Chapter 1

Introduction
1.1 Move-Age programme

This PhD project was part of the Move-Age joint doctorate programme, funded by the European Commission as part of the Erasmus Mundus programme. It entailed a collaboration between Manchester Metropolitan University and Vrije Universiteit Amsterdam on the topic of fall prevention and mobility in elderly. The project was supported by existing expertise, personnel, technique developments and lines of inquiry in both participating research groups (Prof. Dr. I. D. Loram from the School of healthcare science, MMU and Prof. Dr. P. J. Beek and Dr. J. F. Stins from MOVE research Institute Amsterdam, Vrije Universiteit Amsterdam).

1.2 Fall risk factors

The ageing population is confronted with the problem of mobility loss. Approximately one in three older adults will annually lose their balance and experience a fall, and approximately half of these individuals will experience more than one fall per year (Blake et al., 1988; Tinetti et al., 1988; Downton & Andrews, 1991). For older adults (age $\geq 65$) falls are one of the main causes of injury-related hospitalisation and injury-related deaths (Rubenstein, 2006). This also results in a significant global economic cost (Stevens et al., 2006).

Consequently, a significant programme of research and body of literature are aimed at finding risk factors for falls. If elderly with a high propensity to falling can be identified, early interventions might be able to reduce the number of falls. Initially (1990 – 2002), this field of research was dominated by a physiologically oriented approach.

Impairment of vision, peripheral sensation, muscle strength, reaction time, and balance were all found to be risk factors for falls (Lord et al., 1994a; Lord et al., 1994b). In a 1-year prospective study with 341 women, discriminant function analysis with these risk factors differentiated elderly with multiple falls from non-multiple fallers within that year with 75% accuracy (Lord et al., 1994b). In later studies the effects of interventions were investigated. These interventions included strength and balance training (Buchner et al., 1997; Wolf et al., 1997; Campbell et al., 1999a; Day et al., 2002), optimising vision (Day et al., 2002), provision of pace makers to prevent drop attacks (Kenny et al., 2001), environmental modifications to increase safety in the home (Cumming et al., 1999; Day et al., 2002; Nikolaus & Bach, 2003) and reduction
of hazardous medication use (Campbell et al., 1999b). These intervention studies showed improvement for the most vulnerable and high-risk groups. The type and level of frailty were found to be important factors to determine which interventions are suitable for risk prevention. Interventions that reduced fall occurrence in a broader population included physiotherapy (Campbell et al., 1999a; Robertson et al., 2001), group exercise (Day et al., 2002; Barnett et al., 2003; Lord et al., 2003) and multifactorial interventions (Tinetti et al., 1994a; Close et al., 1999).

This physiological approach has advanced our understanding of fall risk. However, subsequent multifactorial fall research has exposed a broader range of fall risk factors (Delbaere et al., 2010a). Cognitive factors such as executive function (Anstey et al., 2009; Delbaere et al., 2010a) and attentional focus (Wong et al., 2008; Wulf, 2013) were also found to be related to balance performance and falls. Executive function is defined as the ability to independently perform complex, goal-directed, and self-serving behaviours (Delbaere et al., 2010a), and is mediated by processes of selection and reinforcement learning operating through frontal basal ganglia networks (D’Esposito et al., 1995; Houk et al., 2007; Cohen & Frank, 2009).

Other factors such as fear of falling and balance confidence showed a strong relation with balance and falls as well (Hadjistavropoulos et al., 2007; Delbaere et al., 2010b). In particular for fear of falling and attentional focus, the mechanisms underlying the relation with balance control and fall risk are not yet clearly identified. From a cognitive motor control perspective, fear is a response that follows when the central nervous system classifies the environment as requiring a fear response (LeDoux, 1998). Fear of falling is selected following perception of the situation and can be reinforced within a vicious cycle of positive feedback leading to reduced mobility. Alternatively, fear of falling can be progressively diminished leading to increased mobility (Loram, 2015). The ability to accurately assess whether an environmental context is potentially threatening is dependent upon executive function which allows one to adapt rationally to the environment by combining sensory analysis with selective inhibition to diminish unnecessary fearful responses (Loram, 2015).

In this chapter we therefore explore the mechanisms by which perceptual context influences balance. Before we examine these mechanisms we will first elucidate the
concept and assessment methods of fear of falling and balance confidence, and their relation with balance control.

1.3 Fear of falling

Following a fall, elderly may lose confidence in their ability to balance, and develop a fear of falling. Fear of falling has been observed in 50% - 60% of reported fallers in multiple community samples (Legters, 2002). Avoidance of physical activity has been acknowledged by 25% - 33% of these fearful individuals (Legters, 2002). This reduction of physical activities may lead to (more) health problems and loss of independence (Vellas et al., 1997). However in many seniors without a history of falls or related injuries, fear of falling has been established as well (Legters, 2002). Furthermore, fear of falling and lowered balance confidence have shown to be predictive of future falls (Cumming et al., 2000; Delbaere et al., 2004; Hadjistavropoulos et al., 2007).

To relate fear of falling and balance confidence to balance performance and fall risk, appropriate measurements and clear conceptualisations are needed. This could lead to the development of new intervention strategies to enhance balance and perhaps reduce risk of falls.

1.3.1 Effect of fear on sensorimotor control

The issue as to how fear could impair balance performance has often been addressed against the backdrop of Bernstein’s degrees of freedom problem (Bernstein, 1967; Higuchi et al., 2002). This problem is based on the argument that actors have multiple ways available to perform a movement to achieve the same goal, because of the abundance of degrees of freedom in our movement system. In terms of kinematic degrees of freedom, moving body segments can display different trajectories and velocities to achieve the same goal. In terms of degrees of freedom in muscular activation one could identify different muscle activation patterns that produce the same movement output. It could be the case that under stressful situations the burden of concurrently coordinating all degrees of freedom becomes too demanding for our nervous system. As a result, certain degrees of freedom are frozen in stressful situations, thereby facilitating control. Therefore, movement becomes more constrained when anxiety increases (Higuchi et al., 2002) and efficient balance performance could be jeopardized.
Arousal accompanied by fear could also lead to aberrant movement patterns (Heckman et al., 2008). Through persistent inward currents in spinal motor neurons, noradrenaline increases the global excitability of the muscles (Heckman et al., 2008). This might enhance levels of co-contraction of antagonistic muscles within the same joint, which in turn increases joint stiffness. Therefore, instead of freezing certain degrees of freedom, fear stimulates our nervous system to generate a general over-excitation of the entire system resulting in stiffening of our joints. Therefore, fear-induced muscle excitation is non-specific. However inhibition of excitation acts through specific localized reciprocal inhibition (Hyngstrom et al., 2008).

1.3.2 Measurement of fear of falling
To assess the presence of fear or anxiety, three components can be distinguished, (1) physiological (e.g., increased autonomic reactivity), (2) behavioural (e.g., cautious and slow gait) and (3) cognitive (subjective estimation of the level of danger and ability to avoid a fall) (Rachman, 1982). Fear responses have shown to be accompanied by increased arousal (Critchley, 2002). Therefore many authors have focussed on physiological arousal to investigate the physiological anxiety component, for example by measuring skin conductance (SC) using two electrodes placed on the hand palm or fingers of a subject (Critchley, 2002; Davis et al., 2009). Additionally, the vocal fundamental frequency has been used to grade the level of anxiety (Weeks et al., 2012). Kinetics (e.g. ground reaction forces) (Carpenter et al., 1999; Carpenter et al., 2001; Laufer et al., 2006; Davis et al., 2009) and kinematics (e.g. 3d motion capture) (Hsu et al., 2007; Park et al., 2012) have been analysed to assess the behavioural aspects of the fear response. With respect to the cognitive component, various self-evaluation questionnaires have been implemented.

With respect to fear of falling the simplest assessments have been limited to ‘yes’ or ‘no’, or graded scale answers to the question: “Are you afraid of falling”, whereas the Survey of Activities and Fear of Falling in the Elderly (SAFE) assesses fear of falling in elderly and provides an index for activity avoidance due to fear (Jorstad et al., 2005). The two parts of the State-Trait Anxiety Index (STAI) are more general self-evaluation questionnaires of anxiety (Gros et al., 2007). One part measures the time specific anxiety of a subject which fluctuates depending on the subject’s current state. The second part aims to measure the more persistent levels of anxiety, related to one’s
personality profile. The STAI questionnaire only taps into the cognitive component of fear, whereas the SAFE aims to tap into the behavioural component as well. In addition, qualitative research has shown that fear of falling is often related to a fear of institutionalisation (e.g. highly dependent nursing homes) or fear of losing the ability to walk, e.g. having to use a wheelchair (Wright et al., 1990).

Thus, a complete understanding of the fear response requires joint investigation of its physiological, behavioural and cognitive components. With respect to balance control, another important cognitive factor that is also related to fear of falling is balance confidence, as discussed in the next section.

### 1.3.3 Falls efficacy and fear of falling

Fear of falling is related to the level of confidence in one’s own balancing skills. The Activity Balance Confidence scale (ABC), Falls Efficacy Scale (FES) and more recently the FES International (FES-I) have been used to measure balance confidence and falls efficacy in the elderly (Jorstad et al., 2005; Hadjistavropoulos et al., 2007; Delbaere et al., 2010b). Falls efficacy refers to beliefs in balancing skills. The relation between fear and beliefs about one’s own ability is now well-established (Barlow, 2008). Correlations as high as 0.86 were found between FES and ABC scores (Hotchkiss et al., 2004). As such, the terms ‘balance confidence’ and ‘falls efficacy’ were considered to be interchangeable (Hadjistavropoulos et al., 2011). In a longitudinal study with community dwelling older adults, fear of falling and fall-efficacy were also found to be correlated (Hadjistavropoulos et al., 2007).

Therefore elderly with increased fear of falling are likely to have low balance confidence as well. However, Butki et al. (2001) found no association between state anxiety and falls-related self-efficacy. Therefore, fear of falling and balance confidence (falls efficacy) are still argued to be distinct dimensions (Moore & Ellis, 2008; Hadjistavropoulos et al., 2011). Furthermore, the FES-I was found to be a predictor for falls (Delbaere et al., 2010b) and falls efficacy (ABC, FES) was also found to be a better predictor for falls than fear of falling (SAFE) (Hadjistavropoulos et al., 2007). As such, one could argue that falls efficacy mediates the relationship between fear of falling and the occurrence of falls.
1.3.4 How does fear of falling affect balance performance?

Fear of falling and falls efficacy are not only related to fall history (Lachman et al., 1998; Fletcher & Hirdes, 2004), but also to future falls (Cumming et al., 2000; Delbaere et al., 2004; Hadjistavropoulos et al., 2007). However, no consensus is established yet on the mechanisms that cause this relation.

Many authors assume that fear of falling induces activity avoidance, which in turn results in decline of balance performance, and thereby increases fall risk. Even though this mechanism is widely accepted, there is no clear evidence for this mechanism. The association between activity avoidance, and fear of falling and falls efficacy seems to be well established (Tinetti et al., 1994b; Petrella et al., 2000; Li et al., 2003; Jorstad et al., 2005; Delbaere et al., 2009), however determining the direction of causality remains problematic. Additionally, a more recent study did not support this relation as they did not find a reduction in planned exercise for elderly with increased concern about falling (Delbaere et al., 2016).

One might also question whether activity avoidance by itself predicts falls. The relation between activity avoidance and falls is undisputed for high levels of activity avoidance, as the adverse effects on balance performance and mobility are evident. Insufficient exercise could increase muscle atrophy, the risk for obesity, neuropathy and other factors that reduce mobility (Balducci et al., 2006; Seguin et al., 2012).

It may therefore come as a surprise that the literature on the relation between avoidance and falls is inconsistent. A weak relation between falls and avoidance was found by Delbaere et al. (2004). However a 6-month prospective study with 492 community-based adults found that activity avoidance did not predict falls, whereas falls efficacy and to a lesser extent fear of falling did predict falls (Hadjistavropoulos et al., 2007). As such, no clear evidence exists that activity avoidance is a necessary component for fear of falling to cause fall risk.

Consequently, two different theories were proposed that did not include activity avoidance (Hadjistavropoulos et al., 2007). First, fear of falling in elderly could be the result of an accurate self-appraisal of balancing abilities and fall risk. In a review on this topic it was concluded that this possibility has not been studied adequately (Hadjistavropoulos et al., 2011). However, this issue was covered by Delbaere et al.
(2016) and they found no support for the theory that fear of falling represents realistic appraisal of balance performance. For participants with high concerns for falls and good balancing abilities, a high fear of falling was still related to future falls. This association was mediated by other psychological/social factors such as depression, community participation, and physical activity.

**Height-induced fear of falling directly impairs balance**

Apart from the first possibility that elderly fear of falling constitutes a realistic appraisal of balancing abilities, an alternative theory states that fear of falling might directly impair balance performance. In support of the latter theory, Delbaere et al. (2006) found reduced dynamic balance performance in elderly with inappropriate high levels of fear, based on the number of previous and prospective falls. Elderly with inappropriately low fear overestimated their balance capacities.

However, most evidence for the theory that fear directly impairs balance performance was found using height-induced postural threat to elicit fear of falling. A frequently used paradigm involves positioning participants on the edge of an elevated platform at different heights to elicit a height-induced fear of falling (Carpenter et al., 1999; Adkin et al., 2000; Carpenter et al., 2001; Carpenter et al., 2004; Laufer et al., 2006; Davis et al., 2009; Horlings et al., 2009; Huffman et al., 2009). Using ground reaction forces (GRF), centre of pressure (COP) excursion data were analysed to assess balancing behaviour of participants. Carpenter et al. found that postural threat induced a tighter control of upright posture, reflecting a ‘stiffening’ strategy (Carpenter et al., 1999; Carpenter et al., 2001; Carpenter et al., 2004). When exposed to postural threat by standing quietly on the edge of an elevated platform, participants had a decreased mean sway amplitude of the COP, calculated as the offset removed root mean square (RMS). In addition, a higher COP mean power frequency (MPF) was found for participants standing at high compared to low elevation. Compared to young healthy adults, elderly were found to show an exaggerated response to postural threat that involved a larger decrease in RMS and larger increase in MPF (Carpenter et al., 2006; Laufer et al., 2006).

In a subsequent study, the effect of postural threat on participants with low vs. high levels of self-reported fear of falling was compared in young healthy adults (Davis et al., 2009). The postural response of the non-fearful group showed the expected
postural patterns (decrease in RMS and increase in MPF) with increased elevation. Conversely, the fearful group showed increased RMS and increased MPF compared to the ground condition. This fearful response for the fearful group indicates that postural threat induces a similar effect of increased frequency of corrective movements. However the increased RMS also indicates an increase instead of a decrease in sway amplitude of COP for the fearful group. Therefore, fear of falling is directly related to hampering regulation of postural sway at height. However, the direction of causality is undetermined, as it is unclear whether fear affected balance control, or whether the altered balance control caused the fear. This also relates to the old James-Lang vs. Canon-Bard discussion on the origin of emotion and the entangled physiological reactions (Cannon, 1987). Nevertheless, Davis et al. (2009) concluded that fearful subjects adopt a different control strategy than non-fearful subjects. However, no changes in self-reported state-anxiety or physiological arousal (SC) were found between the two groups.

While standing at height the depth of vision is larger than standing at ground level and this has shown to destabilise balance (Simeonov et al., 2005). Therefore it was studied whether this disparity in visual feedback could be the main cause of impaired balance at height, instead of the knowledge of danger (Tersteeg et al., 2012). In this experiment, participants walked on a narrow high walkway while sheets placed around the walkway at the same height blocked the sight of drop. The risk and knowledge of danger was retained with this setup. Compared to walking on the walkway without the sheets no difference was found in gait progression and double support duration. Compared to ground level walking these gait parameters as well as physiological arousal were significantly altered. Therefore the main cause of altered balance control and arousal by height-induced postural threat is the knowledge of risk and reckoning of danger, rather than the visual feedback needed for balance control.

In summary, it has been established that fear of falling could lead to decreased balance performance and increased fall risk, but this does not have to be mediated by activity avoidance. Balance performance can be acutely impaired by fear of falling and thus potentially increase fall risk.
1.4 Vestibular balancing reflexes

Balance performance is largely dependent on reflexes that are triggered by feedback from the vestibular organs. Vestibulocollic reflexes mostly comprise three-neuron-arcs, originate primarily from medial vestibular nuclei and have short response latencies (~8-10 ms) (Watson & Colebatch, 1998; Forbes et al., 2014). Conversely, appendicular vestibular reflexes originate from lateral vestibular nuclei and have longer response latencies (~50–60 ms) (Britton et al., 1993; Fitzpatrick et al., 1994; Day et al., 1997; Ali et al., 2003; Son et al., 2008). It is currently debated whether fear of falling could influence balance performance at the level of these vestibular reflexes (Horslen et al., 2015a, b; Reynolds et al., 2015a; Reynolds et al., 2015b).

1.4.1 Inducing vestibular balance reflexes

To study vestibular reflexes, a frequently used method is binaural bipolar Galvanic Vestibular Stimulation (GVS) (Fitzpatrick et al., 1994; Fitzpatrick & Day, 2004; Osler et al., 2013; Horslen et al., 2014). GVS is applied by placing electrodes behind the ears on the mastoid processes. A current applied to these electrodes stimulates the vestibular nerves changing information sent from the vestibular organs to the brain. This creates artificial vestibular feedback of lateral rotation, causing a reflexive counter leaning movement of the whole body in the opposite lateral direction, see Figure 1.1.

The artificial vestibular feedback induced by GVS has been specified in detail by Fitzpatrick and Day (2004). They found that binaural bipolar GVS evokes an afferent signal of angular velocity and angular acceleration about an axis in the sagittal plane, located between the vestibular organs directed backward and 18.8 degrees upward from Reid’s line. Therefore, during normal upright standing when Reid’s line is nearly horizontal, an afferent of roll rotation with a small yaw component is evoked.
The induced body sway is directed towards the anode GVS electrode. Therefore the direction of the balancing sway response depends on head orientation. When standing in a normal upright position with the anode electrode attached behind the right ear and the cathode electrode behind the left ear, the stimulation will induce a sway to the right. However with the head rotated 90 degrees to the left, the anode electrode is positioned on the anterior side with respect to the rest of the body. With this configuration, electrical stimulation causes anterior sway and the weight is shifted towards the toes. Therefore the GVS response is considered craniocentric (Lund & Broberg, 1983). Typically, square wave GVS intensities between 0.5 and 2 mA are used to elicit the balancing sway response (Britton et al., 1993; Fitzpatrick et al., 1994; Fitzpatrick & Day, 2004; Osler et al., 2013).

To test how fear of falling could affect the latency and amplitude of the vestibular balance reflex, one needs to know what muscles and joints are involved and at what latency the balance response occurs. As such, GRF and EMG data of the GVS induced vestibular balance reflex has been collected. These measurements have revealed two
phases of the GVS response; a short- and medium-latency response (Britton et al., 1993; Fitzpatrick et al., 1994; Fitzpatrick & Day, 2004). The lower limb short-latency EMG responses seem to cause a lateral shear GRF peak towards the cathode electrode side, whereas the medium-latency responses seem to cause an opposite anode directed GRF peak (Figure 1.2). This medium-latency GRF peak towards the anode implies an acceleration of the COM in the same direction. Therefore the medium-latency response is assumed to be responsible for the whole-body sway response to the anode side (Fitzpatrick et al., 1994; Fitzpatrick & Day, 2004). However, the contribution of the short-latency response to balancing movements is still unknown (Fitzpatrick & Day, 2004; Horslen et al., 2014). For EMG responses of shank muscles the onset of the short-latency responses ranged from 42 to 65 ms and for medium-latency from 98 to 120 ms post GVS onset (Britton et al., 1993; Fitzpatrick et al., 1994; Ali et al., 2003; Fitzpatrick & Day, 2004; Son et al., 2008; Mian et al., 2010; Muise et al., 2012).

A problem with measurement of these GVS induced vestibular reflexes relates to the naturally occurring body sway when standing upright, which is the same order of magnitude as the GVS induced sway response. Therefore averaging over a large number of trials is needed for reliable measurement of the sway response. In addition, both polarity configurations (anode left and cathode right, vs. anode right and cathode left) should be used in randomised order.

A different method to induce vestibular reflexes is stochastic vestibular stimulation (SVS). With this method a large number of trials is not needed, therefore the time required for data collection is significantly shorter. However, no prominent body sway is produced. Instead of uni-directional discrete square wave GVS; continuous sine wave stimulation including both polarities is used with SVS. Coupling between the balance response (GRF and EMG data) and the SVS stimulation signal is determined using correlation measures for different time lags (cumulant density function). With this method, similar short- and medium-latency vestibular reflexes patterns were found in lower limb EMG and GRF data (Figure 1.2D). (Dakin et al., 2007; Dakin et al., 2010; Mian et al., 2010).
Figure 1.2: Short- and medium-latency vestibular balance response. *A&B*, GVS stimulation starts at 0 s. The EMG response of the soleus and tibialis anterior are shown for two anode-cathode configurations of the GVS electrodes attached behind the participants’ ears. The head was turned to the left so the anode faced either forward or backward, inducing a forward or backward body sway. In both muscles a reciprocal short- and medium-latency pattern of inhibition and activation was observed, depending on the GVS polarity. Only the medium-latency response would explain the observed whole body sway. Redrawn from Fitzpatrick and Day (2004), original data from Fitzpatrick *et al.* (1994). *C*, GVS stimulation starts at 0 s and shear anteroposterior GRF is shown (in the direction of body sway, from cathode towards anode). After an electromechanical delay a comparable bi-phasic short- and medium-latency response pattern is observed, where again only the medium-latency response would explain the observed whole body sway towards anode. Redrawn from Marsden *et al.* (2005). *D*, In this graph the coupling between shear GRF and continuous Stochastic Vestibular Stimulation (SVS) is shown for a range of time lags. The SVS frequency content was 2-25 Hz, excluding prominent body sway. This coupling was quantified using a cumulant density function, which revealed a similar short- and medium-latency response pattern. Participants stood with the head turned 90 degrees to the right. Redrawn from Horslen *et al.* (2014).
1.4.2 **Effect of fear on vestibular balance reflexes**

The debate as to whether fear of falling could influence balance performance at the level of vestibular reflexes has not yet been resolved (Horslen et al., 2015a, b; Reynolds et al., 2015a; Reynolds et al., 2015b). These latter studies concerned a so-called cross-talk debate, which took place in the Journal of Physiology. That debate mainly revolved around the opposing conclusions of two studies that used a height-induced postural threat (standing on an elevated surface) to elicit a fear of falling, combined with GVS (Osler et al., 2013; Horslen et al., 2014).

Osler et al. (2013) used a narrow walkway elevated 3.85 m above ground level to induce postural threat. Applying GVS caused a lateral whole body sway in the direction of the edge of the walkway. Trunk and head kinematics showed that lateral sway amplitude after 800 ms was significantly and substantially attenuated at height compared to standing at ground level. However no difference was found between ground and height within the first 800 ms. Therefore it was concluded that fear of falling does not influence the faster vestibular balancing reflexes. Hence, fear of falling would not affect early reflexive balance control and would only interfere when volitional motor control influences balance as well.

Conversely, Horslen et al. (2014) did find effects of height-induced fear on vestibular reflexes. In that study SVS was used, and shear GRF data was collected instead of kinematics. They found an increased gain of both the short- and medium-latency vestibular balance reflexes at height. As such, a fear of falling would affect this fast reflexive balance control before volitional motor control kicked in.

In the crosstalk debate on this topic the functional implication of these increased short- and medium-latency GRF responses on balance was questioned (Reynolds et al., 2015b). For kinematic data of the trunk and head GVS response, no difference was found within the first 800 ms between ground and height conditions (Osler et al., 2013). Therefore it was argued that the increased short- and medium-latency responses might not be functionally contributing to balancing movements.
1.4.3 Function of short- and medium-latency responses

In the literature on the vestibular balancing reflex, the medium-latency response induced by GVS is assumed to cause the whole body sway. However it is unclear how the short-latency response contributes to balance control.

Cathers et al. (2005) proposed that the short-latency response originated from a different part of the vestibular organs than the medium-latency response, namely the otoliths instead of the semi-circular canals. However subsequent research did not support this possibility (Mian et al., 2010).

Multiple studies supported a possible difference between the short- and medium-latency response in their contribution to balance. In two of them GVS was applied to standing participants with the neck flexed 90 degrees, so the head was facing downward (Cathers et al., 2005; Mian et al., 2010). In this posture, the axis of GVS induced illusory rotation is vertical instead of horizontal and the sway response (measured at the pelvis) towards the anode was abolished (Cathers et al., 2005). Lower limb EMG data also showed an abolished (Cathers et al., 2005) or attenuated medium-latency response (Mian et al., 2010), however the short-latency response was unaffected compared to normal upright standing.

Other studies found further disparity between the short- and medium-latency EMG responses, as the short-latency stimulus threshold was higher (Fitzpatrick et al., 1994) and the short-latency response amplitude seemed to reduce with ageing (Welgampola & Colebatch, 2002). The short-latency response was also attenuated for longer GVS onset rise times whereas the medium-latency response was not, and the bandwidths of coherence between SVS and EMG were different (Dakin et al., 2007). Therefore one might argue that both responses have different neural underpinnings. However, both responses are craniocentric (dependent on head angle) and both responses in the legs are abolished when the participant is seated (Britton et al., 1993; Fitzpatrick et al., 1994). Hence the relative contribution of short- and medium-latency responses to balance remains to be determined.

Measurements of full body kinematics might shed more light on this issue. According to Newton’s second law of motion the GRF is equal to the mass of the body multiplied by the acceleration of the centre of mass. Therefore the short- and medium-latency
GRF responses that were affected by fear of falling should also be found in the acceleration of the centre of mass (COM). As the short-latency response was not found in kinematics data of the head and trunk, this response should be part of the acceleration responses of body parts other than the trunk and head.

Full body kinematics measurements of the effect of fear of falling on vestibular evoked reflexes could uncover the complete movement pattern of the GVS sway response. In addition, kinematic measurement of the short- and medium-latency responses could clarify their interplay and how they contribute to maintaining and restoring balance. This would also provide an answer to the question whether fear of falling modifies vestibular balance reflex movements or not.

1.5 Cognition mediates the effect of fear on motor control

In the field of motor control the effects of psychological state variables on motor performance has been studied extensively, specifically in relation to attentional focus. In normal healthy adults most movements are learned and executed with little attentional effort bypassing explicit volitional control.

1.5.1 Reinvestment

In challenging situations, e.g. when recovering from a fall or in fearful states, individuals may choose to consciously monitor their movements in an effort to enhance motor control (Wong et al., 2008). This conscious control generally involves explicit knowledge or strategies processed in working memory. Explicit knowledge is knowledge that we are aware of and can be verbalized, as opposed to implicit knowledge that we cannot easily verbalize and that we are generally unaware of (Wong et al., 2008). This process of shifting from an implicit and more automated form to a more conscious and explicit form of motor control has been termed reinvestment (Masters, 1992; Masters et al., 1993b). Reinvestment often occurs when an individual is fearful, highly motivated, under pressure, or has difficulty to move successfully (Wong et al., 2008). A high predisposition to reinvest has been associated with e.g. disrupted performance under psychological pressure in sports (Masters et al., 1993b) and with diseases such as Parkinson’s disease (Masters et al., 2007).

To assess the level of reinvestment the Movement Specific Reinvestment Scale (MSRS) has been developed, and is now routinely used in scientific studies and clinical
practice. Elderly with a history of falling have shown to score significantly higher on the MSRS than elderly non-fallers (Wong et al., 2008). Therefore, fear of falling in elderly possibly induces reinvestment and thereby disrupts the automaticity of movements, which may in turn impair efficient balance control. Huffman et al. used a state specific version of the MSRS to study the effect of postural threat and fear of falling on reinvestment in young healthy adults (Huffman et al., 2009). Subjects standing at the edge of an elevated surface 3.2 m above ground had a significantly higher fear of falling. Moreover, they scored significantly higher on the MSRS (Huffman et al., 2009), which suggests that fear induced a change in cognitive strategies.

1.5.2 Motor control mechanisms of reinvestment

The reinvestment response could also be described in terms of sensorimotor control. For this model the relation between fear and impaired motor control could be described as part of an overall feedback loop in the central nervous system. This is a feedback loop of perception, selection and motor control as formulated by Loram (2015), see Figure 1.3. Perception requires sensory analysis, integrating all sensory modalities with prior experience. Acting through central pathways such as the basal ganglia loops, responses are selected. Recent evidence suggests selection converges to a serial process with maximum rate of 2-4 selections per second (refractory response planner) (Loram et al., 2014). The motor system translates selected goals, actions, movements and control priorities into coordinated motor output. Within the slow feedback loop restricted to the voluntary bandwidth of control (2 Hz) the motor system generates coordinated motor responses sequentially from each new selection. With the fast loop restricted to a higher bandwidth (>10 Hz) acting through transcortical, brain stem and spinal pathways, the motor system uses selected parameters to modulate habitual-reflexive feedback (Loram et al., 2011; van de Kamp et al., 2013; Loram et al., 2014).
For healthy adults, most daily life motor tasks are performed through the fast loop with little mental effort. However for elderly with a fear of falling, perception of the task could lead to a decreased confidence in motor control. In addition, it has been proposed that anxiety increases sensitivity to self-motion, through noradrenergic and serotonergic input to the vestibular nuclei (Balaban, 2002). This could increase attentional focus to self-movement. As a result, a strategy could be adopted where motor control is consciously monitored and/or evaluated using mainly the slow volitional loop. In other words, one rethinks the movement from scratch, and reinvestment occurs by shifting to the slow loop. This imposes a heavier load on “sensory analysis” as this area is now analysing the demands of the task and the machinery at its disposal. A resulting maladapted motor response might further undermine perception, creating a vicious cycle.

1.5.3 Internal and external focus of attention

Reinvestment is a possible explanation for the cause of balance impairment and increased fall risk in elderly. For this reason we might ask whether diverting attention...
away from our own body movements could temporarily enhance balance. The constrained action hypothesis formulated by Wulf and Prinz (2001a) states that an internal focus of attention interferes with automaticity by inducing a more conscious and explicit type of control. Conversely, an external focus of attention promotes a more automatic mode of control that employs more unconscious and implicit control processes. In balance tasks and various sports (e.g. swimming, basketball, golf, darts, volleyball, football and frisbee), enhanced performance was found for an external focus compared to an internal focus. A review by Wulf (2013) explores these beneficial effects of external focus on motor performance and motor learning in more detail.

Internal focus is thus defined as a focus of attention to the movement of one’s own body, while external focus is related to the movement effect in the environment. For motor tasks where there is no external object movement to control, only movement of the body itself is involved, e.g. postural control on solid ground. For these tasks external focus instructions were used that direct the focus of attention to a physical surface in the environment on which force is exerted through muscle activity, and which is relevant to successful motor performance, e.g. the ground one is standing on in gymnastics (Lawrence et al., 2011), postural control (Wulf et al., 2007) and golf swing form assessment (An et al., 2013). A limitation that is shared in all research on internal and external focus of attention is that it cannot be measured whether the participant is following the focus instructions or not.

**Beneficial effects of external focus for balance**
The effects of internal/external focus on postural control were only found for balancing tasks that were more challenging than standing on solid ground (Wulf et al., 2007). These balancing tasks involved standing on an unstable surface, e.g. a stabilometer (balance board with mediolateral instability) (McNevin et al., 2003) or an inflated rubber balance disk (Wulf et al., 2007). With the stabilometer the angle of the balance board was measured and balance performance was measured as either RMS deviation from 0 degrees or as ‘time in balance’. This time in balance was calculated as the time in which the balance board was within ±5 degrees deviation from horizontal. Instructions for internal focus were to focus on keeping the feet horizontal. For external focus, instructions were to keep two orange markers horizontal that were attached to the balance board in front of the feet. In both conditions participants were
also instructed to look straight ahead, while concentrating on the feet or markers. This extra instruction to look straight ahead was added to keep visual feedback the same in both conditions. However, participants’ line of sight was not measured in these studies. For the inflated balance disk, performance was measured with a force platform. RMS amplitude of deviation from the mean centre of pressure position was calculated to quantify balance performance. Internal focus instructions were: “Minimise movements of the feet”, and external focus instructions were: ”Minimise movements of the balance disk”.

External focus has been shown to produce benefits on balance performance through repeated measures of the same participants in both internal and external focus conditions in young healthy adults (Wulf et al., 2004; Wulf et al., 2007). Retention studies with different young healthy adults for each condition also showed improved motor learning for external focus in balance tasks (Wulf et al., 1998; Shea & Wulf, 1999; Wulf et al., 2001; McNevin et al., 2003; Wulf & McNevin, 2003; Chiviacowsky et al., 2010).

A possible explanation of the difference in motor performance between internal and external focus of attention conditions is that the internal focus instructions cause the participant to focus too much on moving the feet, while the control of whole body centre of mass movement is reduced. Movements of all body parts need to be coordinated to keep the balance board or disk horizontal. In addition, the external focus instructions are more closely related to the goal of the task. Therefore one could argue that that external focus is advantageous to an internal focus on a subset of body movements, as the whole body needs to be coordinated in order to successfully accomplish the task.

The benefits of external focus for balance performance in postural control were limited, as they were only found for balancing tasks that were different than normal standing on a solid surface (Wulf et al., 2007). However, some support was found for the claim that external focus on a suprapostural task could also improve postural balance performance for standing on solid ground (McNevin & Wulf, 2002). In that study GRF data were collected for participants who were instructed to stand still while lightly touching a loosely hanging sheet with their fingertips. Instructions varied slightly between conditions. For internal focus they were asked to minimise
movements of the finger and for external focus they were instructed to minimise movements of the sheet. No difference in postural sway amplitude was found, but MPF (mean power frequency) was higher for external focus. It was concluded that response frequency and therefore balance responses were improved. One could argue however, that an increase in response frequency without a decrease in postural sway does not necessarily imply that balance responses are improved.

The discussed body of literature on attentional focus supports the beneficial effects of external focus on postural balance performance for young healthy adults. Whether this effect is also present in elderly is insufficiently studied. One study did conclude that external focus causes improved balance learning in healthy elderly. The effect of focus of attention on motor learning in postural control was studied in 32 elderly standing on a stabilometer (Chiviacowsky et al., 2010). On the first day of testing the external focus group had more ‘time in balance’, however this difference between groups was not significant. Learning effects were assessed with retention tests on the next day without focus instructions. These retention tests did show significantly longer ‘time in balance’ for the external focus group, however it was not tested whether the increase of ‘time in balance’ on the second day was larger for external than for the internal focus group. Therefore one could wonder whether this study showed a learning effect. Furthermore, the sample size of 32 participants might be too small for between-subjects comparisons of balance performance. However this study does suggest that the improvement of balance performance by external focus can be extended from the young adults to elderly.

1.5.4 Effects of attentional focus on gait performance
Studies on the effects of attentional focus on balance performance in gait are very scarce and their methodologies have been disputed. Canning (2005) studied gait of Parkinson’s disease patients who carried a tray with glasses during two conditions. For internal focus they were instructed to direct the focus of attention towards walking (“Attend to maintaining big steps while walking”) and for external focus towards balancing the tray of glasses (“Attend to balancing the tray and glasses”). Increased gait velocity and stride length was found for the internal focus condition. This operationalization of internal and external focus was criticised by Wulf (2013), as these instructions refer to two different motor tasks, as opposed to internal and external focus with regard to the same task. Furthermore, the internal focus
instructions did not refer to the body itself.

Shafizadeh *et al.* (2013) compared acute effects of attentional focus on gait as well. They assessed gait of multiple sclerosis patients walking on a treadmill. For internal focus, the patients focussed on foot performance presented on a screen, and for external focus they focussed attention on external markers and auditory information. The authors found increased stride length, step length, step speed and energy expenditure per step for the external focus condition. Based on these findings they concluded that external focus induced improved gait performance. However the different modes of feedback that were used for internal and for external focus might not result in a useful comparison. The difference in gait parameters might just be caused by the extra information that was presented through more sensory channels for the external focus condition. In addition, no dependent variables were tested that were directly related to balance and stability of gait.

In sum, research on the effects of internal and external focus of attention on gait performance in elderly could be improved by using measures of gait performance that have been related to falls in elderly.

### 1.5.5 Effects of dual-tasks on balance and falls

For most circumstances in daily life, balance control is performed with at least one other concurrent task that requires some degree of mental effort, e.g. thinking and/or talking. Therefore a body of literature on fall research in elderly assessed balance and gait performance while a concurrent cognitive task was performed as well. This experimental design is referred to as the dual-task paradigm. These dual-tasks have qualitatively different effects on postural control than fear, as differences in neuromuscular regulation were found which indicate distinct control processes (Stins *et al.*, 2011).

Dual-task performance has been related to fall risk. In a 5-year prospective study, executive function and dual-task gait variability were predictors for falls (Mirelman *et al.*, 2012). Dual-task intervention studies have also shown to improve balance, gait performance and dual-task gait performance in elderly (Dorfman *et al.*, 2014). In addition, dual-tasks have shown to acutely affect balance performance. Stins and Beek (2012) argued that even though fast reflexive postural adjustments are ‘cognitively
impenetrable’, attention demanding control can be exerted to some extent when needed. Evidence was found that some degree of attention might be needed in postural control for sensory integration and to respond to balance perturbations (Shumway-Cook & Woollacott, 2000; Woollacott, 2000; Redfern et al., 2001; Teasdale & Simoneau, 2001). Therefore some studies found that a concurrent cognitive task impairs balance performance (Maylor & Wing, 1996; Andersson et al., 1998; Shumway-Cook & Woollacott, 2000; Condron & Hill, 2002), however other research suggests that this cognitive-motor dual-task acutely improves balance performance (Dault et al., 2001; Andersson et al., 2002; Brown et al., 2002; Deviterne et al., 2005).

To explain these findings it was proposed in several papers that relatively easy (low effort) cognitive tasks improve concurrent balance performance, whereas more demanding cognitive tasks impair concurrent balance performance (Riley et al., 2003; Vuillerme & Nougier, 2004; Deviterne et al., 2005). This U-shaped relation between balance performance and cognitive dual-task difficulty was supported by Huxhold et al. (2006) for both young and older adults.

Lovden et al. (2008) tested whether this U-shaped relation between motor performance and concurrent cognitive task difficulty could be extended to gait. For gait performance the relation between variability of stride-to-stride gait parameters and cognitive task difficulty was tested, however no evidence was found for same U-shaped pattern. The results did show increased gait variability for increased cognitive demand for young adults, but not for elderly.

**Dual-task, internal and external focus of attention**

In line with the theory of reinvestment one could speculate that prevention of internal focus without movement related external focus of attention might also result in improved balance performance. This prevention of internal focus might be achieved through a dual-task. Therefore Wulf and McNevin (2003) investigated the effects of internal and external focus and dual-tasking on balance performance on a stabilometer in a retention study. For the dual-task condition participants were instructed to shadow (i.e. pay attention to) a narrated story played through a speaker system while balancing on the stabilometer. Balance learning occurred in all conditions, however the external focus condition showed increased balance learning compared to the internal focus, dual-task and baseline condition. No significant
difference was found between the control, internal and dual-task conditions. It was therefore concluded that simply distracting balance performers is not enough to improve balance performance. However, the number of participants was relatively small for a between-subjects analysis as 14 participants were included for each of the internal, external and control conditions and 13 for the dual-task condition. Furthermore, in addition to the internal and external focus conditions, the focus of attention or cognitive performance in the dual-task condition was not measured or assessed.

1.6  Analysis of kinematics

1.6.1  Gait stability and variability
To study gait, 3d kinematics of the body can be recorded to measure the movement patterns of the entire body. Spatiotemporal gait parameters, e.g. step length, step width, stance time and swing time can be calculated from these kinematic data. Variability of a gait pattern has been quantified with the coefficient of variation (CV) of spatiotemporal parameters. The CV is calculated as the standard deviation divided by the mean of the parameter and multiplied by 100 to express the variability in percentage of the mean. Gait variability is associated to fall risk (Hausdorff et al., 2001) and fall history (Hausdorff et al., 1997; Toebes et al., 2012).

More recently, the Local Divergence Exponent (LDE) has increased in popularity as a measure of gait stability (Rosenstein et al., 1993; Lockhart & Liu, 2008; Bruijn et al., 2010; Bruijn et al., 2012; Toebes et al., 2012; Rispens et al., 2014; Arvin et al., 2015). LDE, also called local dynamic stability and derived from Lyapunov exponents, can be calculated from kinematic data and is a measure of the average logarithmic rate of divergence of a system. Therefore, an increase in LDE represents a decrease in gait stability. A distinction is made between the short term and the long term LDE, where the short term LDE typically refers to the divergence within the time window of 1 step. Short term LDE was also found to be a predictor for fall history (Liu et al., 2008; Lockhart & Liu, 2008; Toebes et al., 2012) and was suggested to be an indicator of future falls (Lockhart & Liu, 2008). A popular method to calculate LDE was published by Rosenstein (Rosenstein et al., 1993).
Most gait research has focussed on steady state gait. However falls could be related to deteriorated responses to gait perturbations. Therefore gait stability has also been assessed through measurement of responses to mechanical perturbations of the gait pattern (Bruijn et al., 2010). Centre of mass velocity time series of these responses provide valuable information on the response amplitude and the time it takes to return to a normal gait pattern.

### 1.6.2 Statistical Parametric Mapping (SPM)

Balance responses in postural control and gait are measured as time series data. Statistical testing of time series usually involves scalar extraction and qualitative interpretation, e.g. selection of peak times and peak amplitudes. This is needed for most conventional methods of statistical analysis (e.g. ANOVA and student’s t-test) as they cannot handle time series as a whole as input data. However, each point in time is of interest in time series data of balance responses to a perturbation. Therefore a method of statistical analysis is needed that tests the whole time series of a certain variable. SPM is a validated method of statistical analysis where time series can be used as the unit of observation instead of scalar values. This allows for the often-neglected time dependence of the signal to be incorporated in statistical testing. This method is now increasingly used in the field of biomechanics (Pataky, 2012; Robinson et al., 2014; Serrien et al., 2015). SPM for time series is implemented by the open-source toolbox SPM1D (v.M0.1, Todd Pataky 2014, www.spm1d.org,) in Matlab (The MathWorks, Inc., Natick, Massachusetts, United States).

With SPM, traditional scalar tests are repeated for each time sample of the tested signal(s). E.g. with an SPM t-test, one could test at which points in time two groups of signals are significantly different from each other. The output statistic, \( \text{SPM}\{t\} \), contains a trajectory consisting of a t-test value for each time point. The critical threshold of significance is then defined based on the smoothness of the signals (Friston et al., 2007), random field theory expectations (Adler & Taylor, 2007) and the alpha value (typically 5%). The interpretation of significance is similar to a traditional t-test. When the \( \text{SPM}\{t\} \) trajectory exceeds the threshold of significance (alpha) at certain time samples, the null hypothesis is rejected for these time samples. The threshold is often exceeded during one or more time windows of the tested signals, due to interdependence of neighbouring points. Therefore these significant time
windows are called “supra-threshold clusters”. A single p-value is then calculated for each supra-threshold cluster (Adler & Taylor, 2007). See Figure 1.4 for an example.

Figure 1.4: Redrawn from Dingelen et al. (2015). In the top graph mean hip flexion moments are shown for drop vertical jumps (thick line) and single leg drop vertical jumps (thick dashed line). Shaded areas represent standard deviations. The bottom shows the SPM(t) trajectory of an SPM independent samples t-test. The dotted lines indicate the threshold of significance and the shaded areas are the supra-threshold clusters. The p-value is shown for each supra-threshold cluster.
1.7 Conclusions

The research field of human balance control in relation to falls is rapidly expanding. However, the mechanisms relating cognitive sensorimotor control, focus of attention and fear of falling are not well established. Many authors assume that fear of falling causes activity avoidance, which causes decline of balance performance and thereby increases fall risk. Although, this mechanism is widely accepted, no clear evidence for this theory was found. Multiple studies did support a direct relation between fear of falling and balance impairment, without mediation of activity avoidance. Using GVS and height-induced postural threat to induce fear of falling, vestibular balance responses were found to be amplified by fear of falling. However, it is debated whether these amplified vestibular balance responses affect balance performance. Full body kinematic measurements of the GVS induced sway response, could clarify the interplay of the short- and medium-latency response, its relation to fear of falling and to balance performance.

Furthermore, it was suggested that fear increases sensitivity to self-motion. Indeed, elderly with a history of falls show higher levels of reinvestment. Additionally, improved balance performance was found with external focus when balance is challenged. As such, the effects of attentional focus on balance performance are evident. However, a gap of knowledge exists regarding the effects that internal and external focus of attention could have on stability and balance in gait, specifically in elderly. Therefore, future research on the effect of fear on balance performance and studies on attentional focus strategies using gait performance measures that have been related to falls, might provide new intervention strategies to reduce the number of falls in elderly.

1.8 Aim and outline of the thesis

A gap exists in the literature on the effects of fear of falling on balancing reflexes and the effects of attentional focus on gait performance, especially in elderly. Therefore, the general aim of this PhD project was to assess the effects of fear of falling and focus of attention on human balance control.

Chapter 2 of this thesis describes a study conducted at the Manchester Metropolitan University on the effect of fear of falling on balance. Young healthy adults were stimulated with GVS to elicit vestibular balancing reflexes. To induce fear of falling they were stimulated while standing on a narrow 3.85 m high walkway. These
responses were compared to standing at ground level and measured using full body kinematics. The main aim of this study was to investigate whether fear of falling influences vestibular balancing reflexes or not. In addition we aimed to gain insight into the contribution of the short-latency response to balance and its interplay with the medium-latency response. Knowledge of these fundamental balancing mechanisms will expand our understanding of human balance performance and might advance future fall prevention methodologies.

Chapters 3 and 4 elaborate on the effects of attentional focus and fall history on gait variability and stability in elderly. This study was conducted at the Vrije Universiteit Amsterdam. Full body kinematics of elderly was collected while they walked on a split belt treadmill with a virtual reality environment to induce realistic optic flow. In addition, gait was perturbed by unilateral treadmill decelerations at unexpected time intervals. In Chapter 3 we focussed on the effects of attentional focus and fall history on the gait stability and variability of direct balancing responses to the perturbations. Attentional focus and fall history effects on stability and variability of the unperturbed gait bouts between perturbations are investigated in Chapter 4. If external focus would result in increased gait stability, new tools to advance the field of fall prevention could be developed. In Chapter 5 the collective findings in Chapter 2-4 are reviewed in a general discussion.