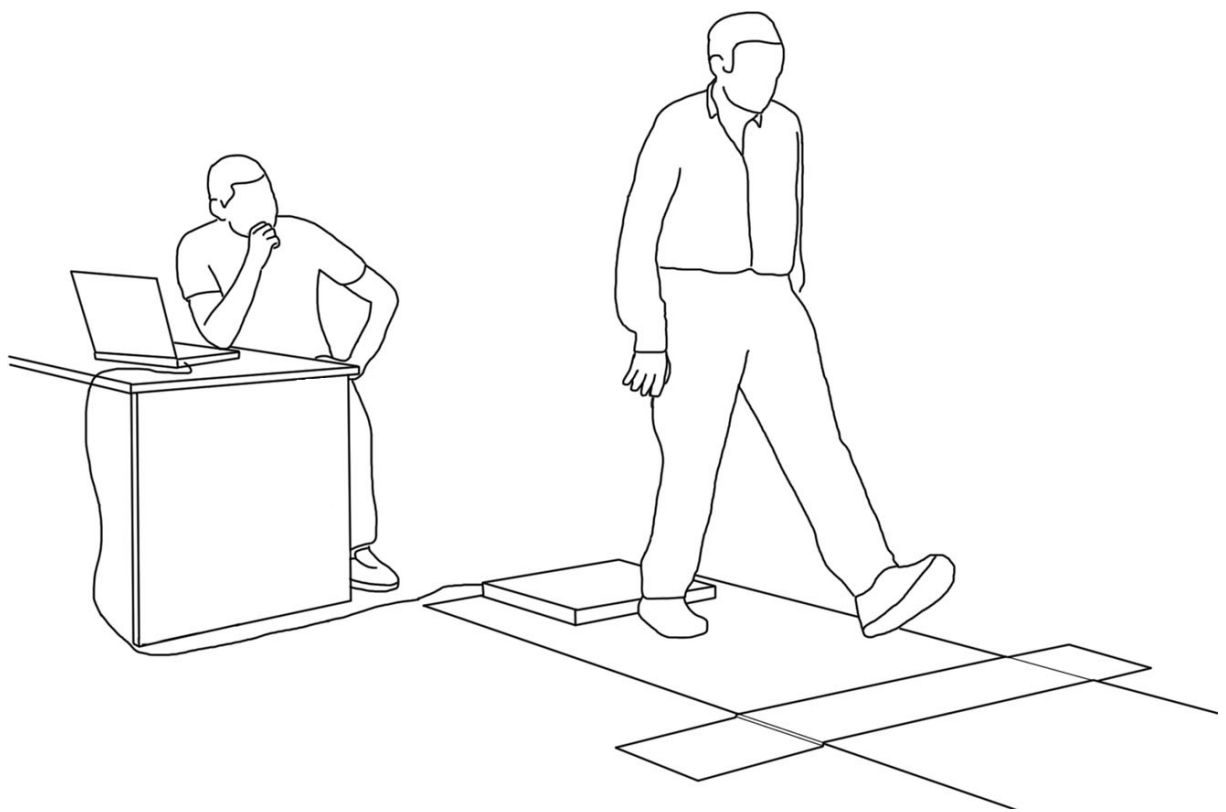# Are age-related changes in perceptual-motor regulation related to an increased falls risk?

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A thesis submitted in total fulfilment of the requirements for the degree of Doctor of Philosophy

December 2018

Action shot of Professor David N. Lee in the curb-approach task.
Artwork: Zachary Conway

Declaration

This thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No parts of this thesis have been submitted towards the award of any other degree or diploma in any other tertiary institution. No other person's work has been used without due acknowledgment in the main text of the thesis. All research reported in the thesis received the approval of the relevant ethics/safety committees (where required). The work presented in this thesis is that of the author and use or presentation of the ideas or work of other academics is referenced throughout.

Steven van Andel   Date: 07/06/2018

Acknowledgements

Many people describe the process of doing their PhD as a journey. As I moved from the Netherland to Australia to start my PhD project, journeying became a great part of my PhD. Such a big part, in fact, that it kind of spoils the analogy. Luckily, from the experiences of the past couple of years I have learned that there is an even better analogy than saying a PhD is like a journey. A PhD, is like a very long MasterChef invention test.

When you start your PhD you are blown away by all the ingredients in the pantry. So many directions you can take the research, so many topics and methods. You start cooking and are hoping that one of the judges (read: supervisors) will visit your bench and give you a push in the right direction. For their great guidance throughout the cook, I thank Dr. Michael Cole and Dr. Gert-Jan Pepping. Both of you have been invaluable throughout the process and I know that this thesis would not have tasted so good without that mentorship. I feel ready to conquer the world of academia and this is all thanks to you. A special thanks to Gert-Jan, you have inspired me ever since my first lesson 'introduction to psychology' in the first year of my bachelor in Groningen. Without you, this Australian thesis and potentially even this research career would never have existed.

Luckily, the plan of the meal becomes clear and the ingredients of the thesis become apparent. It is important to consider your ingredients well, for instance in order to know when you need to add sugar or rather a 'sugar-like substance'. Furthermore, next to the usual staples like eggs, flour and salt (read: determination, motivation and hard work), a thesis in the field of ecological psychology also needs something sweet. For this reason, a quote of J.J. Gibson needs to be included in the introduction. In MasterChef, a crunchy element is always well received, so we decided to use some 'crunchy' technology from the 90s in our methodology[1]. And since it is an invention test, it has to be novel; new methods, new variables and new conclusions!

As any MasterChef viewer could tell you, drama always increases mid-cook. Dr. Matthew Pink[2] warned me for this mid-cook stress. In anticipation of turning 'crazy by thesis', I knew I needed some form of social support. And, as in MasterChef, I found this in my 'fellow competitors', my colleagues and fellow students at the School of Exercise Science. I thank everyone in the school who has helped to make me feel welcome when we just arrived in Australia and who has become a good friend in the years following. I am thankful for the friendships we have built and I know that these

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[1] With all issues one would expect when using tech that is almost as old as I am myself. Our occlusion goggles experienced around 7 different issues in little over a month. I acknowledge Dan Chalkley for not letting these issues turn into months of delays on my thesis. He is very capable in making other people's PhD projects more efficient…
[2] At that time still Mr. Matthew Pink

will remain alive for the years to come. In the end I don't think I really experienced the horrible thesis-related-stress Matt warned me about and I think this is thanks to you.

And how good is[3] that episode they always have, in which friends and family come visit the MasterChef kitchen? I have enjoyed much support from friends and family back in the Netherlands. Many of them have even come and visit us in Australia[4]. I am very grateful for this support and therefore I thank you all! In particular I thank my parents who visited us, even though they are not exactly fond of traveling these types of distances. Success in a doctoral project starts way before the actual project; it starts with the support of your family, for which I want to thank you. Furthermore, the experience of seeing how my dad finished his own 'doctoral-cook' not long ago has been an inspiration in my project.

In the final year of a PhD one question becomes paramount: what will be the hero of the dish? Will we write the chapters focused on theory? Or will we write about the practical implications? Will we use analyses that have been used and tested in different previous studies or will we create our own? I have discovered that for every chapter you need to consider what you make the hero of the dish and how this fits in a 7-course meal, the thesis. But as the judges start the count down, the meal always comes together[5].

Finally, like every world renowned chef will tell you, every recipe needs one final ingredient: a spoonful of love. For this I have found a person that was crazy enough to move to Australia with me, even though I know she still misses friends and family in the Netherlands every day. Myrna, I thank you for all your love and support in these three years. Also, I am especially thankful for the fact that you have pulled me away from my desk every once in a while, to have us experience Australia. I love all of the adventures we have shared in this time and I know there are many more to come.

Eet Smakelijk![6]

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[3] For using the words 'how good is….' I acknowledge EXSC 'lunchtime banter'.
[4] And some particularly supportive in-laws even twice!
[5] I believe footnotes are like the seasoning of the thesis. After this section I will limit myself to only relevant footnotes, however, in this acknowledgements section the footnotes should be taken with a grain of salt.
[6] Dutch for: 'Eat Tastely' or 'enjoy your meal'!

Abstract

Introduction

Decades of research have shown that approximately one in three older adults, aged 65 years or older, falls at least once each year (Campbell et al., 1990; World Health Organization, 2007). This is a problem in our ageing society; as the number of people in this aged cohort continues to increase, leading to an expected increase of falls and falls related medical costs in the coming years (Hendrie, Hall, Arena, & Legge, 2004). The consequences of falling are not only severe in terms of medical costs, for older adults a fall means injuries, decreases in quality of life and could even lead to death (Burns, Stevens, & Lee, 2016).

The current thesis adopts an ecological approach to investigate opportunities for falls prevention. According to an ecological approach, guidance of action is mediated by the perception of 'opportunities for action' or 'affordances' (Gibson, 1979). These affordances are always action scaled; a person perceives possibilities for action in relation to his or her own action system. For instance, a curb might afford 'stepping onto' for me, as I have sufficient leg length and strength to perform a step up, however, it will afford 'climbing onto' for a toddler who's legs might not yet have the length to afford stepping onto the curb. Perception of affordances is therefore influenced by how well a person knows his or her own capabilities or in other words how well one 'calibrates' perception and action. To achieve this calibration, one needs to experience of 'explore' one's action system, or, as Gibson (1979) put it: "…we must perceive in order to move, but we must also move in order to perceive" (p. 213). This cyclic nature of perception forms the basis for the perception and action cycle and perceptual-motor coupling.

The perception and action cycle can help to understand successful movement and therefore potentially to explain movement errors (such as the ones leading to falls) as well. If one component of the perception and action cycle is unsuccessful it could affect success in movement. For instance, if a person would not calibrate properly, making one insecure about one's own action capabilities, it might lead to insecurities in moving around. From this it follows that for successful performance, it is important to successfully couple perception and action.

Since most falls occur during locomotion (Berg, Alessio, Mills, & Tong, 1997), the current thesis aimed to study the perceptual-motor regulation of walking. This thesis builds on the understanding of perceptual-motor coupling established in another locomotor task; the long jump approach, in which an athlete is required to regulate foot placements so that the final footfall of the approach lands exactly on the take-off bar (De Rugy, Taga, Montagne, Buekers, & Laurent, 2002; Lee, Lishman, & Thomson, 1982; Montagne, Cornus, Glize, & Quaine, 2000). Specifically, the main

aim of this thesis is to assess perceptual-motor coupling in older adults using a locomotor pointing paradigm similar to the approach in a long jump and to study changes in perceptual-motor coupling in ageing and their relation to falls risk.

Aims, Methods and Results per Study

The current study incorporates four inter-related studies with differing methods. The first study (described in Chapter 2) is a systematic review, which sought to investigate the perceptual-motor calibration component of the perception and action cycle. The aim of this study was to assess in what conditions calibration occurs most efficiently, with a sub-aim to assess what is known about age-related changes in calibration. Seven databases were screened to identify literature that combined topics related to 'perception', 'action' and 'calibration' or 'scaling'. Twenty-three papers satisfied the inclusion criteria.

Results of the first study showed that calibration occurs rapidly if the movements performed to explore the perceptual and action coupling provide relevant information for perception. For instance, when standing height is raised by placing a participant on 10-cm high blocks, calibration occurred rapidly when participants were allowed to walk with the block (allowing much exploration), but not when only allowed standing stationary with no body movement (Mark, Balliett, Craver, Douglas, & Fox, 1990). Furthermore, this study identified a general limitation in the research on calibration; no studies have been identified that have studied calibration to changed action capabilities in an older cohort.

The second, third and fourth study in this thesis (described in Chapter 4, Chapter 5 and Chapter 6) all use the same 'curb-approach task' to study the regulation of gait towards a target. For each trial in the curb approach task, participants were positioned at the far end of an 8m long GAITRite pressure sensitive walkway (GAITRite®, CIR Systems, Inc., Franklyn, NJ, USA). At a 'go' signal, participants started walking the length of the walkway (placing one footfall on a target that was randomly placed in the first 3 meters of the walk to prevent participants from performing identical walks in each trial), to the end of the walkway where a curb-like platform (L: 2m, W: 1m, H: 0.15m) was positioned. Participants stepped onto the platform and continued to the far end at which a push-button was positioned that signaled the end of the trial. 33 trials were performed per participant.

Outcome measures of the curb-approach task were related to three analyses introduced in previous studies in locomotor pointing (De Rugy, Taga, et al., 2002; Montagne et al., 2000). Firstly, an analysis was introduced that assessed the changes in variability (standard deviation) of the position of foot placements. Secondly, an analysis was introduced that assessed whether the timing of the initiation of adaptations in gait (deviations from a 'standard' step) are related to the total amount of adjustments to be made (indicating a perception-action coupling). Finally, an analysis was introduced

that assessed the strength of perceptual-motor coupling; the degree to which changes in step length depended on the perception of required adjustments.

The second study (as described in Chapter 4) aimed to assess whether successful performance in the curb-approach task required similar perceptual-motor regulation compared to the long-jump run up. Sixteen younger adults were included and ask to perform the curb-approach task. Results confirmed the similarities between the curb-approach and the long jump approach. Regulation seemed to be initiated earlier in the curb-approach compared to the long jump, but a similar pattern was observed in decreasing variability of foot placement and an increasingly stronger perceptual-motor coupling as participants got closer to their target in both tasks. The second study concluded that the curb-approach task would provide an effective paradigm to study perceptual-motor regulation in an older cohort (for whom a long jump would be too demanding).

The third study (Chapter 5) aimed to assess age-related changes in regulation in the curb approach task. In this study, the data collected from the 16 younger participants (study2) was compared to data collected from a cohort of 105 older adults. Results showed that with older age, participants showed less variability in foot placement during their approach. Furthermore, it was shown that with age, participants were more likely to adopt a strategy that involved shortening rather than lengthening of steps. Age-related changes were most prominent in the measures of strength of perceptual-motor regulation. Similar to the younger participants, older participants showed an increased strength of coupling (or in other words; made stronger adjustments) as they got closer to the curb. However, it was also shown that with age the strength of the coupling over all steps increased, indicating that the older participants made stronger gait adaptations.

As the third study identified that age-related changes are most prominent in the measures of perceptual-motor coupling, it was decided to focus the final study (Chapter 6) on the question whether these changes could be related to an increased risk of falls. Ninety-eight participants were included in the analysis for this study, who first performed the curb-approach task and then were entered in a 12 –month follow-up to screen for the occurrence of gait-related falls. Results showed that participants who reported experiencing a gait-related fall showed stronger perceptual-motor coupling (stronger gait adaptations) in stepping onto the curb.

Discussion and Conclusion

The results of this thesis showed that the curb-approach task provides a novel and valid method to measure perceptual-motor regulation of locomotor pointing in in a low demands setting, suitable for the older cohort. Older adults showed stronger gait adaptations compared to their younger counterparts and adaptations in the step onto the curb were stronger still in in older adults prone to experiencing gait-related falls. These results suggest that, in controlling gait, humans are

capable of changing the strength of perceptual-motor coupling in accordance with the difficulty of the task. With age, action capabilities decrease and the curb-approach task becomes harder; our results show that this is met with a strengthening of perceptual-motor coupling. Implications of the current thesis are that in falls risk screenings as well as falls prevention, it is important to consider the entire perception and action cycle. An ecologically-grounded functional approach to healthy aging is advocated which considers a person in relation to his/her behavior and environment (Vaz, Silva, Mancini, Carello, & Kinsella-Shaw, 2017).

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Chapter 1 - General Introduction

Chapter 1 – General Introduction
1.1 Falls and Perceptual-Motor Coupling

In the current aging society, falling in older adults is a major problem (World Health Organization, 2015). An accidental fall has been defined as "inadvertently coming to rest on the ground, floor or other lower level, excluding intentional change in position to rest in furniture, wall or other objects" (World Health Organisation, 2007, p.1). Maintaining balance requires perceptual-motor coupling, as the perceptual systems are used to perceive the orientation of the body and unexpected perturbations, which are used to produce appropriate movements for remaining upright posture (Collins & De Luca, 1993). Whilst falls in older adults have been extensively studied, previous research has mainly focused on organism limited factors, such as physiological and mechanical risk factors, whilst success and failure in perceptual-motor control can primarily be attributed to the relationship between a person and their environment. In this chapter, the relevance of studying falls using such a relational, ecological approach is outlined.

Falls experienced by older adults have been a focus of extensive research over the past three decades, with research reporting that about one in three adults aged 65 and over fall at least once each year (Campbell et al., 1990; Campbell, Reinken, Allan, & Martinez, 1981; Prudham & Evans, 1981; Tinetti, Speechley, & Ginter, 1988). This collective body of research has led to an improved understanding of the risk factors (Ambrose, Paul, & Hausdorff, 2013; Deandrea et al., 2010) and circumstances (Berg et al., 1997) that contribute to the falls experienced by older adults. The consequences of falling for older adults can be significant for both the individual and society. For instance, even non-injurious falls can lead to a fear of falling and decreases in activity levels (King & Tinetti, 1995). Furthermore, due to numerous age-related comorbidities such as osteoporosis, falls are the leading cause of injury in the older cohort (Hartholt et al., 2011) and, in extreme case, can lead to death (Burns et al., 2016).

Falls-related health care costs worldwide are substantial; in the United States of America, total medical costs related to falls in 2015 were reported to be around US\$ 637.5 million and US\$ 31.3 billion for fatal and non-fatal falls, respectively. Costs per faller were reported to be US\$ 26340 for fatal and US\$ 9780 for non-fatal falls (Burns et al., 2016). Similarly, between 2007 and 2009 in the Netherlands, the costs attributed to falls were reported to total € 675.4 million annually; equating to an average of € 9370 per fall (Hartholt et al., 2012). Eighty percent of the costs attributed to falls are related to fractures (mainly hip), followed by about 10% of the total costs relating to concussions (Hartholt et al., 2012). These costs are a serious burden on society and with the growing number of older adults, the costs are expected to increase further in the future (Hendrie et al., 2004; World Health Organization, 2015).

It is this substantial burden of falls on society as well as the individual that provide the relevance for research to focus on falls. This research stream has introduced numerous interventions

aimed at falls prevention, through minimizing the risk factors in older adults. Exercise interventions that provide a challenge to balance seem to be one of the most effective methods for modifying some falls risk factors (El-Khoury, Cassou, Charles, & Dargent-Molina, 2013; Sherrington et al., 2008). In fact, in a previous systematic review and meta-analysis, Sherrington et al. (2008) reported a 17% reduction in falls as a result of regular participation in structured exercise programs. Whilst a 17% reduction in the incidence of falls is a remarkable success that would contribute to reduced morbidity and mortality in this population, it is clear that there is still scope for improvement.

This chapter aims to outline a theory that could provide a rational for future falls prevention studies and interventions that is not organism limited, but considers the relationship between a person and the environment. We will outline falling as a consequence of an error in movement control and will assume the perspective of ecological psychology to explain why errors occur as a result of the interaction between perception and action.

1.2 Exploration, Calibration and Affordance Perception

To understand what causes movement errors, such as falls, it is important to understand how movement is regulated successfully. According to ecological psychology, successful movement comes about through the coupling of perception and action. In the words of the founding father of ecological psychology, James Gibson (1979): "…we must perceive in order to move, but we must also move in order to perceive" (p. 213). In other words, perception is required for the successful performance of action, but at the same time, (exploratory-) action is required to gather the information that serves perception. The current thesis focusses on this perceptual-motor coupling on a holistic level; how movement is controlled through this perceptual-motor coupling. However, to fully understand this coupling, it is important to gain an understanding of the components underlying the coupling. This section will therefore introduce the terms 'exploration', 'calibration' and 'affordance perception' and embed these in the perception and action cycle which, as a whole, underlies perceptual-motor coupling.

The work of James Jerome Gibson is the first to describe that the control of movement is directly dependent upon one's perception of affordances (Gibson, 1979). Affordances can be defined as relations between an animal and it's environment; the 'possibilities for action' that depend both on the demands in the environment as well as the capabilities of the animal (Chemero, 2003, 2009; Gibson, 1979).

Information specifying affordances is picked up by an actor from the environment; for instance in terms of locomotion, an affordance 'path of safe travel' is optically specified and will attract behaviour and a person will be drawn towards traversing this path. Similarly a potential hazard will repel behaviour and a person will seek to avoid the hazard (Gibson, 1958b; Warren, 1998). Perceiving affordances and consequently producing successful movement occurs by exploring

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the abundance of information available from the many different informational arrays (i.e. visual, auditory, and tactile) in the agent-environment system. A person actively explores these arrays in order to guide movement (Gibson, 1979), in the case of locomotion for which information of outside the body is relevant, visual information is dominant. By moving around, a person creates optic flow which is visually picked up. This optic flow can inform the person about their current speed (by flow rate), direction of travel (indicated by the point of flow expansion) as well as time to contact (by rate of expansion of an object's optical size) with potential hazards (Gibson, 1958b; Warren, 1998). This description illustrates the richness of visual information about possibilities for action that can be used in the regulation of locomotion. Furthermore, this affordance perception is highly personalized. A potential 'path of safe travel' for one person might not be safe for another, depending on the person's action capabilities. For instance, a path through a tight junction might be passable for a person with a small shoulder width, but not passable for a person with broader shoulders. In fact, Warren and Whang (1987) studied the ability of individuals with varying degrees of shoulder broadness to judge whether they could safely pass through spaces of different widths. They found that participants decided how to pass through different-sized apertures (frontal or turning) based on how wide their shoulders were. These findings indicate that one's perception of a 'path of safe travel' is influenced by the physical characteristics of the person. This example in the relationship between shoulder width and pass-ability of apertures is just one of the research examples that show that perception of affordances is scaled to the action capabilities of the observer, a result that since then has been repeated in numerous studies (for a review, see Barsingerhorn, Zaal, Smith, & Pepping, 2012).

It should be obvious from the above that the perception of affordances is scaled to one's own action capabilities. This underlines the relevance of accurate perception of both the environment as well as one's own capabilities. Scaling the environment in terms of one's own capabilities has been referred to as (perceptual-motor) calibration (Bingham & Pagano, 1998; Warren, 1984; Withagen & Michaels, 2005, 2007). To be calibrated or 'to know your limits' is sometimes of life saving importance. Take for instance the situation when braking to stop a car. During this task, it is vital that one starts braking early enough to ensure that the braking force that is applied will stop the car without exceeding the maximal braking capabilities of the vehicle (Fajen, 2005c). In a series of studies, Fajen and colleagues showed that 'being calibrated' is relevant to a series of skills such as braking (Fajen, 2005c, 2007b) and overtaking (Morice, Diaz, Fajen, Basilio, & Montagne, 2015) in an automobile (see also Fajen, 2007a). In addition to showing the relevance of calibration to ongoing action, this series of studies also exemplified how people cope with a disturbance in calibration. In the setup of braking a virtual car, the experimenters changed the braking capabilities of the car halfway through the experiment. Participants were shown to be able to

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rapidly regain calibration and learned to slow the vehicle effectively using the new scaling of the brake pedal (Fajen, 2007b). Furthermore, it was shown that participants could successfully calibrate to a new scaling when visual information was limited via optical occlusion that occurred one second after braking was initiated (Fajen, 2007b).

Calibration after a disturbance of one's perception or action is a process that has not only been investigated in ongoing, visually guided actions such as braking; it has also been researched in 'affordance judgements' (the judgement whether a certain action is possible or not). Classic in this line of research are the studies of Mark (Mark, 1987; Mark et al., 1990). In these studies, participants' action capabilities were altered by attaching 10 cm high blocks to their feet; raising their leg length and thus eye height by 10 cm. Subsequently, participants were asked to assess their new capabilities for sitting (in terms of the maximal seat height they could sit on in standardized posture). It was shown that the accuracy of these judgements was dependent on how much the participants could explore their new action capabilities. When participants could walk around between judgements, calibration occurred effectively and participant judgements increased in accuracy quickly. Similarly, when participants were not allowed to walk around, but were allowed to perform stationary movements (such as body sway), calibration still occurred, although slightly less rapid. In contrast, when exploratory movements were restricted (by fixing the head or watching through a peek hole), recalibration did not occur and judgements remained inaccurate (Mark et al., 1990).

Following the studies of Mark and colleagues (Mark, 1987; Mark et al., 1990), Stoffregen, Yang, and Bardy (2005) investigated when people engage in exploration for calibration. Their study also involved a similar judgement of maximal seat height, after raising leg length with 10 cm blocks. In contrast to the studies of Mark (1987; Mark et al., 1990), Stoffregen et al. (2005) measured postural sway during the experiment. Interestingly, this study showed that participants tended to stabilize whilst making these judgments, yet sway increased between judgements. This indicated the duality in the task; when asked to make judgements, participants seemed to minimize sway to stabilize their head and eyes and presumably to facilitate perception. Yet, when no performance goal was present (the time between judgements), postural sway was increased as if switching from a performance-oriented goal to an exploratory goal. Furthermore, Stoffregen and colleagues found that specific aspects of postural sway were associated with successfully calibrating (Stoffregen et al, 2005; see also Reed, 1996). This exemplified the exploratory nature of postural movement; information about the state of the body is created by moving the body around and this information can aid affordance judgements (Bonette, Riley, & Verduijn, 2013; Riccio, 1993; Stoffregen et al., 2005).

1.3 The Perception-Action Cycle

"Perception is active, not passive. It is exploratory, not merely receptive ... Exploratory movements of the eyes, the head, and even locomotor exploration in the surrounding may all be thought of as a search for more information" (Gibson, 1958a)*, p. 43).*

Research in the field of ecological psychology often states that perception and action are coupled in a cyclical manner: perception is required for action and action leads to new perception. The above quote from Gibson (1958a) shows that this is somewhat of an over-simplification; that is to say that more factors are relevant in the perception and action cycle. This quote, in particular, introduced the role of exploration as a means by which action is used to create new information to be perceived. In a description of the perception and action cycle, the role of exploration should not be underestimated.

As stated by Gibson (1979), perception is of affordances; affordances being the relation between an agent and it's environment (Chemero, 2009). Hence, a person needs information about its own action capabilities in that specific environment to provide the basis for calibration. This information is gathered by means of exploration; the process of actively gathering information that specifies the scaling between perception and action. Figure 1.1 shows an interpretation of the perception-action cycle that includes the concepts of exploration and calibration. On the action side, the distinction is made between exploratory and performatory action, resembling the separate phases in the experiment of Stoffregen et al. (2005). In this distinction, note that exploratory action would be the action that is exclusively aimed at generating new information for perception. In
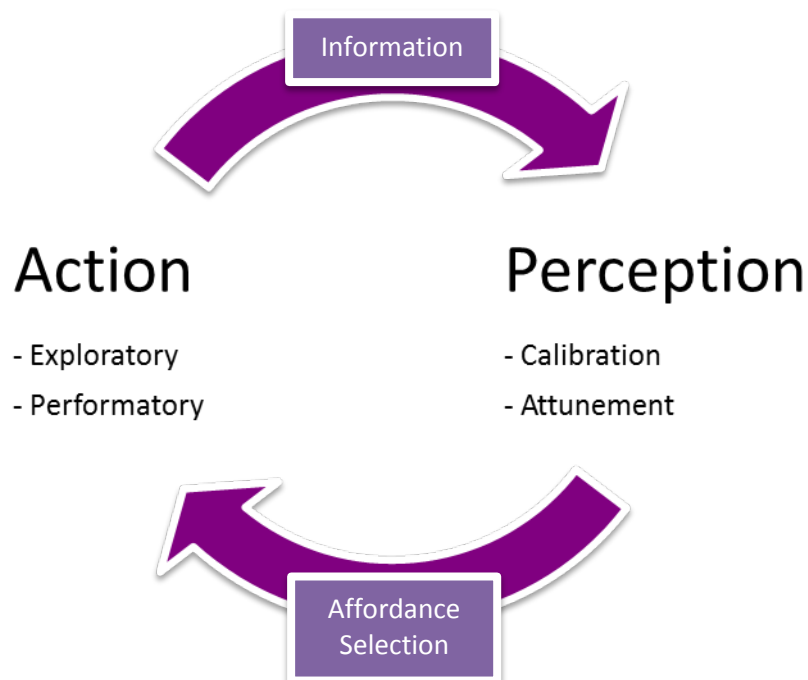
Figure 1.1 The perception and action cycle.

contrast, performatory actions are those that are primarily goal-directed actions; although this does not mean that performatory actions do not result in the acquisition of new information. In fact, in most natural movements, exploration would not be distinguishable from goal-directed action. For instance, when walking towards a target, the progression through the environment is goal-directed, but also generates the optic flow that is informative of heading and walking speed (Warren, 1998).

On the perception side of the model (Figure 1.1), two concepts are introduced: calibration and attunement. As discussed, calibration entails the scaling between action capabilities and the environment. Attunement or 'the education of attention' is a form of perceptual learning that refers to the ability to perceive an optimal (specifying) variable in perceptual judgements and the control of action (Withagen & Michaels, 2005). A sub-optimal or non-specifying variable is an informational variable that is not one-to-one related to an environmental property and using a non-specifying variable judging the environmental property could thus lead to errors. Using experience and feedback, people learn to attune to specifying variables instead on non-specifying variables, which improves their judgements and behaviour (Withagen & Michaels, 2005). In other words, attunement is about identifying and using relevant informational variables.

Finally, a note needs to be made on affordance selection. Affordance selection is the process that determines decision making (Gibson, 1979; Warren, 1988). A person's environment offers possibilities for action, for instance a chair would afford 'sitting-on' and a closed door would afford 'opening and walking through'. Yet, when both a chair and a closed door are present in one's environment (or in fact, when any combination of competing affordances is present), how does one decide what to do? According to Withagen, de Poel, Araújo and Pepping, (2012) this is partly based on the inviting nature of affordances; when an affordance is perceived it will invite a certain behaviour. For instance, for most humans, a chair would invite 'sitting on' more than it does 'climbing onto', although both are afforded actions. This inviting character of certain affordances over others forms the basis for a 'survival of the fittest'-type competition between potential actions until a certain action is selected (Reed, 1996; see Cisek & Kalaska; 2010, for a neurological interpretation). When we say, as above, that perceptual-motor coupling is required for the successful control of action, it implies that all elements of the perception and action cycle are achieved to a satisfactory level. It means that, in successful motor control, an actor has gathered sufficient information through exploration to reach an accurate calibration in a specific task, this leading to the selection of an affordance that guides a successful movement. Any errors in movement control could thus be the result of an error of the components of the perception and action cycle (e.g. insufficient calibration through insufficient exploration). Since calibration seems to be the central concept connecting exploration and affordance perception and there have been suggestions that this process

deteriorates with age (Fernández-Ruiz, Hall, Vergara, & Díaz, 2000), it was decided to focus the first part of the thesis on this concept, to assess its role in explaining falls incidence in older adults. It should be noted, however, that in natural movement these sub-components of the perception and action cycle are hardly distinguishable. For instance, in walking, the performatory action of propelling one's self forward will also serve as exploration and generate information to calibrate the ongoing action. For this matter, we reason it is important in understanding natural movement to have an awareness of the components of the perception and action cycle, but in interpreting natural movement (and the results in the current thesis) a more holistic approach would be appropriate; to analyse the perceptual-motor coupling in general.

1.4 Perceptual-Motor Regulation of Locomotor Pointing and Falls Risk

The perception-action cycle (Figure 1.1) can be used to describe behaviour, whether it be of a performatory or exploratory nature. It also could provide insight in movement errors that might occur. For instance, in biomechanics research, variability in postural control has often been interpreted as noise and unwanted error of the postural system. In line with recent views on postural control (Bonette et al., 2013) our interpretation of the perception-action cycle suggests that variability is not inherently a bad thing. The resultant postural sway could be of an exploratory nature and, hence, result in information that is relevant for motor control (Bonette et al., 2013; Haddad, Rietdyk, Claxton, & Huber, 2013). The postural system is an interesting example of this mechanism as minimizing sway would be the optimal strategy for performance of this system (to remain upright), yet any type of exploration requires the opposite: movement in the system.

As illustrated by this discussion on postural sway, some of the movements that have been biomechanically categorized as errors (such as increased postural sway) but do not hold negative consequences, might in fact be functional (exploratory). Another example of a task in which variability has traditionally been interpreted as error is the long jump run-up. It has been reported that long jumpers attempt to create a stereotypical stride pattern with minimal variability in foot placement throughout their run-up (Lee et al., 1982). However, research has shown that, in fact, footfall variability throughout the run-up is considerable and visual regulation is used to minimize variability in the final couple of strides (Hay, 1988; Lee et al., 1982). Arguably, only the variability that is left in foot placement at the take-off bar could be considered as error as it is the goal of a long jumper to minimize variability at this point.

Similar to the run-up in long jumping, many everyday situations encountered in walking are similar in regulation to the long jump. For instance when we walk across the street to step onto a curb or when we need to place our foot on a stable stone on a bushwalking track. All of these are examples of locomotor pointing; the act of placing either foot at a specific target while maintaining

locomotion (De Rugy, Montagne, Buekers, & Laurent, 2000b). However, these different examples of locomotor pointing activities each have their own unique level of task demands (Montagne, Buekers, De Rugy, Camachon, & Laurent, 2002). That is, the spatiotemporal demands in a long jump are high, as an athlete needs to be as accurate as possible with their foot placement, in spite of their high-speed run up. In walking to step onto a curb, the spatiotemporal demands are much lower; one can take as long as one needs and the placement of the feet is not exactly dictated by the task. Locomotor pointing activities with varying task demands have been shown to have different requirements for control, such that activities that have higher task demands require a greater control. Cornus, Laurant and Laborie (2009) showed this by having participants walk to approach and step over obstacles at different speeds, the strongest control was shown in the task that involved the fastest walking speed. Outside the lab, locomotor pointing is similarly constrained by task demands; when inaccurately placing a foot on a curb, the curb might be rendered a tripping hazard (in this case, variability on top of the curb could arguably be considered 'unwanted error').

The model presented in Figure 1.1 can, in part, explain movement errors (such as errors in foot placement that could lead to falling). As an individual ages, the efficacy of motor systems steadily decline (Larsson, Grimby, & Karlsson, 1978; Lindle et al., 1997), which directly influences action capabilities and, hence, the perception and action cycle. This relationship has been highlighted in research showing that calibration to disturbances in the perceptual information is less efficient and takes longer in older participants (Fernández-Ruiz et al., 2000). On this basis, it could be hypothesized that movement errors in older adults are the result of incomplete calibration and age-related changes in the coupling of perception and action.

As falling could be the result of changes to perceptual-motor coupling, it would be important to assess falls risk in an assessment that monitors both perception and action. However, traditional falls risk screenings often only include items that either assess the perception or the action system separately (e.g. Bloch et al., 2013; Fernie, Gryfe, Holliday, & Llewellyn, 1982; Lord, Menz, & Tiedemann, 2003; Tiedemann, Lord, & Sherrington, 2010; Viccaro, Perera, & Studenski, 2011). One method that would enable the measurement of perceptual-motor coupling is using a locomotor pointing paradigm, which requires a tight coupling of perception and action (De Rugy et al., 2000b; De Rugy, Montagne, Buekers, & Laurent, 2000a; Lee et al., 1982; Montagne et al., 2000). It could be hypothesized that by monitoring the regulation of foot placement in locomotor pointing, it is possible to monitor the effectiveness of perceptual-motor coupling and potentially to explain errors in locomotion.

1.5 Aims of this thesis

This chapter has introduced a model for perceptual-motor coupling, which underlines the relevance of perceptual-motor coupling for successful movement. Following from this model (Figure 1.1), it should be clear that falling in older adults can potentially be explained by using a paradigm that investigates both perception and action. In an athletic context, it was reasoned that locomotor pointing in the long-jumping approach would be an adequate method to study perceptual-motor coupling. The overall aim of this thesis is **to assess whether we can measure perceptual-motor coupling in older adults using a locomotor pointing paradigm and to study changes in perceptual-motor coupling with aging and in relation to falls incidence.** To reach this main aim, this thesis has been divided into sub-aims that will be discussed in the following chapters.

Chapter 2. This chapter singles out perceptual-motor calibration, one component of the perception and action cycle, which underlies perceptual-motor coupling. It was aimed to review the literature on perceptual-motor calibration and aging and assess the current understanding of changes to the perception and action cycle with the aging process. A gap in literature was identified that shows that little is known about calibration in an aging cohort.

Chapter 3. In the third chapter, the general methodology used in Chapters 4, 5 and 6 is introduced. This chapter is aimed at providing a better understanding of the methodology and the outcome variables discussed throughout this thesis.

Chapter 4. The fourth chapter aimed at producing an assessment tool that is able to measure perceptual-motor coupling in a walking task, which can be administered in an aging population and by people at risk of falls. With the development of this tool, the later chapters of this thesis will assess age related as well as falls related differences in perceptual-motor coupling.

Chapter 5. Following chapter 2, which showed the gap of knowledge on age-related changes to perceptual-motor coupling, chapter 5 aimed to address this gap and assess the influence of age on perceptual-motor coupling in a walking task.

Chapter 6. Chapter 6 will investigate whether the age-related differences discussed in chapter 5 also contribute to an elevated falls risk, in particular, the risk for a fall during gait. The results of this thesis will contribute to new knowledge regarding age-related changes in perceptual-motor regulation of walking and will provide important information for understanding the mechanisms of falling. This can be used to design new falls prevention interventions for older cohorts.

Chapter 7. Chapter 7 contains the general discussion to this thesis. In this chapter, results will be summarized and relevance for future research and clinical healthy aging practice will be discussed.

1.6 How to read this thesis

This thesis is founded in the ambition to use perceptual-motor control theory in the applied field of healthy aging. Furthermore, this thesis is built up in seven chapters, three general sections aimed at introducing the thesis and four studies that have all been accepted or submitted to peer-reviewed scientific journals. From this structure, it follows that the chapters in this thesis might follow jargon of the specific field of publication. That is, chapter 2 and 4 have been written in a theory-oriented way, whilst chapter 5 and 6 are written aimed at a more applied audience. For this reason, chapter 2, 4, 5 and 6 will start with a synopsis, which describes the study in plain language and highlights the main points for the flow of the thesis.

Chapter 2 - A Systematic Review on Perceptual-Motor Calibration to Changes in Action Capabilities

The study described in this chapter has been published following peer review. Full reference details are:

Chapter 2 - A Systematic Review on Perceptual-Motor Calibration to Changes in Action Capabilities

2.0 Synopsis and relevance for this thesis

In understanding age-related changes in perceptual-motor coupling in the regulation of walking, the current chapter aimed to investigate perceptual-motor coupling over the lifespan. Following the perception-action cycle described in Section 1.3 The Perception-Action Cycle, in this chapter perceptual-motor calibration was identified as a key concept in this perceptual-motor coupling. The current knowledge was investigated on how calibration is influenced by exploration and whether this process changes over the lifespan.

Using a systematic analysis of the literature, it was found that all studies of calibration have certain mechanisms in common; calibration benefits from the experience of movement or, exploration. In principle, minimal exploration is required to produce optimal calibration, if exploration is performed of a relevant movement, yet more exploration could be required if the exploratory movements are less relevant. Furthermore, the results described in this chapter show that very little are known about the effects of aging on the process of calibration. The maximal average age of the participants in the studies included in the systematic literature analysis was 36 years old; showing a limitation of this field of research in terms generalizability to older adults.

In terms of relevance for the thesis, it is important to understand that for motor control, people make a coupling between perception and action, in other words; perception directly determines the to-be-performed action. This does not mean that this relationship is fixed; when the relation changes (for instance due to changes in action capabilities), the relationship can be rescaled (by the process that is referred to as 'calibration'). To accurately and adequately adapt this scaling, people need to experience the coupling by exploration; moving around and perceiving the consequences of the action.

Exploration and calibration are two of the main concepts in the perception and action cycle. Whilst no clear conclusions can be drawn in terms of the effect of aging on calibration, this chapter gained insight into the process of calibration. It was found that only minimal experience is required for exploration, as long as the information is highly relevant in relation to the movement. In natural movement, it is very hard (arguably impossible) to examine the influence of calibration isolated from the rest of the perception and action cycle as perception and action are intrinsically coupled. As chapter 2 did not clearly identify perceptual-motor calibration as the main element in dysfunction of the perception and action cycle with age, it was decided to focus the experimental studies of this thesis on a more holistic level of perceptual-motor coupling. Using a more holistic design, it was reasoned that generalizability to natural movement could be maximized.

Chapter 2 - A Systematic Review on Perceptual-Motor Calibration to Changes in Action Capabilities
2.1 Introduction

The framework of direct perception suggests that movement is guided by one's perception of *affordances*; that is, the opportunities for action within an individual's environment (Gibson 1979; Stoffregen 2003). Perception of affordances logically requires scaling to action capabilities to allow distinction between the possible and impossible opportunities for action in an individual's surroundings. This scaling is known as *(perceptual-motor) calibration* (Bingham & Pagano, 1998; Warren, 1984; Withagen & Michaels, 2007).

Calibration has generally been observed in research considering the perception of affordances in a certain environment. In an experiment aimed at analyzing stair climbing behavior as a dynamical system, Warren (1984) was one of the first to study perception of affordances. In his seminal study, Warren (1984) assessed individuals' capacities to accurately perceive maximal and optimal climbable stair heights, given their own action capabilities. The results showed that, independent of their height, all participants perceived steps of 0.88 times their leg length to be their maximal climbable stair height. Furthermore, independent of the participant's height, a step that stood 0.26 times the participant's leg length in height was perceived to be the optimal stair height. These findings demonstrated that all participants used a scaling of their body size (in this case leg length) for perception of possibilities for action (in this case stair climbing), indicating that these participants were calibrated to their body size (given that body size is related to their action capabilities). Following the early work of Warren (1984), numerous other studies have focused on the perception of affordances and their scaling with action capabilities in different types of action (see Barsingerhorn, Zaal, Smith, & Pepping, 2012; for a historical overview).

Interested in the mechanisms of calibration, Bingham and colleagues (Bingham & Pagano, 1998; Bingham, Pan, & Mon-Williams, 2014; Coats, Pan, & Bingham, 2014) introduced the 'mapping' theory of calibration, which states that embodied units of perception are matched with embodied units of action. According to this theory, human motor control is governed by one's perception of the environment in terms of their own perception-action system. Calibration can be perturbed following a change of sensory units (e.g. changing the meaning of sensory information) and following action unit changes (e.g. manipulating stride length by adding weights to the body). Both types of manipulation have been considered by previous research.

Sensory units can be manipulated by disturbances of perceptual information. This has been extensively studied by experimentally manipulating information using a prism adaption paradigm (Bingham & Romack, 1999; Redding & Wallace, 1997). In general, these studies show that with practice and feedback, humans are able to adapt (*recalibrate*) to the new mapping. Fernández-Ruiz, Hall, Vergara and Díaz (2000) studied adaptation to vision shifted by prisms and reported differences in learning rates between younger and older adults. Their older group of participants needed more

practice before they completely recalibrated to the new mapping. Whilst these studies do give an interesting insight into the mechanisms of calibration, it is important to note that such a manipulation is unlikely to occur in real life. Arguably, one of the few occurrences of changing the mapping in real life would be when a person starts to wear (multifocal-) glasses, but in this situation, the effects will be smaller compared to the experimental conditions (a person wears glasses with the aim of improving vision, not in order to challenge motor control).

The second way in which calibration can be perturbed is by a change in action capabilities. Changes in action capabilities occur naturally throughout the lifespan, such that as we mature from childhood to adulthood, we develop improved action capabilities and as we age, our capabilities decrease. In addition to these natural changes in action capabilities, one's capabilities can change more rapidly due to biological processes, such as the fatigue experienced by an athlete during a sports match that can decrease strength or running ability. Furthermore, action capabilities can be altered directly, by restrictions imposed by clothing or footwear. For instance, a person could put on shoes with high heels, which will directly influence step size. Considering that these changes could occur at any time, it could be argued that this would be the type of calibration that is predominantly required in everyday motor control.

Considering changes in action capabilities, decreases in capabilities seem to be especially relevant, since these decreases have been linked to the occurrence of falls in an older age bracket (Luyat, Domino, & Noël, 2008). Luyat et al. (2008) hypothesized that the higher incidence of falls in older adults could be the result of misperception of affordances, instigated by not adequately calibrating to the declines in physical function that are associated with aging. Plumert (1995) previously reported a link between decreased accuracy in the perception of action capabilities and a history of accidental injuries in children. Combined, these studies suggest that the falls experienced by older adults may be explained, at least in part, by an impaired capacity for these individuals to calibrate to the age-related changes in their action capabilities.

With the potential relevance of calibration for prevention age related accidents, such as of falls, it is of particular interest to consider what is required for an individual to calibrate to their capabilities. An improved understanding of this process may be of relevance to better understanding the mechanism(s) of age related accidents, as it is well known that their action capabilities decline with age, but it is currently unclear what is required for these individuals to recalibrate to age-related changes in action capabilities.

2.1.1 The current study

Collectively, the existing literature suggests that one's capacity to safely navigate their environment depends upon their ability to calibrate to changes in their action capabilities. Given this understanding, the current study focusses on the process of calibration to changes in action

capabilities. Previous studies have reported that the process of calibration in general is highly dependent on exploration of the perception-action mapping (Adolph, Eppler, Marin, Weise, & Wechsler Clearfield, 2000; Barsingerhorn et al., 2012; Stoffregen, Yang, Giveans, Flanagan, & Bardy, 2009; Yu & Stoffregen, 2012) or feedback on performed movements (Bingham & Pagano, 1998; Withagen & Michaels, 2005).Yet individually, these theoretical studies do not consider practical issues, such as: the amount of exploration allowed; the amount of experience that is required for effective calibration; or the existence of individual differences in this process. The current study aimed to synthesize the existing literature on perceptual-motor calibration to changes in action capabilities with a focus on understanding the effectiveness of calibration.

2.2 Methods

2.2.1 Methods for literature search

A series of systematic searches were performed in seven academic databases: PubMed, EMBASE, Cochrane Library, CINAHL, PsycInfo, SPORTdiscus and Web of Science. These searches placed no restrictions on the publication date of the papers and aimed to identify all relevant literature concerned with perceptual-motor calibration. Each search was structured to include three collections of terms; the first relating to calibration; the second relating to perception; and the third relating to action. The terms included within each of these collections were separated with the operator 'OR', while the three collections of terms were linked with the operator 'AND'.

To be eligible for inclusion in this systematic review, papers were required to: i) be written in Dutch or English; ii) be an original full-length paper (i.e. not a review or conference paper); iii) be peer-reviewed; iv) focus on otherwise healthy individuals (i.e. not a patient group); and v) include a measure of perceptual-motor calibration to a change in action capabilities as the main outcome. To clarify, this means that some papers might include a manipulation of action capabilities but still could be excluded because the focus was not on the calibration or adaptation process. Of the total search results, duplicates were removed and articles were screened based on title and the criteria stated above. After title selection, articles were screened based on the abstract and full text for the same criteria. The resulting papers were supplemented by an analysis of the references that were cited in the reference lists of the included papers and by citation tracking. These additional papers were selected on title and also underwent a screening on abstract and full text, similar to the articles included from the database search. The full details of the search strategy have been provided as Appendix 2.1 Complete Search Strategy

2.2.2 Paper review process

The titles and abstracts of all papers retrieved via the systematic search strategy were independently screened by the authors (SvA, GJP, MHC) based on the outlined inclusion criteria. Any

discrepancies in the reviewers' decisions to include or exclude a paper were discussed until a consensus was reached. The full-text of the papers that appeared to meet the inclusion criteria based on their title and/or abstract were reviewed and all papers that were deemed to meet all of the inclusion criteria were included in the systematic review. For each of these papers, details concerning the study's reference, target population (e.g. age characteristics), response type, primary outcome measures and mechanisms of calibration (if available) were extracted and synthesized.

2.2.3 Quality assessment

Quality assessment of studies was performed with the Crowe Critical Appraisal Tool (CCAT; Crowe, Sheppard, & Campbell, 2012; Crowe & Sheppard, 2011). The CCAT checklist was developed to facilitate the assessment of the methodological quality of a variety of different study designs, including cross-sectional studies. Given the outlined inclusion criteria and the specific scope of this review, the majority of the included studies were expected to be cross-sectional in nature, hence the CCAT was considered to be a suitable instrument for assessing their methodological quality. The CCAT consists of 8 sub-scales that each evaluates a different aspect of the research article. By summing the items within each of these sub-scales, it is possible to identify specific strengths and shortcomings in the methodological reporting of the papers. The scores for the eight sub-scales are then summed and expressed as a percentage to provide an overall measure of the methodological quality of each paper. As the CCAT protocol does not provide a specific method for interpreting the percentage scores, the range of possible scores was divided into quintiles, with papers assessed as being of either; i) very low (0-20%); ii) low (21-40%); iii) moderate (41-60%); iv) high (61-80%); or v) very high (81-100%) methodological quality.

2.3 Results

2.3.1 Selection process

The systematic search of the seven databases resulted in a total of 2054 potential papers being identified. Of these papers, 714 were removed as duplicates and 248 were excluded as they were either written in a language other than English or Dutch (n=27) or they were not considered to be an original full-length research article (n=221). The titles and abstracts of the remaining 1092 papers were independently screened by three reviewers, resulting in the exclusion of a further 874 papers based on title and 202 papers based on abstract. Citation tracking and screening of the reference lists of the remaining 16 studies resulted in the identification of 10 additional papers that were considered potentially relevant for the review. Following full-text review of these 26 studies, three studies were considered ineligible: based on the abstract these studies appeared to consider changes in action capabilities, but analysis of the full text did not indicate a specific manipulation of action capabilities, resulting in a total of 23 studies being included in this review (Figure 2.1).

Chapter 2 - A Systematic Review on Perceptual-Motor Calibration to Changes in Action Capabilities

2.3.2 Quality assessment

On the basis of the CCAT, the methodological quality of the included papers ranged from 58% to 85%, with a mean score of 72%. Three papers (13%) scored a moderate methodological quality, 17 (78%) papers scored high methodological quality and three papers (9%) scored very high methodological quality (Supplementary table 1 in Appendix 2.2 Results from the quality analysis). Many of the papers included in this review scored similarly high for the categories evaluating preliminaries, introduction, data collection and results. However, the categories in which many of the studies recorded their lowest mean scores where related to the reporting of sampling methods and ethical approvals.

In the sampling category, the scores were generally lower because most of the included studies reported using a convenience sample comprising university students, rather than a random sample drawn from the general population. Furthermore, in all but three studies, the general lack of information concerning the participants made it unclear as to which population the results should be generalized. The lower scores reported for the ethics category were generally attributable to the lack of a statement; i) indicating that the study's methods had received approval from a Human Research Ethics committee (17 studies, 74%); and/or ii) outlining that informed consent was obtained from all participants (16 studies, 70%).

2.3.3 Article assessment

For the studies included in this review, the mean age of the participants included in the studies (Table 1) ranged from 14 months (Adolph & Avolio, 2000) to 32.7 years (Experiment 1 by Franchak & Adolph, 2014). Of the 23 included papers, 11 studies reported on the mean age of their participants (47%). Twelve studies (52%) did not specifically report the mean age of their participants; although two (9%) of these did report age ranges, which indicated that the participants were all under 32 years of age. Furthermore, nine of the studies (39%) that did not report a mean age or age range for their participants did state that they recruited a student-based sample. Finally, one study (4%) by Linkenauger, Bülthoff, and Mohler (2014) provided no indication as to the age of their participants.
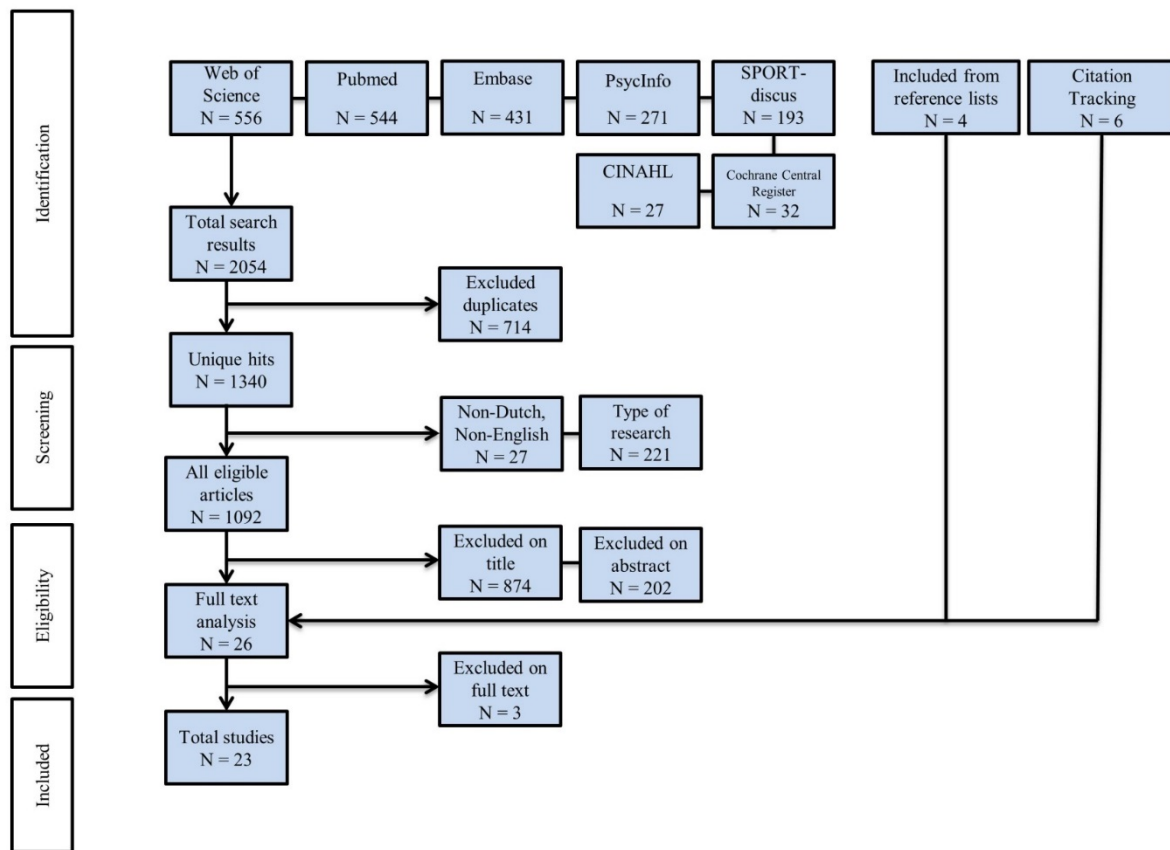
Figure 2.1 Flowchart summarizing the process of article selection

In 15 of the studies (65%), the experiment was set in a real-world environment, while the remaining eight studies (35%) were set in virtual reality. While the specific response type used for each of the real-world and virtual reality studies tended to differ, it typically conformed to one of four response types. Specifically, six of these studies (26%) investigated continuous 'movement control' and three investigated 'action judgements' (13%), in which participants were required to judge the achievability of an affordance (possible or impossible) and respond by acting on an affordance when it was deemed possible. A further 12 studies required participants to make a 'conscious judgement' (52%), in which affordances were not acted on, but rather a verbal or simplified (e.g. button-press) response was given to indicate whether an affordance was possible or impossible. The remaining two studies (9%) involved a 'matching' task, which required participants to indicate the size of an action-relevant object in their environment, following manipulation of their action capabilities (Table 2.1). For simplicity, the following sections are organized to collectively present and analyze the results of the studies that used each of these different response types.

Chapter 2 - A Systematic Review on Perceptual-Motor Calibration to Changes in Action Capabilities
2.3.3.1 Movement control

The six studies that evaluated continuous movement control were all conducted in a virtual reality environment. Four of these studies manipulated the participants' action capabilities within the virtual environment (Bastin, Fajen, & Montagne, 2010; Fajen, 2005c, 2007b, 2008), while the remaining two studies manipulated their actual action capabilities in the real-world setting (Nakamoto, Ishii, Ikudome, & Ohta, 2012; S. Scott & Gray, 2010).

The two studies that manipulated the participants' actual action capabilities both investigated the adaptation of professional baseball players to baseball bats of varying mass. Both studies showed calibration to the new bats to occur. Nakamoto et al. (2012) reported recalibration to take three swings of a weighted bat, whereas Scott and Gray (2010) reported that five swings were required to calibrate to lighter bats than usual and ten swings were required for heavier bats. In contrast, the other four studies manipulated the maximum speed (Bastin et al., 2010) or braking capabilities (Fajen, 2005c, 2007b, 2008) of a vehicle in a virtual driving simulator. In each of the simulated tasks, the participants were required to calibrate to the vehicle's new capabilities. All four of the virtual driving studies showed that participants controlled their motor behavior by taking their vehicle's maximum (speed / braking) capabilities into account.

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Table 2.1 Characteristics of the included studies (N = 21)

	Experimental phase / Group	Experimental group N (Mean age, Spread)[a]	Environment	Task nature	Manipulation achieved with
Bastin et al. (2010)		30 (18.7, SD = 0.9)	Virtual reality	Movement control	Virtual reality
Bourgeois et al. (2014)		80 (24.7, SD = 4.7)	Real world	Conscious judgement	Tool use
Fajen (2005)	exp. 1	30 (20.9 ± NR)	Virtual reality	Movement control	Virtual reality
	exp. 2	30 (19.7 ± NR)			
	exp. 3	12 (18.8 ± NR)			
	exp. 4	10 (20.6 ± NR)			
Fajen (2008)		20 (NR[b])	Virtual reality	Movement control	Virtual reality
Fajen (2007)	exp. 1	36 (NR[b])	Virtual reality	Movement control	Virtual reality
	exp. 2	24 (NR[b])			
Fajen & Matthis (2011)	exp. 3	10 (NR[b])	Virtual reality	Conscious judgement	Virtual reality
	exp. 4	15 (NR[b])			
Franchak & Adolph (2014)	exp. 1	11 (32.7, range = 25-42)	Real world	Action Judgement	Natural process and artificial body extension
	exp. 2	48 (19.9, range = 18-24)			
	exp. 3	12 (20.6, range = 18-22)			
Hirose & Nishio (2001)		16 (21.9, range = 20-32)	Real world	Conscious judgement	Artificial body extension
Ishak et al. (2008)	exp. 1	14 (21.5, range = 18.3-35.5)	Real world	Action judgement	Artificial body extension
	exp. 2	14 (20.1, range = 19.2-21.5)			
	exp. 3	18 (22.6, range = 18.5-38.1)			
Lessard et al. (2009)		18 (NR[b])	Real world	Matching	Artificial body extension
Linkenauger et al. (2014)	exp. 1	12 (NR)	Virtual reality	Conscious judgement	Virtual reality
	exp. 2	11 (NR)			
	exp. 3	12 (NR)			
	exp. 4	12 (NR)			

Table 2.1. (Continued)

	Experimental	Experimental group	Environment	Task nature	Manipulation achieved with
Mark (1987)		5 (NR[b])[c]	Real world	Conscious judgement	Artificial body extension
Nakamoto et al. (2012)		8 (Mean NR, range = 19-22)	Virtual reality	Movement control	Tool use
Pepping & Li (2000)	exp. 1	46 (20.2, range = 19-26)	Real world	Conscious judgement	Artificial body extension
	exp. 2	24 (20.7, range = 18-26)			
	exp. 3	26 (20.3, range = 19-27)			
Pepping & Li (2008)		24 (19.7, SD = 0.5)[c]	Real world	Conscious judgement	Artificial body extension
Pijpers et al. (2007)	exp. 1	16 (Mean NR, range = 19-31)[c]	Real world	Conscious judgement	Natural process
	exp. 2	16 (Mean NR, range = 18-29)[c]			
Regia-Corte & Wagman (2009)		9 (NR[b])[c]	Real world	Conscious judgement	Artificial body extension
Scott & Gray (2010)	exp. 1	30 (23.4, SE = 0.8)	Virtual reality	Movement control	Tool use
	exp. 2	20 (24.1, SE = 0.6)			
Stefanucci & Geuss (2009)	exp. 1	21 (NR[b])	Real world	Matching	Tool use and natural process
	exp. 2	40 (NR[b])			
	exp. 3	10 (NR[b])			
Thomas & Riley (2014)	exp. 1a	21 (19.0, SD = 1.6)	Real world	Conscious judgement	Tool use
	exp. 1b	20 (19.2, SD = 1.3)			
	exp. 2	42 (19.5, SD = 3.1)			
Wagman (2012)	exp. 1	8 (NR[b])[c]	Real world	Conscious judgement	Tool use
	exp. 2	18 (NR[b])[c]			

NR = 'Not Reported'

[a] All age-related data is rounded to one decimal. Where no decimals are reported, these data were not provided in the original study

[b] Though age is not reported, it is reported that this is a student group

[c] Only female participants

2.3.3.2 Action judgement

The three papers that assessed action judgements were set in a real-world environment (Adolph & Avolio, 2000; Franchak & Adolph, 2014; Ishak, Adolph, & Lin, 2008). Two of these studies showed that action judgements were accurate for tasks that involved participants fitting their hand through an opening (Ishak et al., 2008) or attempting to pass through different sized doors with different belly sizes (Franchak & Adolph, 2014). Furthermore, both of these studies provided evidence of recalibration when the dimensions of the body and/or environmental were manipulated. Franchak and Adolph (2014) found that experience in passing through doorways with experimentally-manipulated belly size helped to increase judgement accuracy.

The third study, by Adolph and Avolio (2000) assessed how 14 months old children (re)calibrate their ability to descend slopes. Their results show that these young children were able to adjust to alterations in body weight (manipulated by a weighted vest). Children seemed to use exploratory movements to assess the risks of the descent.

2.3.3.3 Conscious judgement of action boundary

Twelve studies investigated participants' conscious judgement of the boundaries to their action capabilities (Bourgeois, Farnè, & Coello, 2014; Fajen & Matthis, 2011; Hirose & Nishio, 2001; Linkenauger et al., 2014; Mark, 1987; Pepping & Li, 2000, 2008; Pijpers, Oudejans, & Bakker, 2007; Regia-Corte & Wagman, 2008; Thomas & Riley, 2014; Wagman, 2012; Wagman, Taheny, & Hirai, 2014). Of these studies, two required participants to determine the boundaries of their action capabilities in a virtual environment (Fajen & Matthis, 2011; Linkenauger et al., 2014), while ten assessed this judgement during real-world tasks (Bourgeois et al., 2014; Hirose & Nishio, 2001; Mark, 1987; Pepping & Li, 2000, 2008; Pijpers et al., 2007; Regia-Corte & Wagman, 2008; Thomas & Riley, 2014; Wagman, 2012; Wagman et al., 2014).

The studies by Hirose and Nishio (2001) and Mark (1987) investigated the effect of manipulating leg length and eye height by placing 10-cm blocks under the participants' feet. For these studies, the height of a chair (for sitting judgements) or bar (for stepping judgements) was systematically raised or lowered and participants were asked to make a judgement as to when they perceived the height of the chair/bar to be at their new maximum capabilities (e.g. the bar's height represented the highest height that they could safely step over). Both studies reported that participants had an accurate perception of their sitting and stepping abilities after this manipulation and recalibrated to the changing task demands. Despite these findings, Hirose and Nishio (2001) found systematically different judgements between those trials in which the height of the seat or bar was incrementally increased and those trials in which the height was systematically decreased.

Seven of the remaining papers investigated the effect of manipulating participants' reaching capabilities and reported that one's perception of reachable space is rescaled to their action

capabilities (Bourgeois et al., 2014; Pepping & Li, 2000, 2008; Pijpers et al., 2007; Thomas & Riley, 2014; Wagman, 2012; Wagman et al., 2014). Furthermore, if this manipulation was made by using a tool (Wagman, 2012) or a change in posture (Wagman et al., 2014), even when these changes were not yet experienced (e.g. the tool was not held but only viewed), recalibration still occurred. Similarly, Pepping and Li (2008) showed that participants could effectively recalibrate to a reach-with-jumping task performed on different support surfaces, even without prior experience with standing on these surfaces (i.e. using only visual information only). In an attempt to explain how reachable space is recalibrated, Thomas and Riley (2014) compared the direct perception of reachable space (i.e. asking participants how high they can reach with the tool) with an additive model of reachable space (i.e. adding up the participant's perception of reach height and tool length). The direct perception of reachable space proved to better explain judgements compared to a method of using an additive model. Participants also rapidly recalibrate to changes in (virtual) arm size (Linkenauger et al., 2014), changes in the height of their center of mass (Regia-Corte & Wagman, 2008) and changes in walking speed in a virtual reality environment (Fajen & Matthis, 2011).

2.3.3.4 Matching

The two articles that assessed a matching task were conducted in a real-world setting (Lessard, Linkenauger, & Proffitt, 2009; Stefanucci & Geuss, 2009). These studies both showed that perception of distances is scaled to action capabilities. For instance, apertures are perceived to be smaller when the body's width is experimentally increased (Stefanucci & Geuss, 2009). Similarly, gaps to jump over were perceived to be wider when jumping capabilities were impaired by adding weights to the participants' bodies (Lessard et al., 2009). Interestingly, this relationship was only evident for gaps that were actually jumpable; hence there was no observable change in scaling for gaps that were beyond the participants' action boundaries.

2.3.4 Time scale and mechanism of calibration

In general, all of the included studies showed that participants calibrated to their action capabilities and a sub-group of these studies (N = 9) also provided insight into the time scale of calibration. Table 2 provides an overview of these studies and summarizes the amount of practice that is required for calibration to a change in action capabilities. The study by Fajen (2007b) showed that (re)calibration generally occurs very quickly, demonstrating that participants were able to recalibrate to altered brake strength within one second of pressing a vehicle's brake pedal. However, in the study by Mark (1987; as described in Mark et al., 1990), participants needed about 30 minutes to demonstrate calibrated judgements of their maximum sitting and stepping height after their eye height was changed by the addition of 10 cm blocks under their feet.

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Table 2.2 Subset of (N = 8) studies that provide insight in timescale of calibration

	Manipulation of	Timescale of calibration
Fajen (2007)	Brake strength and vision	Recalibration occurred 1 second after brake initiation, even when participants were deprived of vision
Franchak & Adolph (2014)	Belly size (pregnant and artificial)	Pregnant women (high in experience) were very accurate in their judgement of whether it was possible to pass through apertures of different sizes. Participants with artificially-manipulated belly sizes were almost as accurate as pregnant women, but only after practice. Before gaining experience with passing through apertures with an altered belly size, participants were inaccurate.
Lessard et al. (2009)	Jumping ability by ankle weights	Walking 60 meters before block of testing, to induce calibration
Linkenauger et al. (2014)	Arm size in VR	Merely having a virtually altered arm length does not recalibrate perception of reachable space, minimal experience is necessary to induce recalibration
Mark (1987)	Leg length by adding 10 cm blocks under feet	6 judgements were insufficient for rescaling, but after 12 judgements (about 30 minutes [a]) participants had recalibrated
Nakamoto et al. (2012)	Baseball bat weight	Three swings with a weighted bat was enough to induce recalibration weighted bats
Pepping & Li (2000)	Reach-with-jump height by adding weights and changing ground surface	Experiment 1: participants were instructed to jump three times and allowed to walk with weights for 3 minutes, this was sufficient to induce recalibration Experiment 2/3: participants were allowed 1 minute of experience (jumping, but not reaching) on the ground surfaces, this was sufficient to induce recalibration
Scott & Gray (2010)	Baseball bat weight	Adaptation took 5 swings for a lighter bat and 10 swings for a heavier bat

[a] Mark (1987) did not report on this timescale, but Mark et al. (1990, p. 327) did provide this information when discussing previous findings. They reported that in the experiment of Mark (1987), participants were allowed to walk around the room for 1-2 minutes between judgements, coming to roughly 30 minutes for 12 judgements.

2.4 Discussion

The main aim of this systematic review was to synthesize the existing literature on perceptual-motor calibration to changes in action capabilities with a focus on understanding the effectiveness of calibration. Our results suggest that the timeframe for calibration can be highly variable, with studies by Fajen (2007b) showing that recalibration can occur with as little as 1 second of exposure to the altered conditions and other studies showed comparable rapid recalibration (Nakamoto et al., 2012; Pepping & Li, 2000). Similarly, some studies reported that not a specific amount of time was required, but that recalibration occurred with minimal experience (Franchak & Adolph, 2014; Linkenauger et al., 2014; Wagman et al., 2014). The study of Mark (Mark, 1987) illustrated the other side of the spectrum, reporting that participants needed repeated 12 judgements before they responded accurately, taking up about 30 minutes.

Given that the time required for calibration seems to be quite variable, it is important to understand why this timeframe is so variable across different situations. Of interest for this discussion, Wagman et al. (2014) showed that judgments of maximal reaching height were relatively inaccurate without feedback, even without a manipulation of action capabilities. However, the accuracy of participants' judgement of maximal reaching height was significantly improved after they were allowed to perform the actual reaching task (Wagman et al., 2014). In contrast, Mark (1987) did not allow participants to practice the skill that they were judging. While standing stationary with altered leg length, participants were required to judge maximum sitting height. This way, the only information available to participants was information generated by postural sway, not by exploring the capabilities for sitting. Perhaps it is because of this less perfect match between the explored source of information and the skill to be judged that recalibration took a longer period of time. When attempting to replicate the results of Mark (1987), Stoffregen, Yang, and Bardy (2005) reported pilot data (supported by personal communication with L.S. Mark by Stoffregen et al., 2005) that showed that the effects of calibration disappeared when the blocks were attached to the feet of participants, while sitting in a regular chair, with feet on the ground. Sitting with blocks and rising up from the chair had already provided enough information so that further calibration was not necessary; judgements were accurate at the first attempt (Stoffregen et al., 2005). Putting these findings in the context of the results summarized in Table 2, we can conclude that the time required for calibration is mainly dependent on the aptness of the information explored for calibration. When the movement itself is explored, calibration occurs rapidly (e.g. Fajen, 2007; Nakamoto et al., 2011, Franchak & Adoph, 2014, Wagman et al., 2014), but when exploration occurs using less relevant movement, calibration takes longer (e.g, Mark, 1987).

Our results showed a general lack of research investigating calibration to changes in action capabilities in older age. None of the included studies incorporated a group of participants with a

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mean age higher than 33 years old. Given that ageing and neurodegenerative conditions tend to degrade the quality of one's sensory inputs, it is unclear whether the results of these earlier studies would be transferrable to older and/or clinical populations. This is an important focus for future research, especially given the potential influence of deficits in calibration on movement errors (Plumert, 1995) and falls in older adults (Luyat et al., 2008)[7].

If future research would identify calibration as a key factor used in prevention of age-related accidents, then the current study adds to that understanding with the knowledge of when calibration takes a variable amount of time. Older adults need to cope with decreases in their capabilities, underlining the relevance of fast recalibration. The current study shows that calibration is most efficient when actually engaging in the to-be-calibrated activity. Given that the majority of accidents, such as fall, occur during walking (Berg et al., 1997), a hypothesis for future research might be that older adults who have a high risk of falls need to engage in walking activities to aid calibration in fall prevention,.

In the past decennium, the importance of calibration has become apparent with the development of the affordance-based approach of movement control (Fajen, 2007a). Previously, calibrating perceptual and action units has been mainly investigated in the context of the affordance problem (investigating the question how we decide *what* to do), leaving the control problem (*how* to control ongoing action) to information based theories (this division had been first made by Warren (1988) and two separate research streams have developed since). According to Fajen (2005b, 2007a), information based theories would lack the ability to take a person's limit's into account. Fajen illustrated this with a series of investigations of braking in a virtual car. The results of these studies showed that participants always brake in a way that will enable them to stop in time considering their car's maximal brake power, meaning that they must have taken their car's maximal braking capabilities into account in the control of movement (Fajen, 2005a, 2005c, 2007b).

The approach of affordance-based control has shown the relevance of calibration for everyday movement control (for instance in overtaking actions (Morice et al., 2015) and interception tasks (Bastin et al., 2010)). The current study adds to this understanding by providing insight into the mechanisms of calibration. Minimal experience seems to be enough to instigate calibration, as long as there is a strong match between the available perceptual-motor information and the task; in continuous visually controlled movements, this information is abundantly present.

A question that remains after this systematic review is how the perception-action system controls behavior in order to gain the appropriate amount of information to calibrate, before

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[7] Falls risk entails one of the mayor challenges of our modern aging society, as one in three older adults aged 65 and over is reported to fall each year (Campbell et al., 1990), resulting in significant and ever growing medical costs (Hendrie et al., 2004).

engaging in movement. Higuchi, Cinelli, Greig, and Patla (2006) completed an experiment that required participants to pass through apertures in a number of different conditions: walking, walking while holding a bar (with and without the ability to turn the shoulders) and while wheel chairing. They found that in the novel tasks (walking with bar and no shoulder turn and wheelchair riding), participants slowed down in the approach to the aperture. This slowing down would have allowed them to explore the relation between the width of the bar and the width of the aperture in a task unfamiliar to the actor. In contrast, the slowing down was not present in a task in which participants were well experienced: walking (with and without holding a bar), with the ability to turn. Research has shown that experience could be a relevant factor in perceiving affordances, seeming to hold effects in affordance judgements (Hirai, Takada, Matsuura, & Imanaka, 2004; Yasuda, Wagman, & Hirai, 2014) as well as online movement control (Hirai et al., 2011). It would be a relevant field for future research to investigate whether experience actually improves calibration in a skill permanently or whether the process of calibrating improves in efficiency and thus occurs faster. In the context of aging, it might mean that older adults need to get more experience with accident-related situations, for instance by inducing trips and slips in a safe environment, to extend experience in the relevant skills.

Importantly, the results of the methodological quality assessment indicated that the included studies were all of a moderate to very high methodological quality, showing that the studies in this field are generally reported to a high standard. The main shortcomings identified with the quality assessment were a general under reporting with respect to the specific 'sampling' methods used to recruit their participants and insufficient information addressing the 'ethical' aspects.

In the light of the findings of this systematic review, it is important to consider that, within the current literature; there is a general degree of uncertainty regarding the amount of overlap that exists between different types of calibration. For example, in a study by Ishak et al. (2008), affordances for fit-ability were defined by judging the relationship between the size of the participant's hand and the size of an aperture. In contrast, a study by Smith and Pepping (2010) asked participants to judge whether a ball would fit in a specific hole; hence in both studies, affordances were defined by the relationship between the size of an object (the participant's hand or a ball) and the size of the aperture. While the affordance in both tasks is very similar, Ishak et al.'s (2008) study manipulated hand size (action capabilities), while Smith and Pepping (2010) only manipulated aperture size (manipulating in the mapping between perceptual and action units). As this review focused on changes in *action* capabilities, studies that involved environmental manipulation (e.g. Smith and Pepping, 2010) were not included. Future research might seek to establish the differences in calibration in response to the changes affecting the three fundamental components of this process (i.e. sensory information, action capabilities and the mapping of these

two sources). Furthermore, it would be of interest to know whether the results from an experiment involving the manipulation of one's action capabilities could be generalized to what might be expected if one's sensory information was manipulated.

An obvious strength of the current study is that it used a systematic approach to assess the current knowledge on calibration. However, the results are limited by the fact that in the field of perceptual-motor research, a number of different terms can be used to describe calibration. As such, our search may be limited by the fact that it did not identify studies that used, for instance, terms such as 'scaling' or 'tuning', but that could describe the same process. Given the inconsistencies in terminology used by previous research, it is a potential limitation of this study that not all synonyms of 'calibration' have been included in the search of this study. However, by restricting our focus on 'calibration', we focus on research that identifies itself to be about calibration and with that we were able to thoroughly focus on this concept. The fact that so many related terms exist calls for a more universal use of language in this research field.

Concluding, this study shows that the time required for calibration is dependent on the effectiveness of exploration involved. For instance, exploration using postural movements to calibrate sitting capabilities requires more time (Mark, 1987) than when braking capabilities are explored while braking (Fajen, 2007b). This systematic review revealed that there was no literature on the influence of age on the effectiveness of calibration to changed action capabilities, as none of the selected studies were conducted with an older cohort. We identify this as a clear recommendation for future research, especially considering the possible implications for falls (Luyat et al., 2008), as well as other perceptual motor coordination-related accidents in older adults, and the growing theoretical interest into calibration, considering affordance based control (Fajen, 2007a).

Chapter 3 – General Methodology

3.1 Background

A main aim of this thesis has been introduced as: "to assess whether perceptual-motor coupling in older adults can be measured using a locomotor pointing paradigm." The purpose of this chapter is to describe the methodology of this thesis and introduce the curb-approach task, a locomotor pointing task that required participants to approach and step onto a regulation-sized curb. This task was implemented in the experimental studies introduced in Chapter 4, Chapter 5 and Chapter 6.

Perceptual-motor coupling is the coupling established via the perception and action cycle. An adequate coupling implies that all processes (that is; exploration, calibration, attunement and affordance perception, see section 1.3 The Perception-Action Cycle) are performed to an adequate standard. It can be reasoned that perceptual-motor coupling on a holistic level is relevant for success in locomotor pointing. One needs to be attuned to the affordances specified in the demands of the task relative to one's own action system, represented in the distance and time-to-contact to a target (De Rugy, Taga, et al., 2002). Further, one needs to calibrate to determine how to best match the action system to the specific task demands (Rieser, Pick, Ashmead, & Garing, 1995). However, it should be noted that on a functional level, these sub-components of the perception and action cycle are indistinguishable. That is, in natural walking, exploratory behavior specifying action capabilities and task demands are nested in the performatory behavior of propelling one's self forward in order to walk to a goal.

In the previous chapter, we investigated the sub-component of the perception and action cycle that was deemed most likely to influence falls risk: perceptual-motor calibration. A gap was identified in research on an aged population, furthermore it was shown that calibration usually occurs quite rapidly if exploration is efficient. When we consider the nested structure of exploration in performatory action for natural movement, it seems unlikely that calibration would be the sole influencer of falls risk. Therefore, it seems more feasible to study perceptual-motor coupling on a holistic level that would translate better to natural movement. In order to analyze the perceptual-motor control of locomotion on this holistic level, we follow previous studies that have been performed in the long jump run up (Lee et al., 1982; Montagne et al., 2000).

Locomotor pointing has been most predominantly studied in athletic contexts, such as the run up in a long jump (Hay, 1988; Lee et al., 1982; Montagne et al., 2000; Renshaw & Davids, 2006; Scott, Li, & Davids, 1997). Lee and colleagues (1982) were the first to establish that visual guidance of foot placement is required in the long jump approach to make sure that athletes can accurately place their feet at the take-off bar at the end of each run up. They showed that in their acceleration phase,

athletes produce a stereotypical stride pattern and only used the last couple of strides to adjust their step lengths and minimize foot placement variability at the take-off bar (Lee et al., 1982).

Later research further investigated the visual guidance of the last couple of steps; Montagne et al. (2000) introduced three methods to depict the coupling between perception and action in these final strides. Firstly, they introduced an 'inter-trial' analysis, which was largely based on the previous work of Lee's group (Lee et al., 1982). In this analysis, the standard deviation of footfall position relative to the target was computed per step (i.e. the step onto the target, the last step before the target, etc) and plotted for all trials. This analysis showed the variability of foot placement in each stage of the run up and illustrated the stereotypical nature of the start of the run up and the minimization of variability over the last 4 footfalls (Montagne et al., 2000). Second, they introduced an 'inter-step' analysis, in which the relationship was studied between the amount of adjustment made in step length per trial and the onset of adjustments. The total amount of adjustment per trial was measured as the sum of the deviations of a standard step length over all steps in an approach and the step number (relative to the step on target) at which the first significant deviation from a standard step was detected. Results showed a significant linear relationship, indicating a coupling between perception of the adjustments required and the timing of onset in adjustments (Montagne et al., 2000). Finally, an 'intra-step' analysis was introduced. This analysis was aimed at directly measuring the perception-action coupling in each step by assessing the linear relationship between the current state of the actor-environment system and deviations in step length. The current state of the system or 'adjustment required' was measured as the difference between the placement of a single footfall and the average location of that footfall (relative to the footfall on target). Similarly, 'adjustment produced' reflected the deviations in step length, and was measured as the deviation between a single step's length and the average step length at that point in the approach. It was shown that a significant linear relationship was established four steps before reaching the target and that this relationship became stronger as participants closed in on the target. This emphasized the importance of perceptual-motor coupling in these final steps (Montagne et al., 2000).

3.2 Participants

Firstly, a group of 16 young adults were recruited (age between 18 and 40 years). The data from the younger group was required to assess the validity of the systems (Chapter 4) and to provide reference values in comparison to the data collected with the older participants (Chapter 5). Recruitment was directed at the university community (staff and students) and participants were deemed eligible to participate if they had no current injuries to the lower limbs and when they had normal or corrected to normal vision in terms of visual acuity, measured as a visual acuity of better than 0.3 with a Bailey-Lovie chart (Bailey & Lovie, 1976; Lovie-Kitchin, 1988).

Secondly, it was aimed to recruit 100 older adults (age over 60 years) for inclusion in the studies. Recruitment was structures in cooperation with a local community for older adults, by advertisement in their newsletter. One-hundred-and-six people contacted the research team to discuss eligibility. Exclusion criteria were similar to the ones for the young group in terms of vision testing and injuries to the lower limbs. Additionally, participants were excluded if they reported any known balance disorders, proved unable to complete the entire experiment without the use of a walking aid or showed signs of cognitive decline (measured as a Mini-Mental State Examination score of 23 or lower).

3.3 The Curb-Approach Task

The aim of the curb-approach task was to elicit the same type of perceptual-motor regulation as previously studied in sport-based experiments (e.g. Lee et al., 1982; Montagne et al., 2000; Scott et al., 1997), but with lower task demands to allow for participants of all fitness levels (Figure 3.1). In order to represent a natural locomotor pointing setting for all participants, the current task was designed to closely resemble the act of crossing the street and stepping onto a curb. Chapter 4 will further explain the details of the materials and protocol of the curb-approach task as well as discuss the reliability.

3.3.1 Main Outcome: Strength of Perceptual-Motor Coupling

The following chapters in this thesis will apply the analyses introduced by Montagne (2000) in the curb-approach task. In particular, the focus will be on Montagne et al.'s 'intra-step' analysis, measuring the perceptual-motor coupling per step (bottom panel Figure 3.1). From the three analyses introduced in previous research, this analysis is the best fit to achieve the aim of the current thesis; that is, to study changes in perceptual-motor coupling with aging and their potential relationship to falls incidence in this population. In Chapters 4 and 5, all three analyses of Montagne (2000) will be repeated to illustrate the validity of the curb approach task as a measure of locomotor pointing; however, the main outcomes of the thesis will be related to the measurement of perceptual-motor coupling.

Task demands have been shown to be important in determining the strength of the perceptual-motor relationship in locomotor pointing tasks (Cornus et al., 2009; Montagne et al., 2002). Studying a walking approach to step over an obstacle, it was shown that participants exerted a stronger perceptual-motor coupling when task constraints were elevated by either increasing the obstacle size or increasing walking speed (Cornus et al., 2009). An elevated perceptual-motor coupling could thus be interpreted as a strategy to cope with increases in task demands.
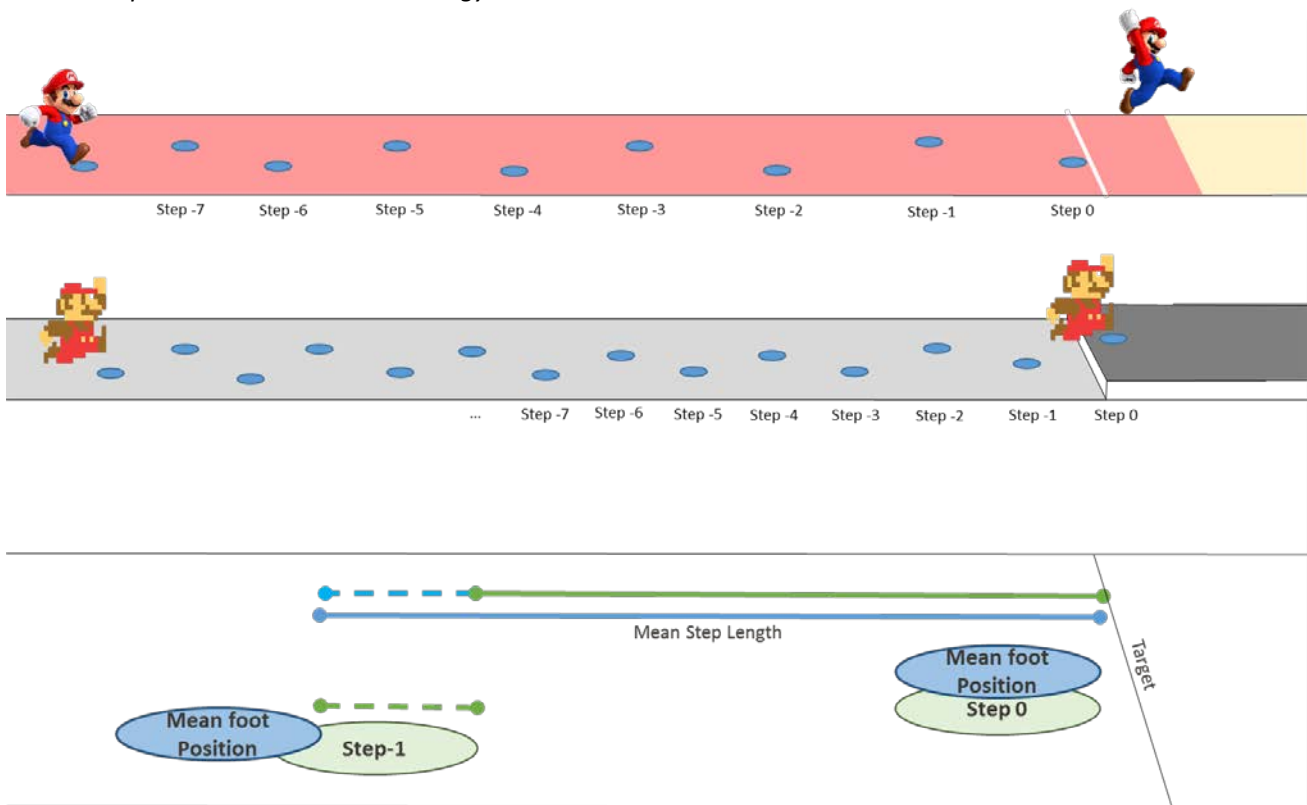
Figure 3.1 Similarities in the long jump approach and a curb-approach task

Figure illustrates how the curb-approach task can be analyzed using a similar method to the long-jump approach, but with its lower task demands it is fit for an older population of participants. Both tasks see the participant move towards a foot placement target, which is clearly specified in the long jump and more flexible in the curb-approach. The bottom part of the figure illustrates the calculation of perceptual motor coupling, being the linear relation between 'adjustment required' (difference between current step position and average position for that step; dashed green line) and 'adjustment produced' (difference between current step length and average step length; dashed blue line).

The strength of perceptual-motor coupling will be the main focus in chapter 5 and 6 of this thesis, in which the influences of age and falls risk on perceptual-motor coupling will be studied. With aging into older adulthood, it is known that action capabilities generally decline (Larsson et al., 1978; Lindle et al., 1997) and these declines have been linked to an increased risk for falls (Ambrose et al., 2013). These declines will lead to an increase in task demands with age that, in turn, will increase falls risk. It could therefore be expected that an elevated perceptual-motor coupling will be recorded in older participants and, in particular, participants who are prone to experiencing a fall.

3.3.2 Statistics and Sample Size

The use of the curb-approach task is novel in this thesis. This task is different from task used in previous studies on locomotor pointing in two ways. Firstly, as introduced above, the curb-approach task is a locomotor task with lower task demands than previous studies, which included running (Montagne et al., 2000) or walking (Cornus et al., 2009) towards to a specific target.

Secondly, previous studies have usually been descriptive in nature and have not reported direct comparisons between conditions or populations in terms of locomotor pointing outcomes. Together, these two factors complicate the statistical analysis, as no standard statistical procedure for locomotor pointing exists and no reference values can be used to perform sample size calculations.

As indicated in Section 3.3.1, the focus of the current thesis is to develop an understanding of how the strength of perceptual-motor coupling is influenced during a walking task that involves stepping up and onto a curb and how this relates to falls risk in older adults. This relationship can be measured as the correlation between the adjustment in step length required and the adjustment in step length produced for each subsequent step (Figure 3.1). Previous studies have shown this relationship to become stronger as participants get closer to their target (Figure 3.2). Following from this, it is important to control for what part of the approach a participant is currently in (within factor). The main interests of this thesis are the effects of age (between factor) and falls incidence (between factor) on the strength of the coupling; hence, the statistical procedure needed to be able to analyze a combination of within and between factors. A Linear Mixed Effects modelling approach was deemed most appropriate for this design (West, Welch, & Galecki, 2007) and this analysis has therefore been implemented in Chapters 5 and 6.

The lack of reference values available from previous research complicated the sample size calculations for the current thesis. Nevertheless, from the outset, the required sample size was guided by the need to be able to identify whether differences in perceptual-motor coupling could discriminate older adults who fell during a 12-month follow-up period (i.e. fallers) from those who did not (i.e. non-fallers). To address this question, it was necessary to recruit a sufficiently large sample of older adults to ensure that there would be a relatively large number of participants (from a
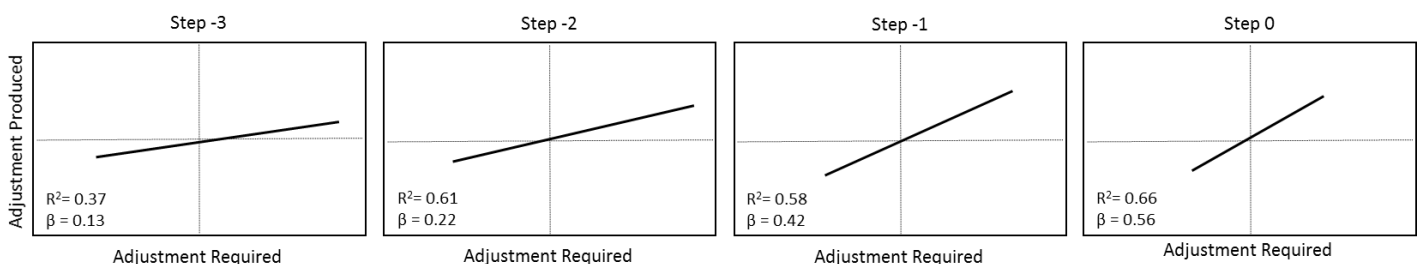
Figure 3.2 Perceptual-motor coupling in the long jumping approach.

Figure adapted from Montagne et al. (2000), showing regression lines without original data points. The adjustment required and produced in the approach to a long jump are depicted, with 'step 0' being the step onto the take-off bar. The β-values, indicating steepness of the regression lines, reveal the trend towards stronger coupling as the participants get closer to the target.

statistical perspective) in both the faller and non-faller groups. Categorization of participants as either a 'faller' or a 'non-faller' was based on whether or not they reported experiencing any falls during a 12-month follow up period that commenced after the data collection session that involved the curb-approach task. It has been well established in previous research that about one in three older adults (age 65 and older) fall at least once each year (Campbell et al., 1990, 1981; Prudham & Evans, 1981). Therefore, in order to achieve a group size of at least 30 fallers, a minimum of 90 participants was considered necessary. Given that previous research suggests that between 2 and 13% of participants will withdraw or otherwise not complete a 12-month follow-up for falls (Hill, Schwarz, Flicker, & Carroll, 1999; Kurz, Oddsson, & Melzer, 2013), the target sample size was increased to a minimum of 100 older adults to accommodate an attrition rate of up to 10%.

Chapter 4 - Perceptual-Motor Regulation in Locomotor Pointing while Approaching a Curb

The study described in this chapter has been published following peer review. Full reference details are:

Andel, S. van, Cole, M. H., & Pepping, G.-J. (2018). Perceptual-motor regulation in locomotor pointing while approaching a curb. Gait & Posture, 60, 164–170. https://doi.org/https://doi.org/10.1016/j.gaitpost.2017.12.006

Chapter 4 - Perceptual-Motor Regulation in Locomotor Pointing while Approaching a Curb

4.0 Synopsis and relevance for this thesis

Chapter 2 described the current knowledge on the mechanisms of perceptual-motor calibration and the influence of age on this process. In summary, no studies have been performed on calibration to changes in action capabilities in older adults. Furthermore, we know that calibration occurs rapidly and with minimal experience if there is a good match between the movement and the information being explored. Whilst it remains unclear how much exploration exactly is required for successful calibration to changed action capabilities in older adults, based on studies of other types of calibration (e.g. to a changed perceptual units; Fernández-Ruiz et al., 2000), it can be assumed that calibration still occurs, but might take more exploration. From this it follows that with an abundance of information, calibration should still be successful. Previous studies have shown that the majority of falls occur during locomotion (Berg et al., 1997). Walking is an act that most older adults perform regularly, which would imply that calibration still should be complete for this activity. Chapter 4 therefore focusses on operationalizing other aspects of the perception-action cycle; the direct coupling between perception and action.

In order to study this perception-action coupling, in chapter 4 we turn to methods that have been developed to measure this coupling in a sports context; the long-jump run up (Montagne et al., 2000). However, a similar coupling is established in any sort of locomotor pointing task. In the curb-approach task is further introduced, this task requires the same type of perceptual-motor coupling as does the long-jumping approach, but due to lower spatiotemporal demands is also achievable for older cohorts.

The results described in chapter 4 outline the similarities between the running approach for a long jump and the walking approach to step onto a curb, showing that the 'curb-approach' task would be a valid measure in analysing locomotor pointing regulation.

Chapter 4 - Perceptual-Motor Regulation in Locomotor Pointing while Approaching a Curb
4.1 Introduction

Placing one's foot onto a target on the ground during gait, otherwise known as 'locomotor pointing', is important in athletic contexts (e.g. the run up for a long jump) as well as everyday walking. Appropriate locomotor pointing in sport is often critical (e.g. every centimeter of error in the long jump run-up is a centimeter lost in the jump) and this has led to extensive study in the sporting context (Berg, Wade, & Greer, 1994; Bradshaw & Aisbett, 2006; Greenwood, Davids, & Renshaw, 2016; Hay, 1988; Lee et al., 1982; Montagne et al., 2000; Panteli, Theodorou, Pilianidis, & Smirniotou, 2014; Renshaw & Davids, 2006; M. A. Scott et al., 1997; Theodorou, Emmanouil, & Tasoulas, 2011) and research on perceptual-motor regulation strategies in locomotor pointing (De Rugy et al., 2000b; De Rugy, Taga, et al., 2002; Montagne et al., 2000). With the aim to devise a suitable task for perceptual-motor regulation in walking, the current study investigated whether these results generalize to the everyday task of approaching and stepping up on to a curb.

Early studies on locomotor pointing were performed in the run up for a long jump (Berg et al., 1994; Bradshaw & Aisbett, 2006; Hay, 1988; Lee et al., 1982; Montagne et al., 2000; Panteli et al., 2014; M. A. Scott et al., 1997; Theodorou et al., 2011). In this event, it is important for an athlete to regulate their running gait in such a way so as to ensure that they end their run-up with their take-off foot as close to the edge of the take-off board as possible. It was shown that this low error is achieved through visual regulation (Lee et al., 1982; Montagne et al., 2000). In the initial stage of the run up, foot placements are more variable, but become more consistent later in the performance when the athlete enters a regulation phase to ensure that they end with minimal error between the positioning of their foot and the edge of the take-off board.

Two previous studies of locomotor pointing have sought to determine when visual regulation was *initiated*, by examining locomotor pointing on a trial-by-trial basis. One study focused on the long jump run up (Montagne et al., 2000) and the other study focused on a walking task that involved participants stepping over an obstacle (Cornus et al., 2009). Both these studies defined the onset of regulation as the moment that steps in the run-up or walk became different from the average step length recorded under steady-state conditions. Results indicated that the onset of regulation was not fixed, but rather, was related to the amount of adjustment required. They showed that if greater adjustment was required, the onset of regulation was earlier compared to runs or walks with lower required adjustment. Ultimately, these results indicated that the onset of regulation was dependent on continuous perception-movement coupling (Cornus et al., 2009; Montagne et al., 2000).

Locomotor pointing is a skill that is often executed in daily life and is important during tasks such as approaching a set of stairs or a curb. Despite this, research has mainly focused on tasks that are not commonplace in daily life, such as sporting tasks (Berg et al., 1994; Bradshaw & Aisbett,

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2006; Greenwood et al., 2016; Hay, 1988; Lee et al., 1982; Montagne et al., 2000; Panteli et al., 2014; Renshaw & Davids, 2006; M. A. Scott et al., 1997; Theodorou et al., 2011) as well as laboratory tasks such as stepping onto or over abstract targets. For some of these studies, the target has only appeared moments before the required step (e.g. (Caetano et al., 2016)) or has been incorporated into specific laboratory equipment, such as treadmills (De Rugy, Montagne, Buekers, & Laurent, 2001) or virtual reality systems (De Rugy et al., 2000b). By incorporating a task that involves an every-day activity, the current study aimed to generalize the findings of previous locomotor pointing research (Cornus et al., 2009; Montagne et al., 2000) to everyday situations. Whilst the current study is still laboratory-based, the required action more closely approximates and, hence is more generalizable to every-day behaviors than any of the preceding studies.

The task used in the current study involved stepping onto a regulation-height - *curb-like* – two meter long platform. Stepping up onto such a curb-like platform is different from stepping on a target or avoiding obstacles in the sense that the spatial demands are lower as a curb does not dictate where and how to step up. A step up can be achieved via any place in front of the curb, to any place on top, as long as the demands of the step stay within a person's action capabilities. These lower accuracy demands allow a step up that would not require a large decrease in walking speed (Bradshaw & Sparrow, 2002). These demands are not as strict as, for instance, those of a long jump, in which locomotor speed requirements are high and each centimeter away from the take-off board means a centimeter shorter jump distance. Compare this to the approach to a curb in which a foot positioned too close to the curb will turn the curb into a tripping hazard and a position too far away will make the curb unreachable. Both of these scenarios have negative consequences for the efficiency of progression.

The current study aimed to investigate whether previous results in locomotor pointing regulation in a setting with higher spatial demands (the long jump approach (Montagne et al., 2000), walking to specific targets (Cornus et al., 2009)) can be generalized to approaching a curb. As age-related declines in cognition and action capabilities make it unethical to evaluate perceptual-motor regulation during high-speed movements, such as the long-jump approach, this study has the potential to provide new opportunities to study this process in an ageing population. However, before being able to use the curb-approaching task as a measurement tool for perceptual-motor regulation, the current study compared regulation in this task to the previous studies of locomotor pointing. Specifically, we aimed to assess whether, similarly to other studies of perceptual-motor regulation (Cornus et al., 2009; Montagne et al., 2000), a decrease in variability of step placement is shown when an individual approaches a curb-like platform and whether this regulation is dependent on the required adjustment (implying a continuous coupling between perception and action).

4.2 Method

4.2.1 Participants.

Sixteen healthy participants (9 males, 7 females) volunteered to participate in the study (mean (SD) age: 25.5 (3.8) years). All participants were recruited from the university environment, had normal or corrected to normal vision and signed a consent form prior to their participation. The protocol of the study was approved by the institutional Human Research Ethics Committee.

4.2.2 Protocol and Materials.

Participants were instructed to walk 8.5-meters along a pressure-sensitive walkway (GAITRite®, CIR Systems, Inc., Franklyn, NJ, USA), starting from a constant starting position at one end of the GAITRite mat and before stepping onto a purpose-built curb-like platform (dimensions LxWxH: 2.00x1.00x0.15 m) positioned at the other end of the walkway (creating a 10-m walk). A switch was fitted to a post (height 1.35 m) at the far end of the platform and participants were instructed to "walk up to the platform, step up and flick the switch at the far end" to signal the end of each trial. Prior to data collection, participants performed a minimum of three practice walks along the walkway and onto the platform to establish their preferred step length, which was used to set up the main experiment. If the experimenter judged one of the three practice walks to be inconsistent in terms of step length (for instance, some participants started their first walk more cautiously), the data from this trial was excluded and an extra walk was performed to ensure a representative average.

The aim of this experiment was to assess similarities between a long jump running approach (Cornus et al., 2009; Montagne et al., 2000) and a walking task, but the dimensions of our lab did not allow our participants enough space to complete a similar number of strides to that which would be used in a long jump approach. Given that research has shown that variability in foot placement accumulates during the initial phase of the long jumping approach (Lee et al., 1982), athletes are inevitably exposed to different task demands each time they enter a regulation phase and variability is minimized. Similarly, when approaching a curb in the real world environment, the conditions that an individual performs under, such as their starting position relative to the curb, are rarely identical over repeated performances. As such, the current study used the following manipulation to promote variability in the demands of each repeat performance and to better replicate the circumstances experienced in real life when entering the regulation phase. Participants were instructed to place one of their first steps on a target mat of anti-slip material (bright blue color, dimensions LxW: 0.30x1.50 m) that was positioned in one of 10 different positions in front of the participant's starting position at evenly spaced distances ranging from 1 to 2.5 times their preferred step length. Participants were asked to place their full foot on the anti-slip material, but were not limited with respect to the

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number of steps that they took to achieve this goal (i.e. some may have taken one step, while others

would have taken two or three steps). Participants were asked to try and incorporate stepping on the

target in their natural gait and to continue walking along the walkway as naturally as possible. The

target mat at the start of the walkway was presented as a secondary goal; their primary goal was

reaching the switch at the end of the walkway. If a participant was unsuccessful in placing the full

foot on the target at the start of the walkway, the trial continued as normal, with the participant

walking further towards the platform (no outcomes were derived from this procedure). An 11th

condition was added in which no target was presented and the participant walked freely towards the

platform. Conditions were repeated three times each and were presented in a random order,

resulting in a total of 33 trials per participant.

Information about the participants' foot placements was automatically collected and

digitized by the GAITRite system; the forefoot centroid computed by GAITRite was extracted and

used to represent the foot position relative to the curb. This foot placement data was exported to

Microsoft Excel. As the GAITRite system was incapable of measuring foot positions on top of the

platform, information about foot placements immediately prior to and on the platform was also

captured using a digital video camera (CASIO, EX-FH100) positioned 2.35m from the edge of the

platform, perpendicular to the direction of walking. Calibration of the video footage was completed

using two reference markers placed 30 cm apart on the closest side of the platform. Videos were

analyzed using Kinovea (version 0.8.15, ©2006-2011 Joan Charmant & Contrib.) by three research

assistants, in order to extract the position of the forefoot from the participants on top of the

platform. Videos from three participants (396 foot placements identified by each assessor; 3

participants * 33 walks * 2 footfalls * 2 coordinates: heel and toe measures) were rated by all three

assistants. Inter-rater reliability was determined to be excellent (ICC=0.99).

To validate the measures derived from the video camera, the footfall data for four

participants were collected using a Vicon 3-dimensional motion analysis system (Vicon Motion

Systems), with a marker positioned on the shoe of the participant approximately on the distal end of

the second metatarsal. Bland-Altman plots (Appendix 4.1 Bland-Altman plots for validation of video

data) illustrated that the error between the GAITRite and Vicon systems (0.09 cm average) and the

video- and Vicon-based measures (0.88 cm before step up and 0.09 cm after) was very low.

4.2.3 Dependent variables.

Using MATLAB (version R2015a, © 1984-2015 The MathWorks, Inc.) a series of dependent variables

were derived from the foot placement data (Cornus et al., 2009; Montagne et al., 2000). Specifically,

inter-trial, inter-step and *intra-step analyses* were performed.

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For the *inter-trial analysis*, the standard deviations around the average position of the foot for each footfall relative to the curb ($SD_{footfall}$) were calculated for each participant across the 33 trials. Specifically, the average placement of the foot for the first step onto the curb was denoted as footfall0, while the average placements of the foot for the preceding steps were labeled relative to footfall0 (footfall-1, footfall-2... footfall-n; see Figure 4.1). Following previous studies (Berg et al., 1994; Cornus et al., 2009; Montagne et al., 2000) the onset of regulation - the average moment at which a participant initiated regulation - was established as the step at which $SD_{footfall}$ started to decrease, without showing an increase at one of the later steps.

Further analysis compared the variability of foot placements right before and after stepping up the curb for each participant. The assessment of whether the minimal variability was found at the former or the later foot placement indicated whether a participant aimed gait towards a constant location before the step up, or a constant position on the pavement.
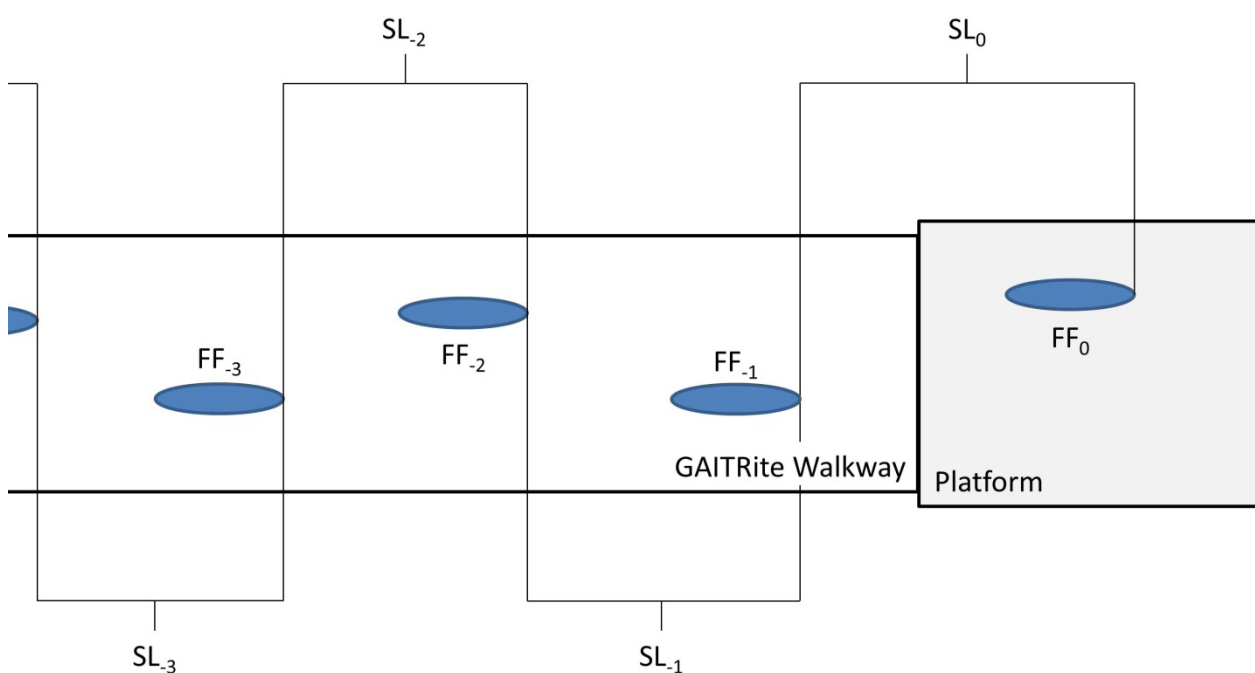
Figure 4.1 Example of footfall coding in the approach to the platform

The first footfall on the platform is coded as FootFall (FF) $_0$ and all other footfall placements are coded in relation to FF_0. The step length onto the platform is coded Step Length (SL) $_0$ and all

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For the *inter-step analysis,* each walk was analyzed individually. A 'standard step length' (SSL) was derived as the mean of the step lengths of the early, steady state steps (step 5-8 counting back from the step onto the platform, similar to (Cornus et al., 2009)). Then, all later steps were compared to this SSL. Steps that were more than 2 SD's larger than the SSL were marked as lengthening steps, whilst those that were more than 2 SD's smaller were marked as shortening steps (Cornus et al., 2009). A trial was considered to be regulated when at least one of its individual steps was marked as either lengthening or shortening. The regulated trials were categorized as; i) lengthening trials when only lengthening steps were used; ii) shortening trials when only shortening steps were used; and iii) mixed trials when a combination of step adjustments was used. The total amount of adjustment per trial (S_{trial}) was using Equation 1.

$$S_{trial} = \sum |SL_i - SSL| \hspace{4cm} \text{Equation 1.}$$

In which SL is the step length with i denoting the step number as in Figure 4.1, SSL represents the standard step length for a given trial. This 'sum of adjustment' per trial was compared to the step number of the first regulated step per trial to assess the relationship between the amount of required adjustment and the onset of regulation.

For the *intra-step analysis,* a standard foot position pattern was calculated per participant, as the mean footfall position for each footfall over all trials (FootFall mean: FFm_i, with i denoting the footfall number as in Figure 4.1). Also, a standard step length pattern was derived as the mean step length per step number for the 33 trials (Step Length mean: SLm_i). Equation 2. represents the adjustment required ($A_{required}$) per footfall (FF_i), with i denoting the footfall number (Figure 4.1).

$$A_{required} = FF_i - FFm_i \hspace{4cm} \text{Equation 2.}$$

This variable was named 'adjustment required' as it represents the error between the current location and the average for that footfall. Similarly, 'adjustment produced' ($A_{produced}$) was computed by using Equation 3 for each step length (SL), with i denoting the step number (Figure 4.1).

$$A_{produced} = SL_i - SLm_i \hspace{4cm} \text{Equation 3.}$$

These values were entered in a linear regression to assess the relationship between the adjustment required in any footfall and the adjustment produced in the following step for all participants (Figure 4.1). Alpha was set to 0.01 for both the *inter-step* and *intra-step analyses* (Cornus et al., 2009).

4.3 Results

4.3.1 Inter-trial analysis.

To allow comparison with previous studies, it was important that our different conditions successfully induced variability in the walking patterns of the participants. Averaged over all participants, six steps before stepping up, $SD_{footfall}$ was 24.95 cm. This is similar to values reported by the previous study of Cornus et al. (Cornus et al., 2009), who use a gymnastics run up track of 25 meters to induce variability in foot placement.

Table 4.1 shows the descriptive information of our participants. There was low variability in step length, cadence and velocity, confirming that there was relative homogeneity in terms of the action capabilities of the participants. Approaching the curb, variability in foot placement decreased (Figure 4.2A and 4.2B), whereas on average, a lengthening of steps was observed in the final two steps (Figure 4.2C and 4.2D). The onset of regulation was variable between participants and spread between eight and four steps before the step up (Table 4.1). Only one participant showed a minimal $SD_{footfall}$ at the last step before stepping up (red data in Figures 4.2B and 4.2D), all others had a minimal $SD_{footfall}$ on the platform (blue data in Figures 4.2B and 4.2D).

Table 4.1 Descriptive information of participants (N=16) gait behavior

	Default Mean (SD)[a]	Range
Step Length (m)	0.77 (0.04)	0.71 to 0.86
Cadence (steps per minute)	111.51 (9.41)	91.16 to 126.52
Velocity (m/s)	1.44 (0.13)	1.17 to 1.80
Start of Regulation (step nr.)	-6.13 (1.31)	-4 to -8

[a] Default step parameters are calculated as the mean of steps early in the trial
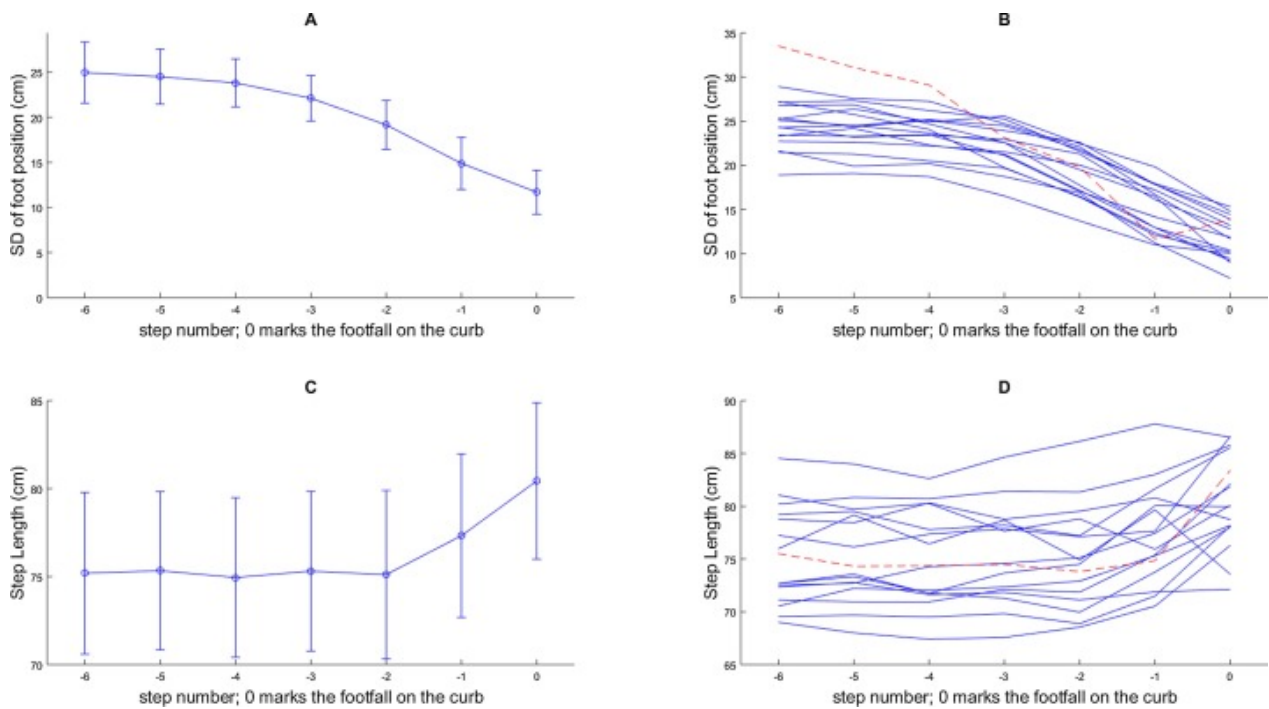
Figure 4.2 Average and Individual data of approach to the curb

Data is represented per footfall leading up to the curb, with 0 being the first footfall on the platform. Panel A shows the mean ± 1SD of toe-curb distance in centimeters for all participants (N=16) over 33 walks. Panel B shows individual data, with standard deviation of footfall position over 33 walks. Panel C shows the mean ± 1SD of step length, for all participants, whereas panel D shows individual data of step length, providing insight into the nature of step adjustments. Blue data represents participants with a minimal SD for the footfall on top of the platform and red data (dashed line) represents the one participant with a minimal SD at step-1.

4.3.2 Inter-step analysis.

The inter-step analysis identified 87% of the trials to be categorized as 'regulated' (over all participants: 460 of 528 trials, range: 73%-100%). In total, 134 trials were classified as lengthening, 221 as shortenings and the remaining 105 were categorized as mixed. Linear regression analyses highlighted significant relationships between the sum of adjustments per trial (a summation of the differences between each step and a standard step in that trial) and the timing of the onset of regulation (Figure 4.3). These relations show that participants initiated regulation earlier in trials that required more adjustment; indicating that the onset of regulation was related to the perception of the adjustment required. Specifically, significant linear relationships were identified for the shortening trials ($Y = -2.63x + 6.06$, in which Y is the total amount of adjustment in the trial and x is the step of regulation onset; $R^2 = 0.10$; $p = 0.001$) and the lengthening trials ($Y = -4.69x + 10.63$; $R^2 = 0.23$; $p < 0.001$), but not the mixed trials ($Y = -1.11x + 12.91$; $R^2 = 0.01$; $p = 0.344$).
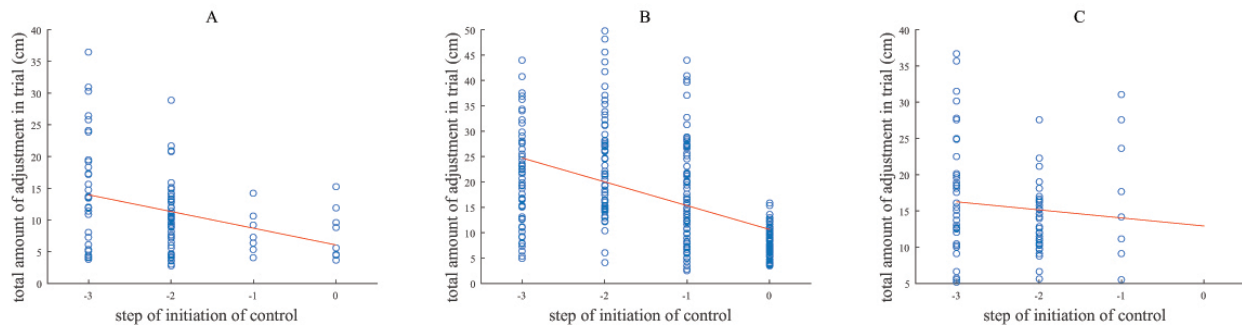
Figure 4.3 The relationship between the total adjustment shown in a walk and initiation of regulation

Displayed for shortening trials (A; N = 221), lengthening trials (B; N = 134) and mixed trials (C; N = 105). A significant linear relationship is evident for shortening (p=0.001) and lengthening (p<0.001), showing that the onset of these types of regulation is dependent on the required amount of adjustment.

4.3.3 Intra-step analysis.

The regression analysis found a significant linear relationship between the amount of adjustment required at a certain footfall and the amount of adjustment produced in the following step (Figure 4.4). This relationship was significant for all steps starting 6 steps away from the platform (Y = 0.02x - 0.01, in which x is the required adjustment and Y is adjustment produced; R^2 = 0.05; p < 0.001) and remained linear with increasing steepness (beta increases from 0.02 at $step_{-6}$ to 0.29 at the $step_0$) and increasing R^2 values towards the last footfall (R^2 = 0.05 at $step_{-6}$ and increases to R^2 = 0.69 at $step_{-1}$). Interestingly, at the step onto the curb ($step_0$), the R^2 value was lower than at the previous step (R^2 at $step_0$ = 0.44).
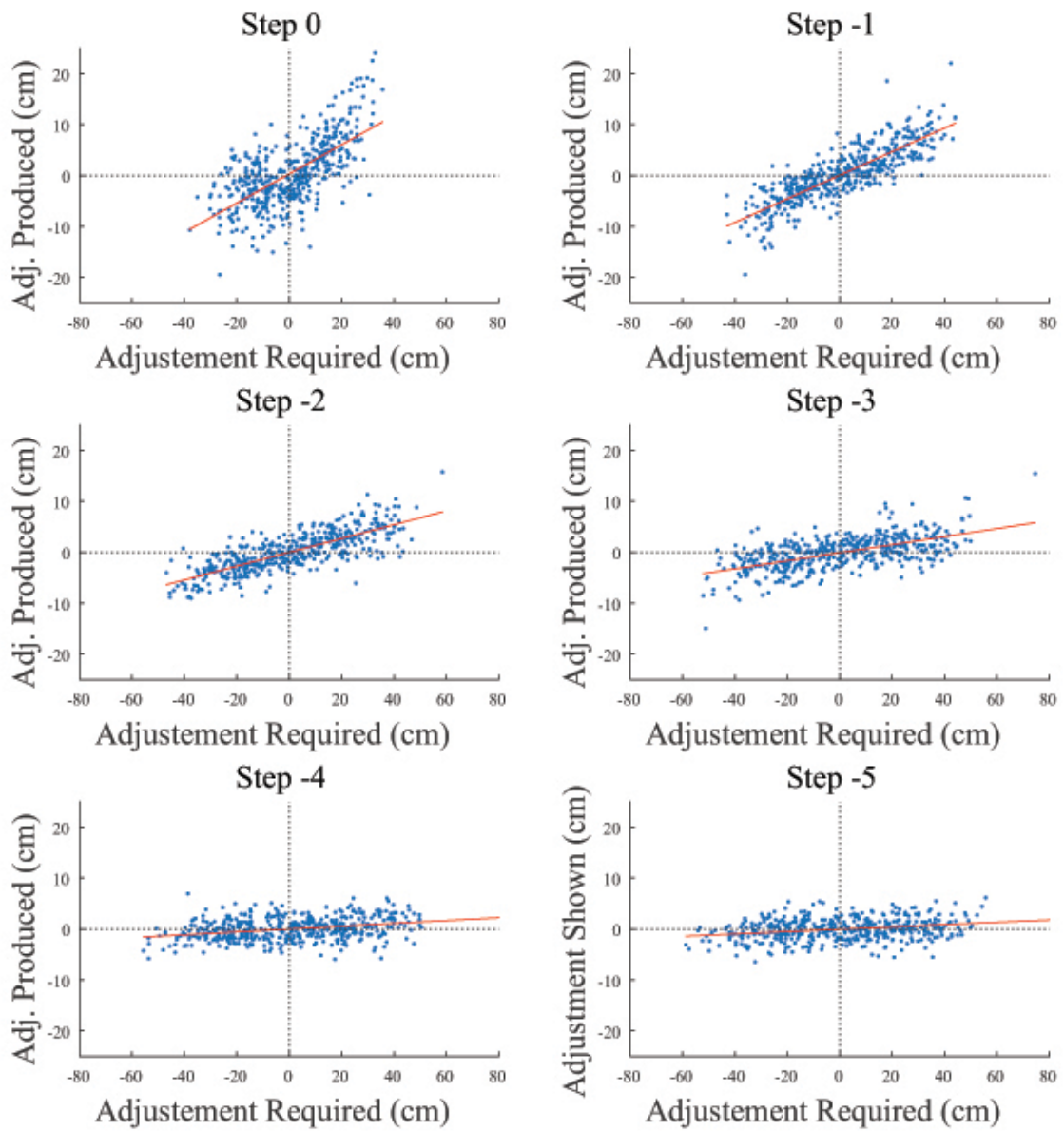
Figure 4.4 Relationship between adjustment required and adjustment produced per step

Linear regression analyses per step number for the required adjustment (Pi-Pmi) and the adjustment produced (Li^{-1}-Lmi^{-1}). The relationship is statistically significant at all measured steps (up to step -6).

4.4 Discussion

The main aim of this study was to assess whether perceptual-motor regulation is evident in the task of approaching and stepping onto a curb-like platform. Overall, the results indicated that a similar type of perceptual-motor regulation is apparent as what has previously been reported in the run-up for long jumping (Hay, 1988; Lee et al., 1982; Montagne et al., 2000) and the approach to step over an obstacle (Cornus et al., 2009).

The results from the inter-trial analysis showed that variability of foot placements decreased when participants drew closer to the curb, similar to previous findings in other locomotor pointing tasks. In a previous study on stepping over obstacles, the standard deviation of footfall position decreased to only 0.05 m (Cornus et al., 2009). Our results were less pronounced. The average minimal variability of the standard deviation of footfall position in the current study was 0.12 m. Our participants initiated regulation earlier. Variability started to decrease as early as eight steps before the minimal variability occurred, whereas five steps before an obstacle was the earliest found in previous research (Cornus et al., 2009).

The finding that regulation of step length variability when approaching a curb was similar compared to that previously reported in studies concerning the long jump approach is interesting and indicates that the task of approaching a curb could be used to measure perceptual-motor regulation. This is particularly relevant since a recent review (Andel, Cole, & Pepping, 2017) showed that research into perceptual-motor research is often performed on convenience samples comprising younger adults and not, for instance, in aging or clinical groups. Long jumping as a task to measure perceptual-motor control would be impractical (if not unethical) for these cohorts but approaching and stepping up a curb could be a representative alternative, to enable measurement of perceptual-motor coupling and the development of diagnostic instruments for atypical perceptual-motor coupling.

Most participants (15 out of 16) regulated their gait to aim for a placement on the platform, as shown by minimal variability being recorded at their footfall on top of the platform. It is interesting to think about why one strategy would be picked over the other. It could be hypothesized that this relates to certain strategies of approaching. Aiming for a standard placement in front of the step up might be reflective of a more cautious strategy; a person can position him or herself in the best location to enable a safe step up. In contrast, other participants might aim for the curb to prioritize smooth progression. The current study found that, in general, our participants lengthened their steps when approaching the platform. This is unsurprising as research has shown that participants prefer to lengthen their steps instead of shortening when confronted with an obstacle (Patla, Prentice, Rietdyk, Allard, & Martin, 1999). This also might be the result of a trade-off between

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the safety of a more cautious walk with smaller shortened steps versus an adjustment using larger

lengthened steps with greater efficiency (Huang, Chen, Wang, Wei, & Wang, 2010). Following this

reasoning, it will be interesting to replicate these results using participants that might be more

tempted to make cautious decisions, such as older adults. With older age, people are known to walk

more cautiously, in order to cope with their decreased gait and balance capabilities. Furthermore,

despite local government regulations, curbs in various cities and countries around the world are

unlikely to be exactly the same height. As a higher curb would be more demanding than a lower curb,

individuals may exhibit different perceptual-motor regulation when approaching these different

obstacles. Future research is required to better understand the influence of such changes on the

relationships between a person, their environment (the curb) and their perceptual-motor regulation.

The results of the regression analyses in the inter-step analysis showed that the moment at

which participants altered their gait patterns was related to the total amount of adjustment required

for the shortening and lengthening trials, but not for mixed trials. These results replicated those of

previous studies that involved stepping over obstacles, which also reported the relationships to be

significant for lengthening and shortening trials, but not mixed trials (Cornus et al., 2009).

The results from the intra-step analysis indicated that the adjustment produced in each step

was related to the required adjustment in the previous foot placement as early as six steps before

step up. Similar relationships have been identified in previous research, though generally they show

the relationship to reach significance later in the task; namely three (Cornus et al., 2009; De Rugy et

al., 2000b) or four steps (Montagne et al., 2000) before the target. Compared with the walking to

step over a target task of Cornus et al. (Cornus et al., 2009), which reported that the relationship

between required- and produced adjustment became stronger throughout the task, our results were

similar in the approach phase, with a slightly weaker relationship for the final step onto the curb.

It is relevant to note that all of our analyses showed that our participants started their

adjustments earlier than indicated by previous studies. It has been reported that with higher spatial

demands, regulation was initiated earlier (Cornus et al., 2009). The spatial demands associated with

our tasks could be considered lower than the demands associated with the experimental tasks used

in previous studies, in which participants were free to choose where to place their feet. A possible

explanation for this finding is that participants were very familiar with our task. Past experiences in

stepping up curbs could have made them more attuned to relevant visual information, making them

recognize important constraints sooner and enabling regulation earlier, compared to the approach

participants were required to make to abstract obstacles in previous study (Cornus et al., 2009).

Another explanation could be the presence of the flick button at the end of the platform. Studies in

the run-up of cricket bowlers have shown that having a vertical reference point (such as the umpire

in cricket or the vertical post with the button in the current study) makes participants regulate earlier in their run (Greenwood et al., 2016; Renshaw & Davids, 2004). Furthermore, it has been shown that a nested task (such as assuming an appropriate posture) could influence regulation even further (Renshaw & Davids, 2004). Our task of flicking a button at the end might have had a similar influence in locomotor pointing towards the platform. Future research should seek to study these effects further and to examine the influence of performing similar tasks in truly natural settings, such as outdoors.

In conclusion, the current study showed that the regulation that has previously been described for locomotor pointing in the long-jump run up (De Rugy, Taga, et al., 2002; Montagne et al., 2000) and stepping over an obstacle (Cornus et al., 2009) is also present when stepping onto a curb. Overall, our analyses showed that participants initiated regulation earlier than shown in previous research and suggests that young people typically aim for a specific position on the curb rather than for a specific placement in front of the curb. The finding that perceptual-motor regulation can be measured in this type of locomotor pointing is an important one. The task described in this paper can now confidently be used as a measure of perceptual-motor regulation in locomotion that has low demands and can be used in any target population. This introduces potential measures for use with older adults and clinical groups, whose frailty might prevent them from being tested with more demanding tasks. Studying perceptual-motor regulation in older cohorts will be an interesting topic of future research as it is currently unknown how age-related declines in action capabilities affect perceptual-motor coupling.

Chapter 5 - Regulation of Locomotor Pointing Across the Lifespan: Investigating Age-Related Influences on Perceptual-Motor Coupling

The study described in this chapter has been published following peer review. Full reference details are:

Andel, S. van, Cole, M. H., & Pepping, G.-J. (2018). Regulation of locomotor pointing across the lifespan: Investigating age-related influences on perceptual-motor coupling. *PLOS ONE*, 13(7), e0200244.

Chapter 5 - Regulation of Locomotor Pointing Across the Lifespan: Investigating Age-Related
Influences on Perceptual-Motor Coupling

5.0 Synopsis and relevance for this thesis

In the previous chapter, the similarities were outlined between the perceptual-motor regulation in the approach for a long jump and in the task central to this thesis; a walking approach to a curb. Chapter 5 expands on this curb-approach task and focusses on the description of age-related changes to the perceptual-motor regulation of a walking approach.

As outlined in section 1.6 *('How to read this thesis')*, in Chapter 5 we shift from a focus on theory and replication of previous analyses towards a focus on clinical implications and the relevance for healthy ageing. In Chapter 5, the results collected from the younger participants in Chapter 4 are compared with older participants of 60 years and older.

In Chapter 5, the same analyses are used as in chapter 4. However, to emphasize on the translation to a practice setting, these analyses are presented in terms of their relevance for healthy ageing (i.e. not in terms of analyses and results, but in terms of 'measures of interest' and their age-related changes). The current chapter describes the influences of age on; 1, the onset of the gait adjustments in locomotor pointing; 2, the strategy of gait adjustment (i.e. lengthening or shortening of steps); and 3, the strength of gait adjustments.

The results of Chapter 5 show no clear effect of age on the onset of step length adjustments. An effect of age was found on the strategy of adjustments; with age, participants seemed to increasingly adopt a shortening strategy. Finally, age-related differences were identified in the strength of gait adaptations. Like the results described in Chapter 4, older participants engaged in stronger adaptations as they got closer to stepping onto the curb. This effect seemed to be magnified by age; the oldest participants engaged in the strongest gait adjustments.

In terms of the relevance for theory, this chapter is important as it shows that older adults need to engage in stronger gait adaptations or in other words a stronger coupling between perception and action. The decreasing action capabilities and flexibility in gait adaptation in the older cohort set higher task demands on the locomotor pointing, which results in the requirement for stronger perceptual-motor coupling. Arguably, these elevated perceptual-motor demands could explain the elevated incidence of falls in the older cohort.

In terms of practical implications these findings are important as they show how the perceptual-motor system changes with age. It is therefore of importance for healthy ageing practitioners to understand that the perception and action systems are coupled and that older adults might need to adjust to the age-related changes in this coupling. This can be achieved by an

(ecologically-grounded) functional approach, in which older adults are supported in performing

functional movements, relevant in their own living environment.

5.1 Introduction

In everyday motor control, humans, young and old, show a great capacity to regulate and

perform successful actions. For instance, consider a long jumper who is running at near maximal

speed, but is still able to guide their foot to the take-off board with amazing accuracy. Research has

shown that this type of locomotor pointing is made possible through an intimate coupling of

perception and action (Buekers, Montagne, De Rugy, & Laurent, 1999; De Rugy et al., 2000a, 2000b;

Hay, 1988; Lee et al., 1982; Montagne et al., 2000). The regulation required for such a task is not

limited to athlete populations, but rather, is also used by members of the general population on a

daily basis when performing locomotor pointing tasks, such as approaching and stepping onto a curb

(Andel, Cole, & Pepping, 2018a). Whilst these studies would suggest that locomotor pointing is a skill

that can be comfortably performed by all humans, research concerning age-related changes in

locomotor pointing in otherwise healthy populations is limited. The current study addressed this

limitation and investigated the effect of age on perceptual-motor coupling in healthy older adults.

Whilst investigating locomotor pointing in the approach of a long jump, Lee and colleagues

(Lee et al., 1982) analyzed the variability in foot placements leading up to the jump and identified

two separate phases in the regulation of foot placements. In the first phase, the variability in foot

placements accumulated as the athlete attempted to produce a stereotypical stride pattern to

optimize acceleration. In the second, 'zeroing-in' or regulation-phase, the athletes were shown to

reduce the accumulated variability in foot placement to initiate the jump from as close to the take-

off board as possible (Lee et al., 1982). Later research assessed when participants initiate this

regulation-phase and showed that this did not contain a fixed number of steps in each trial

(Montagne et al., 2000). Rather, findings showed that the onset of regulation for individual trials was

related to the total amount of adjustment required. That is, if an athlete required large adjustments

to end up with minimum error at the take-off board, he or she would start regulation earlier.

Furthermore, research showed that the adjustments shown during the run-up were achieved

through a tight relationship between perception and action throughout the final steps in a run-up.

That is, results showed that the produced adjustments in a single step were linearly related to the

adjustments required, based upon the previous foot-position of the athlete. In such an assessment of

the relationship between the produced adjustment and a person's position, a strong linear

relationship can only be formed when a person bases their adjustment of step length on their

perception of their location. In accordance with other research [1-6], in the current study this is

interpreted as evidence for *perceptual-motor coupling*. A previous study on locomotor pointing in the

long jump run up that similarly interpreted the relationship between produced and required foot-

placement adjustments as perceptual-motor coupling reported that this relationship was established

about four steps before the jump and that it became increasingly stronger (evidenced by an

increasing steepness of the regression line) as the athletes drew closer to the target (Montagne et

al., 2000).

In subsequent research, it was shown that people exhibit the same perceptual-motor

coupling strategy as shown in the long-jump in other locomotor pointing tasks, such as walking to a

target (Andel et al., 2018; Cornus et al., 2009; De Rugy et al., 2001; De Rugy, Montagne, Buekers, &

Laurent, 2002; De Rugy, Taga, et al., 2002; Montagne et al., 2002). In these studies, the relationship

between the gait adjustments required and gait adjustments produced was measured for each step

in the approach to a target as the degree to which deviations from the average step length were

related to the adjustment required. The adjustment required was measured as the difference

between the location of the foot during the approach (e.g. the fifth last step before reaching the

target) and the mean location of that foot for that step (i.e. the mean location of the foot during the

fifth last step before reaching the target). Similarly, adjustment produced was measured as the

difference between a certain step's length and the average step length (De Rugy et al., 2000b; De

Rugy, Montagne, et al., 2002; Montagne et al., 2002, 2000). A recent study described the strength of

this relationship between adjustment required and adjustment produced as representing the

'strength of perceptual-motor coupling' (Andel et al., 2018a). In this interpretation, a stronger

coupling recorded for a specific step would indicate that more of the required adjustment is being

made in that specific step. For instance, a 100% coupling would indicate that if, at a certain step, a

person is 5cm behind on his/her average approach; they will adjust their next step to be 5cm longer

than their average step. Data over multiple walks can be analyzed using regression analyses for each

step, with a greater steepness (beta values close to 1, indicating close to 100% correction in one step)

indicating stronger perceptual-motor coupling. In a small number of studies, the influence of

changing task constraints on locomotor pointing behavior has been investigated (Cornus et al., 2009;

Montagne et al., 2002) and it was shown that tasks with higher spatiotemporal demands (e.g. smaller

targets or higher movement speeds) led to stronger perceptual-motor coupling as indicated by

higher beta values in the regression analysis. For instance, high spatiotemporal demands in a walking

task have been shown to lead to beta values of around 0.71 in a single step, compared to beta values

of around 0.39 for walking tasks with lower demands (Cornus et al., 2009).

Research into locomotor pointing, to date, has shown that even though aspects of onset and

strength of perceptual-motor regulation might differ between locomotor pointing tasks, all tasks

seem to share common principles. That is, similarities in the regulation of foot placement exist

between tasks performed in high-performance settings (e.g. long jump), as well as in everyday

activities, such as walking to and stepping onto targets (Cornus et al., 2009) and approaching and

stepping onto a curb (Andel et al., 2018a). This is helpful in broadening the understanding of

perceptual-motor coupling in locomotor settings. Further, it provides a vehicle for assessing

perceptual-motor coupling in cohorts of participants that cannot cope with the high demands of

athletic locomotor tasks, such as a long jumping approach. In the current investigation we used a

walking approach to stepping up a curb to study locomotor pointing in a cohort of otherwise healthy

younger and older adults. This task is different from traditional locomotor pointing research in that

the act of stepping onto a curb has no clearly defined target. In such situations where movement is

less constrained by a target, one can expect later initiation of regulation and a less strong perceptual-

motor coupling (Cornus et al., 2009).

The physical and functional decline of an individual's capabilities with age has been well

documented (Larsson et al., 1978; Lindle et al., 1997; Oberg, Karsznia, & Oberg, 1993). These

declines in the motor components of the perceptual-motor system mean that older adults need to

cope with a changing relationship between perceptual and motor function. The current study aimed

to describe how regulation of locomotor pointing changes with this changing relationship between

perceptual and motor function. This aim was achieved by investigating: 1. the onset of regulation; 2.

the strength of perceptual-motor regulation; and 3. how people adjust their steps (i.e. by lengthening

or shortening their steps) in a large group of older adults and a group of younger controls. Cornus

and colleagues (Cornus et al., 2009) found that, when higher task demands were experimentally

implemented, the strength of perceptual-motor regulation increased. It is hypothesized that the age-

related declines to their motor systems experienced by older adults lead to comparatively higher task

demands, and similar to the effects described by Cornus (Cornus et al., 2009), this would lead to

stronger perceptual-motor regulation.

5.2 Methods

5.2.1 Participants

Two groups of participants volunteered to be part of the experiment. The first group

consisted of 17 younger participants (mean age: 25.35 years, SD: 3.76 years, range: 19-33, 10 males,

7 females). The second group composed 105 older adults (mean age: 71.49 years, SD: 5.60 years,

range: 61-86 years, 29 males, 76 females) from a local community of healthy older adults. All

participants had normal or corrected to normal vision, were free of leg injury or known balance

disorders, and were able to stand and walk without the use of a walking aid for the entire length of

the experiment. The younger group was required to be aged between 18 and 40 years (similar to the

age ranges used in previous perception-action research (Andel et al., 2017)), while the older

participants were eligible to participate if they were aged over 60 years and had no cognitive deficits

(measured as Mini Mental State Examination scores > 23). The protocol of the study was identical for

both groups and was approved by the Australian Catholic University's Human Research Ethics

Committee (2015-306H) and all participants signed an informed consent form.

5.2.2 Protocol and materials

Participants completed a series of walking tasks that involved walking along an 8.5-meter

pressure-sensitive walkway (GAITRite, CIR Systems Inc.) to a purpose-built platform that they

stepped up and onto (Figure 5.1). The platform measured 15 cm high, 2 meters long and 1 meter

wide and was designed to conform to standard curb building regulations in Queensland, Australia.

For each trial, participants were instructed to walk the full length of the walkway, step up onto the

platform and press a switch that was situated at a height of 1.35 meters at the end of the platform. A

measure of average step length was established a-priori, to be used for setting up the main

experiment. To record this a-priori measure, participants performed three unconstrained walks over

the pressure-sensitive walkway. A fourth walk was added if the experimenter judged one of the

initial three walks to be dissimilar to the others in terms of step length (some participants
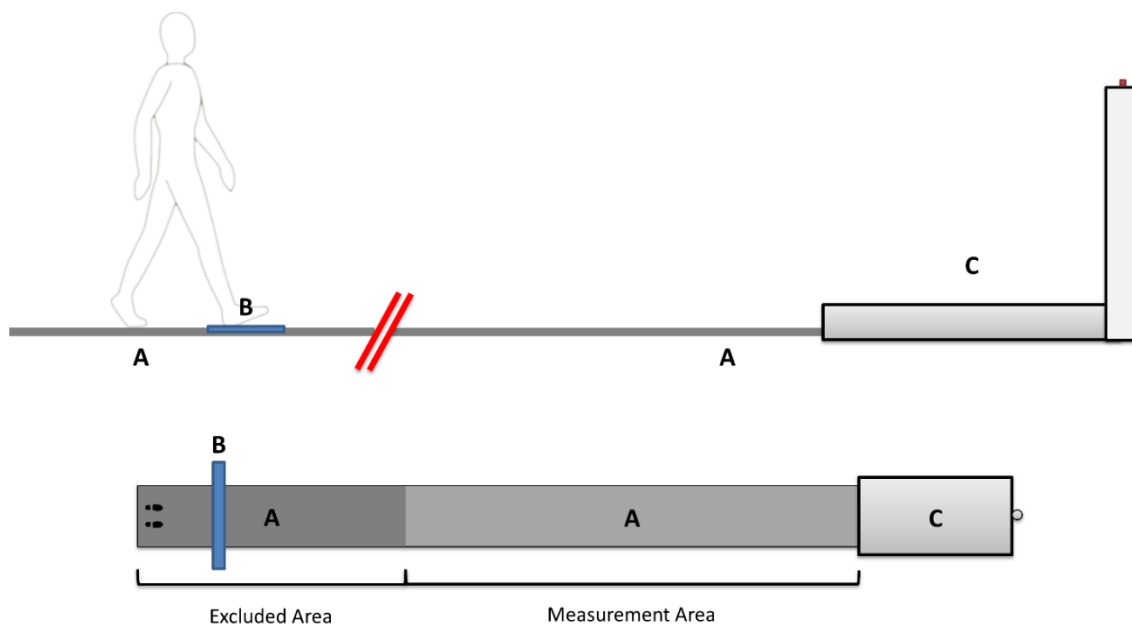
Figure 5.1 Schematic of the experimental set up

A) the 8.5-meter pressure-sensitive walkway, B) the moveable target, and C) the platform (15 cm high, 100 cm wide and 200 cm long) with the flick button at the end (at 1.35 m high).

approached the first walk rather cautious, making the average not representative of their natural

gait). No further outcomes were derived from these a-priori walks.

To facilitate comparison of the current study with previous research and to prevent the

participants from producing the same stereotypical walk each time, they were required to place one

of their early steps onto a target on the ground (a blue anti-slip mat, dimensions: 30 cm long and 150

cm wide), which was placed in 10 different positions ranging from 1 to 2.5 times the a-priori

measured step lengths from the start of the walkway (Andel et al., 2018a). In addition, a final

condition was added in which no early stepping target was presented and the participants completed

the task unconstrained. All 11 conditions were repeated three times in a random order to produce a

total of 33 walks per participant.

The inclusion of the early step target prevented the participants from producing the same

stereotypical walk each time by influencing the participants' step length early in their approach. In

order to not have this influence any outcome measures, footfalls placed in the first 3.5 meters of the

GAITRite were excluded from the analysis. Hence, all the results reported were collected from the

final five meters of the walk before stepping onto the curb (Measurement Area in Figure 5.1)

Information about the placement of each footfall before stepping onto the curb was

collected using the GAITRite system and exported to Microsoft Excel. A digital video camera (CASIO,

EX-FH100), placed 2.35 m from the edge of the platform, perpendicular to the direction of walking

was used to collect information regarding the participants' step onto the curb. In calculating the

participants' step lengths towards this position on the curb, only the horizontal distance between

subsequent steps in the sagittal plane was analyzed. The Kinovea software (version 0.8.15, ©2006-

2011 Joan Charmant & Contrib.) was used to analyze the video data and to extract the first foot

position in the direction of walking on top of the curb for each walk (Andel et al., 2018a). An

assessment of inter-rater reliability was performed by three independent raters based on the videos

for two participants (66 trials). The foot placements derived for these trials were shown to have very

high repeatability (ICC = 0.993). Further calculations and the statistical analyses were performed

using MATLAB (version R2015a, © 1984-2015 The MathWorks, Inc.).

5.2.3 Variables

The following variables were extracted from the dataset and used in the statistical analysis.

Variability in footfall position (SD-footfall)

The variability in footfall position *(SD-footfall)* was calculated for each footfall, and for each

participant to show how variability in positioning changed as participants got closer to the target. As

the variability in foot placement is partly dependent on the length of one's steps (and results could

thus be attributed to step length differences, rather than age), a scaled measure of SD-footfall was

used in all analyses (SD-footfall/Step Length).

Standard step length (SSL)

The participants standard step length *(SSL)* was calculated by averaging the length of the 4

steps starting at least 3.5 meters away from the starting position, for each trial. The standard

deviation around this mean was referred to as the 'SSL-SD'.

Onset of regulation (OnsetReg)

The onset of regulation *on a trial-by-trial level* was designed to identify when significant

adjustments are made in a person's step lengths. *OnsetReg* was calculated relative to SSL. If a step in

was more than two times SSL-SD different from this SSL for that trial, the step was considered to be

an adjusted step (Andel et al., 2018a; Cornus et al., 2009). The first step to be marked as 'adjusted'

within a particular trial was marked as OnsetReg for that trial. OnsetReg were analysed in terms of

step number as well as distance from the curb. Finally, if at least one of the steps within a trial was

considered to be adjusted, the walk itself was marked as *adjusted.* If no steps in the trial were

considered to be adjusted, the trial was marked as *unadjusted*.

Adjustment per trial (Adjust$_{total}$)

For all steps marked as adjusted, the SSL was subtracted from the length of the adjusted

step. As such, when the result was positive, it indicated a *lengthening* step relative to the SSL, while a

negative outcome indicated a *shortening* step relative to the SSL. The absolute value of the sum of

these deviations of the standard step per trial was computed to assess the total adjustment per trial,

or *Adjust$_{total}$*. Based on the classification of adjusted steps as being either lengthening or shortening

steps, the trials as a whole were categorized for their adjustment strategy; a lengthening strategy (all

adjusted steps were longer than the standard steps), a shortening strategy (all adjusted steps were

shorter than the standard step length) or a mixed strategy (at least one adjusted step was longer and

one was shorter than the standard step).

Adjustment required (Adjust_required,)

Adjust_required, was computed for each of the final six foot placements before stepping up and onto the curb-like platform of all adjusted trials, as the difference between the current foot placement and the mean placement for that step, per participant.

Adjustment produced (Adjust_produced)

Similar to *Adjust_required*, the *Adjust_produced* was computed of the final six steps in adjusted trials as the difference between each step and the average step length at that step per participant.

5.2.3 Statistics

Between group differences in strategy

An ANOVA was used to assess differences in the dominant step length adjustment strategy (number of trials in a particular strategy) between age groups. For this analysis, the cohort of older participants was split into three age groups, based on chronological age and compared with each other and the young group. In grouping the participants, it was aimed to keep sample sizes between groups as equal as possible whilst not sorting people of the same chronological age into different groups.

Linear mixed effects modelling

In order to assess the effect of aging on the other variables, a Linear Mixed Effects (LME) Modelling analysis was adopted and these outcomes complemented the above-mentioned analyses. In all LME models, age was included as a continuous variable (in contrast to the between-group analysis above) and the p-value of the coefficients was analyzed to indicate significance of a certain factor and alpha for all models was set to 0.05.

Variability of foot placement

The influence of age on footfall variability was studied using an LME model with the step length scaled variability in foot placement (SD-footfall/Step Length) entered as a dependent variable. It was expected that the relationship between age and SD-footfall might change as participants moved closer to the curb-like platform and that this change would be indicative of an adjustment strategy. Therefore, slopes and intervals were allowed to vary per step number (random effect) in the LME model. The formula below describes the model used, where $Footfall_{number}$ indicates the number of the footfall, counting backwards from the first footfall on top of the curb (this being footfall0, the last footfall before stepping up being footfall-1, etc.).

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$$\frac{SD - Footfall}{Step\ Length} \sim Age + (1 + Age | Footfall_{number})$$

Onset of Regulation

A second LME model was set up to study the influence of age on OnsetReg. Intercepts and slopes of the fixed effects were allowed to vary for the different adjustment strategies (random effect). This resulted in the model below.

$$OnsetReg \sim Adjust_{total} * Age + (1 + Adjust_{total} * Age | Strategy)$$

Step length adjustments

In order to assess the influence of age on step length throughout the walks, the LME model described below was used, in which Footfall$_{number}$ indicated the number of the footfall relative to the curb.

$$SL \sim Age + (1 + Age | Footfall_{number})$$

Strength of perceptual-motor coupling

Finally, a LME model was computed to assess the influence of age on the relationship between Adjust$_{required}$ and Adjust$_{produced}$. Age and Adjust$_{required}$ were entered in the model as fixed factors. The intercept and slope of the fixed effects were allowed to vary for each Footfall$_{number}$ (Footfall$_{number}$ being the number of the footfall relative to the first footfall on the curb; footfall0). This resulted in the following LME model:

$$Adjust_{Produced} \sim Adjust_{Required} * Age + (1 + Adjust_{Required} * Age | Footfall_{number})$$

5.3 Results

5.3.1 Between group differences in strategy

Data for eight of the 105 participants in the older participant group (two males, six females, average age: 75 years, SD: 7.13) were lost due to errors related to the video camera (e.g. insufficient memory or battery power). The remaining 97 older participants were subsequently sub-divided into 3 groups based on their chronological age to give; i) a young-old group (61-68 years); ii) a middle-old group (69-73 years); and iii) an old-old group (74-85 years). Although the specific age ranges used to define these groups were not of equal size, they were guided by the need to match these three cohorts as closely as possible for sample size. No data were lost for the younger group (N=17) and, hence, a total to 114 participants were included in the presented analyses. The descriptive statistics

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of the participants are reported in Table 5.1 for the younger participants and the three older participant sub-groups.

Table 5.1 shows that, when assessing the absolute distance to the curb at which participants started to adjust their steps (OnsetReg in distance), no age-related differences were found. However, when assessing differences in terms of step number between age groups (OnsetReg in step number), significant effects indicated that the young and the middle-old group initiated regulation later compared to the young-old and old-old groups.

Figure 5.2B shows the average step lengths per group over the approach. It was clear that a lengthening strategy was dominant in the younger cohort. None of older groups showed this lengthening strategy.

PERCEPTUAL-MOTOR REGULATION AND FALLS RISK

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Table 5.1 Descriptive Statistics (Mean ± SD) for the Gait Characteristics of Participants Split into Age Categories.

'Standard' Measures were Derived from the Middle of the Walks, ANOVAs with alpha set to 0.05 were used to Identify Significant Effects of Age Category on all Measures Except 'Mean Age'

Measure	Young Age 19-33 yr N=17	Young-Old Age 61-68 yr N=33	Middle-Old Age 69-73 yr N=35	Old-Old Age 74-85 yr N=29
Mean Age (years)	25.35 (3.76)	65.59 (2.19)	70.97 (1.52)	77.96 (3.21)
Standard Step Length (cm) [b]	75.07 (4.46)	68.64 (8.56)	68.60 (7.54)	67.28 (7.88)
Maximal Comfortable Step Length (cm) [bd]	84.48 (4.21)	75.42 (8.69)	75.10 (8.01)	74.31 (9.14)
Standard Walking Speed (m/s) [a]	1.40 (0.14)	1.31 (0.21)	1.31 (0.14)	1.29 (0.18)
Minimal SD-Footfall (cm) [b]	11.56 (2.37)	7.00 (2.98)	7.56 (3.23)	7.32 (3.54)
OnsetReg in steps (step number) [c]	2.70 (0.28)	2.95 (0.28)	2.74 (0.33)	2.95 (0.36)
OnsetReg in distance (cm) [a]	107.37 (19.59)	107.16 (24.94)	95.27 (18.58)	103.56 (18.37

[a] ANOVA testing revealed no significant differences between groups.

[b] Bonferroni corrected post-hoc analysis revealed differences between the young group and three older groups, no differences between older groups were found

[c] Bonferroni corrected post-hoc analysis revealed the Young and Middle-Old groups to be significantly different from the Young-Old and Old-Old groups

[d] Maximal Comfortable Step Length represents the average over the 11th to the 20th biggest steps, representing a step length that was not on a participant's absolute upper limit, but rather was a more functional representation of their maximum step.
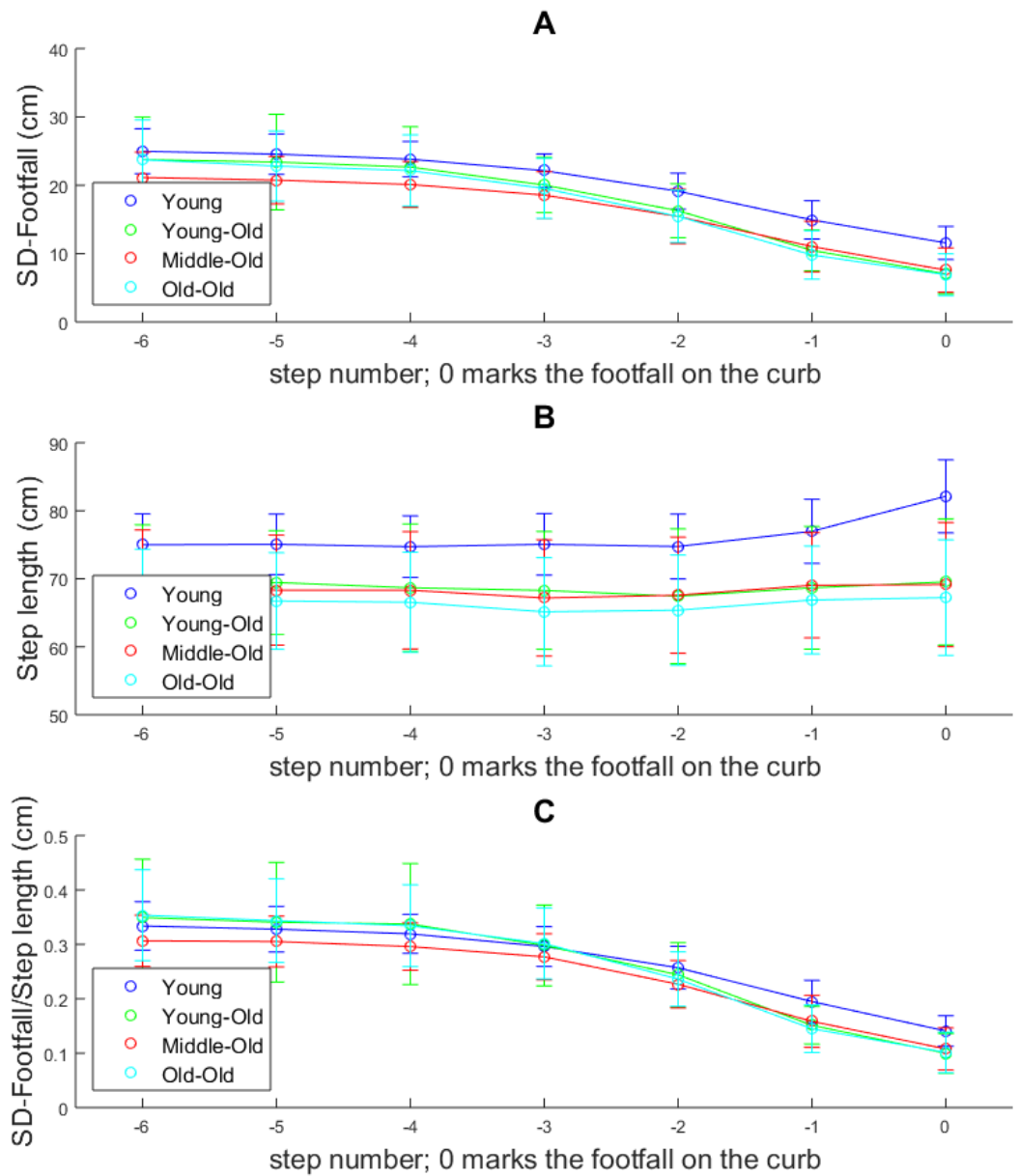
Figure 5.2 Descriptive analysis of locomotor pointing behavior.

Data depicted are split into age categories with Panel A showing the standard deviation of footfall
position (SD-footfall) as a function of the step number before stepping onto the curb. Panel B shows
step length as a function of step number. And panel C shows the SD-footfall scaled by step length
for each step number.

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The distribution of adjustment strategies of step length (lengthening, shortening, mixed) across the different age groups is displayed in Figure 5.3. Effects of age on the distribution of adjustment strategies were investigated using ANOVA testing. The assumption of normality of the data was assessed using Levene's test, which identified no violations to the assumption. The analysis returned a significant main effect for group on the number of lengthening ($F_{(3,113)} = 8.03$, $p < 0.001$) and shortening ($F_{(3,113)} = 7.88$, $p < 0.001$) trials, but not for the number of mixed trials ($F_{(3,113)} = 0.82$, $p = 0.485$). Post-hoc analyses with Bonferroni corrections identified that the younger group exhibited a greater number of lengthening trials than the three older groups, while the older groups all adopted a shortening strategy more often than the younger cohort (all p-values < 0.05). No significant differences were identified amongst the older groups.
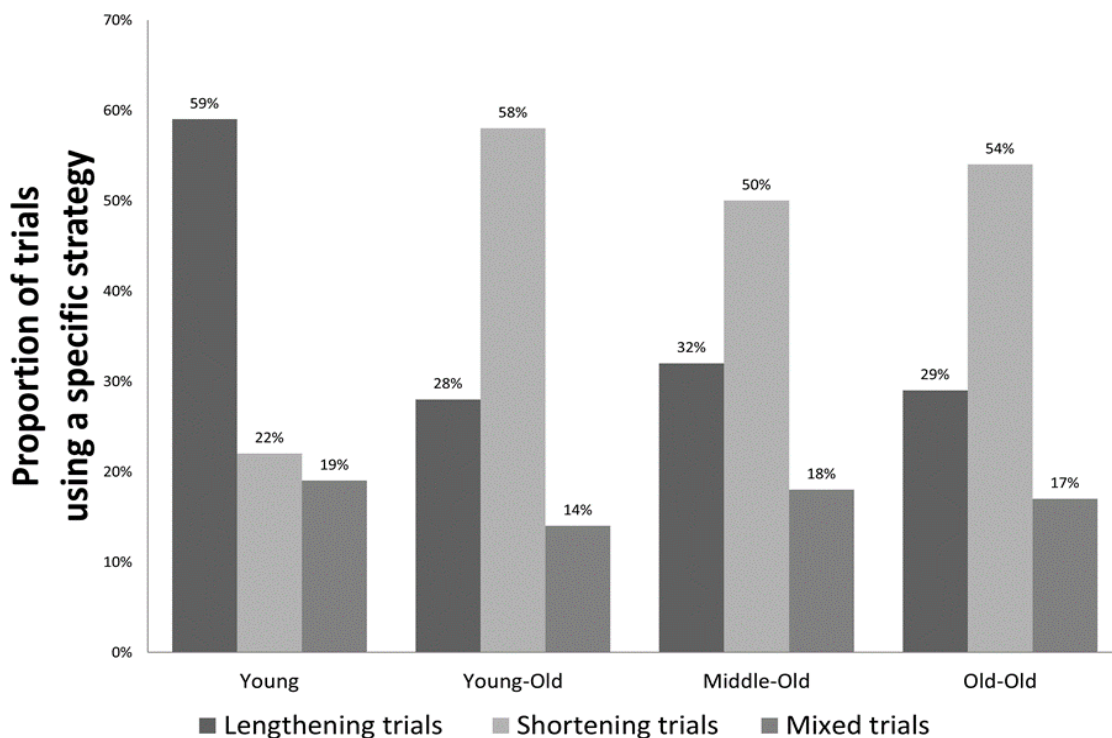
Figure 5.3 Distribution of Lengthening, Shortening and Mixed Trials for the four different age groups.

5.3.2 Linear mixed effects modelling

Variability of foot placement

Results from the LME analysis predicting Footfall-SD corrected for step length are summarized in the table in appendix 5.1. Overall, the model had a R^2 of 0.641. The fixed effect for age was significant, indicating that SD-footfall/Step Length decreased with age. Furthermore, a significant random effect for age was seen at footfall0, footfall-1, footfall-4, footfall-5 and footfall-6. For footfall0 and footfall-1, the negative coefficients indicated that advancing age was related to smaller values of SD-footfall. For footfall-4, footfall-5 and footfall-6, the positive coefficients of the random effect of age on SD-footfall were reversed; that is, increased age was related to increased variability.

Onset of Regulation

Appendix 5.2 summarizes the LME model predicting OnsetReg using Adjust_{total} and age as fixed factors and a random factor for adjustment strategy, producing a R^2 of 0.246. When Adjust_{total} and age were entered in the model together, neither of these fixed factors significantly contributed to the model. Only one random effect reached significance; the OnsetReg occurred later in lengthening trials compared to the other two strategies.

Step length adjustments

The LME analysis that sought to predict step length with age entered as a fixed factor and footfall number entered as a random factor is presented in Appendix 5.3 and reports the R^2 for the model as 0.143. The significant fixed effects for age indicated that step length decreased with age. A significant random effect was only present at step0, with the negative coefficient indicating that this step became shorter with increasing age.

Strength of perceptual-motor coupling

The results from the LME analysis relating the relationship between $\text{Adjust}_{required}$ and $\text{Adjust}_{produced}$ are displayed in the Table in Appendix 5.4 and the results are illustrated in Figure 5.4, with the overall model returning a R^2 value of 0.442. The significant fixed effect of $\text{Adjust}_{required}$ confirmed that the $\text{Adjust}_{required}$ was directly related to the $\text{Adjust}_{produced}$. The interaction between $\text{Adjust}_{required}$ and Age was also significant, indicating that the relationship between $\text{Adjust}_{required}$ and $\text{Adjust}_{produced}$ became stronger with increasing age. From the analysis of the random effects, the following results became apparent. The effect of $\text{Adjust}_{required}$ on $\text{Adjust}_{produced}$ was significantly

Figure 5.4 Strength of Perceptual-Motor Coupling

Figure indicating the relationship between Adjust$_{required}$ and Adjust$_{produced}$ for foot placements leading up to the curb. Footfall-1 is the last foot placement before stepping up (step0). Data depicted are split into age categories to make the effects of age more visually discernable, however it should be noted that, in the statistical analysis, age was included as a continuous variable.

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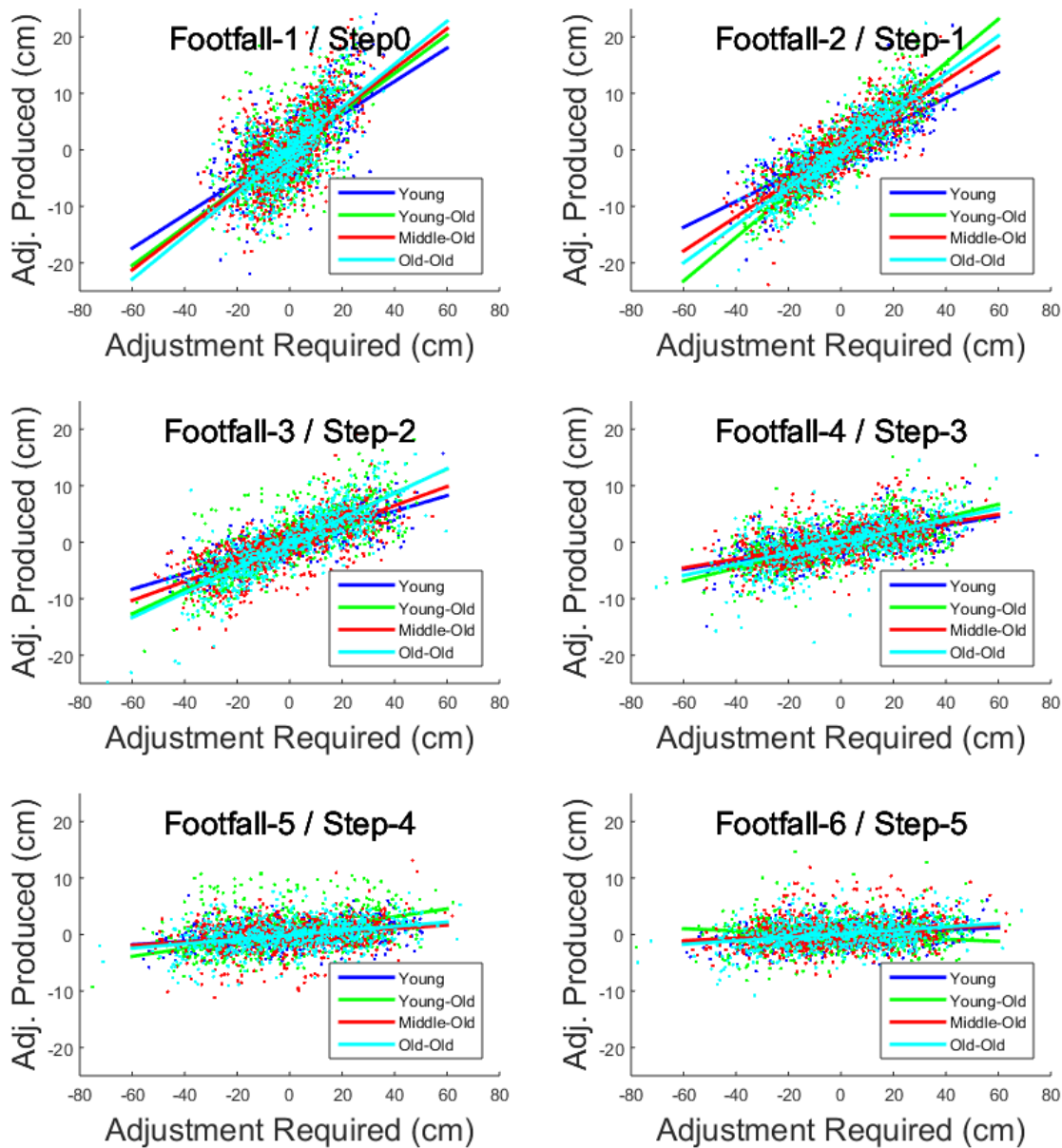However, this effect strengthened in the latter steps (footfall-1 and footfall-2), as indicated by the positive beta values returned for the random effect. Furthermore, the interaction between Adjust$_{required}$ and Age showed a similar trend, with negative coefficients in the early steps (footfall-5 and footfall-6) and positive coefficients in the latter steps (footfall-1 and footfall-2). These findings indicated that the effect of age on the relationship between Adjust$_{required}$ and Adjust$_{produced}$ became stronger as the participants drew closer to the step up. Finally, the negative main effect for age at footfall-1 and footfall-2, as well as the positive main effect for age at ootfall-5 and footfall-6 showed that, increased age generally led to people taking longer steps early on in the walking task, but shorter steps (negative adjustments) as they drew closer to their target (i.e. the curb-like platform).

5.4 Discussion

The aim of the current study was to describe age-related differences in locomotor pointing behavior in terms of when younger and older participants initiated the adjusting of their steps, what strategy they used when regulating their steps (lengthening, shortening or a mixed strategy) and the strength of perceptual-motor coupling in the approach when stepping up a curb. The main results relating to these aims are summarized in Table 5.2. The main findings of this study were that the variability in foot placement was lower for older adults and that younger and older adults used different step length adaptation strategies. Specifically, it was shown that younger participants preferred to lengthen their steps when making an adjustment, whereas older participants more often chose a shortening strategy in regulating to accurately place a footfall on top of the curb. Furthermore, confirming our hypothesis that older age would be associated with stronger perceptual-motor coupling, as participants drew nearer to the curb the relationship between the adjustment required in any single footfall and the adjustment produced in the following step (indicative of the strength of perceptual-motor coupling) became stronger with each additional step toward the curb, and with increasing age. No age-related differences were found in the onset of regulation, though it was found that regulation was initiated later when a lengthening strategy was chosen.

The strength of perceptual-motor coupling was studied as the relationship between the adjustment required and adjustment produced. A steeper regression line (or larger positive coefficients in LME modelling) for this relationship can be interpreted as representing a stronger perceptual-motor coupling. With increasing age, there was a stronger coupling between the perception of the amount of adjustment required in a single footfall and the adjustment produced in the next step, showing that perceptual-motor coupling was influenced by age (i.e. older age was related to stronger coupling).

Table 5.2 Summary of main results relating to the aging process

	Analysis type - Dependent variable	Main results relating to the effects of age
Onset of regulation	LME - OnsetReg	No effect of age was found
Perceptual-motor coupling	LME - Footfall SD / Step Length	Significant fixed effect for age indicated that older age was associated with lower scaled variability; Significant random effect of age at footfalls 0, -1, -4, -5 and -6 indicated that the influence of ageing was most pronounced at the end of the approach (i.e. closer to the target)
	LME - relationship between $Adjust_{required}$ and $Adjust_{produced}$	Significant fixed interaction effect for age and $Adjust_{required}$ indicated that older age was associated with a stronger relation between $Adjust_{required}$ and $Adjust_{produced}$; Significant random effects at footfalls -1, -2, -5 and -6 indicated that the effect of age on the relation between $Adjust_{required}$ and $Adjust_{produced}$ was strengthened as participants got closer to the curb
Adjustment strategy	ANOVA - Number of trials using a strategy	Young group showed more lengthening walks, older groups showed more shortening trials; no differences between older groups.
	LME - Step Length	Significant fixed effect for age indicated older age was associated with taking shorter steps; significant random effect at step0 showed that the final step became especially short with increased age
	LME - relationship between $Adjust_{required}$ and $Adjust_{produced}$	Significant random effect of age at footfalls -1, -2, -5 and -6 indicated that participants took shorter steps towards the end of the walk if they were older

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It is worthwhile to consider whether the age-related differences in perceptual-motor coupling found can be linked to the decreasing action capabilities in the older cohort. It has been well-documented that ageing process influences the individual's action capabilities (Arnold & Bautmans, 2014; Holland, Tanaka, Shigematsu, & Nakagaichi, 2002; Kang & Dingwell, 2008). For instance, reduced functioning in older adults is related to sarcopenia, the age-related loss of skeletal muscle mass (Arnold & Bautmans, 2014), and it has been shown that older adults experience a reduced joint range of motion and decreased strength, which has been shown to influence gait stability (Kang & Dingwell, 2008). As a result, it could be argued, that this allows them less adaptability in the regulation of their walking approach. In contrast, the action capabilities of the younger people, might allow them more adaptability in their movements. More movement adaptability might be related to a greater number of potential actions to successfully perform a movement task. For instance, in the task of crossing the road to step up a curb, the younger adults could choose between shortening and lengthening their strides. Therefore, the younger adults in the current study were less constrained by their action capabilities, which might have expressed itself in lower task demands, and subsequently, less strong perceptual-motor coupling in the final strides before stepping up the curb.

The effects of age on the strength of perceptual-motor coupling are relevant in relationship to the findings of previous studies. When comparing their findings from locomotor pointing experiments involving walking with findings of pointing in the long jump approach, Cornus and colleagues (Cornus et al., 2009) argued that the later initiation of regulation in their participants was related to the lower spatiotemporal demands of walking compared to a running long jump approach (Cornus et al., 2009). This follows the reasoning that the strength of perceptual-motor coupling is varied relative to the spatiotemporal demands of the task. Consistent with this idea, participants are expected to exert stronger control when their action system's tolerance is at risk of being exceeded; that is, when they need to operate near their action-boundaries. Conversely, when participants can operate well within the action system's tolerance, and well within their action boundaries, less stringent control, and weaker (or more intermittent) perceptual-motor coupling will be observed (Barton, Matthis, & Fajen, 2017). In relation to the findings of the current study, this would suggest that age-related declines in motor function, and the related reduced adaptability, is associated with the finding that older participants showed stronger perceptual-motor coupling in the final step onto the curb. This finding could lead to new hypotheses for future studies into whether and how the system's tolerance is perceived by older adults with possible implications for healthy aging interventions.

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Another main finding was that the younger participants preferred to lengthen their steps when approaching the curb, whereas older adults generally chose a shortening strategy. This is in accordance with previous studies that have reported similar behaviors for younger and older adults when approaching a step or obstacle (Caetano et al., 2016; Laessoe & Voigt, 2013; Patla et al., 1999). It has been argued that younger people aim to maintain forward momentum, both for the sake of progression as well as stability (Barton et al., 2017). In contrast, older adults are more likely to slow down due to anxiety and to allow for more time to plan their movements (Laessoe & Voigt, 2013). In addition to these potential reasons, we propose an alternative explanation for this finding. As research has shown that older adults are less well attuned to their action capabilities (Comalli, Franchak, Char, & Adolph, 2013; Sakurai et al., 2013; Zivotofsky, Eldror, Mandel, & Rosenbloom, 2012), it is reasonable to argue that older adults are also less attuned to their maximal step length (i.e. their action boundary). If an older adult is uncertain of his or her action boundary, there may be greater uncertainty about whether lengthening their step would result in an action that was outside the safe area of their action capabilities. With this uncertainty, a shortening strategy might be perceived as the safer option. This explanation would fit well in the growing body of research that relates an inability to perceive one's own capabilities to movement errors (Cordovil, Araújo, Pepping, & Barreiros, 2015; Croft, Pepping, Button, & Chow, 2018; Plumert, 1995) and in particular falls in older adults (Andel et al., 2017; Lafargue, Noël, & Luyat, 2013; Luyat et al., 2008; Sakurai et al., 2013).

The participants for the cohort of older adults were recruited from a local community of healthy older individuals. As such, these older adults may have had a greater interest in maintaining an active lifestyle. It is well described that people become more sedentary as they get older (Davis & Fox, 2007) and that many age-related declines can be slowed or reversed with regular exercise (Bherer, Erickson, & Liu-Ambrose, 2013; Liberman, Forti, Beyer, & Bautmans, 2017). Given the significant variation that exists in the activity profiles of older adults, the ageing process must be considered a very individual process. That is, two people of the same chronological age may have very different activity levels and, hence, very different perceptual-motor function. This would call for a more functional approach to ageing research. That is, future research might seek to not merely outline the effects of age, but to focus more on functional variables that are more descriptive of the ageing process. Future studies should investigate whether the interpersonal differences in perceptual-motor coupling in locomotor pointing could be better explained using a functional variable (e.g. step length or perceptual-motor coupling) rather than chronological age (Vaz et al., 2017).

5.5 Conclusion

Perceptual-motor coupling was studied in an ageing cohort using a task that involved approaching and stepping onto a curb-like platform. Results showed that older age is associated with

steeper positive regression slopes between the adjustment required in foot placement and the

adjustment produced in the following step. In the context of this and similar research, this increase in

regression slope can be interpreted as a stronger perceptual-motor coupling. This effect was

particularly strong in the final steps before the step-up. An argument is put forward in which the

decreasing action capabilities of the ageing cohort lead to an increase of task demands in stepping

onto a curb, which could explain the stronger coupling shown by the older participants. Furthermore,

it was found that younger adults, on average, lengthened their steps when regulating their step

lengths during their approach toward a curb. Older adults did not show this increase in step length in

the final steps and more often showed a shortening strategy. Future research should focus on the

question whether this change in regulation is similar for all populations or the possibility that fall risk

in older adults might be associated with differences in perceptual-motor coupling.

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The study described in this chapter has been accepted for publication in a peer-reviewed journal. Preliminary reference details are:

Andel, S. van, Cole, M. H., & Pepping, G.-J. (in press). Gait-related falls are associated with gait adaptations when stepping onto a curb: a prospective falls study. *Journal of Aging and Physical Activity.*

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6.0 Synopsis and relevance for this thesis

Chapter 6 describes the final experimental study of this thesis. The aim of this chapter was to understand whether the age-related changes in perceptual-motor regulation, as identified in Chapter 5, lead to an increased risk of falls. In the previous chapter, it was found that age-related changes in perceptual-motor regulation are most pronounced in the measures of perceptual-motor coupling, or in other words, in the strength of gait adaptations. Chapter 6 therefore focusses mostly on the measures of perceptual-motor coupling in the curb-approach task.

To assess the differences between fallers and non-fallers, a prospective falls follow-up is included in this study. Participants who entered in the experiment were screened for the occurrence of falls in the 12 months following their assessment in the curb-approach task.

Following an ecologically-grounded functional approach to falls risk, it is important to understand not only the older adult at risk for falls, but to consider the individual in relation to the environment and the task. Considering that most falls occur during gait and that the curb-approach task measures perceptual-motor regulation of gait, it was decided to focus the analysis on the occurrence of gait-related falls and not just any fall.

Results in Chapter 6 show that participant who prospectively reported one or more gait-related fall showed stronger adaptations in gait as they stepped onto the curb. No differences were apparent in any other step before reaching the curb; only this last step showed a stronger perceptual-motor coupling for fallers compared to non-fallers.

The finding that differences between fallers and non-fallers are apparent in the final step of the sequence implies that older adults at risk of falls leave more of the required adjustments to be made in the last step. It is reasoned that this provides insight into the mechanisms of gait-related falls; it is known that older adults need to cope with decreases in their action systems, if greater adjustments need to be made in this last step, yet the capabilities to make these adjustments decrease, it could lead to movement errors and for instance trips, slips, stumbles and falls. These results provide new hypotheses that need to be tested considering falls prevention training. It should be assessed whether functional training can be used to train older adults to engage in gait adaptations earlier, so that smaller adaptations are left for the last moment. This could reduce risks and therefore possibly, prevent falls.

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6.1 Introduction

It is estimated that about one in three older adults fall at least once each year (Campbell et al., 1981; Tinetti et al., 1988; World Health Organization, 2007), making accidental falls a significant physical, psychological and financial burden on society (Hartholt et al., 2011). Falls-related medical costs are significant and predicted to grow further with the increasing number of older adults (Burns et al., 2016; Hartholt et al., 2012; Hendrie et al., 2004). As the majority of falls occur during gait (Berg et al., 1997), the current study aimed to establish the relationship between perceptual-motor control in gait and the high incidence of gait-related falls measured prospectively in a cohort of older adults.

Recent studies have proposed that falls might be related to a decline in an individual's ability to perceive their own action capabilities (Luyat et al., 2008; Sakurai et al., 2013). For instance, research has shown that, older participants were unaware of the age-related declines that affected their ability to stand on inclined surfaces (Luyat et al., 2008). These findings call for an approach to falls risk assessment that considers the entire perceptual-motor system and the intrinsic scaling of perception and action (Andel et al., 2017).

A locomotion task in which perceptual-motor regulation has been well studied is the task of approaching and placing a foot on a target on the ground, known as *locomotor pointing* (Lee et al., 1982). The mechanisms of locomotor pointing have been established in research concerning the long jump approach (De Rugy et al., 2000b; De Rugy, Taga, et al., 2002; Lee et al., 1982; Montagne et al., 2000) and later generalized to walking tasks (Andel et al., 2018a; Cornus et al., 2009). Collectively, this body of evidence shows that adjustments in step length during the approach to a target are informed by the athlete's perception; showing evidence of a *perceptual-motor coupling*. Montagne and colleagues (2000) operationalized this informational coupling as the relationship between athletes' perception of their current position and the adjustments made in a following step. For instance, they showed that, if long jumpers in a certain phase of their approach (say, n steps from the take-off bar), perceive themselves to be closer to the take-off bar than they normally would be (at step n) they will compensate by shortening their following step. In other words, they perceive an 'adjustment required' in their position and couple this onto the change of their step length ('adjustment produced'). The strength of this coupling (i.e. the steepness of the regression line between adjustment required and adjustment produced) was shown to increase as people drew closer to their target in both the long jump and other locomotor pointing tasks (Andel et al., 2018; Cornus et al., 2009; De Rugy et al., 2000, 2002; Lee et al., 1982; Montagne et al., 2000).

The strength of perceptual-motor coupling has been shown to change when a person is confronted with different tasks that pose different demands for locomotor pointing (Montagne et al.,

2002). For instance, when investigating locomotor pointing to step over an obstacle, Cornus and colleagues (2009) showed that the strength of perceptual-motor coupling increased both when the walking speed and the obstacle size were increased. These results illustrate that, when individuals are confronted with higher task demands in a locomotor pointing task, they show stronger perceptual-motor coupling (Andel, Cole, & Pepping, in press).

It is important to realize that task demands in locomotor pointing are determined not only by the task, but also by the person completing the task; that is, if a person with limited capabilities completes a locomotor pointing task, the relative task demands are increased. In the example of stepping up a curb, this task is more challenging for a person with weaker legs, compared to a well-trained athlete. It is well established that older adults experience declines in muscle mass that lead to a functional decline in the locomotor system (Larsson et al., 1978; Oberg et al., 1993). Given that such impairments to the locomotor system have been identified as risk factors for falls (Ambrose et al., 2013), it could be reasoned that these deficits lead to higher task demands in locomotor pointing. The current study, therefore, hypothesized that an elevated incidence of gait-related falls would be associated with increased perceptual-motor coupling requirements during the approach to stepping up a curb.

6.2 Methods

6.2.1 Participants.

One hundred and six participants volunteered to enter the study (number of females: 77, mean age: 71.4 yr, standard deviation: 5.6 yr). Participants were eligible to be included if they were 60 years or older, were able to stand and walk without a walking aid for the entire length of the experiment, had no signs of cognitive decline (Mini Mental State Examination score >23) and had normal or corrected to normal vision (Bailey-Lovie High Contrast Sensitivity <0.30 LogMAR). No participants were excluded based on these criteria. The protocol of the study gained written approval by the institutional human research and ethics committee and all participants signed an informed consent form.

6.2.2 Materials and protocol.

An 8.5-meter long GAITRite pressure-sensitive walkway (GAITRite®, CIR Systems, Inc., Franklyn, NJ, USA) was positioned in front of a purpose-built platform similar in dimensions to a regulation-sized curb (L: 200 cm, W: 100 cm, H: 15 cm). Participants were instructed to use their natural walking pace to walk along the walkway toward the platform and were required to step onto the curb, continue to the end of the landing and flick a switch (Height 135 cm). The GAITRite system recorded foot placements during the approach and the positioning of the first footfall on top of the

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curb was collected using a digital video camera (CASIO, EX-FH100) that was positioned 2.35m from the edge of the platform, perpendicular to the direction of walking. The use of a video camera to collect data for the first footfall on top of the curb was necessary, as the GAITRite system does not allow gait to be measured on two surfaces of differing heights. Video footage of the first step on top of the curb was digitized by the first author and two research assistants using Kinovea Video analysis software (version 0.8.15, ©2006-2011 Joan Charmant & Contrib.). The gait measures derived from the digitisation process by the three raters for two participants (n = 66 trials) were shown to have very high inter-rater reliability (ICC = 0.993) and the outcomes of this process are reported elsewhere (Andel et al., 2018a).

Prior to commencing the experiment, participants were asked to perform three walks over the set-up to: i) familiarize themselves with the protocol; and ii) collect an a-priori measure of their average step length. The three trials used to determine the a-priori step length measure were used to inform the set-up of the different conditions in the experiment and, hence, were not used to derive any of the reported outcome measures. As the task was foreign to the participants, some approached the first of the familiarization trials with some caution, which resulted in biased average step length. If this was the case, a fourth walk was requested for the calculation of the a-priori step length to ensure a representative average.

The experiment aimed to assess how participants minimize variability in their foot placements in stepping onto the curb. It was, therefore, important to introduce a higher degree of variability in the foot placements early in the approach. To this end, participants were required to place one of their early footfalls on a non-slip mat (L: 30 cm, W: 150 cm) that was positioned in ten different positions ranging 1 to 2.5 times the step length measured a-priori from a fixed starting position. An 11th condition was included in which no mat was presented and participants walked unconstrained. All conditions were repeated three times in random order, resulting in the total of 33 trials per participant.

Participants received instructions for the completion of a 12-month follow-up assessment to screen for the occurrence of falls. The following definition of a fall was provided: 'an unintentional coming to the ground or some lower level not as a result of a major intrinsic event (e.g., stroke or syncope) or overwhelming hazard' (Tinetti et al., 1988). If participants were unsure whether a fall fit this definition, they were prompted to submit information about circumstances surrounding the incident to limit the risk of under-reporting and to allow appropriate classification by the researchers. Only gait-related falls were considered in the analysis. Falls occurring in non-steady-state gait and falls occurring during other activities which might involve short or atypical bouts of gait, such as

'gardening' or 'treadmill walking' were excluded. All participants were given the option to either complete these calendars on paper-based forms that they returned via post, or electronically using a web-based survey ('Google Forms', Google LLC, Mountain View, CA, USA). Wording of the questions in both versions of the calendars was identical with participants asked questions like "Did you experience any falls this month?" and "Did you suffer any injuries?". All participants were instructed to return one calendar at the start of each month (for which the web-based participants received an email reminder). In situations where a participant did not submit a response to the questionnaire, they were reminded to do so halfway through the subsequent month via email or phone (depending on personal preference) and then weekly until a response was received. If a response was not received after six weeks, the participant was considered to have withdrawn from the study. If, at the moment of withdrawing, the participant had already reported one or more gait-related fall, the participant's data were included in the analyses (unless requested otherwise by the participant). However, if no fall had yet occurred, data was excluded from further analyses, as it was not possible to confidently classify the participant as a faller or non-faller based on the available data.

6.2.3 Outcome Variables and Statistical Analyses.

The primary outcome variable of the statistical analyses was the degree to which gait-adaptability, i.e. the step-length adjustment, was based on the participant's position before that step. This was measured as the relationship between the 'adjustment required' (AR) and the 'adjustment produced' (AP); AR being the difference between the current footfall's location and the average location for that footfall per participant over all 33 trials; and AP was measured as the difference between the length of each step and the average step length for that step per participant over all trials (Figure 6.1). Following previous locomotor pointing protocols (Andel et al., 2018a; Cornus et al., 2009; Montagne et al., 2000), this relationship was calculated in all trials that showed at least one step with a significant adjustment in step length. For this study, a significant adjustment in step length was defined as being more than two standard deviations different from the average step calculated over four steps in the middle of the walk (over all trials, 84% met this criterion with no significant differences in percentage between non-fallers and fallers). This relationship was analyzed for the last six steps leading to the curb, with the last being the step onto the platform.

A Linear Mixed Effects (LME) modelling analysis was performed using Matlab (R2018A) to assess differences between groups in terms of the relationship between AR and AP when approaching the curb. AP was included as the dependent variable, while AR was included as a fixed factor. To assess whether this relationship was different for non-fallers and fallers, the prospective falls classification was included as a random factor and slopes were allowed to vary per step number. Furthermore, the interaction between the falls category and step number was included as a random

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factor in the LME model. Step numbers were defined with 'Step0' being the step leading onto the curb and 'Step-n' being the nth step before stepping onto the platform. The resulting coefficients from the model were interpreted with an alpha of 0.05 and the full model is specified below.

$$AP \sim AR + (-1 + AR|Step) + (-1 + AR|FallsCategory) + (-1 + AR|Step * FallsCategory)$$

6.3 Results

Of the 106 participants, ninety (85%) chose to complete the 12-month follow-up using the web-based form (mean age: 71.3 yr, SD: 5.8), while 16 (15%) chose the paper-based method (mean age: 71.8, SD: 4.8). Three participants withdrew from the follow-up after failing to respond to any communication; one of these participants was still included in the analyses as the withdrawal occurred after reporting a gait-related fall prior to the withdrawal. In a small number of trials, it was not possible to derive the outcomes from the video data due to technical errors arising during the data collection process. Pilot measures showed that mean values and error measures were not severely affected if the missing data were less than 10% of the total collection (i.e. maximum 3 trials) and, hence, participants who were missing the video-based outcomes for 3 or fewer trials were kept in the analysis, otherwise participants were excluded (N=6).

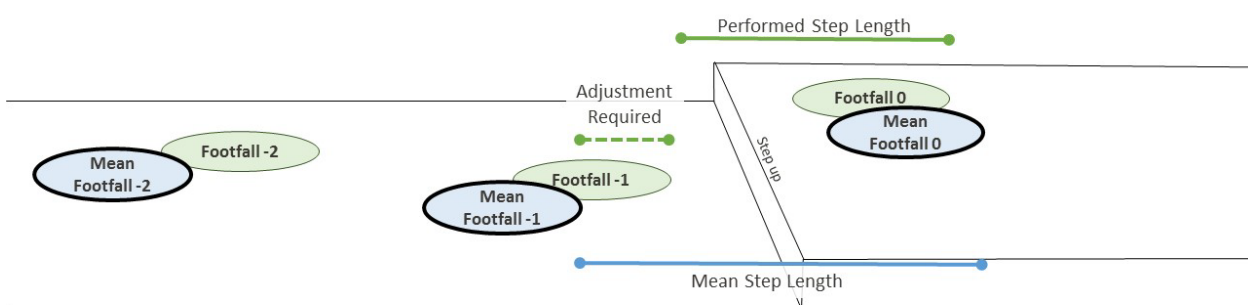

Figure 6.1 Measures collected to compute Adjustment Required (AR) and Adjustment Produced (AP) per step.

AR (dashed line) is the difference between any footfall's location and the mean location of that footfall over all trials per participant. AP is the difference between any step length and the mean step length for that step in the approach, per participant (difference between solid lines).

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After exclusions, 98 participants were left in the analysis and these participants reported a total of 77 falls in the prospective follow-up. Two of these falls did not fit the definition of a fall as used by the current study (i.e. were caused by overwhelming hazards) and were thus excluded, leading to 75 reported falls experienced by 36 participants. Of these falls, participants reported 28 to be without injury, 39 falls led to minor injuries (e.g. small bruises, cuts or swelling, not requiring medical attention), six falls caused moderate injuries (e.g. severe bruising, cuts or sprains, not requiring medical attention) and two falls caused severe injuries requiring medical attention (e.g. fractures, dislocation, head injury). Of the 75 falls, 40 were classified as gait-related falls, experienced by 28 participants; these participants were marked as fallers in the statistical analysis. Table 1 summarizes the mean age, mobility, vision and mental state of the two study groups, with independent samples t-tests indicating no significant differences between the fallers and non-fallers.

Table 6.1 Descriptive Statistics; means (SD) for non-fallers (N = 70) and fallers (N=28)

	Non-Fallers	Fallers
Age (years)	71.5 (5.7)	70.4 (4.6)
Timed Up and Go (s)	9.3 (1.6)	9.0 (1.3)
Bailey-Lovie High Contrast Visual Acuity (LogMAR)	0.06 (0.11)	0.09 (0.12)
Mini Mental State Examination (score out of 30)	29.1 (1.1)	29.0 (0.6)
Percentage step ups with right foot	52 (0.25)	51 (0.22)

Note. Between group differences were assessed using an independent samples t-test for all variables, no significant differences were found.

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As introduced in the Methods section, perceptual-motor coupling can be measured during the approach to a target (i.e. the curb) by analyzing how participants minimize their footfall variability as they draw closer to the target. For this reason, the variable placement of a 'target step' was introduced early in the approach, to induce variability. Figure 6.2A shows that this manipulation was successful, illustrated by the high variability of footfalls early in the approach, which was systematically lowered as participants drew closer to stepping up and onto the curb (marked 'footfall 0' in Figures 6.2 A and B). Furthermore, Figure 6.2B confirms the homogeneity between the groups in terms of how they completed the task. A similar strategy was shown in terms of changing step length in the approach to the curb by both groups.
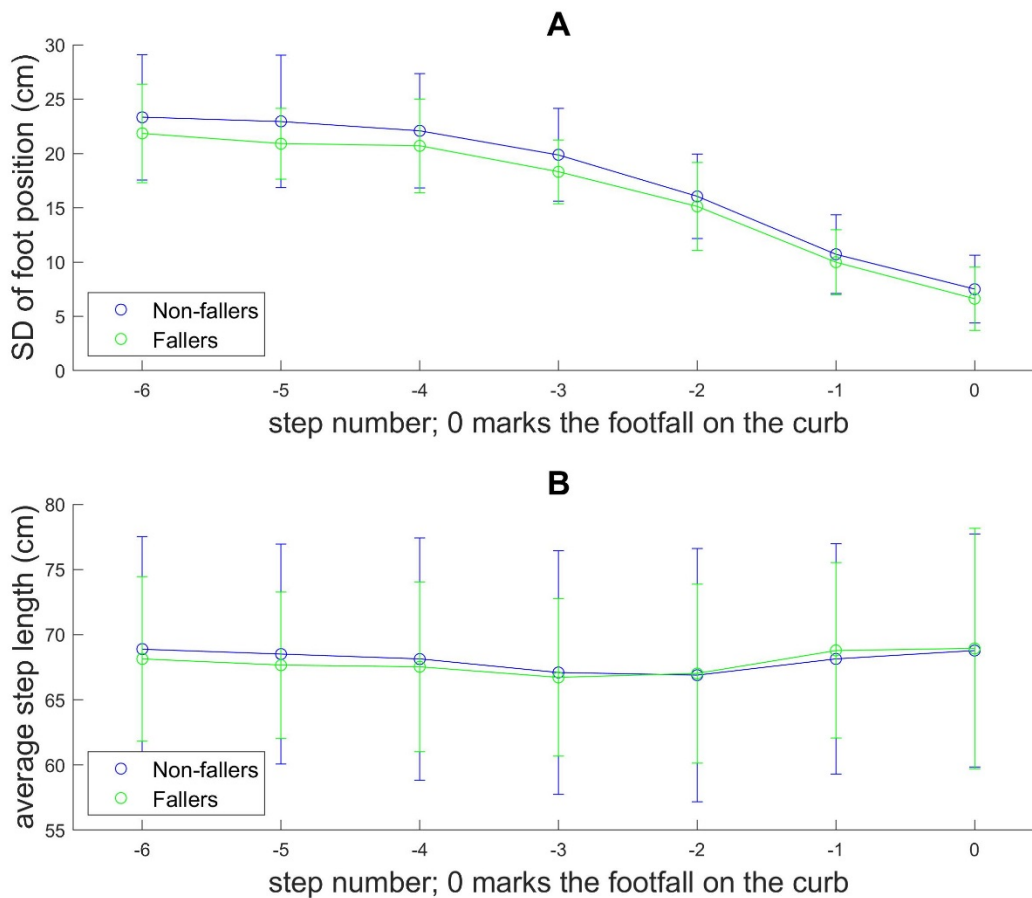
Figure 6.2 Average approach to the curb for fallers and non-fallers.

Panel A depicts the variability in footfall location as participants get closer to stepping onto the curb (step 0 being the step onto the curb-landing). It is apparent that both fallers and non-fallers reach minimal variability in foot placement with their step onto the curb. Panel B shows the average step length produced by participants of both groups in their approach to step-up.

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Table 6.2 summarizes the results of the Linear Mixed Effects Modelling analysis. A significant main effect was found for AR (beta = 0.196, pred. SE = 0.066, p = 0.003), showing the relationship between AR and AP over the entire walk. Furthermore, a significant random effect for step number was identified, with positive coefficients at Step0 and Step-1, and negative coefficients at Step-5 and Step-6. These effects illustrate that the relationship between AR and AP increases as one moves closer to the curb. Analyzing all steps in the walk together, the main effect for grouping was not statistically significant (beta < 0.001, pred. SE < 0.001, p = 1.000), showing no difference between groups over all steps. However, a significant Group*Step interaction was found, which indicated that fallers showed a stronger relationship between AR and AP during the last step up and onto the curb (beta =0.035, pred. SE =0.016, p = 0.032). The results for the final four steps are summarized in Figure 6.3.
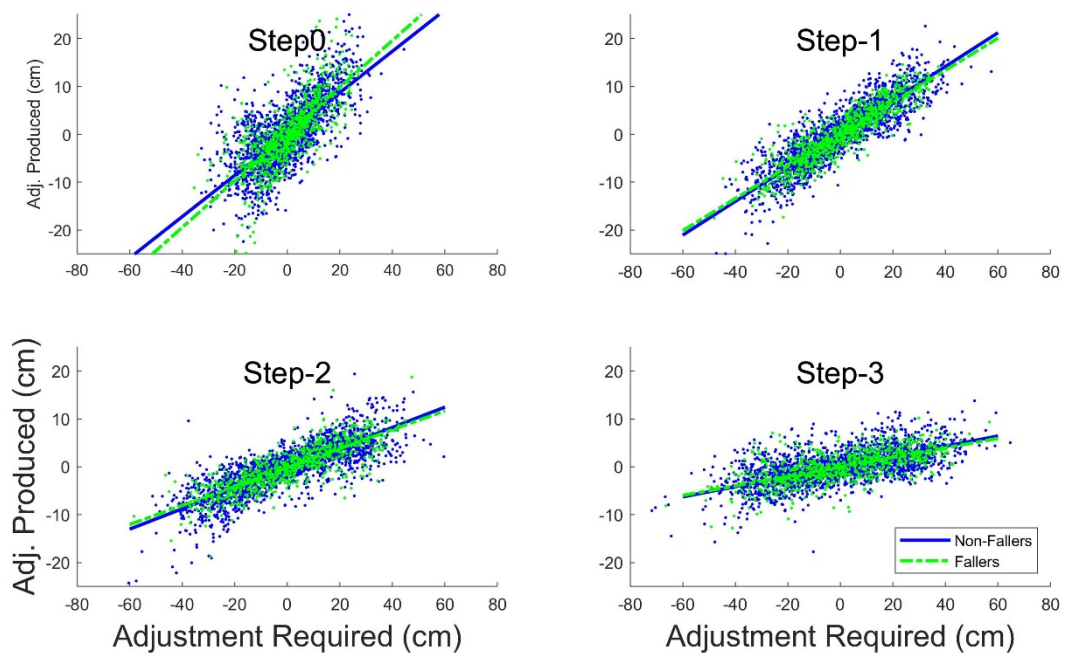
Figure 6.3 The relationship between adjustment required and adjustment produced per step for fallers and non-fallers.

Step0 indicating the step onto the curb and Step-N indicating the N'th step before reaching the curb. Non-falling older adults are depicted blue (solid line) and fallers are depicted green (dashed line). Significant differences between groups in relationship are apparent only at Step0.

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Table 6.2 Results of the Linear Mixed Effects Modelling Analysis Comparing Participants with and without a Gait-Related Fall

		Fixed Factors		
		Beta	SE	p value
Intercept		-0.004	0.026	0.874
Adjustment Required		0.196	0.066	**0.003**

		Random Factors		
		Beta	Pred. SE	p value
	Falls Grouping	< 0.001	< 0.001	1
Step0	Main effect step number	0.264	0.068	**< 0.001**
	Interaction with Gait Fall	-0.03	0.016	0.063
	Interaction without Gait Fall	0.035	0.016	**0.032**
Step-1	Main effect step number	0.148	0.067	**0.028**
	Interaction with Gait Fall	0.005	0.016	0.729
	Interaction without Gait Fall	-0.003	0.016	0.856
Step-2	Main effect step number	0.01	0.067	0.883
	Interaction with Gait Fall	0.005	0.015	0.744
	Interaction without Gait Fall	-0.005	0.015	0.753
Step-3	Main effect step number	-0.092	0.067	0.171
	Interaction with Gait Fall	0.001	0.015	0.95
	Interaction without Gait Fall	-0.003	0.015	0.867
Step-4	Main effect step number	-0.15	0.067	**0.026**
	Interaction with Gait Fall	0.009	0.015	0.577
	Interaction without Gait Fall	-0.011	0.015	0.467
Step-5	Main effect step number	-0.18	0.067	**0.008**
	Interaction with Gait Fall	-0.01	0.015	0.505
	Interaction without Gait Fall	0.007	0.015	0.643

Note. P-values significant at an alpha of 0.05 are presented boldfaced

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6.4 Discussion

The aim of the current study was to establish the relationship between perceptual-motor control in gait and the incidence of gait-related falls that occurred during a 12-month follow-up period and to test whether the incidence of gait-related falls is associated with specific gait adjustments. The results showed that gait adaptations in any step during the approach were related to the required adjustment, based on the foot placement before that step. The strength of this relationship increased as participants drew closer to stepping onto the curb. It was shown that during the final step onto the curb, participants who had experienced a gait-related fall exhibited significantly stronger relationships between the required adjustment and the produced gait adaptation than participants who did not report a gait-related fall.

The results confirm our hypothesis that gait-related falls are associated with increased perceptual-motor coupling requirements during the approach to stepping up a curb, and that the required perceptual-motor coupling increases with increasing task demands (Montagne et al., 2002). It is important to note that stronger or weaker perceptual-motor coupling should not be interpreted as inherently better or worse in terms of falls risk. That is, all participants in this study successfully completed the task of stepping up the curb, without tripping and falling. As such, it should be concluded that all participants produced an adequate degree of perceptual-motor coupling to safely perform the task. However, these results were recorded in a laboratory-based experiment with a simple task and no distracting factors. If older adults with an elevated falls risk need to produce a stronger coupling in this simple task, it seems reasonable to assume that their required coupling is also higher in more complex locomotor pointing tasks in the natural world. Previous studies have already shown that older adults at risk for falls generally use a sub-optimal gaze strategy in these type of situations (Chapman & Hollands, 2006; Young & Hollands, 2010). Future reasearch is required to investigate whether the mechanism behind falls during walking is actualy related to not meeting the elevated demands for perceptual-motor coupling in a natural, complex environment, with many potential distractors.

The functional declines in the locomotor system that are associated with a reduced muscle mass (Larsson et al., 1978; Oberg et al., 1993), could have made the task of approaching a curb more demanding for older adults who are prone to falling, which might have led to greater perceptual-motor demands in this task. Theoretically, in coping with these higher demands, it would be more efficient to produce a slightly stronger coupling over multiple steps in the approach, instead of producing one step with relatively large adaptations. However, older adults who reported falling seemed to use this latter strategy and left the relatively large adaptations to be made in the very last step. It is important to consider why fallers did not 'spread out' making the required adjustments

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over multiple steps. Future studies are required to distinguish whether it is this 'late timing' of adjustments that is the mechanism behind the higher incidence of falling. Potentially, this interpretation of gait adaptability could provide new insights into falls prevention interventions.

The current study used a perceptual-motor control framework to explain falls risk. According to this framework, risk needs to be interpreted as a relational concept; that is, as the relationship between the individual and their environment (Cordovil et al., 2015). Too often, the field of gerontology focuses on just the individual (e.g. this person is at risk of falling) or the environment (e.g. this situation is dangerous), rather than on the relationship between them (i.e. this person is at risk of falling when placed in a specific environment). A functional approach to healthy ageing broadens the field to consider the person within the environment (Vaz et al., 2017). For instance, rather than prescribing lower limb strength training for falls prevention, practitioners could prescribe a functional alternative, in order to strengthen the limbs as well as challenge the perceptual-motor system. In these tasks, participants should be required to couple perception and action with each step. An example of this could be a guided bushwalking intervention, where the environment demands an accurate foot placement with each step to limit the risk of tripping or slipping resulting from inaccurate placement. The demands of such a task require a strong coupling between perception and action for each step, which could be effective practice for older adults to engage in strong coupling in any situation. Future reasearch is required to study the effectiveness of such an intervention for falls prevention. In agreement with previous findings (Berg et al., 1997), the current study found that the majority of falls (53%) occurred during gait-related activities. The percentage of participants who reported at least one fall (37%) was slightly higher than the commonly reported 33% for adults aged 65 years and older (Campbell et al., 1981; Tinetti et al., 1988; World Health Organization, 2007). Given that the current study included slightly younger participants over the age of 60 years, slightly lower falls rates were expected. The elevated falls rate might be linked to the participant recruitment, which was organized in cooperation with a local community for healthy aging. This might have resulted in a sample that was more active compared to the general older population. Increased activity levels might have led our participants to engage in more risky behaviors and risky situations, leading to an elevated falls rate. Even though the falls rate in the current study was higher than expected, this only led to the report of two falls (3%) that required medical attention. Further studies should identify whether a higher physical activity level in older adults is related to a greater familiarity with their perceptual-motor system (Andel et al., 2017), which might have helped them to minimize the negative consequences of these falls.

The methods of falls assessment can be considered a strength of the current study. A daily falls diary that is returned monthly is generally regarded as the gold standard for recording falls (Peel,

2000; Stark, Silianoff, Kim, Conte, & Morris, 2015). To our knowledge, the current study was the first to have used an electronic, web-based survey to collect falls information. The finding that 85% of participants chose to use the online version of the diaries was unexpected, as it is often assumed that older adults prefer to use conventional media. This is a promising finding, as methods using paper-based calendars are considered to be strenuous and labor intensive (Hannan et al., 2010).

In conclusion, the current study investigated gait adaptability in older adults in a walking approach towards and stepping onto a curb. Older adults who had experienced a gait-related fall during the 12-month follow-up exhibited significantly tighter regulation of gait adaptations in the step leading onto the curb. This finding underlines the importance of a functional approach to assessing physical function and falls risk in older populations and should be used to design novel falls prevention interventions.

Chapter 7 - General Discussion

7.1 Summary of Findings

This thesis aimed to investigate age related changes in perceptual-motor coupling and relate these age-related changes to a performance indicator of success in perceptual-motor control; the incidence of falls. To achieve this aim, a model of perception and action coupling was used with the potential to explain movement errors such as perturbations that could lead to a fall in terms of failures in perceptual-motor coupling (Figure 1.1). Based on an understanding of the perception and action cycle, this thesis includes four inter-related studies, described in the previous chapters.

The aim of Chapter 2 was to review previous literature and assess current knowledge on perceptual-motor calibration to changes in action capabilities, with a particular focus on aging cohorts. Results provided insights into the process of perceptual-motor calibration; showing that calibration is highly dependent on the effectiveness of exploring one's action capabilities. For instance, when someone's leg length is experimentally altered by the addition of blocks under one's feet, calibration is effective when the person is only allowed to stand stationary, experiencing only postural movements (Mark, 1987). However, calibration occurs quicker when there is a better match between information and action capabilities and people are, for instance, allowed to walk with the blocks attached to their feet (Mark et al., 1990). Next to these insights into the process of calibrating, in Chapter 2 it was concluded that very little is known about age-related changes in perceptual-motor calibration.

In Chapter 2, perceptual-motor calibration was identified as one of the key components in the perception and action cycle and age-related changes to calibration could play a role in falls risk for older adults. However, in natural movement, it is very hard (arguably impossible) to isolate the effects of calibration from the rest of the perception and action cycle, without experimentally changing the task and limiting generalizability to natural movement. As falls occur predominantly during natural locomotion (Berg et al., 1997), it was decided to focus the experimental studies of this thesis on the perception-action cycle on a more holistic level; the level of perceptual-motor coupling. Perceptual-motor calibration is one of the underlying mechanisms in this coupling, but was not deemed the appropriate level of measurement for an analysis that aimed to generalize to walking in a natural (non-laboratory) environment. Chapter 3 described the general methodology used in this thesis. A methodology that enabled quantification of the strength perceptual-motor coupling in gait adaptations for cohorts of all ages. Based on descriptions of perceptual-motor coupling in the long jumping approach (Lee et al., 1982; Montagne et al., 2000), a new task was introduced in which participants were required to approach and step onto a curb platform. This curb-approach task is a locomotor pointing task with lower task demands compared to the long jump approach, making it fit to be performed by a wide range of people with differing capabilities. Furthermore, Chapter 3

discussed the effect of changes in task demands on the strength of perceptual-motor coupling in locomotor pointing. It has been shown that increases in task demands lead to a stronger perceptual-motor coupling (Cornus et al., 2009; Montagne et al., 2002). Based on this, it was expected that an increase in task demands, caused by decreased action capabilities due to ageing (Lindle et al., 1997; Oberg et al., 1993) would lead to an increased strength of perceptual-motor coupling with age.

The aims described in Chapter 4 were to assess the validity of the curb-approach task and to assess whether it required participants to produce the same type of control shown by long jumpers with the point of difference was that testing involved an everyday task. Results showed the curb-approach task required participants to engage in similar perceptual-motor coupling compared with long jumpers. A particularly interesting result was that in the long-jump approach and the curb-approach, perceptual-motor coupling or the strength of gait adaptations increased as a participant got closer to the target. This was demonstrated via a strong linear relation between the participants' perceived foot location and the adjustments they made in terms of step length (compared with the mean foot location and mean step length of that participant in that point in the walk). It was concluded that the curb-approach task provided an effective means of measuring perceptual-motor coupling in populations who might not be able to cope with the high demands of a long jump, such as older adults.

The aim of Chapter 5 was to use the curb-approach task to study age-related changes to how people regulate their locomotor pointing behavior. It was shown that with age, people were more likely to choose a strategy of shortening step lengths and that they engaged in a stronger coupling between perception and action. It was reasoned that this increased strength of perceptual-motor coupling was required to cope with the age-related declines in action capabilities experienced by the aging cohort.

The final study included in this thesis was described in Chapter 6. It was aimed to assess whether the age-related changes to the strength in perceptual-motor coupling are related to an elevated incidence of falls during gait. This study included a one-year follow-up in which participants were required to report any falls that occurred in the 12 months following their measurements in the curb approach task. Participants were grouped for the occurrence of one or more falls during gait in their 12-month follow-up. The focus on falls during gait (as opposed to falls in any activity) was chosen to represent an ecologically grounded outcome measure as perceptual-motor coupling in gait was measured. Results revealed that fallers showed significantly stronger gait adaptations in their step onto the curb compared with participants who did not report on experiencing a fall in gait. This is indicative of a strategy of late gait adjustments of the older adults at risk for falls. Results confirm

that differences in perceptual-motor coupling during walking might be indicative of the risk for experiencing a fall in gait.

Together, the experimental studies of this thesis provide new insight into the changes to the perceptual-motor system with age. Perception and action coupling has been well described in the literature in numerous movements (Warren, 2006), but typically, little attention is paid to differences in this coupling between people or (age-) groups. We showed that the demands for perceptual-motor control change with age, as could be expected through an interpretation of the task constraints (Newell, 1986). That is, changes in organismic constraints (age-related declines to the action system) lead to an elevation of task demands. As we age, performing a step-up becomes harder and thus stronger coupling between perception and action is required to guide movement successfully. This thesis is one of the first works to show this relationship between age-related changes to the action system and changes in coordination.

Although the current thesis did not directly investigate the mechanisms of falling, it should be considered how these changes in perceptual-motor coupling might be related to errors in movement control. We showed that people at risk for falls engage in stronger control even in the simple task of stepping onto a curb. Following a constraints led approach (Newell, 1986), with an age-related decrease in action capabilities, a similar increase in task demands would be present in any task or natural movement. With these increased demands on perceptual-motor control, it becomes increasingly likely that the demands are not always met, leading to a movement error and potentially a fall. This was not observed during the easy task performed in these laboratory-based experiments, but it should be considered that demands are much higher when engaging in locomotor activity outside controlled environments, where one needs to concurrently interact with any number of obstacles and distractors. This leads to a general recommendation for future studies to further investigate these effects and assess them in environments that bring a bigger challenge to perceptual-motor control

To reiterate, the overall aim of this thesis was **to assess whether a locomotor pointing paradigm; the curb-approach task, can be used to measure perceptual-motor coupling in older adults and whether this coupling is related to aging and to falls risk.** In four inter-related studies, it was shown that the curb-approach task is a suitable measurement tool for perceptual-motor coupling in an aged cohort. Furthermore, it was shown that age-related and fall-risk-related differences can be measured in the strength of perceptual-motor coupling. Both age (Oberg et al., 1993) and falls risk (Ambrose et al., 2013) have been related to decreases in people's action capabilities. It was expected that these decreases would lead to relatively higher task demands for people with higher age and falls risk, which would lead to these people engaging in stronger perceptual-motor coupling. This hypothesis

was met, as in Chapter 5 it was shown that people with increasing age showed stronger perceptual-motor coupling throughout their approach and in Chapter 6 it was shown that fallers show a stronger perceptual-motor coupling with stepping onto the curb. These results provide important new insights into the changes to perceptual-motor coupling with aging, an important topic in the light of our aging society. Moreover, these results could provide the basis for new falls prevention interventions. What remains in this chapter is a discussion of how these results fit into an ecologically grounded functional approach to healthy aging and what recommendations can be made based on this thesis.

7.2 Recommendations for Perception and Action Research

One of the major findings of this thesis, as outlined in Chapter 5 , was that perceptual-motor coupling changed with the aging process. It is an important direction for future research in perception and action to expand on research into aging. Worldwide, the proportion of people living into old age is rising (World Health Organization, 2015), making the older age bracket an important cohort for study. Age-related changes in perceptual-motor coupling in this older cohort could lead to increased risk taking and an increased incidence of accidental injuries (Cordovil et al., 2015), which due to the increasing frailty within this cohort could have severe consequences in terms of injury and associated medical costs (Burns et al., 2016; Hartholt et al., 2011; Hendrie et al., 2004). It would be feasible to apply a theoretical stance in the field of healthy aging, a stance founded in perception and action theory. To achieve this, it is important for perception and action research to target healthy aging.

Future innovations in assessing age-related differences in adjustments of gait should include direct changes in action capabilities. It is known that young participants can rapidly recalibrate their braking behavior when the brake strength of a virtual car is altered (Fajen, 2007b) however, whether older participants would be equally efficient remains unknown. Such research could be particularly relevant for road safety considering the increasing number of older adults still driving a car in older age (Lyman, Ferguson, Braver, & Williams, 2002). Similarly, there are many situations in which perception and action couplings need to be recalibrated to a direct change in action capabilities. Examples include changes in gait capabilities that occur when walking with weighted shopping bags or balance changes due to a change in footwear. For safety and injury prevention, it would be important to study how older participants calibrate to these changes.

Another topic for futures studies in the perception and action domain would be to study the neuroscience behind perceptual-motor control and aging. It has been an emergent topic in recent years to study the neural underpinnings of theories of perception and action (Cisek & Kalaska, 2010; de Wit, de Vries, van der Kamp, & Withagen, 2017). Furthermore, it is well known that the neural system undergoes certain degradation with age (Raz et al., 2005). Future research could be directed

at the role of the brain in perceptual-motor functioning and whether potential declines in functioning can be related to declines in the neural system.

7.3 Recommendations for Falls Risk Assessments and the Field of Gerontology

Recently, Vaz and colleagues published a position paper discussing the role of perception and action theory in clinical rehabilitation practice (Vaz et al., 2017). They argued that traditional theories of rehabilitation, grounded in neurophysiology, are in general overly mechanistic. Practitioners aim therapy at solving organism-limited problems; issues within the individual, and thereby hope to improve functioning of a person within an environment. Functioning is based in the interaction between an individual and the environment, it would therefore make more sense to attempt to improve functioning by engaging in functional therapies (Vaz et al., 2017). The current thesis supports these views in a rehabilitation setting, but also for the field of gerontology. Like in rehabilitation settings, interventions in gerontology are often organism limited and do not consider the functional coupling between a person and an environment.

Falls risk assessments are traditionally mainly about individual-limited factors such as gait speed in a laboratory setting (Viccaro et al., 2011) or postural sway whilst standing stationary (Fernie et al., 1982). In contrast, a recent 'ecological stance' on risk taking dictates that (falls-)risk should always be interpreted within the relation between person and the environment (Cordovil et al., 2015). That is, it is important to not just identify a person as 'at risk' for falling, but to interpret this risk in relation to this person's environment and tasks to engage in. Arguably, if only the person was to be assessed, the best course of action for an 'at risk' person is to spend all day sitting in a chair; so that he or she would not fall. Yet, when the interaction between individual, environment and task is considered, it is reasonable to suggest that a person is only really at risk when a risky action is attempted in a risky environment. Falls risk assessments could use this insight to better cover the ecological concept of risk by assessing falls risk in functional tasks. The curb-approach is one example of a task in which participants are required to perform a functional skill (e.g. walking) in an environment simulating a setting in which a fall might occur (e.g. an everyday pavement).

Another reason discussed by Vaz et al. (2017) to vouch for the application of perception and action theory in rehabilitation practice, which also applies in healthy aging, is a general limitation for evidence-based practice. Although evidence-based practice is generally accepted as a high standard of practice, it is not without limitation (Kemm, 2006).That is, in producing evidence, researchers need to make decisions on the optimal populations for the research to focus on. Often, falls risk is assessed in otherwise healthy older adults or specific patient groups with one disease or disorder. However, in the general population, the amount of people with multiple health conditions increases with age (Ferraro, 1980). The generalizability of evidence based on healthy older adults or specific

patient groups towards the general community is therefore limited. Furthermore, research design, as well as interpreting the results is done through the framework of theory. Understanding theory can thus provide information of why an intervention is effective in a specific population and these principles can often be generalized to the wider community. By interpreting the theoretical underpinnings of an intervention and striving for theory-based as well as evidence-based practice, one can design new interventions that by the same principles can be confidently applied to a wider population.

The methodology of this thesis has been designed using an understanding of perception and action theory. It is a strength of this thesis that the curb approaching task is a task that is not organism-limited; it involves functional movement and an interaction between the individual and the environment. Despite the focus in this thesis on relatively healthy populations, the same methods can be used to study patient groups. Furthermore, the application of perception and action theory as described in Chapter 1 provides opportunities for theory-based application and interventions in healthy aging.

7.4 Recommendations for Falls Prevention

The final study of this thesis (Chapter 6) investigated differences in gait adaptations between participants who were prone to experiencing a gait-related fall and participants that were not. It was found that participants who reported experiencing a gait-related fall showed stronger gait adaptations when stepping onto a curb compared to people without such a gait-related fall. This study did not find differences between fallers and non-fallers when participants were grouped on the basis of any type of fall. Only the distinction between 'gait fallers' and 'non-gait fallers' revealed differences in perceptual-motor coupling. This further corroborates the argument around an ecologically-grounded functional approach in healthy aging; as expected, a *gait* experiment was found to be sensitive for distinguishing between *gait* fallers and non-fallers.

Future falls prevention interventions should be constructed according to the principles of an ecologically-grounded functional approach; to enable older adults to practice functional skills (that involve the entire perception and action cycle) in an appropriate environment. As research has shown that most falls occur during walking (Berg et al., 1997) it is not surprising that walking interventions have been found a highly effective tool for falls prevention (Okubo et al., 2016). Furthermore, it is important to consider what type of activity can be designed that involves the entire perception and action system. Consider for instance the difference between treadmill walking and bushwalking. In case of treadmill walking, it hardly matters where one places a foot as long as the foot will end up on the treadmill and therefore step length adjustments could be less dependent on perception of task demands. In contrast, in the case of bushwalking a calibrated perceptual-motor

coupling needs to be made for each step in order to prevent falling, which would provide the required challenge to and training of the perceptual-motor system. The current thesis could provide the basis for new interventions that fit the challenges of a changing society (World Health Organization, 2018); training the perceptual-motor system in order to keep older adults healthy, active and mobile. Future research is required to assess whether an intervention that highly challenges perceptual-motor coupling in a functional setting can indeed aid healthy aging.

7.5 General Limitations and Recommendations

Although many of the limitations to the current thesis have already been described in the previous chapters, there are a number of general limitations that warrant consideration. One of the limitations to the current set-up of the curb approach task was the need to integrate two different measurements systems (GAITRite and video-based), as introduced in Chapter 4. These two systems needed to be combined to enable measurement of footfall position in the approach as well as on top of a raised platform. Although Chapter 4 showed that using video footage of the step up is a valid method for collecting this data, using a single system would not have required any synchronization and, hence, would have been less labor intensive to process. For future applications of the curb-approach task, it is recommended to identify and utilize a system that is capable of measuring foot position on multiple levels (i.e. ground and step up).

A second potential limitation of the current thesis was the sample size, which was guided by the a-priori goal to have a minimum of 30 participants in the faller and non-fallers groups, rather than specifically being supported by previously published evidence. Unfortunately, the reference values that would have been necessary to produce an appropriate sample size estimate were not available for the curb-approach task, as this is the first collection of studies to evaluate perceptual-motor coupling during this activity. Nevertheless, it can be considered a strength of the current thesis that significant differences were established between fallers and non-fallers in Chapter 6, which indicated that the sample of participants recruited for this study provided sufficient statistical power.

A final limitation of the current thesis is the scope of the research. The current thesis investigated the perception-action cycle in gait for older adults on a holistic level; that is, it investigated perceptual-motor coupling, which can be considered the outcome of the entire perception and action cycle (the exploration, calibration and affordance selection processes, see Section 1.3 The Perception-Action Cycle), rather than each component independently. This holistic approach was taken to maximize generalizability, but it limits the theoretical implications of the current thesis. Future research is required to study the particular components of the perception-action cycle in an older cohort. That way, inferences can be made about whether different components of the perception-action cycle are affected by age differently. Currently, it remains

unknown whether age influences the processes of exploration, calibration and affordance selection separately or whether the system changes as a whole.

7.6 Concluding remarks

This thesis aimed to develop a measurement tool for perceptual-motor regulation, to assess age related differences in perceptual-motor regulation and to assess differences between fallers and non-fallers. The curb-approach task described in this thesis, was deemed an appropriate tool for measuring perceptual-motor coupling in locomotor pointing and was therefore used as an assessment tool. It was shown that the strength of perceptual-motor coupling increased as participants got nearer the curb and that this was most prominent in the older participants. Furthermore, it was shown that participants who reported a fall in gait in the 12-month follow-up showed stronger perceptual-motor coupling when stepping onto the curb. These results were as expected based on the hypothesis that with increasing task demands, a stronger coupling will be shown. It was reasoned that the task demands in stepping onto a curb increase due to age-related declines to the locomotor system. These results add to a growing body of studies that advocate an ecologically grounded functional approach in clinical practice situations. According to such an approach, falls risk assessments should be performed taking into account the coupling between individual and environmental factors and falls prevention would benefit from practice of the entire perceptual-motor system.

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Appendices

Appendix 2.1 Complete Search Strategy

PubMed search

("Calibration"[Mesh] OR Calibration OR Calibrations OR Calibrate OR Calibrates OR Calibrated OR

Recalibrates OR Recalibration OR Recalibrations OR Recalibrate OR Recalibrates OR Recalibrated)

AND

("Perception"[Mesh] OR Perception OR Perceptions OR Perceptual OR "Visually guided" OR

Affordance OR "Perceptuo motor" OR Perceptuomotor OR Sensory OR Sensorimotor)

AND

("Movement"[Mesh] OR "Motor Skills"[Mesh] OR Movement OR "Motor Skills" OR Action OR

Actions)

Embase search (Ovid) (Limited to Embase only)

exp calibration/ OR (Calibration or Calibrations or Calibrate or Calibrates OR Calibrated or

Recalibrates or Recalibration or Recalibrations or Recalibrate or Recalibrates or Recalibrated)

AND

exp perception/ or (Perception or Perceptions or Perceptual or "Visually guided" or Affordance or

'Perceptuo motor' or Perceptuomotor or Sensory or Sensorimotor)

AND

exp "movement (physiology)"/ OR exp motor performance/ OR (Movement or "Motor Skills" or

Action or Actions)

PsycInfo (Ovid)

(Calibration or Calibrations or Calibrate or Calibrates or Calibrated or Recalibrates or Recalibration or

Recalibrations or Recalibrate or Recalibrates or Recalibrated).mp.

AND

(Perception or Perceptions or Perceptual or "Visually guided" or Affordance or 'Perceptuo motor' or

Perceptuomotor or Sensory or Sensorimotor).mp.

AND

("movement (physiology)".mp. or exp motor performance/ or (Movement or "Motor Skills" or Action

or Actions).mp.) [mp=title, abstract, heading word, table of contents, key concepts, original title,

tests & measures]

Cochrane Central Register of Controlled Trials (CENTRAL)

MeSH descriptor: [Calibration] explode all trees OR Calibration or Calibrations or Calibrate OR

Calibrates or Calibrated or Recalibrates or Recalibration or Recalibrations or Recalibrate or

Recalibrates or Recalibrated

AND

MeSH descriptor: [Perception] explode all trees OR Perception or Perceptions or Perceptual or

"Visually guided" or Affordance OR "Perceptuo motor" OR Perceptuomotor OR Sensory OR

Sensorimotor

AND

MeSH descriptor: [Movement] explode all trees OR MeSH descriptor: [Motor Skills] explode all trees

OR Movement or "Motor Skills" or Action or Actions

CINAHL

(MH "Calibration") OR Calibration OR Calibrations OR Calibrate OR Calibrates OR Calibrated OR

Recalibrates OR Recalibration OR Recalibrations OR Recalibrate OR Recalibrates OR Recalibrated

AND

(MH "Perception+") OR Perception OR Perceptions OR Perceptual OR "Visually guided" OR

Affordance OR "Perceptuo motor" OR Perceptuomotor OR Sensory OR Sensorimotor

AND

(MH "Motor Skills+") OR (MH "Movement+") OR Movement OR "Motor Skills" OR Action OR Actions

Cochrane Central Register of Controlled Trials (CENTRAL)

MeSH descriptor: [Calibration] explode all trees OR Calibration or Calibrations or Calibrate OR

Calibrates or Calibrated or Recalibrates or Recalibration or Recalibrations or Recalibrate or

Recalibrates or Recalibrated

AND

MeSH descriptor: [Perception] explode all trees OR Perception or Perceptions or Perceptual or

"Visually guided" or Affordance OR "Perceptuo motor" OR Perceptuomotor OR Sensory OR

Sensorimotor

AND

MeSH descriptor: [Movement] explode all trees OR MeSH descriptor: [Motor Skills] explode all trees

OR Movement or "Motor Skills" or Action or Actions

Web of Science search

Calibration OR Calibrations OR Calibrate OR Calibrates OR Calibrated OR Recalibrates OR

Recalibration OR Recalibrations OR Recalibrate OR Recalibrates OR Recalibrated

AND Perception OR Perceptions OR Perceptual OR "Visually guided" OR Affordance OR "Perceptuo

motor" OR Perceptuomotor OR Sensory OR Sensorimotor

AND

Movement OR "Motor Skills" OR Action OR Actions


SPORTdiscus

Calibration OR Calibrations OR Calibrate OR Calibrates OR Calibrated OR Recalibrates OR

Recalibration OR Recalibrations OR Recalibrate OR Recalibrates OR Recalibrated

AND

Perception OR Perceptions OR Perceptual OR "Visually guided" OR Affordance OR "Perceptuo motor"

OR Perceptuomotor OR Sensory OR Sensorimotor

AND

Movement OR "Motor Skills" OR Action OR Actions

Appendix 2.2 Results from the quality analysis

Supplementary table 1 Results from the CCAT quality assessment for the included papers (N = 23)

	Prelim-inaries	Intro	Design	Sample	Data Collect	Ethics	Results	Disc	Total %	Quality
Adolph & Avolio (2000)	4	3	5	4	5	3	4	4	80	High
Bastin et al. (2010)	5	5	4	2	4	3	4	3	75	High
Bourgeois et al. (2014)	3	3	2	2	4	4	4	1	58	Moderate
Fajen (2005)	5	5	4	2	5	3	4	3	78	High
Fajen (2008)	5	3	4	2	4	4	4	3	73	High
Fajen (2007)	4	4	3	2	4	3	4	4	70	High
Fajen & Matthis (2011)	4	3	3	2	4	3	4	3	65	High
Franchak & Adolph (2014)	3	5	3	3	5	3	4	2	70	High
Hirose & Nishio (2001)	4	3	3	2	5	1	4	2	60	Moderate
Ishak et al. (2008)	4	3	4	3	4	3	5	2	70	High
Lessard et al. (2009)	5	2	3	2	5	2	4	1	60	Moderate
Linkenauger et al. (2014)	5	5	3	4	5	3	5	4	85	Very High
Mark (1987)	5	5	4	1	4	2	3	4	70	High
Nakamoto et al. (2012)	3	5	4	4	4	4	3	3	75	High
Pepping & Li (2000)	5	4	5	2	4	4	4	3	78	High
Pepping & Li (2008)	4	5	4	2	4	5	4	4	80	High
Pijpers et al. (2007)	4	3	4	1	5	4	4	3	70	High
Regia-Corte & Wagman (2008)	4	3	4	1	5	3	4	3	68	High
Scott & Gray (2010)	5	5	5	4	4	2	5	4	85	Very High
Stefanucci & Geuss (2009)	3	3	4	2	4	8	4	4	65	High
Thomas & Riley (2014)	4	4	3	2	5	2	4	3	68	High
Wagman (2012)	5	4	5	1	5	2	4	5	78	Very High
Wagman et al. (2014)	5	4	5	1	5	1	4	5	75	High

Appendix 4.1 Bland-Altman plots for validation of video data
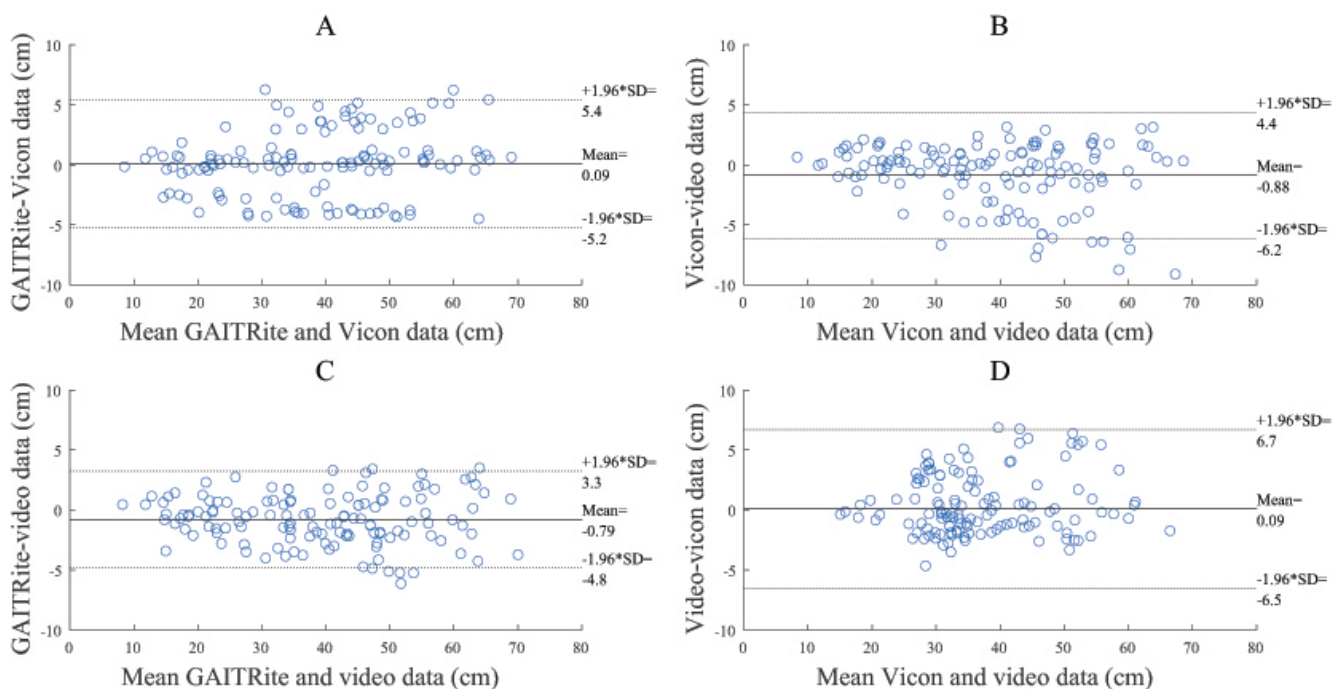
Supplementary Figure 1 Bland-Altman plots, indicating the error between different measurement systems

A subset of (N=4) participants is displayed. Data for the comparisons made between the systems for the last step before stepping up on the platform (step-1) are presented in Panels A through C. Specifically, Panel A shows the differences between the GAITRite and Vicon measures, Panel B shows the differences between the Vicon and video data, and Panel C shows the differences between the GAITRite and video data. Panel D shows the comparisons made between the outcomes measures derived from the Vicon and video data for the first step on top of the platform (step0) and was the only step for which video data was used in reported analyses.

Appendix 5.1 Linear Mixed Effects Model Predicting SD-footfall

Supplementary table 2 Fixed and Random factors in a Linear Mixed Effects Model Predicting

Standard Deviation of Foot Placement (SD-footfall)

	Fixed Factors		
	Beta	SE	p value
Intercept	22.18	1.852	**< 0.001**
Age	-0.073	0.01	**< 0.001**

	Random Factors		
	Beta	Pred. SE	p value
Footfall 0 - Intercept	-8.1	1.789	**< 0.001**
Footfall 0 - Age	-0.023	0.005	**< 0.001**
Footfall-1 - Intercept	-5.321	1.789	**0.003**
Footfall-1 - Age	-0.015	0.005	**0.003**
Footfall-2 - Intercept	-1.043	1.789	0.56
Footfall-2 - Age	-0.003	0.005	0.56
Footfall-3 - Intercept	1.89	1.789	0.291
Footfall-3 - Age	0.005	0.005	0.291
Footfall-4 - Intercept	3.676	1.789	**0.04**
Footfall-4 - Age	0.011	0.005	**0.04**
Footfall-5 - Intercept	4.228	1.789	**0.018**
Footfall-5 - Age	0.012	0.005	**0.018**
Footfall-6 - Intercept	4.67	1.789	**0.009**
Footfall-6 - Age	0.013	0.005	**0.009**

Note. P-values significant at an alpha of 0.05 are presented boldfaced

Appendix 5.2 Linear Mixed Effects Model Predicting the Start of Regulation

Supplementary table 3 Fixed and Random factors in a Linear Mixed Effects Model Predicting the Start of Regulation (TrialRegulationStart)

	Fixed Factors		
	Beta	SE	p value
Intercept	-2.551	0.474	**< 0.001**
Total Adjustment	-0.021	0.034	0.53
Age	0.004	0.006	0.495
Total Adjustment*Age	< 0.001	< 0.001	0.599

	Random Factors		
	Beta	Pred. SE	p value
Shortening - Intercept	-0.496	0.485	0.306
Shortening - Total Adjustment	0.019	0.034	0.589
Shortening - Age	0.012	0.006	0.062
Shortening - Total Adjustment*Age	0	0	0.374
Lengthening - Intercept	1.117	0.48	**0.02**
Lengthening - Total Adjustment	-0.028	0.034	0.403
Lengthening - Age	-0.011	0.006	0.085
Lengthening - Total Adjustment*Age	0	0	0.449
Mixed - Intercept	-0.621	0.502	0.216
Mixed - Total Adjustment	0.01	0.035	0.782
Mixed - Age	-0.001	0.007	0.878
Mixed - Total Adjustment*Age	0	0	0.889

Note. P-values significant at an alpha of 0.05 are presented boldfaced

Appendix 5.3 Linear Mixed Effects Model Predicting Step Length

Supplementary table 4 Fixed and Random factors in a Linear Mixed Effects Model Predicting Step Length (SL)

	Fixed Factors		
	Beta	SE	p value
Intercept	80.863	1.299	**< 0.001**
Age	-0.19	0.021	**< 0.001**

	Random Factors		
	Beta	Pred. SE	p value
Step 0 - Intercept	2.789	1.37	**0.042**
Step 0 - Age	-0.054	0.027	**0.042**
Step -1 - Intercept	-0.744	1.368	0.586
Step -1 - Age	0.014	0.026	0.586
Step -2 - Intercept	0.198	1.368	0.885
Step -2 - Age	-0.004	0.026	0.885
Step -3 - Intercept	0.323	1.368	0.813
Step -3 - Age	-0.006	0.026	0.813
Step -4 - Intercept	-0.545	1.368	0.691
Step -4 - Age	0.011	0.026	0.691
Step -5 - Intercept	-0.832	1.368	0.543
Step -5 - Age	0.016	0.026	0.543
Step -6 - Intercept	-1.189	1.368	0.385
Step -6 - Age	0.023	0.026	0.385

Note. P-values significant at an alpha of 0.05 are presented boldfaced

Appendix 5.4 Linear Mixed Effects Model Predicting the Step Length adjustments

Supplementary table 5 Fixed and Random factors in a Linear Mixed Effects Model Predicting the Step Length adjustment produced in each step (Adjustproduced)

	Fixed Factors		
	Beta	SE	p value
Intercept	< 0.001	0.119	0.997
Adjust$_{required}$	0.112	0.034	**0.001**
Age	< 0.001	0.002	0.796
Adjust$_{required}$*Age	0.001	< 0.001	**0.005**

	Random Factors		
	Beta	Pred. SE	p value
Footfall-1 - Intercept	0.203	0.064	**0.002**
Footfall-1 - Adjust$_{required}$	0.117	0.034	**0.001**
Footfall-1 - Age	-0.003	0.001	**0.001**
Footfall-1 - Adjust$_{required}$*Age	0.001	0	**0.002**
Footfall-2 - Intercept	0.146	0.063	**0.022**
Footfall-2- Adjust$_{required}$	0.096	0.034	**0.005**
Footfall-2 - Age	-0.002	0.001	**0.015**
Footfall-2 - Adjust$_{required}$*Age	0.001	0	**0.004**
Footfall-3- Intercept	0.001	0.063	0.99
Footfall-3 - Adjust$_{required}$	0.01	0.034	0.762
Footfall-3 - Age	0	0.001	0.937
Footfall-3 - Adjust$_{required}$*Age	0	0	0.568
Footfall-4 - Intercept	-0.06	0.063	0.341
Footfall-4 - Adjust$_{required}$	-0.045	0.034	0.194
Footfall-4 - Age	0.001	0.001	0.297
Footfall-4 - Adjust$_{required}$*Age	0	0	0.138
Footfall-5 - Intercept	-0.116	0.063	0.064
Footfall-5 - Adjust$_{required}$	-0.077	0.034	**0.025**
Footfall-5 - Age	0.002	0.001	**0.05**

Supplementary table 5 (continued)

Footfall-5 - Adjust$_{required}$*Age	-0.001	0	**0.02**
Footfall-6 - Intercept	-0.173	0.063	**0.006**

Footfall-6 - Adjust$_{required}$	-0.102	0.034	**0.003**
Footfall-6 - Age	0.003	0.001	**0.005**
Footfall-6 - Adjust$_{required}$*Age	-0.001	0	**0.006**

Note. P-values significant at an alpha of 0.05 are presented boldfaced

Research Portfolio

Study 1 - A systematic review on perceptual-motor calibration to changes in action capabilities

Full reference:

Andel, S. van, Cole, M. H., & Pepping, G.-J. (2017). A systematic review on perceptual-motor calibration to changes in action capabilities. Human Movement Science, 51, 59–71. https://doi.org/10.1016/j.humov.2016.11.004

"I acknowledge that my contribution to the above paper is 60 percent"

Steven van Andel   Date: 7/06/2018

"I acknowledge that my contribution to the above paper is 15 percent"

[Signature]

Michael Cole   Date: 13/06/2018

"I acknowledge that my contribution to the above paper is 25 percent"

Gert-Jan Pepping   Date: 20/06/2018

Acceptance letter:

Steven Van Andel

Ms. Ref. No.: HMS-D-16-00216R2
Title: A Systematic Review on Perceptual-Motor Calibration to Changes in Action Capabilities Human Movement Science

Dear Mr. Steven van Andel,

I am pleased to confirm that your paper "A Systematic Review on Perceptual-Motor Calibration to Changes in Action Capabilities" has been accepted for publication in Human Movement Science.

Your accepted manuscript will now be transferred to our production department and work will begin on creation of the proof. If we need any additional information to create the proof, we will let you know. If not, you will be contacted again in the next few days with a request to approve the proof and to complete a number of online forms that are required for publication.

When your paper is published on ScienceDirect, you want to make sure it gets the attention it deserves. To help you get your message across, Elsevier has developed a new, free service called AudioSlides: brief, webcast-style presentations that are shown (publicly available) next to your published article. This format gives you the opportunity to explain your research in your own words and attract interest. You will receive an invitation email to create an AudioSlides presentation shortly. For more information and examples, please visit http://www.elsevier.com/audioslides

Thank you for submitting your work to this journal.

With kind regards,

Peter Jan Beek
Editor-in-chief Human Movement Science

****
For further assistance, please visit our customer support site at http://help.elsevier.com/app/answers/list/p/7923. Here you can search for solutions on a range of topics, find answers to frequently asked questions and learn more about EES via interactive tutorials. You will also find our 24/7 support contact details should you need any further assistance from one of our customer support representatives.

Study 2 - Perceptual-motor regulation in locomotor pointing while approaching a curb

Full reference:

Andel, S. van, Cole, M. H., & Pepping, G.-J. (2018). Perceptual-motor regulation in locomotor pointing while approaching a curb. Gait & Posture, 60, 164–170. https://doi.org/https://doi.org/10.1016/j.gaitpost.2017.12.006

"I acknowledge that my contribution to the above paper is 65 percent"

Steven van Andel   Date: 7/06/2018

"I acknowledge that my contribution to the above paper is 15 percent"

[Signature]

Michael Cole   Date: 13/06/2018

"I acknowledge that my contribution to the above paper is 20 percent"

Gert-Jan Pepping   Date: 20/06/2018

Acceptance letter:

Steven Van Andel

Dear Mr. van Andel,

I am pleased to inform you that your manuscript "Perceptual-Motor Regulation in Locomotor Pointing while Approaching a Curb" that you and your co-authors submitted has been accepted for publication in Gait and Posture. You will receive the proofs in due course.

When your paper is published on ScienceDirect, you want to make sure it gets the attention it deserves. To help you get your message across, Elsevier has developed a new, free service called AudioSlides: brief, webcast-style presentations that are shown (publicly available) next to your published article. This format gives you the opportunity to explain your research in your own words and attract interest. You will receive an invitation email to create an AudioSlides presentation shortly. For more information and examples, please visit http://www.elsevier.com/audioslides.

Your accepted manuscript will now be transferred to our production department and work will begin on creation of the proof. If we need any additional information to create the proof, we will let you know. If not, you will be contacted again in the next few days with a request to approve the proof and to complete a number of online forms that are required for publication.

Thank you for submitting your work to this Journal.

Yours sincerely

Harald Boehm
Associate Editor
Gait and Posture

Study 3 - Regulation of Locomotor Pointing Across the Lifespan: Investigating Age-Related Influences on Perceptual-Motor Coupling

Full reference:

Andel, S. van, Cole, M. H., & Pepping, G.-J. (2018). Regulation of locomotor pointing across the lifespan: Investigating age-related influences on perceptual-motor coupling. *PLOS ONE*, 13(7), e0200244.

"I acknowledge that my contribution to the above paper is 60 percent"

Steven van Andel   Date: 7/06/2018

"I acknowledge that my contribution to the above paper is 15 percent"

[Signature]

Michael Cole   Date: 13/06/2018

"I acknowledge that my contribution to the above paper is 25 percent"

Gert-Jan Pepping   Date: 20/06/2018

Acceptance letter:

Steven Van Andel

CC: michael.cole@acu.edu.au, gert-jan.pepping@acu.edu.au

PONE-D-17-43665R4
Regulation of Locomotor Pointing Across the Lifespan: Investigating Age-Related Influences on Perceptual-Motor Coupling

Dear Dr. van Andel:

I am pleased to inform you that your manuscript has been deemed suitable for publication in PLOS ONE. Congratulations! Your manuscript is now with our production department.

If your institution or institutions have a press office, please notify them about your upcoming paper at this point, to enable them to help maximize its impact. If they will be preparing press materials for this manuscript, please inform our press team within the next 48 hours. Your manuscript will remain under strict press embargo until 2 pm Eastern Time on the date of publication. For more information please contact onepress@plos.org.

For any other questions or concerns, please email plosone@plos.org.

Thank you for submitting your work to PLOS ONE.

With kind regards,

PLOS ONE Editorial Office Staff
on behalf of

Dr. Yih-Kuen Jan
Academic Editor
PLOS ONE

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Study 4 - Gait-Related Falls are Associated with Gait Adaptations when stepping onto a Curb: a Prospective Falls Study

Preliminary reference:

Andel, S. van, Cole, M. H., & Pepping, G.-J. (in press). Gait-related falls are associated with gait adaptations when stepping onto a curb: a prospective falls study. *Journal of Aging and Physical Activity.*

"I acknowledge that my contribution to the above paper is 65 percent"

Steven van Andel   Date: 7/06/2018

"I acknowledge that my contribution to the above paper is 15 percent"

[Signature]

Michael Cole   Date: 13/06/2018

"I acknowledge that my contribution to the above paper is 20 percent"

Gert-Jan Pepping   Date: 20/06/2018

Acceptance letter:

27-Jul-2018

Dear Mr. van Andel:

It is a pleasure to accept your manuscript entitled "Associations Between Gait-Related Falls and Gait Adaptations when Stepping onto a Curb: a Prospective Falls Study" in its current form for publication in the Journal of Aging and Physical Activity.

The In Press and MedLine listings should be available approximately 6 weeks from now.

Thank you for your fine contribution. On behalf of the Editors of the Journal of Aging and Physical Activity, we look forward to your continued contributions to the Journal.

Sincerely,
Dr. Phil Chilibeck
Editor in Chief, Journal of Aging and Physical Activity phil.chilibeck@usask.ca

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Confirmation of Ethics Approval

ACU
AUSTRALIAN CATHOLIC UNIVERSITY

Human Research Ethics Committee
Committee Approval Form

Principal Investigator/Supervisor: Dr Gert-jan Pepping

Co-Investigators: Dr Michael Cole

Student Researcher: : Steven Van Andel (HDR Student)

Ethics approval has been granted for the following project:
Investigating Perceptual-Motor Calibration During a Locomotor Task

for the period: 30/06/2017

Human Research Ethics Committee (HREC) Register Number: 2015-306H

Special Condition/s of Approval
Prior to commencement of your research, the following permissions are required to be submitted to the ACU HREC:

The data collection of your project has received ethical clearance but the decision and authority to commence may be dependent on factors beyond the remit of the ethics review process and approval is subject to ratification at the next available Committee meeting. The Chief Investigator is responsible for ensuring that outstanding permission letters are obtained, interview/survey questions, if relevant, and a copy forwarded to ACU HREC before any data collection can occur. Failure to provide outstanding documents to the ACU HREC before data collection commences is in breach of the National Statement on Ethical Conduct in Human Research and the Australian Code for the Responsible Conduct of Research. Further, this approval is only valid as long as approved procedures are followed.

Clinical Trials: You are required to register it in a publicly accessible trials registry prior to enrolment of the first participant (e.g. Australian New Zealand Clinical Trials Registry http://www.anzctr.org.au/) as a condition of ethics approval.

It is the Principal Investigators / Supervisors responsibility to ensure that:
1. All serious and unexpected adverse events should be reported to the HREC with 72 hours.
2. Any changes to the protocol must be reviewed by the HREC by submitting a Modification/Change to Protocol Form prior to the research commencing or continuing. http://research.acu.edu.au/researcher-support/integrity-and-ethics/
3. Progress reports are to be submitted on an annual basis. http://research.acu.edu.au/researcher-support/integrity-and-ethics/
4. All research participants are to be provided with a Participant Information Letter and consent form, unless otherwise agreed by the Committee.
5. Protocols can be extended for a maximum of five (5) years after which a new application must be submitted. (The five year limit on renewal of approvals allows the Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

Researchers must immediately report to HREC any matter that might affect the ethical acceptability of the protocol eg: changes to protocols or unforeseen circumstances or adverse effects on participants.

K. Pashley.

Signed: ....   Date: .... 31/05/2016.....