speed for stair ascent between age groups ($p > .097$; YA: $0.72 \text{ m/s} \pm 0.07$, LROA: $0.63 \text{ m/s} \pm 0.09$, HROA: $0.62 \text{ m/s} \pm 0.12$).

4.3.1 Effect of walking speed

The ANCOVA revealed that walking speed significantly contributed to the variance in step length ($F_{(2, 20)} = 4.810$, $p = .041$, $\eta^2 = .202$) and a-p distance between COM and ankle of the leading leg ($F_{(2, 20)} = 4.428$, $p = .049$, $\eta^2 = .189$). Walking speed also made a significant contribution to the variance in COM acceleration variability in a-p direction ($F_{(2, 20)} = 10.771$, $p = .004$, $\eta^2 = .362$), m-l direction ($F_{(2, 20)} = 13.587$, $p = .002$, $\eta^2 = .417$) and vertical direction ($F_{(2, 20)} = 4.944$, $p = .039$, $\eta^2 = .206$).

4.3.2 Group differences in stepping characteristics and COM control

The results for stepping characteristics and COM control for all groups are presented in Table 4.1. There were no statistically significant group differences in vertical and horizontal foot clearances, step width or step length between all three groups.

There was a main effect of group for variability in COM acceleration in a-p ($F_{(2, 20)} = 7.009$, $p = .005$, $\eta^2 = .425$) and m-l directions ($F_{(2, 20)} = 4.443$, $p = .026$, $\eta^2 = .319$). Pair-wise comparisons indicated that in YA the a-p COM acceleration was less variable

than in LROA ($p=.015$) and HROA ($p=.008$). Pair-wise comparisons also revealed that YA were less variable in m-l COM acceleration than HROA ($p=.033$).

Table 4.1: Mean (SD) and mean intra-subject variability (SD) for spatial stepping characteristics and COM acceleration during stair ascent across conditions.

	YA	LROA	HROA
Vertical foot clearance (cm)			
Mean	8.8 (3.0)	8.3 (2.7)	8.1 (2.4)
Variability	0.6 (0.2)	0.9 (0.5)	0.6 (0.2)
Horizontal foot clearance (cm)			
Mean	5.3 (1.6)	4.9 (1.5)	5.5 (2.0)
Variability	1.9 (0.5)	3.2 (1.7)	2.2 (0.8)
Step width (cm)			
Mean	19.3 (2.1)	18.0 (1.6)	16.2 (3.4)
Variability	1.7 (0.6)	2.0 (0.6)	2.2 (0.8)
Step length (cm)			
Mean	25.9 (0.9)	27.0 (1.1)	27.0 (1.4)
Variability ^w	1.6 (0.7)	1.6 (0.7)	1.3 (0.4)
A-p distance between COM and ankle (cm)			
Mean ^w	0.6 (2.3)	-0.7 (3.4)	0.2 (2.7)
Variability	1.2 (0.4)	1.5 (0.6)	1.1 (0.4)
COM acceleration in a-p direction (m/s²)			
Mean	-0.06 (0.39)	0.18 (0.40)	0.21 (0.72)
Variability ^w	0.48 (0.16) * +	0.75 (0.34)	0.76 (0.46)
COM acceleration in m-l direction (m/s²)			
Mean	-0.06 (0.12)	0.02 (0.23)	-0.1 (0.28)
Variability ^w	0.33 (0.10) +	0.42 (0.27)	0.44 (0.25)
COM acceleration in vertical direction (m/s²)			
Mean	3.06 (1.89)	2.31 (1.75)	1.52 (2.23)
Variability ^w	1.53 (1.06)	1.26 (0.94)	1.07 (0.53)

* significant difference ($p < .05$) between YA and LROA, + significant difference ($p < .05$) between YA and HROA, ^w significant effect of walking speed ($p < .05$)

4.3.3 Effect of altering ambient light levels

The data for all visual conditions are presented in Table 4.2. The main effect of light for walking speed was significant ($F_{(1, 20)} = 17.245$, $p < .001$, $\eta^2 = .463$), indicating that all participants walked slower when lights were dimmed. There was an interaction between light and group for the a-p distance between COM and ankle of the leading leg ($F_{(2, 20)} = 5.281$, $p = .015$, $\eta^2 = .357$). Post hoc t-tests revealed that LROA moved the COM more anteriorly (lights on: -0.9 ± 3.3 cm, lights dimmed: -0.4 ± 3.5 cm, $t_{(6)} = -3.430$, $p = .002$) and HROA positioned the COM further back, but not behind the ankle (lights on: 0.4 ± 2.6 cm, lights dimmed: 0 ± 2.9 cm, $t_{(7)} = 3.104$, $p = .007$), when lights were dimmed compared to lights on (Figure 4.2). There was a main effect of light for COM acceleration variability in m-l direction ($F_{(2, 20)} = 9.153$, $p = .007$, $\eta^2 = .325$), showing reduced variability when lights were dimmed.

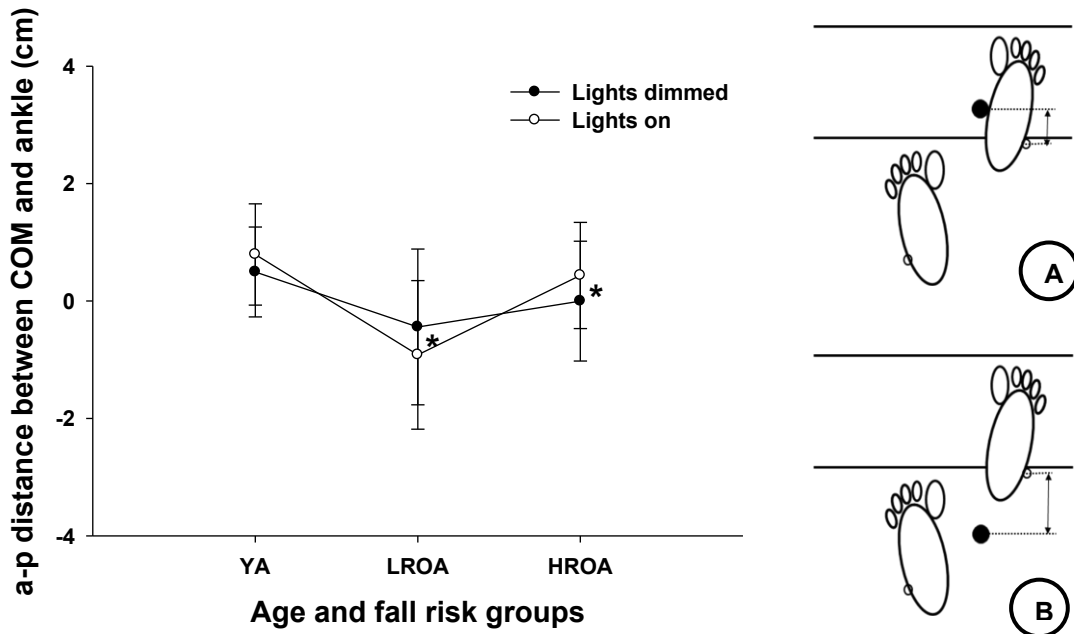


Figure 4.2: When lights were dimmed, LROA located the COM further in front of the ankle ($p=.002$) and HROA located the COM behind the ankle ($p=.007$) compared to lights on. YA keep the COM in front of the ankle, irrespective of ambient illumination. Positive values indicate COM location (●) in front of the ankle of the leading leg (A), negative values indicate COM location behind the ankle (B). Data represent mean \pm standard error

4.3.4 Effect of stair edge contrast

There was an interaction between group and contrast for horizontal foot clearance ($F_{(2, 20)} = 4.632$, $p=.023$, $\eta^2=.328$). Post-hoc t-test showed that only YA increased the horizontal foot clearance when stair edge contrast was high (high contrast: 5.7 ± 1.6 cm, low contrast: 5.0 ± 1.5 cm, $t_{(7)}=5.864$, $p=.001$) (Figure 4.3). There was a main effect of contrast for vertical foot clearance ($F_{(2, 20)} = 5.855$, $p=.026$, $\eta^2= .236$), showing that high stair edge contrast led to larger clearance in all groups.

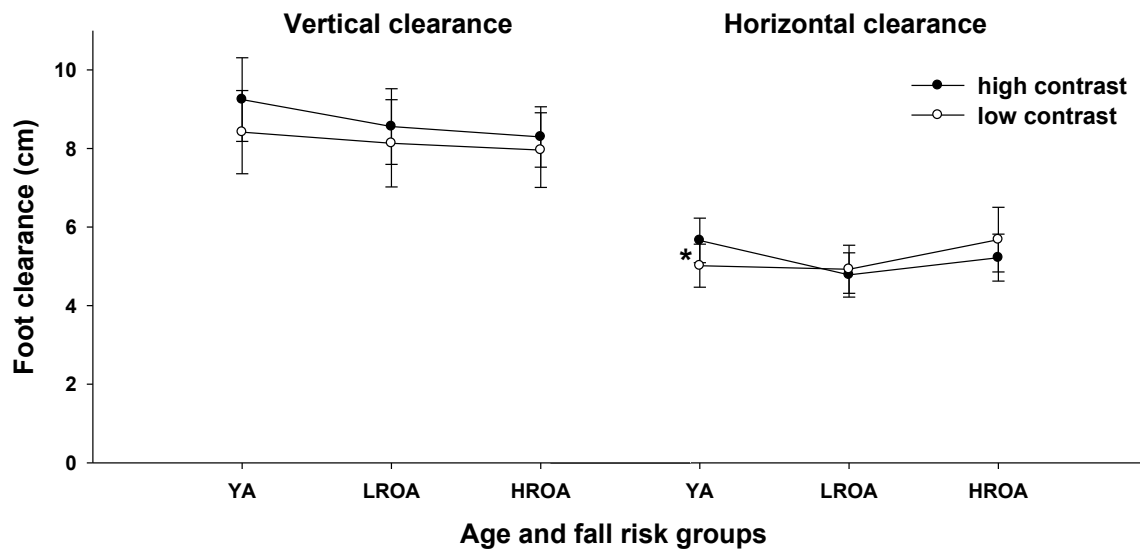


Figure 4.3: All participants increased the vertical foot clearance when stair edge contrast was high. YA significantly reduced the horizontal clearance with low stair edge contrast ($p=.001$). Data represent mean \pm standard error.

There was a main effect for contrast for horizontal foot clearance variability ($F_{(2,20)} = 6.530$, $p=.019$, $\eta^2=.256$), showing that variability was reduced when stair edge contrast was low.

4.3.5 Additional analysis of the effect of handrail use on COM acceleration

Multivariate analysis revealed that handrail use in HROA did not affect COM and its variability in any direction ($p>.187$). Likewise, handrail use did not affect mean or variability of a-p COM position with respect to the leading leg ($p>.174$).

Table 4.2: For stair ascent, data and results are presented as mean (SD) for all visual conditions across groups.

	Stair edge contrast		Ambient light	
	high	low	bright	dimmed
Walking speed (m/s)				
Mean	0.66 (0.11)	0.66 (0.10)	0.67 (0.11)*	0.65 (0.10)
Variability	0.46 (0.28)	0.38 (0.21)	0.46 (0.28)	0.38 (0.21)
Vertical foot clearance (cm)				
Mean	8.7 (2.5)*	8.2 (2.8)	8.3 (2.5)	8.6 (2.9)
Variability	0.7 (0.4)	0.7 (0.3)	0.7 (0.4)	0.7 (0.2)
Horizontal foot clearance (cm)				
Mean	5.2 (1.6)	5.2 (1.9)	5.1 (1.7)	5.4 (1.8)
Variability	2.4 (1.3)*	2.3 (1.5)	2.5 (1.5)	2.3 (0.8)
Step width (cm)				
Mean	17.8 (2.8)	17.9 (2.8)	18.0 (2.8)	17.7 (2.8)
Variability	2.0 (0.8)	2.0 (0.6)	1.9 (0.7)	2.1 (0.7)
Step length (cm)				
Mean	26.5 (1.3)	26.7 (1.2)	26.7 (1.3)	26.5 (1.3)
Variability	1.5 (0.6)	1.5 (0.6)	1.4 (0.6)	1.6 (0.6)
A-p distance between COM and ankle (cm)				
Mean	0.2 (2.9)	0.0 (2.8)	0.1 (2.8)	0.0 (2.8)
Variability	1.3 (0.6)	1.2 (0.5)	1.2 (0.5)	1.3 (0.6)
COM acceleration in a-p direction (m/s²)				
Mean	0.11 (0.48)	0.10 (0.59)	0.10 (0.51)	0.11 (0.57)
Variability	0.67 (0.37)	0.65 (0.37)	0.66 (0.36)	0.66 (0.38)
COM acceleration in m-l direction (m/s²)				
Mean	-0.06 (0.22)	-0.04 (0.23)	-0.04 (0.19)	-0.06 (0.25)
Variability	0.40 (0.20)	0.40 (0.24)	0.41 (0.25)*	0.38 (0.19)
COM acceleration in vertical direction (m/s²)				
Mean	2.16 (2.06)	2.43 (2.08)	2.13 (2.20)	2.46 (1.92)
Variability	1.42 (0.97)	1.16 (0.76)	1.36 (1.0)	1.22 (0.75)

* significant difference within one visual condition ($p < .05$)

4.4 Discussion

4.4.1 Differences between age groups in stepping behaviour and COM control

It was predicted that OA would ascend stairs with the same foot clearances, but more variable step width than YA. Interestingly and only partially in line with the hypothesis, the present study found that YA, LROA and even HROA demonstrated almost identical mean values for vertical and horizontal foot clearances as well as similar mean step length and step width when ascending a flight of stairs at preferred speed. It was previously shown that fit OA demonstrate the same foot clearance as YA during single step ascent (Heasley et al., 2005) and this finding can now be extended to LROA and HROA during mid-stair walking. Heasley et al. (2004) calculated the vertical and horizontal foot clearance by creating a virtual marker at the shoe tip sole and this position would provide the true minimum distance between shoe tip and stair edge. When comparing the present results of the vertical and horizontal foot clearance with data reported by Heasley et al. (2004 & 2005), it appears that LROA and HROA cleared the stair edges with similar vertical but much less horizontal distance when taking the thickness of the shoe and sole of ~4 cm into account. The smaller horizontal distance between foot and stair edge in the present study may be explained by the calculation of the foot clearances over the two middle stairs of a staircase, whereas Heasley et al. (2004 & 2005) positioned their participants at half a foot length in front of the single step, which may contribute to larger horizontal foot clearance. The finding that step width, step length and the variability in these measures is also comparable between groups leads to two inferences: Firstly, the base of support for COM movements remained unaffected by age and fall risk. Secondly, foot prepositioning during the terminal swing phase and foot placement on the stair were also unchanged by age and fall risk. During overground walking, one age-related change is a reduction

in stride length (Winter, 1991; Lord et al., 1996). Because of the restricted foot placement possibilities on the stairs, resulting in similar foot placement patterns across groups, it is likely that age-related decline in muscle strength and power generation is counteracted by other means in order for OA to ascend stairs safely. For example, ascending OA have been shown to shift the power generation from the knee to the ankle of the trailing leg compared to YA (Reeves et al., 2009).

Even when walking speed was taken into account, LROA and HROA were found to demonstrate greater variability of COM acceleration in a-p direction than YA which might be a result of a variable trunk position in the sagittal plane across trials. The present study also found that HROA were more variable in m-l COM acceleration than YA. This finding supports the idea of impaired m-l movement control in older age during locomotion (Mian et al., 2007b; Chapman & Hollands, 2010; Dean et al., 2007; Maki et al., 2000). Reduced control of m-l balance variability could be due to age-related weaker hip abductors which normally facilitate a stable pelvis in the coronal plane during stance and therefore limit lateral pelvic movements and compensatory movements of the trunk. Indeed, OA have been previously shown to ascend stairs with increased hip adduction during stance, combined with increased inversion at the ankle compared to YA (Karamanidis & Arampatzis, 2009). This may contribute to an unstable lower body with increased m-l COM acceleration variability during stair ascent.

4.4.2 Fall risk-related differences in stepping behaviour and balance control

The present findings did not reveal differences in stepping behaviour or balance control between LROA and HROA. The similarity in mean values and variability measures suggest that ascending stairs is performed in a similar manner by LROA and HROA.

4.4.3 Effect of manipulating ambient light levels

The results indicated that walking speed decreased in all groups but foot clearance and stepping parameters remained unaffected by dimming the lights. It is possible that slower walking speed facilitated the acquisition and processing of proprioceptive information about stair height and depth, collected by the participant during ascending the first two stairs, resulting in unchanged foot clearance patterns irrespective of ambient illumination levels.

Although the absolute differences between the illumination conditions were not large, the results of the COM position with respect to the leading leg were somewhat surprising. On average at initial contact on the stair, YA kept the COM in front of the ankle irrespective of ambient illumination. LROA ascended stairs with the COM located behind the ankle but moved the COM by 0.5 cm anteriorly when illumination was reduced and HROA positioned the COM 0.4 cm in front of the ankle but moved it back to ankle level when lights were dimmed (Figure 4.2). It has been shown in other overground walking studies that the pelvis follows the trunk in OA whereas in YA the trunk follows the pelvis (McGibbon & Krebs, 2001), indicating a more flexed trunk posture in OA while walking, affecting the a-p COM position. Although LROA clearly displayed riskier balance behaviour than HROA by placing the COM behind the ankle during full illumination, they also demonstrated a sensible strategy by positioning the COM more anteriorly when illumination was reduced, possibly to reduce the risk of a backward and downward fall. The result that HROA demonstrated an anteriorly positioned COM might also be explained by the occasional use of the handrail in comparison to LROA. There is no reasonable explanation why HROA located the COM further back when lights were dimmed. However, it is conceivable that a reduction in light levels alters the ability to use vision for balance regulation and other non-visual information, such as proprioceptive information from the neck muscles, may be used to

regulate the body orientation in space with respect to the staircase. Furthermore, this proprioceptive information may be less accurate in HROA.

It was predicted that variability in step width would increase when illumination was reduced. The present finding showed that step width variability was unaffected by ambient illumination, suggesting a stable base of support for the COM movement. Indeed, when lights were dimmed, control of lateral balance was better as evidenced by a reduction in the variability of m-l COM acceleration in all participants.

4.4.4 Effect of manipulating stair edge contrast

The UK Building Regulations stipulate the use of highlighted stair edges in public places to help staircase users with foot placement (Document M, Department for Communities and Local Government, 2006). In Chapter 2 it has been shown that stair edges were predominantly fixated during stair ascent and proposed that high stair edge contrast may act as visual cue for gaze fixation. Therefore, it was predicted that foot clearances would increase as a compensation strategy when stair edge contrast was low and the exact position of the stair edge may not have been detected easily. However, the present findings of increased vertical foot clearance in all groups and increased horizontal foot clearance in YA indicate that highlighted stair edges may have acted as visual cue for an object to be avoided. This result is in contrast to Heasley et al. (2004) who found increased vertical and horizontal clearances in OA when the vision was impaired. It is conceivable that there are different underlying mechanisms. For example, impairing vision reduces the confidence to ascend stairs, whereas highlighted stair edges increase the awareness of the stair edge location. Therefore, it could be that foot clearance does not only increase when visual information about stair edge position is less reliable but increases also when stair edges are clearly marked and attract attention. The present findings support the idea

that highlighted stair edges act as point of interest in the visual scene and may be used to regulate vertical and horizontal foot clearances, particularly in the YA.

COM measures were unaffected by stair edge contrast, suggesting that stair edge contrast may not be the visual cue leading to improved balance control in any of the groups. It could also be that balance may not be a primary problem during stair ascent. Insufficient foot clearance, resulting in slips and trips, may act as trigger for falls rather than instability itself. Therefore, it might be interesting to study recovery strategies in YA and OA after tripping during stair ascent.

4.4.5 Effect of handrail use on COM control

Only participants from the HROA group used the handrail, which is in line with previous observations (Hamel & Cavanagh, 2004) and suggests that the handrail is used primarily to aid balance during stair ascent (Reeves et al., 2008a). The finding that handrail use in HROA changed neither COM acceleration in any direction, nor COM position in relation to the leading leg, and nor the variability in these measures, might be explained by the very small group size (four participants in each group). In addition, HROA may still be able to control their COM acceleration while ascending stairs. In fact, it has previously been shown that handrail use in OA does not result in significant improvements in coronal plane balance measurements but leads to safer stair ascent by redistributing the power generation from the ankle plantarflexors of the trailing leg to the knee extensor muscles of the leading leg (Reeves et al., 2008a). The present finding that handrail use did not affect m-l COM acceleration variability indicates that external support did not improve balance control in the coronal plane and is therefore consistent with the findings of Reeves et al. (2008a).

4.5 Conclusion

In summary, the present findings provide evidence that differences in balance control, the ability to clear stair edges and position the feet accurately on the stairs during stair ascent is insufficient to explain the increased fall risk in the OA groups. A reduction in ambient illumination levels led to slower walking speed and improved m-l balance control and highlighted stair edges appear to have acted as visual cue to increase the vertical foot clearance in both YA and OA. However, foot placement and balance control remained unaffected by stair edge contrast. Handrail use was only demonstrated in the HROA group, but this external support did not affect the balance measures during stair ascent.

CHAPTER 5

Stepping characteristics and Centre of Mass control during stair descent: effects of age, fall risk and visual factors

5.1 Introduction²

One third of OA 65 years of age and over experiences at least one fall within a year (Campbell et al., 1981) and the likelihood to fall increases with increasing age (Sattin et al., 1990). Falls while descending stairs are particularly dangerous and often result in head injuries and lower limb injuries including fractures (Svanström, 1974). The costs of falls-related injuries to both the individual and health services are extremely high (Scuffham et al., 2003). Depending on the acquired injury, a fall can even result in the end of independent living of the faller or even death. Therefore it is important to elucidate the mechanisms underlying stair falls before exploring possible and appropriate interventions for their prevention.

Older age is associated with increased movement variability during both overground and stair walking which may contribute to an increased risk of falling. For example, OA demonstrate more variability in foot placement (Chapman & Hollands, 2006), step length (Kang & Dingwell, 2008) and step width (Thies et al., 2005) during walking than YA.

During stair descent variability in minimum foot clearance (i.e. the distance between heel and stair edge) is increased (Hamel et al., 2005) and unnecessary lower

² The data in this chapter have been published in *Gait & Posture* (2011); 34 (2): 279-284.

limb movements in the frontal and transverse planes are present in OA compared to YA (Mian et al., 2007b). However, balance control in the sagittal and coronal planes remains unaffected in fit OA (Mian et al., 2007a; Lee & Chou, 2007; Reeves et al., 2008b). Characteristics of stepping patterns and balance control in fallers or OA with a higher risk of falling remain unknown because the selection of older participants for single step and stair negotiation studies have hitherto only included very healthy OA (Simoneau et al., 1991; Mian et al., 2007a; Larsen et al., 2008; Heasley et al., 2004) or OA without a history of falling (Buckley et al., 2005a; Buckley et al., 2005b; Hortobagyi & DeVita, 2000; Heasley et al., 2005).

Catching the foot on the stair edge and misplacement of the foot on the stair are the main causes of falls during stair descent (Templer, 1994). Therefore it is likely that visual detection of stair edges and locations for safe foot placement are crucial for safe stair negotiation. In Chapter 2, it has been shown that YA and OA during stair negotiation spend the majority of time fixating aspects of the stair, which suggests that stair edges are points of interest. It was also shown that OA fixate stairs for longer and are less variable in the extent they look ahead than YA. Altering the visually available information about stairs affects the walking behaviour of YA and OA. For example, experimentally blurring the vision in OA results in prolonged step execution time and larger amount of body weight borne by the trailing leg (Buckley et al., 2005b). Blurring vision also increases the foot clearance, although high or low stair edge contrast has little effect on this measure (Simoneau et al., 1991).

The effect of manipulating ambient light levels on stepping patterns varies between young and old age groups. During stair descent, YA clearly increase their foot clearance when lights are dimmed whereas OA show no change in mean foot clearance but demonstrate increased variability in this measure (Hamel et al., 2005). In addition to appropriate visual information about the staircase, sufficient muscle strength is needed for safe stair descent. Even OA with mild balance impairments have lower

hip and knee extensor strength and weaker hip and knee flexors than stable OA (Lin & Woollacott, 2005), which is likely to affect the stability of the stance leg and the foot trajectory during the swing phase.

Although many studies have highlighted age-related differences between YA and fit OA in stepping behaviour when vision is experimentally reduced, it remains unknown how the stepping pattern and balance control changes in OA with a higher risk of falling under manipulated visual conditions. Therefore, the main aim of the present study was to characterise age-related changes to stepping behaviour and balance control during stair descent that are likely to contribute to a higher risk of falling in OA. The secondary aim was to investigate the relative effects of experimentally manipulating ambient illumination and stair edge contrast on stepping and balance control and to describe the differences in these effects between YA, LROA and HROA. Because of the association between impaired balance and reduced muscle strength (Lin & Woollacott, 2005) and the affected stepping pattern under manipulated visual conditions (Hamel et al., 2005; Simoneau et al., 1991) it is hypothesised that HROA show smaller foot clearances and more variability in step width and balance control than LROA and YA, particularly with reduced ambient illumination levels and low stair edge contrast (Hamel et al., 2005; Simoneau et al., 1991).

5.2 Methods and data analysis

Participant selection and inclusion, stairs and equipment and experimental protocol were described in detail in Chapter 3.

Measures of spatial parameters for stepping behaviour included: (1) vertical and (2) horizontal foot clearances, (3) step width and (4) step length. Foot clearances were calculated as the vertical and the horizontal distance between heel marker and stair edge in the sagittal plane during the swing phase (Figure 5.1). Step width was

calculated as the m-l distance between left and right ankle markers at initial contact on the stairs. Step length was calculated as the a-p distance between left and right ankle markers. Measurements of balance control included (5) a-p distance between COM position and ankle marker position of the leading leg and (6) a-p, m-l and vertical COM acceleration at initial contact on the stairs.

Group mean values and intra-subject variability of the dependent variables were used to analyse mean and variability differences between groups. One standard deviation calculated from 5 trials in each condition for each participant was used as the measure for variability. Because stepping movements and balance control (Lee & Chou, 2007) differ between midstair walking and transition phases from upper landing to stair and stair to lower landing, stairs 3 and 2 were used for data analysis for stair descent (Figure 3.1, B). Data analysis for vertical and horizontal foot clearances during stair descent included only five LROA as the position of the heel markers in two participants were lost due to technical problems.

Age and fall-risk related differences in the foot overlap over the stair edge was also explored and calculated as the perpendicular distance between the toe-heel marker vector and stair edge and this value was normalised on foot length.

Since four out of eight HROA occasionally used the handrail and external support was previously shown to improve balance (Reeves et al., 2008a; Dickstein & Laufer, 2004), the COM data were further explored for differences between handrail users and non-users in the HROA group. COM data were averaged across conditions and analysed by a multivariate ANOVA.

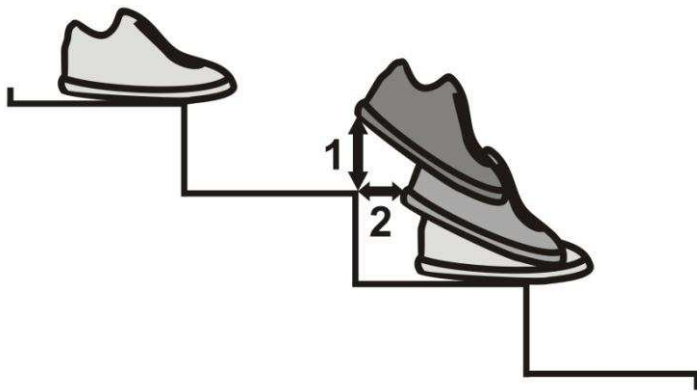


Figure 5.1: Definition of vertical (1) and horizontal (2) foot clearance during the swing phase for stair descent

5.3 Results

There was a main effect of group for walking speed ($F_{(2, 20)} = 8.737$, $p = .002$, $\eta^2 = .466$), showing that LROA ($0.62 \text{ m/s} \pm 0.10$, $p = .017$) and HROA ($0.58 \text{ m/s} \pm 0.10$, $p = .002$) descended the stairs slower than YA ($0.81 \text{ m/s} \pm 0.10$).

5.3.1 Effect of walking speed

The results of ANCOVA revealed that walking speed significantly contributed to explaining the variance in COM acceleration in a-p direction ($F_{(2, 20)} = 8.919$, $p = .008$, $\eta^2 = .319$) and COM acceleration variability in a-p direction ($F_{(2, 20)} = 12.757$, $p = .002$, $\eta^2 = .402$).

5.3.2 Group differences in stepping characteristics and COM control

The results for stepping characteristics and COM control for all groups are presented in Table 5.1. There was a main effect of group for vertical ($F_{(2, 18)} = 11.050$, $p = .001$, $\eta^2 = .554$) and horizontal ($F_{(2, 18)} = 13.983$, $p < .001$, $\eta^2 = .622$) foot clearance. Pair-wise comparisons indicated that LROA demonstrated a significantly larger vertical foot clearance than HROA ($p = .001$) and that HROA cleared the stair edge with significantly

smaller horizontal distance than LROA ($p < .001$) and YA ($p = .007$) (Figure 5.2). There was a significant main effect of group on step width variability ($F_{(2,20)} = 5.564$, $p = .013$, $\eta^2 = .369$). Pair-wise comparisons showed that YA had smaller step width variability than LROA ($p = .018$) and HROA ($p = .021$). A main effect of group was found for COM acceleration variability in a-p ($F_{(2,20)} = 4.073$, $p = .034$, $\eta^2 = .300$) and m-l direction ($F_{(2,20)} = 4.592$, $p = .024$, $\eta^2 = .326$); pairwise comparison indicated that HROA showed more variability in a-p ($p = .031$) and m-l COM acceleration than YA ($p = .021$).

Table 5.1: Mean (SD) and mean intra-subject variability (SD) for spatial stepping characteristics and COM acceleration during stair descent across conditions.

	YA	LROA	HROA
Vertical foot clearance (cm)			
Mean	7.3 (1.5)	9.1 (1.5) §	5.6 (1.1)
Variability	0.93 (0.3)	1.22 (0.4)	1.23 (0.6)
Horizontal foot clearance (cm)			
Mean	7.6 (1.0) +	8.0 (0.7) §	5.6 (0.7)
Variability	0.94 (0.1)	1.23 (0.2)	1.1 (0.2)
Step width (cm)			
Mean	19.7 (2.0)	18.0 (2.3)	18.4 (4.4)
Variability	1.56 (0.3) * +	2.35 (0.8)	2.31 (0.7)
Step length (cm)			
Mean	27.5 (1.0)	27.2 (1.1)	27.4 (0.9)
Variability	1.34 (0.4)	1.10 (0.2)	1.18 (0.2)
A-p distance between COM and ankle (cm)			
Mean	2.8 (1.9)	2.4 (2.3)	2.1 (1.3)
Variability	1.1 (0.3)	0.9 (0.2)	1.0 (0.3)
COM acceleration in a-p direction (m/s²)			
Mean ^w	1.50 (0.68)	1.37 (0.54)	1.33 (1.00)
Variability ^w	0.68 (0.22) +	0.64 (0.32)	0.76 (0.48)
COM acceleration in m-l direction (m/s²)			
Mean	0.09 (0.13)	- 0.14 (0.36)	0.12 (0.31)
Variability	0.31 (0.11) +	0.43 (0.22)	0.50 (0.27)
COM acceleration in vertical direction (m/s²)			
Mean	- 0.51 (1.58)	0.31 (0.54)	- 0.52 (0.92)
Variability	0.87 (0.51)	0.66 (0.43)	0.61 (0.27)

* sig. difference ($p < .05$) between YA and LROA, + sig. difference ($p < .05$) between YA and HROA, § sig. difference ($p < .05$) between LROA and HROA, ^w sig. effect of walking speed ($p < .05$)

5.3.3 Effect of altering ambient light levels

Table 5.2 shows the data for all visual conditions across groups. There was a main effect of light for walking speed ($F_{(2,20)} = 14.313$, $p = .001$, $\eta^2 = .417$), indicating that walking speed was reduced when lights were dimmed (lights on: 0.68 ± 0.16 m/s, lights dimmed: 0.66 ± 0.15 m/s). There was an interaction between light and group for step length ($F_{(2,20)} = 7.110$, $p = .005$, $\eta^2 = .428$). Pair-wise comparison indicated that HROA demonstrated decreased step length (lights on: 27.5 ± 0.8 cm, lights dimmed: 27.1 ± 1.0 cm, $p = .006$) and YA increased step length (lights on: 27.3 ± 1.0 cm, lights dimmed: 27.8 ± 1.0 cm, $p = .002$) when lights were dimmed.

5.3.4 Effect of stair edge contrast

There was a main effect of contrast for walking speed ($F_{(2,20)} = 4.923$, $p = .038$, $\eta^2 = .198$), indicating that walking speed was reduced when stair edges were highlighted. There was an interaction between contrast and group for horizontal foot clearance ($F_{(2,18)} = 4.558$, $p = .026$, $\eta^2 = .349$). When stair edge contrast was low, YA demonstrated a significant decrease in horizontal foot clearance compared to high stair edge contrast (high contrast: 7.9 ± 2.9 cm, low contrast: 7.4 ± 4.2 cm, $t_{(7)} = 2.901$, $p = .011$) (Figure 5.2).

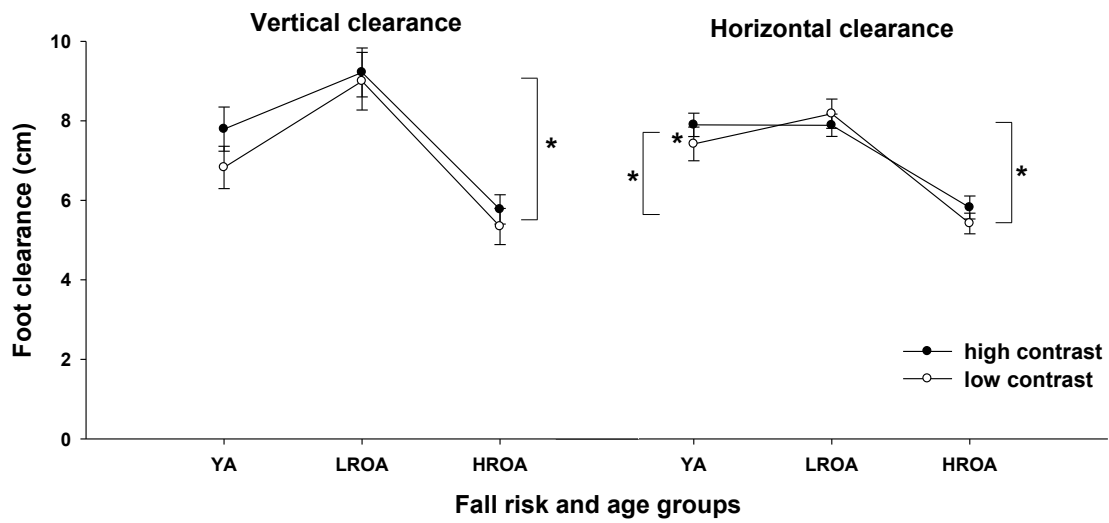


Figure 5.2: HROA cleared the stair edges with less vertical distance than LROA ($p=.001$). Horizontal foot clearance was significantly smaller in HROA than in LROA ($p<.001$) and YA ($p=.007$). When stair edge contrast was low, YA reduced horizontal foot clearance ($p=.011$). Data represent mean \pm standard error.

The interaction between contrast and group was significant for vertical COM acceleration variability ($F_{(2,20)} = 3.895$, $p=.038$, $\eta^2=.291$). Post-hoc analysis showed that HROA varied the COM acceleration downwards more when stair edge contrast was low (high contrast: $0.51 \pm 0.24 \text{ m/s}^2$, low contrast: $0.71 \pm 0.23 \text{ m/s}^2$, $t_{(7)} = -2.986$, $p=.009$) (Figure 5.3).

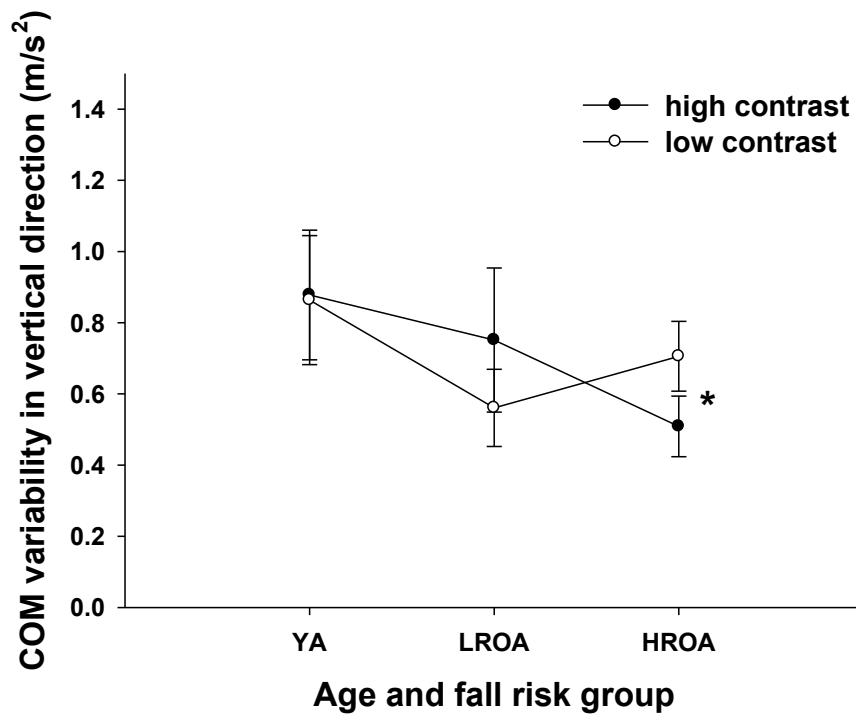


Figure 5.3: HROA showed significantly reduced COM acceleration variability in the vertical direction when stair edge contrast was high ($p=.009$), whereas COM acceleration in YA was not affected by stair edge contrast. Data represent mean \pm standard error.

There was a significant interaction between contrast and group for a-p distance between COM and ankle of the leading leg ($F_{(2,20)} = 7.895$, $p=.003$, $\eta^2=.454$). Post-hoc analysis indicated that LROA demonstrated significantly larger a-p distance between COM and ankle when contrast was high (high contrast: 2.6 ± 2.3 cm, low contrast: 2.2 ± 2.2 cm, $t_{(6)} = 2.722$, $p=.017$) (Figure 5.4). There was a main effect of contrast for the a-p distance between COM and ankle ($F_{(2,20)} = 14.097$, $p=.001$, $\eta^2=.426$), indicating that all participants located the COM further back when stair edge contrast was low.

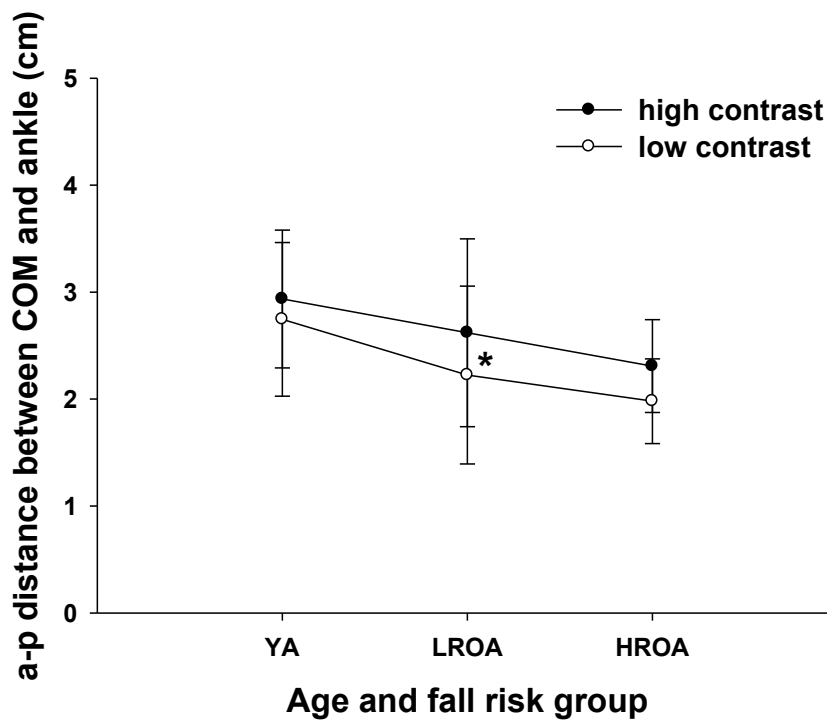


Figure 5.4: All groups demonstrated more posteriorly positioned COM with respect to the ankle of the leading leg when stair edge contrast was high. This effect was only statistically significant in LROA. Data represent mean \pm standard error.

5.3.5 Additional analysis of foot position relative to the stair edge and the effect of handrail use on COM acceleration

There were no significant differences between participant groups in the mean measure how much their toes overlap the stair edges ($F_{(2, 20)} = 0.062$, $p = .940$, $\eta^2 = .006$).

HROA using the handrail showed reduced vertical COM acceleration ($F_{(1,2)} = 8.417$, $p = .027$, $\eta^2 = .584$) than HROA not using the handrail (handrail use: $-1.2 \pm 0.36 \text{ m/s}^2$, non-use: $0.15 \pm 0.85 \text{ m/s}^2$).

Table 5.2: For stair descent, data are presented as mean (SD) for all visual conditions across groups.

	Stair edge contrast		Ambient light	
	high	low	bright	dimmed
Walking speed (m/s)				
Mean	0.66 (0.15)*	0.68 (0.15)	0.68 (0.16)*	0.66 (0.15)
Variability	0.42 (0.24)	0.48 (0.25)	0.49 (0.29)	0.42 (0.19)
Vertical foot clearance (cm)				
Mean	7.4 (1.9)	6.8 (2.0)	7.1 (1.8)	7.1 (2.1)
Variability	1.2 (0.7)	1.0 (0.5)	1.2 (0.7)	1.1 (0.5)
Horizontal foot clearance (cm)				
Mean	7.1 (1.3)	6.8 (1.5)	7.0 (1.3)	7.0 (1.4)
Variability	1.1 (0.3)	1.1 (0.3)	1.1 (0.3)	1.1 (0.3)
Step width (cm)				
Mean	18.7 (3.2)	18.7 (3.2)	18.8 (3.3)	18.7 (3.0)
Variability	2.1 (0.8)	2.0 (0.9)	2.0 (0.8)	2.1 (0.8)
Step length (cm)				
Mean	27.3 (1.0)	27.5 (0.9)	27.5 (0.9)	27.4 (0.9)
Variability	1.2 (0.5)	1.2 (0.4)	1.2 (0.5)	1.3 (0.4)
A-p distance between COM and ankle (cm)				
Mean	2.6 (1.8)*	2.3 (1.9)	2.3 (1.8)	2.6 (1.9)
Variability	1.0 (0.4)	1.0 (0.4)	1.0 (0.4)	1.0 (0.4)
COM acceleration in a-p direction (m/s²)				
Mean	1.36 (0.82)	1.44 (0.72)	1.41 (0.74)	1.39 (0.81)
Variability	0.69 (0.34)	0.70 (0.32)	0.73 (0.41)	0.67 (0.31)
COM acceleration in m-l direction (m/s²)				
Mean	0.04 (0.32)	0.02 (0.29)	0.06 (0.34)	0.00 (0.27)
Variability	0.41 (0.24)	0.42 (0.22)	0.42 (0.25)	0.40 (0.20)
COM acceleration in vertical direction (m/s²)				
Mean	-0.28 (1.23)	-0.25 (1.12)	-0.33 (1.28)	-0.20 (0.11)
Variability	0.71 (0.46)	0.72 (0.39)	0.73 (0.48)	0.70 (0.37)

* significant difference within one visual condition ($p < .05$)

5.4 Discussion

This is the first study to describe differences in the effects of manipulating both ambient light levels and stair edge contrast on stepping and balance characteristics between YA and OA. Another novel aspect of this study is the inclusion of OA with mild balance impairments and reduced stair walking confidence.

5.4.1 Differences between age groups in stepping behaviour and COM control

Interestingly, LROA showed the largest mean vertical foot clearance of all groups, possibly as a precaution to avoid a trip or fall during stair descent. However, the results are, as expected, in line with previous studies showing no statistically significant differences in mean foot clearance behaviour in LROA compared to YA (Hamel et al., 2005). These authors calculated the foot clearance as minimum distance between shoe sole and stair edge during the swing phase without distinguishing between vertical and horizontal clearance. The foot clearance results of the present study in LROA would be similar to those reported in OA by Hamel et al. when taking the thickness of the shoe and the sole into account. Foot clearances in YA in the present study appear smaller than those reported by Hamel et al.. When the distance between toe marker and shoe sole is considered, HROA descend stairs with alarmingly little foot clearance. Step width variability was significantly increased in both OA groups compared to YA. This finding is line with previous walking studies (Grabiner et al., 2001; Owings & Grabiner, 2004) and suggests that OA exhibit a similar variable stepping pattern during stair descent. A variable step width contributes to a variable base of support for the COM movement which may add to the difficulty to control balance in OA. Indeed, the present findings showed that m-l COM acceleration variability was significantly greater in HROA than in YA. Variable step width and

variable m-l balance control add to the notion that movement control in the coronal plane deteriorates with increasing age, resulting in larger hip and pelvis ranges of motion (Mian et al., 2007b) and lateral foot placement errors (Chapman & Hollands, 2010) contributing to instability and increased likelihood of falling (Maki et al., 2000). Another finding was the increased a-p COM acceleration variability in HROA compared to YA. At initial contact, the COM is lowered down to the next stair while displaced anteriorly (Zachazewski et al., 1993). The present findings suggest that HROA were less able to control the a-p and m-l acceleration of the COM simultaneously than YA. This clearly increases the risk of a stair fall.

5.4.2 Fall risk-related differences in stepping behaviour

In line with the hypothesis, HROA demonstrated significantly less vertical and horizontal foot clearances than LROA. This behaviour may increase the risk of HROA to catch their heels on the stair edge during the swing phase and therefore increases the likelihood of a trip and subsequent fall. It has previously been reported that OA demonstrate greater stance leg extension and compensatory lower leg stiffness than YA (DeVita & Hortobagyi, 2000b). In addition, not only do elderly fallers demonstrate reduced concentric and eccentric muscle strength in knee and ankle joints (Perry et al., 2007), lower limb muscle strength is already significantly reduced in OA with very mild balance impairments (Lin & Woollacott, 2005). Although not tested, it is likely that reduced muscle strength, i.e. the hip extensors and knee extensors, in HROA could explain the resulting foot trajectory during swing leading to smaller foot clearances than in LROA.

5.4.3 Effect of manipulating ambient light levels

Although all participants walked slower when ambient lighting was reduced, ambient illumination levels appeared to have little effect on stepping behaviour. When lights were dimmed, step length decreased in HROA, suggesting that these individuals either adopted a safer stepping pattern to avoid overstepping or underestimated the stair edge location. On the contrary, step length increased in YA when lights were dimmed, which could be caused by an overestimation of the stair edge location as previously shown for close targets in darkness (Crane & Demer, 1997). It could be argued that reduced step length under dimmed lights might be a better strategy than increasing the step length, but step length should not be reduced too much as this increases the likelihood of foot placement problems on the stair run. Step width and its variability did not change in YA and OA with changing illumination levels, a finding which is consistent with that of other walking studies (Thies et al., 2005). Interestingly, manipulating ambient illumination levels had no effect on vertical or horizontal foot clearances and their variability in any of the groups. Unaffected foot clearance is consistent with the findings of Hamel et al. (2005) but, unlike these authors, increased variability in this measure in OA was not observed in the present study.

5.4.4 Effect of manipulating stair edge contrast

Walking speed decreased when the stair edge contrast was high. A possible explanation is that although the attachment of the black edge strip to the stairs was perfectly flat and safe, the participants walked slower and more cautiously because they did not want to trip over the attached edge strip.

It was expected that increased stair edge contrast would lead to a safer and more stable gait pattern characterised by less variable foot placement and reduced stepping and COM movement variability. However, foot placement on the stairs was

unaffected by stair edge contrast in all age groups. Instead, the results suggest that highlighted stair edges result in differences in the measures of posture and balance in all groups: YA increased the horizontal foot clearance, which remained unchanged in the OA, confirming previous findings (Simoneau et al., 1991). LROA positioned the COM more posteriorly to the anterior limit of the base of support, which can be considered to be a sensible strategy to reduce the likelihood of anterior falls. HROA demonstrated a reduced variability in the vertical COM acceleration, which suggests a more consistent and controlled lowering of the COM to the next stair. The finding that increased stair edge contrast improves posture and balance rather than stepping characteristics suggests that improved visual description of stair edges may provide richer optic flow that is primarily used to regulate balance. This is in contrast to previous walking (Graci et al., 2009) and obstacle crossing (Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006) studies where a reduction, not an increase, of peripheral optic flow information leads to increased foot clearance and step length to avoid tripping. Fixating a specific point in space at a consistent distance ahead in the direction of travel has been shown to help OA to increase head stabilisation (Cromwell et al., 2002). The previous finding that particularly OA tended to look a relatively constant number of steps ahead when descending stairs (Chapter 2) may help to provide a constant optic flow to facilitate balance.

5.4.5 Effect of handrail use on COM control in HROA

As during stair ascent, only participants from the HROA group used the handrail while descending stairs. This is in line with previous observations (Hamel & Cavanagh, 2004) and suggests the notion that the handrail is primarily used to aid balance during stair descent (Reeves et al., 2008a). The finding that handrail use resulted in reduced vertical COM acceleration suggests that these individuals loaded their upper limbs,

possibly in addition to increased stiffness in the lower limbs (DeVita & Hortobagyi, 2000b) to resist the downward displacement of the COM in order to make it more controllable. Because of the handrail use the overall HROA group mean for vertical COM acceleration becomes similar to that of YA, also indicating improved vertical stability in HROA. However, m-l COM control remained unaffected in contrast to improved m-l stability with light touch during walking (Dickstein & Laufer, 2004).

5.5 Conclusion

The findings show that HROA descended stairs with significantly smaller foot clearances than LROA which may increase the likelihood of a trip or fall. Improving the stair edge visibility increases the horizontal foot clearance in YA and leads to adjustments to balance control in OA that result in greater stability. However, a reduction of ambient light had no effect on foot clearance or balance control. Handrail use is beneficial for HROA as it helps to control balance in the vertical direction.

CHAPTER 6

Head posture during stair ascent and descent and the effect of age, fall-risk and visual factors

The previous chapters have investigated how manipulating stair edge visibility affects stepping behaviour and balance control in YA and OA with either a lower or higher risk of falling. Apart from general age-related differences in m-l balance control it was found that highlighted stair edges increased foot clearance during stair ascent and improved stability during stair descent, particularly in OA. These findings suggest that increased visual input might help to improve balance during stair descent in OA. However, previous research has shown that non-visual information also contributes to balance during locomotion. For example, head stability declines with reduced availability or quality of vision, particularly in OA (Cromwell et al., 2002) and a stable head posture is necessary for maintaining balance (Pozzo et al., 1990). Furthermore, neck muscles have been shown to provide proprioceptive information about head posture in relation to the trunk (Ivanenko et al., 2000), and it has also been shown that this non-visual information is used by the CNS for aligning the body with aspects in the environment to help with balance control during locomotion (Courtine et al., 2003; Bove et al., 2001). Therefore the next chapter presents an investigation into the effects of manipulating ambient illumination and stair edge contrast on head posture and head posture control in YA, LROA and HROA.

6.1 Introduction

Stair negotiation has different biomechanical requirements and poses a greater challenge to the balance control systems of the CNS than overground walking. For example, range of motion in hip, knee and ankle joints in the sagittal plane is larger during stair negotiation (Livingston et al., 1991; Andriacchi et al., 1980; Protopapadaki et al., 2007) than during overground walking. The vertical COM displacement, which depends on the stair height, is significantly greater and the forward trunk lean during stair ascent has been shown to be twice as large compared to overground walking (Krebs et al., 1992). The GRF curve for stair ascent and descent in the sagittal plane differs significantly from that during overground walking (Stacoff et al., 2005; Protopapadaki et al., 2007) and is associated with different force distribution and power generation patterns around hip, knee and ankle joints (Novak & Brouwer, 2010; Protopapadaki et al., 2007).

There is evidence that a stable head posture is beneficial to the balance control systems by providing a stable reference frame for the visual and vestibular systems (Menz et al., 2003a; Pozzo et al., 1990) and reliable proprioceptive information about body alignment in space (Ivanenko et al., 1999; Ivanenko et al., 2000). Given the larger range of lower limb movements and different trunk posture during stair negotiation versus overground walking, maintaining a stable head posture may be more challenging during stair negotiation than during overground walking. Indeed, in YA head stabilisation has been shown to decrease from walking overground to stair ascent and to decrease even further during stair descent compared to overground walking and stair ascent (Cromwell & Wellmon, 2001).

A stable head posture during locomotion helps to maintain a stable image of the environment on the retina. Maintaining a stable image on the retina is achieved by the vestibulo-ocular reflex and contributes to normal visual acuity (Crane & Demer, 1997).

Visual acuity is adversely affected by the image motion across the retina (Demer & Amjadi, 1993) and starts to deteriorate when image velocity exceeds 4 °/s (Grossman et al., 1989; Crane & Demer, 1997). During walking and running, visual acuity has been shown to decrease compared to standing, but the vestibulo-ocular reflex is mainly preserved. Saccades during voluntary head rotations, presumably while standing, occur more frequently compared to walking in place and running in place, which means that the insufficient vestibulo-ocular reflex needed to be complemented (Grossman et al., 1989). Therefore, a stable head posture is important for providing a stable platform for sampling accurate visual information about features in the environment. The importance of visual information in controlling head posture is evidenced by the finding that reducing vision has been shown to have an effect on head posture. For example, it has been shown that individuals tilt the head further down when walking in darkness (Pozzo et al., 1990), when walking with eyes closed (Hirasaki et al., 1993), or when the lower visual field is occluded (Marigold & Patla, 2008b) than when walking with normal vision.

Head posture control is not only important for providing a stable reference frame for the visual system, but has also been implicated as important in providing non-visual sensory information that is useful for alignment of the body segment. The head is stabilised by the neck muscles and therefore neck muscle proprioception is likely to provide the CNS with important information regarding head posture and stability. Indeed, manipulating proprioceptive input to neck muscles has been shown to affect the perceived postural relationship between head and trunk, leading to adaptations to body orientation and steering behaviour during locomotion. For example, during walking with normal visual and vestibular input, symmetrically applied neck muscle vibration has been shown to generate the illusion of a backward trunk lean leading to an increase in walking speed (Ivanenko et al., 2000). During walking without visual input, unilaterally applied neck muscle vibration resulted in a deviated walking path

towards the non-vibrated side (Bove et al., 2002; Courtine G et al., 2006; Bove et al., 2001). These findings suggest that visual, vestibular and proprioceptive information is integrated leading to task-specific adaptations of body orientation which serve to keep the COM within the safe limits of the base of support.

During overground walking, the trunk is not a passive structure carrying the neck and head, but acts as a dampener of a-p and m-l accelerations (Menz et al., 2003a) which would otherwise radiate to the head and lead to less controlled head posture and more head movement. Indeed, trunk and neck segments have been shown to attenuate the accelerations from the lower limbs and pelvis resulting in decreased head acceleration, particularly in the sagittal plane (Kavanagh et al., 2004). Head stabilisation is achieved by counteracting vertical head movements in the sagittal plane with head movements around a m-l movement axis (Pozzo et al., 1990). Fit OA have been shown to demonstrate good head stability during overground walking which has been attributed to OA reducing the movements from the lower limbs by walking slower with less cadence (Cromwell et al., 2002) and by tighter coupling of the head and trunk movements than YA (Kavanagh, Barrett & Morrison, 2005). It has also been shown that OA adopt different strategies in a-p trunk and head accelerations than YA, aiming to support balance during the single stance phases of the gait cycle (Kavanagh et al., 2004). However, previous literature has also highlighted some age-related differences in stabilising the head posture. For example, although the general pattern of acceleration attenuation from pelvis to shoulder and from shoulder to head remained preserved in older age, OA were less able to use the neck segment to dampen the accelerations compared to YA, leading to increased head acceleration (Mazza et al., 2008). Other age-related differences during walking are evidenced by the findings that OA are able to stabilise their head as well as YA when fixating a point in space straight ahead (Cromwell et al., 2002) and that OA tend to angle the head further down than YA (Hirasaki et al., 1993). However, age-related changes to head posture and stabilisation

during stair negotiation, particularly in OA with impaired balance, have not yet been studied. It also remains unknown whether improvement of visual input, e.g. by enhancing the visibility of stair edges, affects head posture and stabilisation during stair negotiation.

The present study aimed to investigate sagittal head posture in OA with either lower or higher risk of falling during stair ascent and descent. A second aim was to investigate the effect of manipulating visual input on head posture control. Based on the results of previous walking studies (Cromwell et al., 2002) it was hypothesised that, in the sagittal plane, (1) OA would demonstrate a similar range of head movement and movement velocity as YA, but increased variability in head posture. Previously it has been shown that the head is tilted further down when vision is denied (Pozzo et al., 1990, Hirasaki et al., 1993) or reduced (Marigold & Patla, 2008b) and it is therefore hypothesised that all participants would orientate their head further down when ambient illumination is significantly reduced in the laboratory. It is also hypothesised that in YA, LROA and HROA high stair edge contrast would lead to a more stable head posture with reduced head movement range and angular head velocity and reduced variability because it has been previously shown that OA stabilise their head as well as YA when fixating a specific point in space (Cromwell et al., 2002).

6.2 Method and data analysis

Participant characteristic, stairs and apparatus, experimental design and protocol, data preparation and statistical analysis are described in Chapter 3.

Outcome measures were (1) angular excursion, calculated as difference between maximum and minimum head pitch angle, (2) mean head pitch angle, (3) head pitch angle variability, (4) mean angular head velocity (5) angular head velocity variability

and (6) peak angular head velocity. Variability measurements were calculated as one standard deviation of the head pitch angle and angular head velocity over one gait cycle and averaged per condition. All variables were analysed within one gait cycle. For stair ascent, the analysed gait cycle began with initial contact on stair 2 (0% of gait cycle) and finished with initial contact of the same leg on stair 4 (100% of gait cycle). For descent, the gait cycle started with initial contact on stair 4 (0% of gait cycle) and ended with initial contact of the same leg on stair 2 (100% of gait cycle).

The head pitch angle was calculated as the angle between spontaneously adopted head posture during standing while looking straight ahead ($=0^\circ$) and tilted head posture during stair negotiation (Figure 6.1). Negative head angle values describe a downward tilted head.

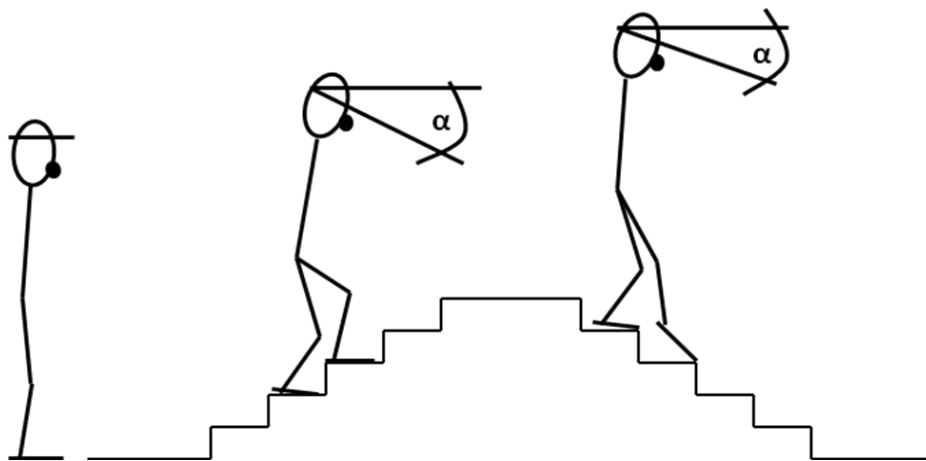


Figure 6.1: Head angles (α) in the sagittal plane were calculated with reference to spontaneously adopted head posture during standing.

6.3 Results

Table 6.1 presents the data of all outcome measures for stair ascent and Table 6.2 presents the data for stair descent for each group across conditions.

Table 6.1: Head data are presented as mean (SD) for all groups across conditions for stair ascent.

	YA	LROA	HROA
Angular excursion (°)	8.9 (2.9)*	5.7 (1.5)	6.7 (2.1)
Mean head pitch angle (°)	-19.1 (12.0)	-20.5 (11.4)	-25.1 (12.2)
Head pitch angle variability (°)	2.6 1.0)*	1.7 (0.5)	2.0 (0.8)
Mean angular head velocity (°/s)	1.5 (4.2)	-1.1 (2.7)	-1.2 (2.5)
Angular head velocity variability (°/s)	17.7 (3.2)	14.1 (4.4)	14.5 (3.3)
Peak angular head velocity (°/s)	35.7 (6.8)	29.4 (15.2)	29.7 (8.7)

* sig. difference ($p < .05$) between YA and LROA, + sig. difference ($p < .05$) between YA and HROA, § sig. difference ($p < .05$) between LROA and HROA

Table 6.2: Head data are presented as mean (SD) for all groups across conditions for stair descent.

	YA	LROA	HROA
Angular excursion (°)	8.7 (3.8)*	4.3 (0.8)	6.2 (1.3)
Mean head pitch angle (°)	-28.2 (11.9)	-33.6 (10.7)	-38.8 (16.0)
Head pitch angle variability (°)	2.5 (1.2)*	1.2 (0.2)	1.7 (0.4)
Mean angular head velocity (°/s)	5.0 (6.9)	0.6 (1.3)	1.3 (1.3)
Angular head velocity variability (°/s)^w	22.4 (6.2)	14.0 (2.7)	17.6 (3.4)
Peak angular head velocity (°/s)^w	45.4 (15.1)	27.7 (7.1)	36.0 (7.3)

* sig. difference ($p < .05$) between YA and LROA, + sig. difference ($p < .05$) between YA and HROA, § sig. difference ($p < .05$) between LROA and HROA, ^w sig. effect of walking speed ($p < .05$)

6.3.1 Effect of walking speed

For stair ascent, the results of the ANCOVA revealed that walking speed did not significantly contribute to the variance in any of the outcome measures.

For stair descent, the results of the ANCOVA revealed that walking speed significantly contributed to the variance in angular head velocity variability ($F_{(2,20)}=9.606$, $p=.006$ $\eta^2=.336$) and peak angular head velocity ($F_{(2,20)}=5.275$, $p=.033$, $\eta^2=.217$).

6.3.2 Effect of age group and fall risk

For stair ascent, there was a significant main effect of age on angular head excursion ($F_{(2,20)}=4.637$, $p=.023$, $\eta^2=.328$) and head pitch variability ($F_{(2,20)}=4.525$, $p=.025$, $\eta^2=.323$), indicating that LROA moved their head within less range in the sagittal plane ($p=.022$) and with less variability ($p=.023$) than YA.

For stair descent, there was a significant main effect of group on angular excursion ($F_{(2,20)}=4.715$, $p=.022$, $\eta^2=.332$) and head angle variability ($F_{(2,20)}=6.780$, $p=.006$, $\eta^2=.416$), indicating that LROA moved their head with less range ($p=.021$) and were less variable in head posture ($p=.006$) than YA. The main effect of group on head velocity variability was significant ($F_{(2,20)}=3.814$, $p=.040$ $\eta^2=.286$), but pairwise comparisons did not reveal differences between groups ($p>.071$).

Figure 6.2 shows the mean head pitch angle for stair ascent and descent for all groups. Although statistically not significant, during stair ascent HROA tended to angle their head further down than YA and LROA. During stair descent, HROA and LROA tended to tilt the head further down than YA (Figure 6.2). Furthermore, all groups tended to angle the head further down during stair descent compared to ascent.

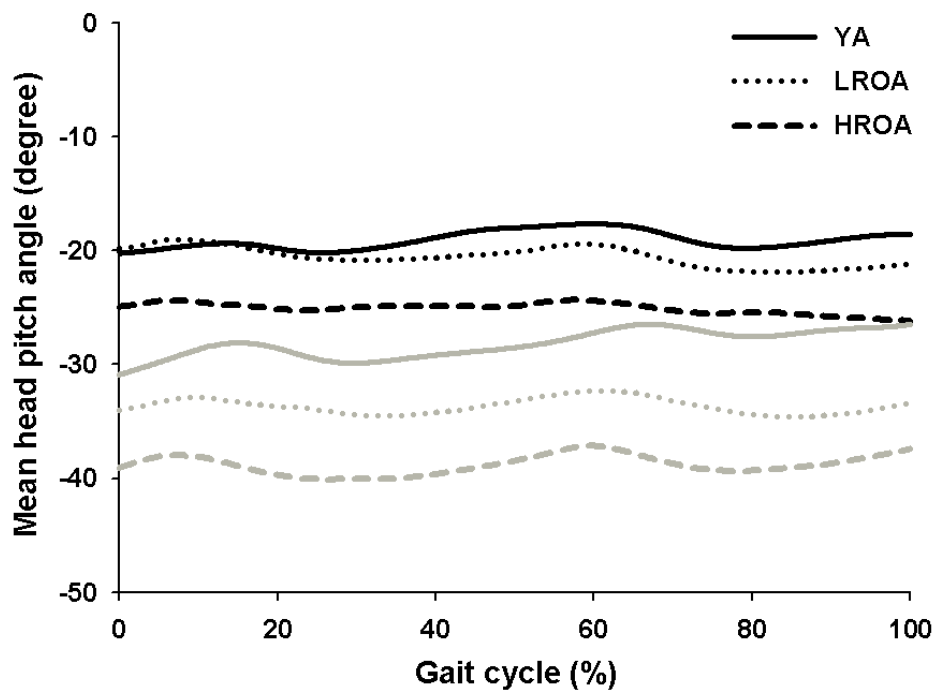


Figure 6.2: Mean head pitch angle during one gait cycle stair ascent (black lines) and stair descent (grey lines) for YA, LROA and HROA across conditions.

The mean head velocity profiles for one gait cycle are shown in Figure 6.3. During stair descent the range of head angle velocity was larger than during ascent. Also, the velocity profile was very variable in mid stance, whereas during descent, the velocity profile within one gait cycle was roughly the same for all groups with positive peaks in early and late stance and negative peaks in mid stance and early swing.

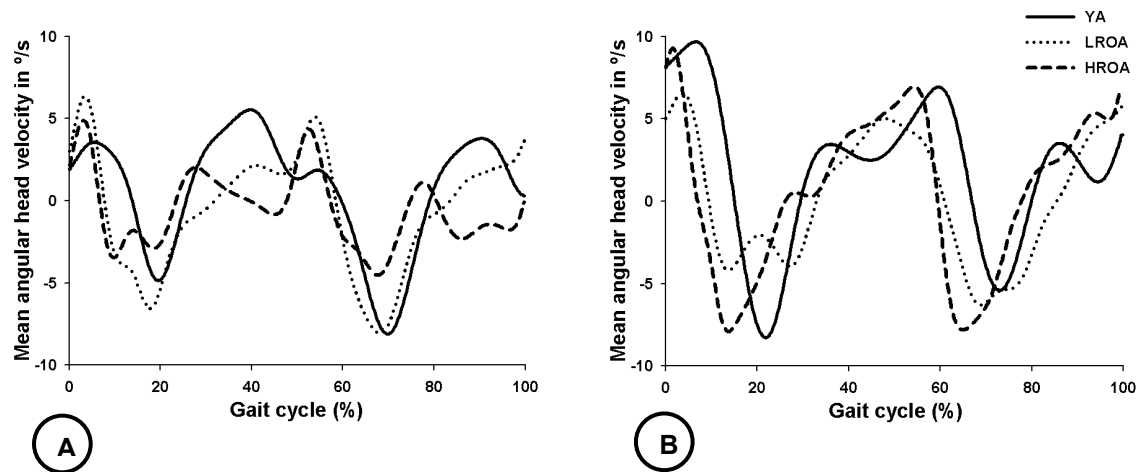


Figure 6.3: Mean angular head velocity for all groups across conditions for stair ascent (A) and descent (B). Positive values represent head velocity while the head is angled upwards and negative values represent head velocity while the head is tilted downwards.

6.3.3 Effect of ambient illumination and stair edge contrast

For stair ascent and descent, manipulating the ambient illumination and the stair edge contrast did not significantly affect any outcome variables ($F_{(2,20)} < 2.461$, $p > .132$, $\eta^2 < .116$) (Tables 6.3 and 6.4).

Table 6.3: Head data are presented as mean (SD) for all visual conditions across groups for stair ascent.

	Stair edge contrast		Ambient light	
	high	low	bright	dimmed
Angular excursion (°)	7.1 (2.4)	7.2 (2.8)	7.1 (2.7)	7.1 (2.6)
Mean head pitch angle (°)	-21.8 (11.8)	-21.4 (12.3)	-22.0 (11.6)	-21.2 (12.5)
Head pitch angle variability (°)	2.1 (0.7)	2.2 (1.0)	2.1 (0.9)	2.1 (0.9)
Mean angular head velocity (°/s)	-0.01 (3.7)	-0.41 (3.3)	0.21 (3.6)	-0.64 (3.3)
Angular head velocity variability (°/s)	15.5 (3.7)	15.5 (4.1)	15.6 (4.2)	15.4 (3.7)
Peak angular head velocity (°/s)	31.5 (8.2)	31.9 (13.1)	32.7 (13.0)	30.7 (8.3)

Table 6.4: Head data are presented as mean (SD) for all visual conditions across groups for stair descent.

	Stair edge contrast		Ambient light	
	high	low	bright	dimmed
Angular excursion (°)	6.5 (3.2)	6.5 (2.8)	6.4 (2.9)	6.5 (3.0)
Mean head pitch angle (°)	-33.6 (13.6)	-33.5 (14.1)	-33.8 (13.7)	-33.2 (13.9)
Head pitch angle variability (°)	1.8 (1.0)	1.8 (0.8)	1.8 (0.9)	1.8 (1.0)
Mean angular head velocity (°/s)	2.3 (4.5)	2.4 (4.7)	2.3 (4.7)	2.4 (4.5)
Angular head velocity variability (°/s)	18.3 (5.8)	18.0 (5.3)	18.2 (5.6)	18.1 (5.6)
Peak angular head velocity (°/s)	37.3 (13.5)	36.1 (12.1)	36.6 (14.0)	36.8 (11.5)

6.4 Discussion

This is the first study to investigate age-related differences in head posture during stair ascent and descent. A further new aspect is the inclusion of OA with mild balance impairments and less confidence to negotiate stairs.

6.4.1 Effect of age group and fall risk

It was hypothesised that OA would demonstrate similar range of head movement and movement velocity as YA, but increased variability in head posture. Contrary to the hypothesis, the findings show that LROA ascended and descended stairs with a significantly less variable head posture than YA.

During stair ascent, both the angular excursion and the head pitch variability in LROA were significantly smaller than in YA. This finding indicates that LROA moved their head within a smaller range and with less variability than YA, suggesting a more rigorous control of head posture than YA. A possible explanation for this behaviour could be that LROA guided their gaze towards the staircase whereas YA looked around, moving the head as well. This hypothesis is consistent with the findings from the study in Chapter 2, whereby YA were found to ascend stairs with more variability in how far they looked ahead than the OA group, which would be comparable with the LROA group of the present study. Furthermore, there was a trend for OA, particularly HROA, to angle their head further down than YA (Figure 6.2). It is likely that participants positioned the head to facilitate the acquisition of visual information about the staircase. It has been shown that eye movements precede head movements and the amplitude of the head movement is smaller than that of the eyes (Delreux et al., 1991). Therefore, the findings of the present study suggest that all participants guided their gaze towards the stairs and that HROA looked less far ahead than LROA and LROA looked less far ahead than YA.

A smaller peak angular head velocity indicates better head stabilisation (Cromwell et al., 2002). During stair ascent, the peak angular head velocity in LROA and HROA was very similar to that previously reported for OA during overground walking, while OA did not demonstrate other gait adaptations to increase lower body stability, such as slower walking speed than YA (Cromwell et al., 2002). Comparable walking speed and peak angular head velocity would suggest that, in OA, the head posture was as efficiently stabilised during stair ascent as during overground walking. In contrast, peak angular head velocity in ascending YA was clearly reduced compared to previous results during overground walking (Cromwell et al., 2002) which indicates that YA ascended stairs with more control of their head posture compared to overground walking. Taking the results from OA and YA together, the findings suggests that, compared to overground walking, the head posture required increased stabilisation during stair ascent and OA were less able to do so. In addition, the angular excursion in YA was greater than in LROA, but smaller than previously reported (Cromwell & Wellmon, 2001). The finding that YA moved their head within a larger range but with reduced peak angular head velocity and OA moved their head within a smaller range but with comparatively larger peak velocity also supports the notion that OA have a reduced ability to stabilise the head and that maintaining a stable head posture during stair ascent is more challenging than during overground walking. During stair descent, both the angular excursion and head angle variability in YA were also significantly larger than in LROA. Again, in combination, these findings indicate that LROA moved their head within a smaller range and with less variability than YA, suggesting a better head posture control than YA. As observed during stair ascent, there was a trend for LROA and HROA to angle the head further down than YA while descending stairs (Figure 6.2). YA and LROA angled their head down by approximately 30° which roughly equals the staircase angle of 32°. Given the stair dimensions, the average height of the participants and the mean head pitch angle, it is unlikely that any

of the groups had looked at the stairs during the investigated gait cycle. It is conceivable that- on average- YA and LROA aligned their head with the staircase angle to provide the CNS with additional proprioceptive information about the amount of decline and therefore stair location in relation to the body and possibly feet. It has been previously shown that aligning the head with aspects in the scene provides the CNS with a spatial reference frame which is used to adjust and coordinate body movements. This has been shown for locomotor tasks such as turning (Hollands et al., 2001; Hollands et al., 2004), walking around a corner (Grasso et al., 1998) and stepping on the spot (Reed-Jones et al., 2009a; Reed-Jones et al., 2009b). Therefore, it is proposed that the downward tilted head posture during stair descent may not only be used to provide visual information about stepping locations, but may help with providing additional information about body posture in space with respect to the staircase that can then be translated into appropriate stepping actions and balance control.

It has previously been suggested that OA walk slower than YA to aid head stability during walking (Cromwell et al., 2002) and that YA select their preferred walking speed to maintain optimal head stability and adapt cadence and step length to surface challenges for this purpose (Menz et al., 2003a). The present findings are in line with the results of these previous studies and showed that LROA and HROA descended stairs significantly slower than YA (Paragraph 5.3). In addition, walking speed partially explained the variance in angular head velocity variability and peak angular head velocity. The mean values for peak angular head velocity were slightly lower in YA and LROA and slightly higher in HROA compared to other overground walking studies (Cromwell et al., 2002). This result implies that YA and LROA maintained a stable head posture during stair descent, which is comparable to that during overground walking and that LROA may benefit from slower walking speed to improve head stabilisation. In contrast, HROA descended the stairs with the slowest

walking speed and tended to exhibit larger peak angular head velocity compared to the results from Cromwell's et al. (2002) walking study. Given the present result that walking speed explained part of the variance in peak angular head velocity, this would imply that, during stair descent, HROA are less able to maintain a stable head posture than YA and LROA.

6.4.2 Effect of ambient illumination and stair edge contrast

Based on previous findings (Pozzo et al., 1990; Hirasaki et al., 1993; Pozzo et al., 1991), it was hypothesised that participants would angle their head further down when lights were dimmed compared to lights on. It was further hypothesised that improved visual input by highlighted stair edges would aid a stable head posture with reduced head movement range and angular head velocity and reduced variability. The findings showed that neither illumination nor stair edge contrast affected any of the outcome measures.

For stair ascent and descent, the findings showed that ambient illumination and stair edge contrast had no effect on head posture or head movement velocity measures. It has been previously shown that OA were able to stabilise the head to the same extent as YA when fixating a target while walking (Cromwell et al., 2002). However, the finding that none of the participants demonstrated reduced variability of head posture or movement when stair edge contrast was high suggests that a more stable head posture during stair negotiation may not be facilitated with visual cues only. It may be that OA require explicit instructions on where to fixate their gaze while ascending or descending stairs in order to increase head posture stability. Another explanation for unchanged head posture and head movement velocity measures when manipulating the stair edge contrast would be that non-visual sensory information

about stair properties and body alignment in space are sufficient or more important for negotiating stairs within reasonable limits of safety than highlighted stair edges.

6.5 Summary and conclusion

The present findings show that LROA may ascend stairs with better head movement control than YA as indicated by smaller angular head excursion and head pitch angle variability. However, when comparing head stabilisation in YA and OA with that reported in previous overground walking studies (Cromwell et al., 2002), YA demonstrated a more stable head posture during stair ascent than during overground walking whereas LROA and HROA did not demonstrate a similarly increased stabilisation of head posture as YA. During stair descent, YA and LROA tended to orientate the head downwards, roughly in alignment with the staircase angle. Given the stair dimensions and the position of the analysed gait cycle on the stair, the adopted head posture suggests that proprioceptive information about the body in relation to the staircase is collected rather than visual information about stair edge locations. However, the findings also indicated that HROA were less able to maintain a stable head posture during stair descent, which may contribute to increased risk of falling. A reduction in ambient illumination did not result in a more tilted head and high visibility of stair edges did not improve head posture or head posture control, suggesting that other, non-visual, sensory information are used to adapt body alignment and stepping actions during stair negotiation.

CHAPTER 7

General discussion

Specific age-related changes have been previously shown during overground walking, but given the increasing number of falls on stairs in OA, it is important to study behavioural changes in older age during stair negotiation before considering and implementing interventions to reduce fall risk in this population. As described in the introduction (Chapter 1), the aim of the present thesis was to investigate gaze and stepping behaviour, balance control and head posture during stair negotiation. The new aspects of these studies were firstly, to provide data and to compare age-related differences in gaze behaviour during stair negotiation and secondly, to study stepping behaviour, balance and head posture control in YA and OA with lower or higher risk of falling under manipulated visual information.

7.1 Summary of findings of the experimental chapters

The first study (Chapter 2) aimed to provide data about gaze behaviour during midstair negotiation and to investigate age-related differences. The findings clearly showed that stair location in the visual scene is important information for ascending and descending stair users. The results showed that YA and OA direct their gaze towards the stairs and look on average three steps ahead in both walking directions. Furthermore, OA fixated the stairs for longer than YA in both walking directions and OA were less variable in the extent they looked ahead during ascent than YA. These findings lend support to the

suggestion that OA require more time to process visual information describing a step and transform it into an appropriate stepping movement.

The aim of the second and third studies (Chapters 4 and 5) was to investigate the effect of manipulated visual information about the staircase on stepping behaviour and balance control during stair ascent in YA and OA with either lower or higher risk of falling. As stair ascent and stair descent are biomechanically two different tasks, analysis and discussion of the results were carried out separately.

For stair ascent, the findings indicated that the ability to clear stair edges, to place the feet on the stairs and to control balance is unaffected in OA with mild balance impairments and reduced confidence to negotiate stairs. A reduction in ambient illumination levels led to slower walking speed and increased lateral balance control. Highlighted stair edges appeared to have acted as visual cue to increase the vertical foot clearance in YA, LROA and HROA. However, foot placement on the stair and balance control remained unaffected by stair edge contrast. Handrail use was only observed in HROA, but this external support did not affect balance during stair ascent.

For stair descent, the findings showed that HROA descend stairs with significantly smaller vertical and horizontal foot clearance than LROA which might increase the likelihood of a trip or fall. Highlighting the stair edges led to an increase in horizontal foot clearance in YA and to adjustments to balance control in LROA and HROA that resulted in greater stability. However, a reduction of ambient light had no effect on foot clearance or balance control. Handrail use assisted HROA to control balance in the vertical direction.

The aim of the fourth study (Chapter 6) was to investigate age- and fall risk-related differences in sagittal head posture control during stair negotiation and whether improved stair edge visibility facilitates a more stable head posture, particularly in the

OA. The present findings showed that LROA are less variable in their head posture better than YA in both walking directions. Compared to overground walking, head posture control in HROA ascending and descending stairs is affected, which may contribute to increased risk of falling. Changes to ambient illumination or stair edge contrast did not affect head posture or head posture control.

7.2 Similarities and differences between stair ascent and descent on gaze behaviour, stepping characteristics, balance and head posture control

As mentioned before, stair ascent and stair descent are two different activities and main differences are the COM movement and muscle activity. During stair ascent the COM is moved up to the next stair during the “vertical thrust” phase and during stair descent it is lowered down to the next stair in a controlled manner during mid and late stance (Zachazewski et al., 1993). Muscle activity of hip and knee extensor muscles and ankle plantarflexors is concentric during stair ascent and eccentric during stair descent. Analysis of gaze behaviour, stepping characteristics, balance and head posture control has shown some similarities but also differences between both walking directions which are discussed in more detail in the following sections.

7.2.1 Age- related changes in gaze behaviour and head posture control

YA and OA directed their gaze towards the stairs and looked on average three steps ahead during stair ascent and looked on average slightly further ahead during stair descent. These findings were recently replicated by two studies, testing YA during midstair negotiation (den Otter & Mouton, 2009; Miyasike-Dasilva et al., 2011). Directing the gaze towards future stepping locations implies that central vision is used to guide foot placement on the stairs in both walking directions. It has been shown in

obstacle crossing studies that peripheral cues about object location, while vision of the legs was obstructed, lead to foot clearance of the leading and trailing leg similar to full vision, suggesting that peripheral cues about object location were interpreted with respect to the head rather than feet (Rietdyk & Rhea, 2006). The present findings showed differences in head posture alignment for both stair walking directions. During stair ascent, the head was angled down between 19° and 25°, which is less than the staircase angle of 32° and more than during overground walking (Pozzo et al., 1990; Cromwell & Wellmon, 2001). On one hand, it might be difficult to ascend stairs without collecting visual information when the head is tilted down since the staircase is unintentionally in view. On the other hand, it could be that the head is aligned to optimise sampling visual information from the lower visual field to aid stair ascent as previously shown for walking over uneven ground (Marigold & Patla, 2008a) and during obstacle avoidance tasks (Marigold et al., 2007). During stair descent the head was angled down on average by 28° (YA) and 33° (LROA) which roughly equals the staircase angle of 32°. Given previous findings that head posture provides the CNS with non-visual information about the spatial relationship between aspects in the environment and the body in order to organise whole-body movements (Rietdyk & Rhea, 2006; Grasso et al., 1998; Reed-Jones et al., 2009b), it is proposed that YA and LROA integrate central visual and proprioceptive information about stair edge location to plan and execute appropriate stepping actions and to control balance during stair descent. The importance of non-visual information is also supported by the finding that gaze behaviour between transition phases and midstair walking is unchanged (Miyasike-Dasilva et al., 2011), although it would be reasonable to suggest that the transition from stair to floor requires more visual on-line control of foot placement, particularly when an increase in walking speed and stride length was observed (Lee & Chou, 2007). However, Lee & Chou (2007) have also shown that step width decreases and lateral balance control reduces during the transition from stair to lower landing,

which could be the cost for maintaining the midstair gaze behaviour pattern. But it is also possible that head posture gives adequate information about foot placement locations to master the transition phase, although head posture has not yet been directly measured during the transition between stair and lower landing. In contrast to YA and LROA, HROA angled the head down by 38° while descending stairs, which is more than the staircase angle of 32° . It is proposed that, during stair descent, central visual information might be more important for this older adult group than peripheral vision or proprioceptive information about stair location with respect to the head derived from the head posture.

Overall, the mean head angles in YA were found to be comparable with those reported for YA during stair negotiation by Cromwell & Wellmon (2001). Like the results from these authors, the head in the present study was tilted further down during stair descent than during stair ascent not only for YA but also for LROA and HROA. Given the age-related decline in the sensory systems along with reduced musculoskeletal properties and reduced confidence in stair walking, the present findings of head posture control in LROA and HROA add to the notion that stair descent is a highly challenging task (Zachazewski et al., 1993; McFadyen & Winter, 1988).

7.2.2 Differences between participant groups in stepping behaviour and balance control

In both walking directions, YA were significantly less variable in the COM acceleration in the sagittal and coronal planes than HROA whereas LROA demonstrated comparable m-l COM acceleration variability to YA. The finding that LROA demonstrated good m-l balance in both walking directions is in line with previous walking (Dean et al., 2007; Chapman & Hollands, 2010) and stair walking studies (Mian et al., 2007a; Lee & Chou, 2007), as these studies found no differences in balance

control between YA and fit OA who would be comparable with the LROA group in the present study. However, the finding that COM acceleration in the m-l direction is more variable in HROA than in YA points to deteriorating lateral balance with increasing age which needs to be actively controlled as previously shown for walking (Bauby & Kuo, 2000). Increased m-l COM variability could be attributed to reduced muscle strength in e.g. hip abductors and peroneus muscles and inaccurate sensory feedback from proprioceptors. The present studies have shown that impaired m-l balance can be found in frail and less confident OA who were also slightly older than LROA. Mian et al. studied two different groups of fit OA for two separate studies investigating age-related differences in kinematics and COM control during stair descent and found increased pelvis and hip movements in the coronal plane (Mian et al., 2007b), but no age-related effect of m-l COM control (Mian et al., 2007a). In the light of the second study, the authors explain the presence of increased range of pelvis and hip movements in the first mentioned study with underlying sensorimotor impairment which is not associated with increased age and conclude that m-l balance control during stair descent is preserved in healthy OA. However, one could also argue that increased range of pelvis and hip movements are adaptations of fit OA to keep the lateral COM displacement under control to the same extent as YA. Therefore it would be useful to include frail OA in stair negotiation studies to learn more about changes in kinematics and balance control with increased age and increasing risk of falling.

Only during stair descent, step width was more variable in LROA and HROA than in YA. This finding also adds to the above mentioned impairment in OA to control lateral movements. Eccentric muscle activity has been shown to be challenging for older fallers and non-fallers (Carville et al., 2007) and during stair descent, knee extensor muscles of the stance leg need to lower the full body mass down to the next stair when foot placement on the stair is prepared at the same time. The challenge to control balance in all three directions with only one leg in contact with the stair and

prepositioning of the swing foot for initial contact may be the reason for variable step width. Although controlling the step width is important, step length is far more restrained by the dimension of the stair run. However, it appears that overall all groups were similarly able to control foot placement in the a-p direction in both walking directions.

7.2.3 Differences between OA with lower and higher risk of falling

One important finding of the present study was that vertical and horizontal foot clearances were the same in LROA and HROA during stair ascent, but HROA demonstrated significantly less clearance than LROA while they descended stairs. This finding indicates that the ability to ascend stairs with sufficient foot clearance was preserved in HROA, but descending stairs increased the chance of catching the heel on the stair edge with potentially serious consequences in this OA group. Reduced clearance during stair descent could also be explained by the greater challenge of simultaneously controlling the COM movement in three directions (a-p, m-l and vertical), by the swing trajectory of the leading leg because of muscle weakness in the lower limbs (Frontera et al., 2000; Scott et al., 2007; Lin & Woollacott, 2005) and by impaired eccentric activation of the knee extensor muscles (Carville et al., 2007).

On first sight, the allocation of OA to the fall risk groups seems to be a limitation in the study design, since HROA were slightly older than LROA and displayed very mild active balance impairments. The aim was to assign participants to fall risk groups on the basis of an active balance assessment (BBS) and their reported fear of falling (MFES, SSEQ) because, as discussed in more detail in paragraph 1.1, impaired balance is only one factor among many contributing to increased fall risk. Given the findings in the present study, it can be concluded that OA with relatively mild balance impairments but reduced confidence to negotiate stairs already displayed specific

changes in stepping behaviour and COM control which may be accessible to intervention.

7.2.4 Effect of manipulating ambient illumination on stepping parameters, balance and head posture control

A reduction in ambient illumination led to reduced walking speed in both walking directions. This finding is consistent with previous walking studies (Kesler et al., 2005) and studies requiring accurate foot placement during walking under low light conditions (Alexander et al., 2005). Slower walking speed during reduced ambient illumination may be a good strategy to increase foot placement accuracy during stair negotiation, particularly in the restricted a-p direction. However, the findings suggest a constant foot placement pattern but challenged balance control in LROA and HROA during stair ascent and well controlled balance but affected foot placement on the stairs in HROA and YA during stair descent when illumination was reduced. It could be argued that there are different priorities with respect to foot placement behaviour and balance between both walking directions, which might be related to possible resulting problems when a fall occurs. For example, during stair descent, the base of support for COM movement becomes larger in HROA because they demonstrated an increase in step length when illumination was reduced compared to normal ambient illumination. A larger base of support in the a-p requires is beneficial for balance control in this direction, resulting in the observed unchanged COM behaviour between the two illumination conditions. It might be that a stair user during stair descent prioritises balance control over foot placement because he can anticipate how far down he would fall if a forward fall occurred.

Some studies have shown that eyes adapt well in situations when ambient illumination changes (McMurdo & Gaskell, 1991; Dieterle & Gordon, 1956). However,

these studies measured adaptation after initial exposure to bright white light followed by total darkness (McMurdo & Gaskell, 1991; Dieterle & Gordon, 1956). These conditions differ to those used in the presented studies under which participants required a few minutes of adaptation time when laboratory lights were turned from their maximum brightness of 220 lux to a minimum brightness of 1 lux. However, the fact that manipulating illumination only had an effect on one measure of older adult performance (step length during stair descent) suggests that there was little difference between participant groups in the extent to which they adapted to the different lighting conditions. Furthermore, no significant interactions between light and contrast conditions were found for any of the outcome measures. This indicates that altering light and contrast conditions in combination did not affect stepping behaviour, balance or head posture control during stair ascent or descent.

During stair ascent and descent, average head posture remained unaffected by changes in ambient illumination, contrary to previous studies (Pozzo et al., 1990). The most likely explanation for the difference in results is that, in the present study, the light in the laboratory was only dimmed, still allowing the sampling of visual information whereas Pozzo et al. investigated locomotion in “darkness”, without specifying how “darkness” was achieved. However, in line with Pozzo et al., head posture control was found to be unaffected by illumination and other sensory input, such as proprioceptive information originating from neck muscles or vestibular information, may be employed.

7.2.5 Effect of manipulating stair edge contrast on stepping parameters, balance and head posture control

During stair ascent and descent, highlighted stair edges significantly changed the foot clearance pattern, although these changes were only consistent in the YA. They significantly increased the horizontal clearance in both walking directions when stair

edges were highlighted, whereas high stair edge contrast facilitated increased vertical clearance in both OA groups while ascending stairs. It appears that high stair edge contrast acted as visual cue mainly for YA in both walking directions. The finding, that foot clearance in OA is unaffected by highly visible stair edges during stair descent, is consistent with previous studies (Simoneau et al., 1991).

Changes in stair edge contrast exclusively affected foot clearance during stair ascent and mainly posture and balance measures during stair descent in all groups. The finding that balance during stair descent was particularly improved in HROA under good stair edge visibility conditions suggests firstly, that stair edges are points of interest and high stair edge contrast may provide richer optic flow that is primarily used to regulate balance and secondly, that HROA may rely more on visual input to regulate balance than LROA or YA. However, the finding that highlighted stair edges led to increased foot clearances during stair ascent and increased horizontal foot clearance in YA is in contrast to previous walking (Graci et al., 2009) and obstacle crossing (Rietdyk & Rhea, 2006; Rhea & Rietdyk, 2007) studies where a reduction, not an increase, of peripheral optic flow information led to increased foot clearance and step length to avoid tripping. However, fixating a specific point in space at a consistent distance ahead in the direction of travel has been shown to help OA to increase head stabilisation similar to that of YA (Cromwell et al., 2002) which is considered to be important for maintaining balance. The finding from Chapter 2 that particularly OA tended to look a relatively constant number of steps ahead when descending stairs may help to provide constant optic flow information which helps to facilitate balance in OA.

Highlighted stair edges did not affect head posture control in either walking direction. It could be that highlighted stair edges may have a more local effect such as on foot clearance, rather than a generalised effect on whole-body orientation and balance.

7.2.6 Effect of handrail use on balance control in HROA

In the present study, only HROA used the handrail and exploration of the handrail data revealed that handrail use had almost no effect on balance measures in either walking direction. Only vertical COM acceleration was reduced when these individuals descended the stairs. This finding underlines the previously discussed challenge of controlled lowering of the COM, particularly in HROA. Although the effect of light touch is plane-specific (Dickstein & Laufer, 2004), it is surprising that handrail use in the present study had no effect on lateral balance which was previously shown by these authors. That handrail use did not affect lateral balance could well be due to the very small subject number in each group. Therefore, the result should be interpreted with caution and future studies investigating the effect of handrail use in HROA should include more participants. Furthermore, it is not sufficient to investigate the effect of handrail use on a-p and m-l balance as before (Reeves et al., 2008a), but also to analyse the characteristics of vertical COM displacement with handrail use.

7.3 Limitations

The allocation of OA to fall risk groups could be seen as possible limitation of these studies. It is acknowledged that there is no gold standard on how to identify OA with increased risk of falling because of the large number of fall risk factors and possible assessments. Furthermore there is no consensus among researchers- some prefer to allocate OA to fall risk groups based on the number of previous falls within a specified time period and others prefer to allocate OA to fall risk groups based on cut-off points in assessments. Allocating OA to fall risk groups on the basis of a specific cut-off point obviously implies that a reliable cut-off point was identified in earlier studies. Based on previously identified factors contributing to increased risk of falling, the idea was to allocate older participants to fall risk groups based on a valid active balance

assessment (BBS) and their reported fear of falling (MFES) and confidence to negotiate stairs (SSEQ) which appeared to be relevant to and sufficient for the aims of the undertaken studies. Furthermore, it was intended that the fall risk assessment could be completed in a time-efficient manner because of the duration of the following data collection. Another aspect is that, although travel arrangements were made for older participants, these studies relied on OA willing to travel to the laboratory for data collection. But as previously shown, OA with fear of falling (Zijlstra et al., 2007; Deshpande et al., 2008a) and previous falls (Fletcher & Hirdes, 2004) reduce their outdoor activities and it may well be that OA with fear of falling and/ or more severe balance impairments have not volunteered to participate in these studies. However, even OA with very mild active balance impairments were shown to have significant deterioration in muscle strength (Lin & Woollacott, 2005) and the results from the presented studies suggest that stair negotiation behaviour is affected in OA with even mildly affected balance and reduced confidence to negotiate stairs.

Another limitation of these studies may be the lack of muscle strength testing which may have been beneficial for explaining some results such as differences between LROA and HROA in foot clearance. Again, it was intended that the duration of data collection would not be excessive, particularly not for OA. In future studies it might be worth including strength testing for relevant muscle groups to get an idea about how stair negotiation performance in otherwise healthy LROA and HROA is affected by sarcopenia.

The effect of handrail use in HROA should be interpreted with some caution as the group size was very small (four participants using and four participants not using the handrail). Furthermore, there was no objective measurement of how much force participants applied to the handrail. For example, light touch for guidance had no effect on a-p COM acceleration, but one would have expected that a-p COM acceleration during stair ascent would be greater with handrail use if handrail users draw on this

external support to pull themselves up. In addition, m-I COM acceleration variability during stair descent might be reduced with handrail use. Some research has been conducted into measuring applied forces while grasping the handrail after balance perturbation during stair negotiation, but participants included only YA (Maki et al., 1998). Other studies included OA without the need to hold on to the handrail (Reeves et al., 2008a) or without objectively measuring performance changes (Hamel & Cavanagh, 2004).

The simultaneous recording of eye movements and 3D motion data during stair negotiation in YA, LROA and HROA would have been beneficial for integrating and interpreting the results of head posture control in relation to gaze behaviour. Both the portable eye tracker and the Vicon motion capture system track movements with infrared light, resulting in interference of the Vicon system with data acquisition from the eye tracker simply because of the necessary positioning of the equipment in the laboratory: the motion capture cameras had to be angled down from a certain height to capture the position of head markers. The infrared light sent by the cameras would have been reflected on a specific part of the eye tracker, which should only reflect the infrared light coming from the eye tracker. Therefore, other equipment may be used together for eye movement and 3D motion capture recordings.

Furthermore, data from additional overground walking trials would have been given information about head posture control during overground walking which could have been directly compared with the head posture data during stair negotiation in the same participants without using results from other publications for comparison. As pointed out before, the duration of data collection was already quite time-consuming and a second session for data collection was thought to be not feasible due to the already mentioned recruitment circumstances.

7.4 Directions for further research

Based on the findings and limitations of the presented studies, the following section describes directions for further research which may help to extend the knowledge about functional changes in older age and their underlying mechanisms.

Falls on stairs most often occur within the first and last three steps of a flight of stairs (Templer, 1994). Therefore, it would be useful to investigate gaze behaviour during these transition phases, which has been studied very recently, but for YA only (Miyasike-Dasilva et al., 2011). Furthermore, it would be useful to investigate gaze behaviour and balance not only on stairs, but also during the transition onto vertical and horizontal escalators, because of the high incidence of falls in OA using escalators (Steele, O'Neil, Huisinigh & Smith, 2010).

When characterising age-related differences in balance control during stair negotiation, previous studies have used descriptions of the relationship between COM and COP for describing a-p and m-l balance (Reeves et al., 2009; Reeves et al., 2008b; Lee & Chou, 2007). Only one previous study included the characteristics of vertical COM movement (Mian et al., 2007a). Given the finding that only 10% of fallers on stairs fell sideways, but 50% fell forward and 40% fell backward (Svanström, 1974), it is reasonable to assume that controlling the COM movement in the vertical direction is as important as controlling the COM in the sagittal and coronal planes. Therefore, analysis of the vertical COM movement should be included in future studies. OA with less confidence to negotiate stairs are more likely to use a handrail while ascending or descending a flight of stairs (Hamel & Cavanagh, 2004). One limitation of the presented studies was the small number of participants in HROA using the handrail. Therefore, future studies investigating the effect of handrail use on balance control and recovery strategies after tripping should include a larger sample size. Cromwell et al.

(2002) have shown that OA are able to stabilize the head to the same extent as YA when they fixate a target in the direction of travel. It might be worth investigating how stepping behaviour and balance control change in HROA when they are told to fixate the stair edges while ascending or descending a flight of stair, because this intervention would be an efficient strategy to reduce their risk of falling on stairs.

The studies in this thesis have shown that visual information during stair negotiation is used and that manipulation of visual information results in adaptations in stepping behaviour and balance control in YA and OA. In addition, there was some support for the idea that head posture may provide proprioceptive information about body posture in space with respect to the staircase which may help to control stepping actions and balance. However, individuals may not only use central or peripheral vision during stair negotiation to guide foot placement but also proprioceptive information about body posture in space in relation to the staircase. In order to gain more insight in the processes of how the CNS controls balance during stair negotiation, the interaction between visual and proprioceptive information should be studied. Anecdotal experience suggests that obstruction of the visual field leads to realignment of body and head posture to allow an- at least partially- unobstructed view of the stairs. For example, when carrying a large box or a tray down the stairs, individuals tend to move the carried object out of the visual field by rotating the upper trunk or by lifting up the object (if it is not too heavy or too difficult to balance). The question remains how the CNS weights visual and proprioceptive information and if this process is the same for stair ascent and descent. Furthermore, manipulating the proprioceptive information from the neck muscles by vibrating them during stair negotiation would give valuable information about the role of head posture and its effect on body alignment in space when the body is not only moved forward, but also either upward or downward. Furthermore, it would be useful to collect eye and head movement data as well as balance measures

simultaneously to enhance the knowledge about how visual and non-visual information are integrated to control balance during stair negotiation.

One limitation of the studies presented in Chapters 4 and 5 was the lack of muscle strength testing. Given the lack of studies linking muscle strength to stair negotiation performance, further research into this subject is needed as it was previously shown that resistance training improves muscle strength (Ferri et al., 2003; Thompson et al., 2003) which is associated with improved performance during obstacle avoidance (Lamoureux et al., 2003) and increased ankle power generation after tripping (Pijnappels et al., 2008). Even if non-frail OA were shown not to reduce kinematic differences between OA and YA after 12 months exercise training (Mian et al., 2007b), it might be worth including HROA in future intervention studies because these individuals are in need of reducing their fall risk. In addition, more task-specific exercises such as eccentric muscle work for the lower limb muscles to improve balance and to increase foot clearance during stair descent should be included in future intervention studies. Furthermore, this thesis has added evidence to the knowledge that OA have difficulties to control lateral stepping movements and balance during stair negotiation. Therefore, muscle groups controlling these movements should be included in strength assessments and training, e.g. hip abductor muscles and ankle pronator muscles.

7.5 Conclusion

The undertaken studies provided evidence that YA and OA direct their gaze towards stair edges when ascending and descending the middle part of a staircase. Furthermore, OA fixated the stairs longer before stepping onto them and tended to fixate stairs with less variability than YA. OA with relatively mild active balance impairments and reduced stair walking confidence displayed specific changes in

stepping behaviour and COM control during stair negotiation compared to OA with unaffected balance and good stair walking confidence. Sufficient illumination and highlighted stair edges were shown to improve balance and posture in YA and OA. Good visible stair edges acted as visual cue to increase foot clearance in order to avoid contact with the stair edge which is known to be one trigger for trips and falls on stairs. However in OA, balance was challenged during stair negotiation, particularly during stair descent, and handrail use helped HROA to lower their COM down in a controlled manner. Although LROA ascended and descended stairs with less variable head posture control than YA, head posture was less stable in OA during stair negotiation compared to overground walking. During stair descent, YA and LROA roughly aligned the head with the staircase angle which suggests that proprioceptive information about stepping location in relation to the head are also used for safe stair negotiation. However, HROA appeared to rely more on visual information as they angled the head further down than YA and LROA while descending stairs. The findings from this thesis suggest that there are differences in stepping behaviour and balance control between OA with either lower or higher risk of falling. Therefore, it would be wise to include YA as well as OA with different balance abilities, perceived fear of falling or less confidence to negotiate stairs in future studies to expand the knowledge about changes in body function and performance in older age and when balance is compromised.

GLOSSARY

COM-The Centre of Mass of an object is the one point in space where the object's mass is concentrated and balanced. The COM of the human body is roughly located below the navel and in front of the 4th lumbar vertebra.

COP- The Centre of Pressure is the location of the vertical ground reaction force vector on the floor. COP data are usually collected with a force plate.

COM-COP separation- distance between the COP curve and the vertically to the floor projected COM curve. This measure is used to describe dynamic balance: a small COM-COP separation indicates better balance and a larger COM-COP separation indicates that balance is challenged or even impaired.

Coronal plane- divides the body into an anterior and posterior part. Movements in this plane are medio-lateral movements such as hip abduction.

Foot clearance- describes the distance between toe and stair edge (stair ascent) or heel and stair edge (stair descent) during the swing phase.

Gait cycle- refers from initial contact of one leg (0%) to initial contact of the same leg on the next stair (100%) For the purpose of this thesis, gait cycle events are used accordingly to the convention for overground walking.

Kinematics- describes the displacement of the body or body parts such as the angular displacement of joints, movement velocity and acceleration, but without taking moments or forces into account which cause the displacement.

Kinetics- includes the moments and forces that act on the body or body parts resulting in spatial displacement of the body or body parts.

Leading leg- refers to the leg which is located in front of the contralateral leg. With respect to gait cycle events this includes the phase between mid swing of one leg to mid stance of the same leg when the contralateral leg goes past and becomes the leading leg.

OA- includes adults aged 65 and over without specification of potential fall risk.

Sagittal plane- divides the body into left and right. Movements in this plane are movements in the direction of progression such as hip flexion.

Trailing leg- refers to the leg which is located behind the contralateral leg. With respect to gait cycle events this includes the phase between mid stance of one leg to mid swing of the same leg. When the trailing leg swings past the contralateral leg it becomes the leading leg.

Transverse plane- divides the body into an upper and lower part. Movements in this plane are rotations such as external rotation of the hip.

APPENDIX A

School-internal General Health Questionnaire

The University of Birmingham
School of Sport and Exercise Sciences
General Health Questionnaire

Name:
Address:
.....
.....
Phone:

Name of the responsible investigator for the study:

Doerte Zietz

Please answer the following questions. If you have any doubts or difficulty with the questions, please ask the investigator for guidance. These questions are to determine whether the proposed exercise is appropriate for you. Your answers will be kept strictly confidential.

1.	You are.....	Male	Female
2.	What is your exact date of birth? Day..... Month.....Year..19..... So your age is..... Years		
3.	When did you last see your doctor? In the: Last week..... Last month..... Last six months..... Year..... More than a year.....		
4.	Are you currently taking any medication?	YES	NO
5.	Has your doctor ever advised you not to take vigorous exercise?	YES	NO
6.	Has your doctor ever said you have "heart trouble"?	YES	NO
7.	Has your doctor ever said you have high blood pressure?	YES	NO
8.	Have you ever taken medication for blood pressure or your heart?	YES	NO

9.	Do you feel pain in your chest when you undertake physical activity?	YES	NO
10.	In the last month have you had pains in your chest when not doing any physical activity?	YES	NO
11.	Has your doctor (or anyone else) said that you have a raised blood cholesterol?	YES	NO
12.	Have you had a cold or feverish illness in the last month?	YES	NO
13.	Do you ever lose balance because of dizziness, or do you ever lose consciousness?	YES	NO
14.	a) Do you suffer from back pain b) if so, does it ever prevent you from exercising?	YES YES	NO NO
15.	Do you suffer from asthma?	YES	NO
16.	Do you have any joint or bone problems which may be made worse by exercise?	YES	NO
17.	Has your doctor ever said you have diabetes?	YES	NO
18.	Do you feel exhausted after walking the stairs in your home?	YES	NO
19.	a) Did you fall recently b) if so, how often within the last year?	YES	NO
20.	a) Did you have joint(s) replaced b) If so, which joint(s)	YES	NO
21.	Do you know of any reason, not mentioned above, why you should not exercise?	YES	NO
21.	Are you accustomed to vigorous exercise (an hour or so a week)?	YES	NO

I have completed the questionnaire to the best of my knowledge and any questions I had have been answered to my full satisfaction.

Signed:

Date:

Health Questionnaire:

Notes for the investigator

This questionnaire is for use in circumstances where you are intending to carry out a procedure which has been approved by the Ethics Subcommittee (Section 2 of the *Health and Safety Issues* document) but where a health screen is indicated. Questions 3 and 4 should be used to test, discretely, the veracity of the other answers.

If your subject is within the age group specified (usually 18 to 30 years) and has answered NO to questions 5-20 and YES to question 21, you may include him or her in your study.

If you are using this, or a similar, questionnaire for subjects outside this age range or with possible pathologies, you must have agreed with the Ethics Subcommittee the criteria for accepting subjects into the study and safeguarding their health.

APPENDIX B

Berg Balance Scale

Participant number:

Date:

Item No.	Item description		Score
1	Sitting to standing <i>Please stand up. Try not to use your hands for support.</i>	4 able to stand without using hands and stabilize independently 3 able to stand independently using hands 2 able to stand using hands after several tries 1 needs minimal aid to stand or to stabilize 0 needs moderate or maximal assist to stand	
2	Standing unsupported <i>Please stand for two minutes without holding.</i>	4 able to stand safely 2 minutes 3 able to stand 2 minutes with supervision 2 able to stand 30 seconds unsupported 1 needs several tries to stand 30 seconds unsupported 0 unable to stand 30 seconds unassisted	
3	Sitting unsupported <i>Please sit with arms folded for 2 minutes.</i>	4 able to sit safely and securely 2 minutes 3 able to sit 2 minutes under supervision 2 able to sit 30 seconds 1 able to sit 10 seconds 0 unable to sit without support 10 seconds	
4	Standing to sitting <i>Please sit down.</i>	4 sits safely with minimal use of hands 3 controls descent by using hands 2 uses back of legs against chair to control descent 1 sits independently but has uncontrolled descent 0 needs assistance to sit	
5	Transfers	4 able to transfer safely with minor use of hands 3 able to transfer safely definite need of hands 2 able to transfer with verbal cueing and/or supervision 1 needs one person to assist 0 needs two people to assist or supervise to be safe	
6	Standing with eyes closed <i>Please close your eyes and stand still for 10 seconds.</i>	4 able to stand 10 seconds safely 3 able to stand 10 seconds with supervision 2 able to stand 3 seconds 1 unable to keep eyes closed 3 seconds but stays steady 0 needs help to keep from falling	
7	Standing with feet together <i>Place your feet together and stand without holding.</i>	4 able to place feet together independently and stand 1 minute safely 3 able to place feet together independently and stand for 1 minute with supervision 2 able to place feet together independently but unable to hold for 30 seconds 1 needs help to attain position but able to stand 15 seconds feet together 0 needs help to attain position and unable to hold for 15 seconds	

8	Reaching forward with outstretched arm <i>Lift arm to 90 degrees. Stretch out your fingers and reach forward as far as you can.</i>	4 can reach forward confidently >25 cm 3 can reach forward >12 cm safely 2 can reach forward >5 cm safely 1 reaches forward but needs supervision 0 loses balance while trying/requires external support	
9	Retrieving object from floor <i>Pick up the shoe/slipper which is placed in front of your feet.</i>	4 able to pick up slipper safely and easily 3 able to pick up slipper but needs supervision 2 unable to pick up but reaches 2-5cm from slipper and keeps balance independently 1 unable to pick up and needs supervision while trying 0 unable to try/needs assist to keep from losing balance or falling	
10	Turning to look behind <i>Turn to look directly behind you over toward left shoulder. Repeat to the right.</i>	4 looks behind from both sides and weight shifts well 3 looks behind one side only other side shows less weight shift 2 turns sideways only but maintains balance 1 needs supervision when turning 0 needs assist to keep from losing balance or falling	
11	Turning 360° <i>Turn completely around in a full circle. Pause. Then turn a full circle in the other direction.</i>	4 able to turn 360 degrees safely in 4 seconds or less 3 able to turn 360 degrees safely one side only in 4 seconds or less 2 able to turn 360 degrees safely but slowly 1 needs close supervision or verbal cueing 0 needs assistance while turning	
12	Placing alternate foot on stool <i>Place each foot alternately on the step/stool. Continue until each foot has touched the step/stool four times.</i>	4 able to stand independently and safely and complete 8 steps in 20 seconds 3 able to stand independently and complete 8 steps >20 seconds 2 able to complete 4 steps without aid with supervision 1 able to complete >2 steps needs minimal assist 0 needs assistance to keep from falling/unable to try	
13	Standing with one foot in front <i>Place one foot directly in front of the other. If you feel that you cannot place your foot directly in front, try to step far enough ahead that the heel of your forward foot is ahead of the toes of the other foot.</i>	4 able to place foot tandem independently and hold 30 seconds 3 able to place foot ahead of other independently and hold 30 seconds 2 able to take small step independently and hold 30 seconds 1 needs help to step but can hold 15 seconds 0 loses balance while stepping or standing	
14	Standing on one foot <i>Stand on one leg as long as you can without holding.</i>	4 able to lift leg independently and hold >10 seconds 3 able to lift leg independently and hold 5-10 seconds 2 able to lift leg independently and hold = or >3 seconds 1 tries to lift leg unable to hold 3 seconds but remains standing independently 0 unable to try or needs assist to prevent fall	
	Total		/ 56

APPENDIX C

Modified Falls Efficacy Questionnaire

Participant number:

Date:

How confident/ sure are you that you do each of the activities without falling?

	Not confident at all	Fairly confident	Completely confident
1. Get dressed and undressed	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2. Prepare a simple meal	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3. Take a bath or a shower	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4. Get in/ out of a chair	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5. Get in/ out of bed	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6. Answer the door or telephone	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7. Walk around the inside of your house	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
8. Reach into cabinets or closet	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9. Light housekeeping	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10. Simple shopping	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
11. Using public transport	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
12. Crossing roads	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
13. Light gardening or hanging out the washing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
14. Using front or rear steps at home	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

APPENDIX D

Stair Self-Efficacy Questionnaire

Participant number:

Date:

1. How confident are you that you can negotiate the stairs in your home without losing your balance?

Going down the stairs

No Confidence

0 1 2 3 4 5 6 7 8 9 10

Complete Confidence

Going up the stairs

No Confidence

0 1 2 3 4 5 6 7 8 9 10

Complete Confidence

2. How confident are you that you can negotiate a flight of stairs rapidly, without losing your balance?

Going down the stairs

No Confidence

0 1 2 3 4 5 6 7 8 9 10

Complete Confidence

Going up the stairs

No Confidence

0 1 2 3 4 5 6 7 8 9 10

Complete Confidence

3. How confident are you that you can negotiate the stairs not using the handrail without losing your balance?

Going down the stairs

No Confidence

0 1 2 3 4 5 6 7 8 9 10

Complete Confidence

Going up the stairs

No Confidence

0 1 2 3 4 5 6 7 8 9 10

Complete Confidence

4. How confident are you that you can negotiate stairs that are poorly lit without losing your balance?

Going down the stairs

No Confidence

0 1 2 3 4 5 6 7 8 9 10

Complete Confidence

Going up the stairs

No Confidence

0 1 2 3 4 5 6 7 8 9 10

Complete Confidence

5. How confident are you that you can negotiate stairs in a crowd of people without losing your balance?

Going down the stairs

No Confidence Complete Confidence
0 1 2 3 4 5 6 7 8 9 10

Going up the stairs

No Confidence Complete Confidence
0 1 2 3 4 5 6 7 8 9 10

6. How confident are you that you can negotiate stairs that are not in your home without losing your balance?

Going down the stairs

No Confidence Complete Confidence
0 1 2 3 4 5 6 7 8 9 10

Going up the stairs

No Confidence Complete Confidence
0 1 2 3 4 5 6 7 8 9 10

7. How confident are you that you can negotiate outdoor stairs or steps without losing your balance?

Going down the stairs

No Confidence Complete Confidence
0 1 2 3 4 5 6 7 8 9 10

Going up the stairs

No Confidence Complete Confidence
0 1 2 3 4 5 6 7 8 9 10

8. How confident are you that you can recover from a loss of balance on stairs to prevent yourself from falling?

Going down the stairs

No Confidence Complete Confidence
0 1 2 3 4 5 6 7 8 9 10

Going up the stairs

No Confidence Complete Confidence
0 1 2 3 4 5 6 7 8 9 10

BIBLIOGRAPHY

Alexander N, Ashton-Miller J, Giordani B, Guire K & Schultz A (2005). Age differences in timed accurate stepping with increasing cognitive and visual demand: a walking trail making test. *Journal of Gerontology: Medical Sciences*, 60A, 1558-1562.

Andriacchi T, Andersson G, Fermier R, Stern D & Galante J (1980). A study of lower-limb mechanics during stair-climbing. *J.Bone Joint Surg.Am.*, 62, 749-757.

Angelaki D & Hess B (2005). Self-motion-induced eye movements: effects on visual acuity and navigation. *Nat.Rev.Neurosci.*, 6, 966-976.

Bahill T, Brockenbrough A, Troost B (1981). Variability and development of a normative data base for saccadic eye movements. *Investigative Ophthalmology & Visual Science* 21 (1), 116- 125.

Baltes P, Staudinger U & Lindenberger U (1999). Lifespan Psychology: Theory and application to intellectual functioning. *Annual Reviews in Psychology*, 50, 471-507.

Barlow H (1952). Eye movements during fixation. *Journal of Physiology* 116 (3), 290-306.

Bauby C & Kuo A (2000). Active control of lateral balance in human walking. *J.Biomech.*, 33, 1433-1440.

Berard J, Fung J, McFadyen B & Lamontagne A (2009). Aging affects the ability to use optic flow in the control of heading during locomotion. *Exp Brain Res.*, 194, 183-190.

Berg K, Wood-Dauphinee S, Williams J & Gayton D (1989). Measuring balance in the elderly: preliminary development of an instrument. *Physiotherapy Canada*, 41, 304-311.

Bohannon R (1997). Comfortable and maximum walking speed of adults aged 20-79 years: reference values and determinants. *Age Ageing*, 26, 15-19.

Bove M, Courtine G & Schieppati M (2002). Neck muscle vibration and spatial orientation during stepping in place in humans. *J.Neurophysiol.*, 88, 2232-2241.

Bove M, Diverio M, Pozzo T & Schieppati M (2001). Neck muscle vibration disrupts steering of locomotion. *J.Appl.Physiol*, 91, 581-588.

Brenton R, Phelps C, Rpijas P, Woolson R (1986). Interocular differences of the visual field in normal subjects. *Invest Ophthalmol Vis Sci*, 27, 799-805.

Brown M, Marmor M, Vaegan, Zrenner E, Brignell M, Bach M (2006). ISCEV Standard for clinical electro-oculography (EOG) 2006. *Doc Ophthalmol*, 113, 205-212.

Buckley J, MacLellan M, Tucker M, Scally A & Bennett S (2007). Visual guidance of landing behaviour when stepping down to a new level. *Exp. Brain Res.*, DOI 10.1007/s00221-007-1096-8.

Buckley J, Heasley K, Scally A & Elliott D (2005a). The effects of blurring vision on medio-lateral balance during stepping up or down to a new level in the elderly. *Gait & Posture*, 22, 146-153.

Buckley J, Heasley K, Twigg P & Elliott D (2005b). The effects of blurred vision on the mechanics of landing during stepping down by the elderly. *Gait & Posture*, 21, 65-71.

Bullock-Saxton J, Wong W & Hogan N (2001). The influence of age on weight-bearing joint reposition sense of the knee. *Exp. Brain Res.*, 136, 400-406.

Burke D, Hagbarth K, Lofstedt L & Wallin B (1976). The responses of human muscle spindle endings to vibration of non-contracting muscles. *J.Physiol*, 261, 673-693.

Butterworth S (1930). On the theory of filter amplifiers. *Experimental Wireless & The wireless engineer*, 10, 536-541.

Campbell A, Reinken J, Allan B & Martinez G (1981). Falls in old age: a study of frequency and related clinical factors. *Age and Ageing*, 10, 264-270.

Carville S, Perry M, Rutherford O, Smith I & Newham D (2007). Steadiness of quadriceps contractions in young and older adults with and without a history of falling. *Eur.J.Appl.Physiol*, 100, 527-533.

Chapman G & Hollands M (2006). Evidence for a link between changes to gaze behaviour and risk of falling in older adults during adaptive locomotion. *Gait & Posture*, 24, 288-294.

Chapman G & Hollands M (2007). Evidence that older adult fallers prioritise the planning of future stepping actions over the accurate execution of ongoing steps during complex locomotor tasks. *Gait & Posture*, 26, 59-67.

Chapman G & Hollands M (2010). Age-related differences in visual sampling requirements during adaptive locomotion. *Exp Brain Res.*, 201, 467-478.

Chen H, Ashton-Miller J, Alexander N & Schultz A (1991). Stepping over obstacles: gait patterns of healthy young and old adults. *J.Gerontol.*, 46, M196-M203.

Chou Y, Wagenaar R, Saltzman E, Giphart J, Young D, Davidsdottir R & Cronin-Golomb A. (2009). Effects of optic flow speed and lateral flow asymmetry on locomotion in younger and older adults: a virtual reality study. *J.Gerontol.B Psychol.Sci.Soc.Sci.*, 64, 222-231.

Coile C, Baker H (1992). Foveal dark adaptation, photopigment regeneration, and aging. *Visual Neuroscience*, 8, 27-39.

Courtine G, De Nunzio A, Schmid M, Beretta M & Schieppati M (2006). Stance- and Locomotion-Dependent Processing of Vibration-Induced Proprioceptive Inflow From Multiple Muscles in Humans. *Journal of Neurophysiology*, 97, 772-779.

Courtine G, Papaxanthis C, Laroche D & Pozzo T (2003). Gait-dependent integration of neck muscle afferent input. *Neuroreport*, 14, 2365-2368.

Craik R, Cozzens B & Freedman W (1982). The role of sensory conflict on stair descent performance in humans. *Exp. Brain Res.*, 45, 399-409.

Crane B & Demer, J (1997). Human gaze stabilization during natural activities: translation, rotation, magnification, and target distance effects. *J.Neurophysiol.*, 78, 2129-2144.

Cromwell R, Newton R & Forrest G (2002). Influence of vision on head stabilization strategies in older adults during walking. *Journal of Gerontology: Medical Sciences*, 57A, M442-M448.

Cromwell R & Wellmon R (2001). Sagittal plane head stabilization during level walking and ambulation on stairs. *Physiother.Res.Int.*, 6, 179-192.

Cromwell R, Newton R & Forrest G (2001). Head stability in older adults during walking with and without visual input. *J Vestib.Res.*, 11, 105-114.

Cubbridge R (2005). *Eye Essentials: Visual fields*. Elsevier: Butterworth-Heinemann.

Cumming R, Ivers R, Clemson L, Cullen J, Hayes M, Tanzer M, Mitchell P (2007). Improving vision to prevent falls in frail older people: a randomized trial. *J A Geriatr Soc*, 55, 175-181.

Curcio C, Sloan K, Kalina R, Hendrickson A (1990). Human photoreceptor topography. *J Comp Neurol*, 292, 497-523.

Dean J, Alexander N & Kuo A (2007). The effect of lateral stabilization on walking in young and old adults. *IEEE Trans.Biomed.Eng*, 54, 1919-1926.

Delreux V, Abeele S, Lefevre P & Roucoux A (1991). Eye-head coordination: influence of eye position on the control of head movement amplitude. In Paillard J (Ed.), *Brain and space* (pp. 38-48). Oxford: Oxford University Press.

Demer J & Amjadi F (1993). Dynamic visual acuity of normal subjects during vertical optotype and head motion. *Invest Ophthalmol.Vis.Sci.*, 34, 1894-1906.

den Otter R & Mouton L (2009). Where and how far ahead do we look when we ascend or descent a staircase? Poster presentation at the conference of the *International Society for Posture and Gait Research*, Bologna.

Department for Communities and Local Government (2006). Building Regulations 2000. Approved Document K (Protection from falling, collision and impact) . http://www.planningportal.gov.uk/uploads/br/BR_PDF_ADK_1998.pdf (accessed 24.04.2009) [On-line].

Department for Communities and Local Government (2006). Building Regulations 2000, Approved Document M (Access to and use of buildings).

http://www.planningportal.gov.uk/uploads/br/BR_PDF_ADM_2004.pdf (accessed 24.04.2009) [On-line].

Deshpande N, Metter E, Bandinelli S, Lauretani F, Windham B & Ferrucci L (2008a). Psychological, physical, and sensory correlates of fear of falling and consequent activity restriction in the elderly: the InCHIANTI study. *Am.J.Phys.Med.Rehabil.*, 87, 354-362.

Deshpande N, Metter E, Lauretani F, Bandinelli S, Guralnik J & Ferrucci L (2008b). Activity restriction induced by fear of falling and objective and subjective measures of physical function: a prospective cohort study. *J.Am.Geriatr.Soc.*, 56, 615-620.

Deshpande N & Patla A (2007). Visual-vestibular interaction during goal directed locomotion: effects of aging and blurring vision. *Exp Brain Res.*, 176, 43-53.

DeVita P & Hortobagyi T (2000a). Age causes a redistribution of joint torques and powers during gait. *J.Appl.Physiol*, 88, 1804-1811.

DeVita P & Hortobagyi T (2000b). Age increases the skeletal versus muscular component of lower extremity stiffness during stepping down. *J.Gerontol.A Biol.Sci.Med.Sci.*, 55, B593-B600.

Di Fabio R, Zampieri C & Greany J (2003). Aging and saccade-stepping interactions in humans. *Neuroscience Letters*, 339, 179-182.

Dickstein R & Laufer Y (2004). Light touch and center of mass stability during treadmill locomotion. *Gait & Posture*, 20, 41-47.

Dieterle P, Gordon E (1956). Standard curve and physiological limits of dark adaptation by means of the Goldmann-Weekers adaptometer. *Brit J Ophthal*, 40, 652-655.

Ditchburn R, Ginsborg B (1953). Involuntary eye movements during fixation. *Journal of Physiology* 119 (1), 1-17.

Evans W (1995). What is sarcopenia? *J.Gerontol.A Biol.Sci.Med.Sci.*, 50 Spec No, 5-8.

Ferri A, Scaglioni G, Pousson M, Capodaglio P, Van Hoecke J & Narici M (2003). Strength and power changes of the human plantar flexors and knee extensors in response to resistance training in old age. *Acta Physiol Scand.*, 177, 69-78.

Fletcher P & Hirdes J (2004). Restriction in activity associated with fear of falling among community-based seniors using home care services. *Age Ageing*, 33, 273-279.

Frontera W, Hughes V, Fielding R, Fiatarone M, Evans W & Roubenoff R (2000). Aging of skeletal muscle: a 12-yr longitudinal study. *J.Appl.Physiol*, 88, 1321-1326.

Geruschat D, Hassan S, Turano K (2003). Gaze behaviour while crossing complex intersections. *Optom Vis Sci.* 80, 515-528.

Gittings N & Fozard J (1986). Age related changes in visual acuity. *Exp.Gerontol.*, 21, 423-433.

Grabiner P Biswas S & Grabiner, M. D. (2001). Age-related changes in spatial and temporal gait variables. *Arch.Phys.Med.Rehabil.*, 82, 31-35.

Graci V, Elliott D & Buckley J (2009). Peripheral visual cues affect minimum-foot-clearance during overground locomotion. *Gait & Posture*., 30, 370-374.

Grasso R, Prevost P, Ivanenko Y & Berthoz A (1998). Eye-head coordination for the steering of locomotion in humans: an anticipatory synergy. *Neurosci.Lett.*, 253, 115-118.

Grossman G, Leigh R, Bruce E, Huebner W & Lanska D (1989). Performance of the human vestibuloocular reflex during locomotion. *J.Neurophysiol.*, 62, 264-272.

Gunatilaka A, Clapperton A & Cassell E (2004). Preventing home fall injuries: structural and design issues and solutions. *Hazard*, 59, 1-24.

Haegerstrom-Portnoy G, Brabyn J, Schneck M, Jampolsky A (1997). The SKILL card, An Acuity test of reduced luminance and contrast. *Investigative Ophthalmology & Visual Science*, 38, 207-218.

Hahn M & Chou L (2004). Age-related reduction in sagittal plane center of mass motion during obstacle crossing. *J.Biomech.*, 37, 837-844.

Hamel K & Cavanagh P (2004). Stair Performance in People Aged 75 and Older. *Journal of the American Geriatric Society*, 52, 563-567.

Hamel K, Okita N, Higginson J & Cavanagh P (2005). Foot clearance during stair descent: effects of age and illumination. *Gait & Posture*, 21, 135-140.

Hamel K, Okita N, Bus S & Cavanagh P (2005). A comparison of foot/ground interaction during stair negotiation and level walking in young and older women. *Ergonomics*, 48, 1047-1056.

- Harley C, Wilkie R & Wann J (2009). Stepping over obstacles: attention demands and aging. *Gait & Posture*., 29, 428-432.
- Heasley K, Buckley J, Scally A, Twigg P & Elliott D (2004). Stepping up to a new level: effects of blurring vision in the elderly. *Invest Ophthalmol.Vis.Sci.*, 45, 2122-2128.
- Heasley K, Buckley J, Scally A, Twigg P & Elliott D (2005). Falls in older people: effects of age and blurring vision on the dynamics of stepping. *Invest Ophthalmol.Vis.Sci.*, 46, 3584-3588.
- Helbostad J, Vereijken B, Hesseberg K & Sletvold O. (2009). Altered vision destabilizes gait in older persons. *Gait & Posture*, 30, 233-238.
- Herman T, Inbar-Borovsky N, Brozgol M, Giladi N & Hausdorff J (2009). The Dynamic Gait Index in healthy older adults: the role of stair climbing, fear of falling and gender. *Gait & Posture*., 29, 237-241.
- Hill K, Schwarz J, Kalogeropoulos A & Gibson S (1996). Fear of falling revisited. *Archives of physical medicine and rehabilitation*, 77, 1025-1029.
- Hill K, Schwarz J, Flicker L & Carroll S (1999). Falls among healthy, community-dwelling, older women: a prospective study of frequency, circumstances, consequences and prediction accuracy. *Aust.N.Z.J.Public Health*, 23, 41-48.
- Hirasaki E, Kubo T, Nozawa S, Matano S & Matsunaga T (1993). Analysis of head and body movements of elderly people during locomotion. *Acta Otolaryngol.Suppl*, 501, 25-30.

Hollands M, Sorensen K & Patla A (2001). Effects of head immobilization on the coordination and control of head and body reorientation and translation during steering. *Exp. Brain Res.*, *V140*, 223-233.

Hollands M, Ziafra N & Bronstein A (2004). A new paradigm to investigate the roles of head and eye movements in the coordination of whole-body movements. *Exp Brain Res.*, *154*, 261-266.

Hortobagyi T & DeVita P (2000). Muscle pre- and coactivity during downward stepping are associated with leg stiffness in aging. *J.Electromyogr.Kinesiol.*, *10*, 117-126.

Hurley M, Rees J & Newham D (1998). Quadriceps function, proprioceptive acuity and functional performance in healthy young, middle-aged and elderly subjects. *Age Ageing*, *27*, 55-62.

Ivanenko Y, Grasso R & Lacquaniti F (1999). Effect of gaze on postural responses to neck proprioceptive and vestibular stimulation in humans. *J.Physiol*, *519 Pt 1*, 301-314.

Ivanenko Y, Grasso R & Lacquaniti F (2000). Neck muscle vibration makes walking humans accelerate in the direction of gaze. *J.Physiol*, *525 Pt 3*, 803-814.

Jackson G, Owsley C (2000). Scotopic sensitivity during adulthood. *Vision Research*, *40*, 2467-2473.

Johnson L, Buckley J, Scally A & Elliott D (2007). Multifocal spectacles increase variability in toe clearance and risk of tripping in the elderly. *Investigative Ophthalmology Visual Science*, *48*, 1466-1471.

Kandel E, Schwartz J & Jessell T (2000). *Principles of neural science*. (4th ed.) London: McGraw-Hill.

Kang H & Dingwell J (2008). Separating the effects of age and walking speed on gait variability. *Gait & Posture*., 27, 572-577.

Karamanidis K & Arampatzis A (2009). Evidence of mechanical load redistribution at the knee joint in the elderly when ascending stairs and ramps. *Ann.Biomed.Eng*, 37, 467-476.

Kavanagh J, Barrett R & Morrison S (2004). Upper body accelerations during walking in healthy young and elderly men. *Gait & Posture*, 20, 291-298.

Kavanagh J, Barrett R & Morrison S (2005). Age-related differences in head and trunk coordination during walking. *Hum.Mov Sci.*, 24, 574-587.

Kesler A, Leibovich G, Herman T, Gruendlinger L, Giladi N & Hausdorff J (2005). Shedding light on walking in the dark: the effects of reduced lighting on the gait of older adults with a higher-level gait disorder and controls. *J.Neuroeng.Rehabil.*, 2, 27.

Konczak J, Meeuwsen H & Cress M (1992). Changing affordances in stair climbing: the perception of maximum climbability in young and older adults. *J Exp.Psychol.Hum.Percept.Perform.*, 18, 691-697.

Krebs D, Wong D, Jevsevar D, Riley P & Hodge W (1992). Trunk kinematics during locomotor activities. *Phys.Ther.*, 72, 505-514.

Kuang T, Tsai S, Hsu W, Cheng C, Liu J & Chou P (2008). Visual impairment and falls in the elderly: the Shihpai Eye Study. *J.Chin Med.Assoc.*, 71, 467-472.

Kubo K, Ishida Y, Komuro T, Tsunoda N, Kanehisa H & Fukunaga T (2007). Age-related differences in the force generation capabilities and tendon extensibilities of knee extensors and plantar flexors in men. *J.Gerontol.A Biol.Sci.Med.Sci.*, 62, 1252-1258.

Lachman M, Howland J, Tennstedt S, Jette A, Assmann S & Peterson E (1998). Fear of falling and activity restriction: the survey of activities and fear of falling in the elderly (SAFE). *J.Gerontol.B Psychol.Sci.Soc.Sci.*, 53, 43-50.

Lamoureux E, Sparrow W, Murphy A & Newton R (2003). The effects of improved strength on obstacle negotiation in community-living older adults. *Gait & Posture*, 17, 273-283.

Larsen A, Puggaard L, Haemaelaenen U & Aagaard P (2008). Comparison of ground reaction forces and antagonist muscle coactivation during stair walking with ageing. *Journal of Electromyography and Kinesiology*, 18, 568-580.

Lauretani F, Bandinelli S, Bartali B, Di Iorio A, Giacomini V, Corsi A, Guralnik J, Ferrucci L (2006). Axonal degeneration affects muscle density in older men and women. *Neurobiol.Aging*, 27, 1145-1154.

Lee H & Chou L (2007). Balance control during stair negotiation in older adults. *Journal of Biomechanics*, 40, 2530-2536.

Lexell J, Henriksson-Larsen K, Winblad B & Sjostrom M (1983). Distribution of different fiber types in human skeletal muscles: effects of aging studied in whole muscle cross sections. *Muscle Nerve*, 6, 588-595.

Lexell J, Taylor C & Sjoström M (1988). What is the cause of the ageing atrophy? Total number, size and proportion of different fiber types studied in whole vastus lateralis muscle from 15- to 83-year-old men. *J.Neurol.Sci.*, 84, 275-294.

Li L, Haddad J & Hamill J (2005). Stability and variability may respond differently to changes in walking speed. *Hum.Mov Sci.*, 24, 257-267.

Lin S & Woollacott M (2005). Association between sensorimotor function and functional and reactive balance control in the elderly. *Age Ageing*, 34, 358-363.

Livingston L, Stevenson J & Olney S (1991). Stairclimbing kinematics on stairs of differing dimensions. *Arch.Phys.Med.Rehabil.*, 72, 398-402.

Lord S, Dayhew J & Howland A (2002). Multifocal Glasses Impair Edge-Contrast Sensitivity and Depth Perception and Increase the Risk of Falls in Older People. *Journal of the American Geriatrics Society*, 50, 1760-1766.

Lord S, Lloyd D & Li S (1996). Sensori-motor function, gait patterns and falls in community-dwelling women. *Age Ageing*, 25, 292-299.

Lowrey C, Reed R & Vallis L (2007). Control strategies used by older adults during multiple obstacle avoidance. *Gait & Posture.*, 25, 502-508.

Lowrey C, Watson A & Vallis L (2007). Age-related changes in avoidance strategies when negotiating single and multiple obstacles. *Exp Brain Res.*, 182, 289-299.

Lu T, Chen H & Chen S (2006). Comparisons of the lower limb kinematics between young and older adults when crossing obstacles of different heights. *Gait & Posture*, 23, 471-479.

Lythgo N, Begg R & Best R (2007). Stepping responses made by elderly and young female adults to approach and accommodate known surface height changes. *Gait & Posture*, 26, 82-89.

Maentyaervi M & Laitinen T (2001). normal values for the Pelli-Robson contrast sensitivity test. *Journal of cataract and refractive surgery*, 27, 261-266.

Maki B, Perry S & McIlroy W (1998). Efficacy of handrails in preventing stairway falls: a new experimental approach. *Safety Science*, 28, 189-206.

Maki B (1997). Gait changes in older adults: predictors of falls or indicators of fear. *J.Am.Geriatr.Soc.*, 45, 313-320.

Maki B, Cheng K, Mansfield A, Scovil C, Perry S, Peters A et al. (2008). Preventing falls in older adults: new interventions to promote more effective change-in-support balance reactions. *J.Electromyogr.Kinesiol.*, 18, 243-254.

Maki B, Edmondstone M & McIlroy W (2000). Age-related differences in laterally directed compensatory stepping behavior. *J.Gerontol.A Biol.Sci.Med.Sci.*, 55, M270-M277.

Marigold D & Patla A (2008a). Age-related changes in gait for multi-surface terrain. *Gait & Posture*, 27, 689-696.

Marigold D & Patla A (2008b). Visual information from the lower visual field is important for walking across multi-surface terrain. *Exp Brain Res.*, 188, 23-31.

Marigold D, Weerdesteyn V, Patla A & Duysens J (2007). Keep looking ahead? Re-direction of visual fixation does not always occur during an unpredictable obstacle avoidance task. *Exp Brain Res.*, 176, 32-42.

Masciocchi C, Mihalas S, Parkhurst D & Niebur E (2009). Everyone knows what is interesting: salient locations which should be fixated. *J. Vis.*, 9, 25-22.

Mazza C, Iosa M, Pecoraro F & Cappozzo A (2008). Control of the upper body accelerations in young and elderly women during level walking. *J. Neuroeng. Rehabil.*, 5, 30.

McFadyen B & Winter D (1988). An integrated biomechanical analysis of normal stair ascent and descent. *Journal of Biomechanics*, 21, 733-744.

McFadyen B & Prince F (2002). Avoidance and accommodation of surface height changes by healthy, community-dwelling, young, and elderly men. *J. Gerontol. A Biol. Sci. Med. Sci.*, 57, B166-B174.

McGibbon C & Krebs D (2001). Age-related changes in lower trunk coordination and energy transfer during gait. *J. Neurophysiol.*, 85, 1923-1931.

McMurdo M & Gaskell A (1991). Dark adaptation and falls in the elderly. *Gerontology*, 37, 221-224.

Meeuwssen H, Sawicki T & Stelmach G (1993). Improved foot position sense as a result of repetitions in older adults. *J. Gerontol.*, 48, 137-141.

Menant J, Steele J, Menz H, Munro B & Lord S (2008). Effects of footwear features on balance and stepping in older people. *Gerontology*, 54, 18-23.

Menz H, Lord S & Fitzpatrick R (2003a). Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. *Gait & Posture*, 18, 35-46.

Menz H, Lord S & Fitzpatrick R (2003b). Age-related differences in walking stability. *Age Ageing*, 32, 137-142.

Menz H, Lord S & Fitzpatrick R (2007). A structural equation model relating impaired sensorimotor function, fear of falling and gait patterns in older people. *Gait & Posture*, 25, 243-249.

Mian O, Narici M, Minetti A & Baltzopoulos V (2007a). Centre of mass motion during stair negotiation in young and older men. *Gait & Posture*, 26, 463-469.

Mian O, Thom J, Narici M & Baltzopoulos V (2007b). Kinematics of stair descent in young and older adults and the impact of exercise training. *Gait & Posture*, 25, 9-17.

Mills P, Barrett R & Morrison S (2008). Toe clearance variability during walking in young and elderly men. *Gait & Posture*., 28, 101-107.

Miyasike-Dasilva V, Allard F & McIlroy W (2011). Where do we look when we walk on stairs? Gaze behaviour on stairs, transitions, and handrails. *Exp Brain Res.*, 209, 73-83.

Moreland J, Richardson J, Goldsmith C & Clase C (2004). Muscle weakness and falls in older adults: a systematic review and meta-analysis. *J.Am.Geriatr.Soc.*, 52, 1121-1129.

Mulavara A, Verstraete M & Bloomberg J (2002). Modulation of head movement control in humans during treadmill walking. *Gait & Posture*, 16, 271-282.

Murphy J & Isaacs B (1982). The post-fall syndrome. *Gerontology*, 28, 265-270.

Novak A & Brouwer B (2010). Sagittal and frontal lower limb joint moments during stair ascent and descent in young and older adults. *Gait & Posture*.

Owings T & Grabiner M (2004). Step width variability, but not step length variability or step time variability, discriminates gait of healthy young and older adults during treadmill locomotion. *J Biomech.*, 37, 935-938.

Patla A & Vickers J (2003). How far ahead do we look when required to step on specific locations in the travel path during locomotion? *Exp Brain Res.*, V148, 133-138.

Patla A, Davies T & Niechwiej E (2004). Obstacle avoidance during locomotion using haptic information in normally sighted humans. *Exp Brain Res.*, 155, 173-185.

Patla A & Greig M (2006). Any way you look at it, successful obstacle negotiation needs visually guided on-line foot placement regulation during the approach phase. *Neurosci.Lett.*, 397, 110-114.

Patla A & Vickers J (1997). Where and when do we look as we approach and step over an obstacle in the travel path? *Neuroreport*, 8, 3661-3665.

Perry J (1992). *Gait analysis. Normal and pathological function*. Thorofare: SLACK Incorporated.

Perry M, Carville S, Smith I, Rutherford O & Newham D (2007). Strength, power output and symmetry of leg muscles: effect of age and history of falling. *Eur.J.Appl.Physiol*, 100, 553-561.

Pickard C, Sullivan P, Allison G & Singer K (2003). Is there a difference in hip joint position sense between young and older groups? *J.Gerontol.A Biol.Sci.Med.Sci.*, 58, 631-635.

Pijnappels M, Reeves N, Maganaris C & van Dieen J (2008). Tripping without falling; lower limb strength, a limitation for balance recovery and a target for training in the elderly. *J.Electromyogr.Kinesiol.*, 18, 188-196.

Pijnappels M, van der Burg P, Reeves N & van Dieen J (2008). Identification of elderly fallers by muscle strength measures. *Eur.J.Appl.Physiol*, 102, 585-592.

Pitts D (1982). Visual acuity as a function of age. *J.Am.Optom.Assoc.*, 53, 117-124.

Powell L & Myers A (1995). The Activities-specific Balance Confidence (ABC) Scale. *J.Gerontol.A Biol.Sci.Med.Sci.*, 50A, M28-M34.

Pozzo T, Berthoz A & Lefort L (1990). Head stabilization during various locomotor tasks in humans. I. Normal subjects. *Exp Brain Res.*, 82, 97-106.

Pozzo T, Berthoz A, Vitte E & Lefort L (1991). Head stabilization during locomotion. Perturbations induced by vestibular disorders. *Acta Otolaryngol.Suppl*, 481, 322-327.

Protopapadaki A, Drechsler W, Cramp M, Coutts F & Scott O (2007). Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals. *Clin.Biomech.(Bristol., Avon.)*, 22, 203-210.

Puell M, Palomo C, Sanchez-Ramos C & Villena C (2004). Normal values for photopic and mesopic letter contrast sensitivity. *J.Refract.Surg.*, 20, 484-488.

Pulos E (1989). Changes in rod sensitivity through adulthood. *Investigative Ophthalmology & Visual Science*, 30, 1738-1742.

Pyykkoe I, Jantti P & Aalto H (1990). Postural control in elderly subjects. *Age Ageing*, 19, 215-221.

Rauch S, Velazquez-Villasenor L, Dimitri P & Merchant S (2001). Decreasing hair cell counts in aging humans. *Ann.N.Y.Acad.Sci.*, 942, 220-227.

Reed-Jones R, Reed-Jones J, Vallis L & Hollands M (2009a). The effects of constraining eye movements on visually evoked steering responses during walking in a virtual environment. *Exp Brain Res.*, 197, 357-367.

Reed-Jones R, Hollands M, Reed-Jones J & Vallis L (2009b). Visually evoked whole-body turning responses during stepping in place in a virtual environment. *Gait & Posture*, 30, 317-321.

Reelick M, van Iersel M, Kessels R & Rikkert M (2009). The influence of fear of falling on gait and balance in older people. *Age Ageing*, 38, 435-440.

Reeves N, Spanjaard M, Mohagheghi A, Baltzopoulos V & Maganaris C (2008a). Influence of light handrail use on the biomechanics of stair negotiation in old age. *Gait & Posture*, 28, 327-336.

Reeves N, Spanjaard M, Mohagheghi A, Baltzopoulos V & Maganaris C (2008b). The demands of stair descent relative to maximum capacities in elderly and young adults. *J Electromyogr.Kinesiol.*, 18, 218-227.

Reeves N, Spanjaard M, Mohagheghi A, Baltzopoulos V & Maganaris C (2009). Older adults employ alternative strategies to operate within their maximum capabilities when ascending stairs. *J.Electromyogr.Kinesiol.*, 19, e57-e68.

Rhea C & Rietdyk S (2007). Visual exteroceptive information provided during obstacle crossing did not modify the lower limb trajectory. *Neurosci.Lett.*, 418, 60-65.

Rietdyk S (2006). Anticipatory locomotor adjustments of the trail limb during surface accommodation. *Gait & Posture.*, 23, 268-272.

Rietdyk S & Rhea C (2006). Control of adaptive locomotion: effect of visual obstruction and visual cues in the environment. *Exp Brain Res.*, 169, 272-278.

Robbins S, Waked E & McClaran J (1995). Proprioception and stability: foot position awareness as a function of age and footwear. *Age Ageing*, 24, 67-72.

Robinson D (1963). A method of measuring eye movement using a sclera search coil in a magnetic field. *IEEE Transactions on bio-medical engineering*, 10, 137-145.

Robinson D (1965). The mechanics of human smooth pursuit eye movement. *Journal of Physiology* 180 (3), 569-591.

Sattin R, Lambert Huber D, DeVito C, Rodriguez J, Ros A, Bacchelli S, Stevens J, Waxweiler R (1990). The incidence of fall injury events among the elderly in a defined population. *Am.J Epidemiol.*, 131, 1028-1037.

Scott G, Menz H & Newcombe L (2007). Age-related differences in foot structure and function. *Gait & Posture.*, 26, 68-75.

Scuffham P, Chaplin S & Legood R (2003). Incidence and costs of unintentional falls in older people in the United Kingdom. *J Epidemiol.Community Health*, 57, 740-744.

Serrador J, Lipsitz L, Gopalakrishnan G, Black F & Wood S (2009). Loss of otolith function with age is associated with increased postural sway measures. *Neurosci.Lett.*, 465, 10-15.

Shumway-Cook A & Woollacott M (2001). *Motor Control. Theory and Practical Applications*. (2 ed.) Philadelphia: Lippincott Williams & Wilkins.

Shumway-Cook A, Baldwin M, Polissar N & Gruber W (1997). Predicting the probability for falls in community-dwelling older adults. *Phys.Ther.*, 77, 812-819.

Simoneau G, Cavanagh P, Ulbrecht J, Leibowitz H & Tyrrell R (1991). The influence of visual factors on fall-related kinematic variables during stair descent by older women. *J Gerontol.*, 46, M188-M195.

Skelton D, Kennedy J & Rutherford O (2002). Explosive power and asymmetry in leg muscle function in frequent fallers and non-fallers aged over 65. *Age Ageing*, 31, 119-125.

Sorensen K, Hollands M & Patla A (2002). The effects of human ankle muscle vibration on posture and balance during adaptive locomotion. *Exp Brain Res.*, V143, 24-34.

Spector R (1990). *Visual fields. In: Clinical Methods. The history, physical and laboratory examinations.* Walker H, Hall W, Hurst J (3rd ed.) Boston: Butterworths.

Stacoff A, Diezi C, Luder G, Stuessi E & Kramers-de Quervain I (2005). Ground reaction forces on stairs: effects of stair inclination and age. *Gait & Posture*, 21, 24-38.

Steele G, O'Neil J, Huisingh C & Smith G (2010). Elevator-related injuries to older adults in the United States, 1990 to 2006. *J.Trauma*, 68, 188-192.

Strotmeyer E, de Rekeneire N, Schwartz A, Resnick H, Goodpaster B, Faulkner K, Shorr R, Vinik A, Harris T, Newman A (2009). Sensory and motor peripheral nerve function and lower-extremity quadriceps strength: the health, aging and body composition study. *J.Am.Geriatr.Soc.*, 57, 2004-2010.

Svanström L (1974). Falls on stairs: an epidemiological accident study. *Scandinavian journal of social medicine*, 2, 113-120.

Tatler B, Baddeley R & Vincent B (2006). The long and the short of it: spatial statistics at fixation vary with saccade amplitude and task. *Vision Res.*, 46, 1857-1862.

Templer J (1994). *The staircase. Studies of hazards, falls, and safer design.* (2 ed.) Cambridge: MIT Press.

Terao Y, Andersson N, Flanagan J & Johansson R (2002). Engagement of gaze in capturing targets for future sequential manual actions. *Journal of Neurophysiology*, 88, 1716-1725.

Thelen D, Brockmiller C, Ashton-Miller J, Schultz A & Alexander N (1998). Thresholds for sensing foot dorsi- and plantarflexion during upright stance: effects of age and velocity. *Journal of Gerontology: Medical Sciences*, 53A, M33-M38.

Thies S, Richardson J & Ashton-Miller J (2005). Effects of surface irregularity and lighting on step variability during gait: a study in healthy young and older women. *Gait & Posture*., 22, 26-31.

Thompson K, Mikesky A, Bahamonde R & Burr D (2003). Effects of physical training on proprioception in older women. *J Musculoskelet.Neuronal.Interact.*, 3, 223-231.

Tiedemann A, Sherrington C & Lord S (2007). Physical and psychological factors associated with stair negotiation performance in older people. *J Gerontol.A Biol.Sci.Med.Sci.*, 62, 1259-1265.

Timmis M, Bennett S & Buckley J (2009). Visuomotor control of step descent: evidence of specialised role of the lower visual field. *Exp Brain Res.*, 195, 219-227.

Timmis M, Johnson L, Elliott D & Buckley J (2010). Use of single-vision distance spectacles improves landing control during step descent in well-adapted multifocal lens-wearers. *Invest Ophthalmol.Vis.Sci.*, 51, 3903-3908.

Tinetti M, Richman D & Powell L (1990). Falls efficacy as a measure of fear of falling. *Journal of Gerontology: Psychological Sciences*, 45, P239-243.

Tomlinson B & Irving D (1977). The numbers of limb motor neurons in the human lumbosacral cord throughout life. *J.Neurol.Sci.*, 34, 213-219.

Trepel M (2004). *Neuroanatomie- Struktur und Funktion*. (3.Auflage) München: Urban & Fischer.

Van der Geest J, Frens M (2002). Recording eye movements with video-oculography and sclera search coils: a direct comparison of two methods. *Journal of Neuroscience Methods*, 114, 185-195.

Verschueren S, Stephan P, Kaat D & Jacques D (2002). Effects of tendon vibration on the spatiotemporal characteristics of human locomotion. *Exp. Brain Res.*, V143, 231-239.

Vickers J (2007). Perception, cognition and decision training: The quite eye in action. Leeds, England: Human Kinetics.

Vivekanada-Schmidt P, Anderson R, Reinhardt-Rutland A, Shields T (2004). Simulated impairment of contrast sensitivity: Performance and gaze behaviour during locomotion through a built environment. *Optom.Vis.Sci.* 81, 844-852.

Wagner R, Galiana H (1992). Evaluation of three template matching algorithms for registering images of the eye. *IEEE Transactions on biomedical engineering*, 29, 1313-1319.

Warren W (1984). Perceiving affordances: visual guidance of stair climbing. *J.Exp.Psychol.Hum.Percept.Perform.*, 10, 683-703.

Wijlhuizen G, de Jong R & Hopman-Rock M (2007). Older persons afraid of falling reduce physical activity to prevent outdoor falls. *Preventive Medicine*, 44, 260-264.

Winn B, Whitaker D, Elliott D, Phillips N (1994). Factors affecting light-adapted pupil size in normal human subjects. *Investigative Ophthalmology & Visual Science*, 35, 1132-1137.

Winter D (1990). *Biomechanics and motor control of human movement*. (2nd ed.) Hoboken, New Jersey: John Wiley & Sons, Inc.

Winter D (1991). *The biomechanics and motor control of human gait: normal, elderly and pathological*. (2nd ed.) Waterloo: University of Waterloo Press.

Winter D (1995). Human balance and posture control during standing and walking. *Gait & Posture*, 3, 193-214.

Winter D (2005). *Biomechanics and motor control of human movement*. (3rd ed.) Hoboken, New Jersey: John Wiley & Sons, Inc.

Wolfson L, Judge J, Whipple R & King M (1995). Strength is a major factor in balance, gait, and the occurrence of falls. *J.Gerontol.A Biol.Sci.Med.Sci.*, 50 Spec No, 64-67.

Woollacott M, Shumway-Cook A & Nashner L (1986). Aging and posture control: changes in sensory organization and muscular coordination. *Int.J.Aging Hum.Dev.*, 23, 97-114.

Yee R, Schiller V, Lim V, Baloh F, Baloh R, Honrubia V (1985). Velocities of vertical saccades with different eye movement recording methods. *Investigative Ophthalmology & Visual Science* ., 26, 938-944

- Yen H, Chen H, Liu M, Liu H & Lu T (2009). Age effects on the inter-joint coordination during obstacle-crossing. *J.Biomech.*, 42, 2501-2506.
- Young W & Hollands M (2010). Can telling older adults where to look reduce falls? Evidence for a causal link between inappropriate visual sampling and suboptimal stepping performance. *Exp Brain Res.*, 204, 103-113.
- Zachazewski J, Riley P & Krebs D (1993). Biomechanical analysis of body mass transfer during stair ascent and descent of healthy subjects. *J.Rehabil.Res.Dev.*, 30, 412-422.
- Zietz D & Hollands M (2009). Gaze behavior of young and older adults during stair walking. *J.Mot.Behav.*, 41, 357-366.
- Zijlstra G, van Haastregt J, van Eijk J, van Rossum E, Stalenhoef P & Kempen G (2007). Prevalence and correlates of fear of falling, and associated avoidance of activity in the general population of community-living older people. *Age and Ageing*, 36, 304-309.