STEPPING INTO RECALIBRATION: AN EXPLORATION OF AGE-RELATED EFFECTS

by

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Spring altijd in het diepe, het ondiepe doet namelijk zeer

‘Always jump in the deep, the shallow hurts.’

Papa & Mama

Abstract

In the United Kingdom, about a third of adults aged over 65 years fall each year (Public Health England, 2018). In older age, recalibration is thought to be necessary to cope with acute and long-term changes within the perceptual and musculoskeletal systems. Recalibration is the rescaling of the perceptual-motor system, which happens after there is a disturbance to the system (Franchak, 2017; Withagen & Michaels, 2004). However, it is possible that recalibration is affected by older age, thereby slowing down the negotiation of actions in new contexts, which could potentially lead to falls in older adults. A systematic review of the literature showed that while young adults recalibrated relatively fast to disturbances to the perceptual-motor system, no research had yet focused on recalibration in older adults. Therefore, the aim of this thesis was to explore whether there are age-related effects in the recalibration to action disturbances. The systematic review also showed the importance of investigating the timeframe of recalibration using a trial-by-trial analysis of the rearrangement process. In the first study, we investigated age-related differences in the recalibration of their affordance perception after disturbing their action boundaries. No recalibration was found in this judgement study, which also showed that the availability of relevant information was essential for recalibration to occur. The two subsequent studies investigated perceptual-motor everyday activities, stair climbing and obstacle crossing, using kinematic measures. An innovative methodology was applied, which identified the timeline of recalibration as the point where a stable movement pattern emerged. By investigating everyday activities, we found that both young and older adults recalibrated quickly, albeit not in the same way. Age-related differences showed that young adults recalibrated faster than older adults in a predictable environment (climbing stairs of a fixed height), but the young adults recalibrated slower when faced with an unpredictable environment (crossing obstacles of varying heights). It seems that the process of recalibration was intact in both groups, but recalibration speed may have been constrained by reduced action capabilities and perceived consequences of the task in the older group. These findings have broader theoretical and practical implications for future research in recalibration.

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Glossary

Action boundaries are participants' maximum action capabilities (Chapter 4).

Active exploration is the generation and pick-up of information for perception through action. Looking around, scanning and exploring the environment are the most common activities of perception (Chapter 1).

Affordances are the behavioural possibilities in a certain environment for a particular animal (Chapter 1).

Attunement happens when a person converges onto the most useful informational variable(s) that are available and can guide a successful action (Chapter 2).

Baseline is where the perception-action coupling is calibrated for a given task. Measurement at baseline is crucial to establish that the skill is well-calibrated (Chapter 2).

Breakpoint: see the point of recalibration for the definition (Chapter 3).

Calibration is defined as the scaling of action to the perceptual information (Chapter 2).

Direct measures of recalibration are those where data is collected throughout the rearrangement period (Chapter 2).

Disturbance to the perception-action coupling where performance is affected. The disturbance can be directed at the action system or the perceptual system (Chapter 2).

Indirect measures of recalibration are those where data is collected before and after, but not during, the rearrangement period (Chapter 2).

Information for perception is generally provided in the optic array and the optic flow and specifies properties of the environment (Chapter 1).

Point of recalibration is the point where the initial rearrangement is split from the final rearrangement and classified as the point when recalibration is completed (Chapter 3).

Post-rearrangement period consists of rescaling perception and action back to baseline levels (Chapter 2).

Rearrangement period consists of rescaling perception and action to information. During this period, performance can be measured trial-by-trial to capture, for example, whether recalibration is gradual or sudden (Chapter 2).

Recalibration happens after a disturbance in either perception or action renders the perception-action link inaccurate, thereby initiating the rescaling of that link (Chapter 2).

Removal is when the disturbance is removed, and performance is affected again (often known as after-effect; Chapter 2).

Chapter 1
Introduction

To get a better understanding of what this thesis is about, we would like to introduce Mrs Poorthuis, an active 90-year-old woman from the Netherlands. In this first chapter, she is going on holiday to the United Kingdom to meet her granddaughter. When she arrives at Gatwick airport, her rental car is already waiting for her. After getting into the rental car, driving it feels a little odd because the pedal force of the car is different from her car back home and it takes her a while to get used to the rental car. In general, we adapt quickly to disturbances such as those imposed by driving an unfamiliar car. However, not much is known about how this happens or how long it takes. Imagine what would happen if we did not adapt as fast or if older adults such as Mrs Poorthuis were unable to adapt.

The present thesis investigates the process of "getting used to" a disturbance, known as *recalibration.* More specifically, we are interested in exploring whether there are age-related differences in the recalibration to action disturbances. Recalibration has its roots in ecological psychology; a theoretical approach by J.J. Gibson (1966, 1979) that inspires the current thesis. Therefore, before discussing recalibration more in depth in the next chapter, we will start by presenting the ideas behind the ecological approach to perception and action.

1.1 Gibson's ecological approach

Traditional cognitive approaches in psychology view perception as indirect in the sense that perception is mediated by cognitive processes. From their point of view, people only perceive impoverished information, which is thought to provide a poor basis for perception. Hence, they have to process this information in order to gain knowledge of the environment. That is to say; people perceive their environment indirectly because they use mental representations of the world or objects in the environment to perceive and guide their actions.

In contrast to the cognitive approach, Gibson's ecological approach argued that the information available in the environment is rich (Gibson, 1979). He stated that people, like other animals, co-evolved with their environments, and consequently, the environment already provides all the relevant information that animals can directly pick up and use. This led to the development of the *theory of direct perception.* In this theory,

Gibson argued that the information is made available in the environment through actions, and therefore, it is often related to the actions of the animal in that environment. In other words, perception is required for the interaction between animal and environment. This means that not only does perception inform action through the pick-up of information that is specific to it, but action is also considered essential to reveal information for perception. Hence, perception and action are coupled with the information available in the environment (see figure 1.1). We will further discuss J.J. Gibson's theory of direct perception using three essential concepts: information, affordances, and active exploration.

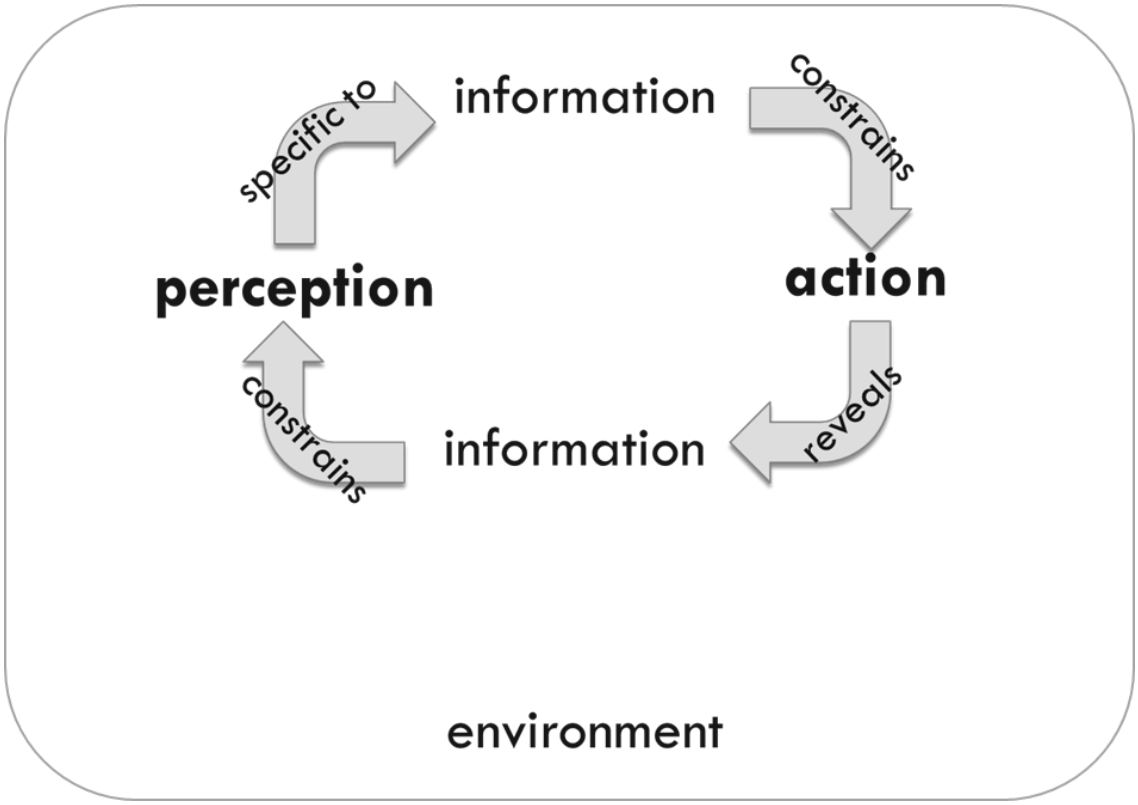

Figure 1.1 An illustration of the theory of direct perception. Perception and action are coupled through the information available in the environment. Perception is specific to the information available in the environment which constrains and guides action while simultaneously action reveals information which constrains perception.

1.1.1 Information

Gibson argued that stimulus information for perception is not poor and meaningless but can *specify* properties of the environment (Gibson, 1979). In general, the optic array and the optic flow provide all the information needed for visual perception. The role of the animal is to pick up relevant information available in the optic array. In other words, information in the Gibsonian sense is available in structured light, sound, or another medium that directly relates to the to-be-perceived environmental property and the to-be-performed action (Michaels & Carello, 1981). An animal can directly perceive an environmental property by picking up information that is specific to it. Information about the environment is always information relative to an animal and information for an animal. This means that information specifies meaningful relationships between animals and their environments and therefore, guide the behaviour of animals. An important concept in explaining the animal-environment relationship is the *agency* of animals. Reed (1996) defined this as follows: animals regulate their behaviour with respect to the action possibilities in their environment by using the information that is available in ambient arrays. This relationship between information, animal, and environment is further unravelled through the concept of affordances.

1.1.2 Affordances

Animals can actively pick up meaningful information specifying action possibilities or affordances in the environment. *Affordances* are the behavioural possibilities in a certain environment for a particular animal. Gibson claimed that all functional purposes of objects are directly perceivable, for instance, a chair affords sitting. Some objects could even afford multiple possibilities for action. For example, the chair might also afford standing on if someone needs to reach for something on a shelf. The definition of the term affordance has received considerable attention in the literature. For Michaels and Carello (1981), affordances are what the environment offers the animal, while later discussions view affordances as invitations for action (Withagen, de Poel, Araújo, & Pepping, 2012). The latter authors claimed that although multiple affordances can *invite* behaviour, not all affordances do so (cf. Rietveld & Kiverstein, 2014; Withagen et al., 2012). One object can afford many different actions, but the majority of these affordances do not invite behaviour. Rietveld and Kiverstein (2014) claimed that the field of affordances determines how a set of affordances can invite actions from an animal at a certain moment in time. The invites differ in strength and change over time, which leads the animal to act (Withagen et al., 2012). As the animal's needs and concerns change over time, the

landscape of affordances and its invitations are dynamic and change accordingly. In further developing the theory of affordances, Withagen and colleagues (2017) developed a new dynamical model of the animal-environment relationship that incorporates the new definition of affordances. In the model, the *agency* is conceptualised as the animal's capacity to modulate to what extent they are influenced by different affordance invitations in the environment (Withagen et al., 2017).

Fajen (2005) contributed to the theory of affordances in two main ways. First he suggested that affordances can be divided into two types: body-scaled affordances and action-scaled affordances. Body-scaled affordances are those defined by one's body dimensions, such as leg length in stair climbing (Warren, 1984; see also 1.2.2). In contrast, action-scaled affordances are defined by one's action capabilities, such as the fielder's maximum running speed in catching a fly ball (Oudejans, Michaels, Bakker, & Dolné, 1996). Second, Fajen (2005, 2007) presented the *affordance-based control framework* whereby instead of moving to null some error, meaning that the value of the specifying variable moves to some ideal value, people move so the ideal state does not cross the action boundary which separates possible from impossible actions. This means that a person perceives the ideal deceleration of braking in units of maximum possible deceleration. So, when a person detects information about the ideal state relative to their maximum action capabilities, they perceive whether or not an action is possible thereby perceiving the affordance.

1.1.3 Active exploration

Another important concept in the relationship between information, animal, and environment or perception-action coupling involves *active exploration* (E.J. Gibson, 1988; J.J. Gibson, 1979). As previously described, perception informs action through the pick-up of information that is specific to the action. In order to do this, animals need to move around to generate and pick up this information. Looking around, scanning and exploring the environment are the most common activities of perception. More generally, movement, no matter how small and whether exploratory or performatory, generates information which is an essential aspect of perception and action. A crucial characteristic of generating information is that it is an active process in which action is as important to perception as perception is to action. For this reason, research has generally ensured that active exploration was embedded in the research tasks as it is essential for picking up information for action. However, a recent study showed even when exploration is not prescribed, most participants spontaneously explore information for example by

approaching and practising actions that are closer to the limit of their capabilities (Labinger, Monson, & Franchak, 2018). This means that participants may naturally seek opportunities to explore the environment in order to recalibrate.

1.2 Direct perception: important applications of the theory

1.2.1 Tau

In understanding the perceptual control of action, identifying the information source(s) available for its guidance seemed a first logical step. David Lee studied the prospective guidance of action in the detection of *invariants in the optic flow*. His studies revealed important sources of information for several activities, including locomotion, hitting and catching a baseball (Lee, 1974, 1976). In the latter two actions, whether moving to catch a ball, or moving to hit a ball, the timing for these actions is essential, and Lee showed that time-to-contact provides that timing information. Time-to-contact (TTC) is specified by the size of the object's retinal image divided by its rate of expansion (*tau*). In other words, the invariant tau specifies time-to-contact between the observer and the object in the environment. Observers directly perceive TTC without having to perceive an object's distance or approach speed. Behaviours that are regulated by using TTC also include long jumping (Lee, Lishman, & Thomson, 1982), golf club movements in putting tasks (Craig, Delay, Grealy, & Lee, 2000), or car braking to avoid collisions (Gray, 2011). Time-to-contact is the most researched informational variable, and this is mainly because it is challenging to identify informational variables which effectively guides action.

1.2.2 Scaling invariants

In developing Gibson's ecological approach, research in affordance perception has found *invariant relationships* between intrinsic individual properties and the environment (e.g. Konczak, Meeuwsen, & Cress, 1992; Warren, 1984; Warren & Whang, 1987). First, Warren (1984) explored the relationship between the individual dimensions and affordances by asking participants to judge stair heights and their ability to climb them (Warren, 1984). The results showed that maximal stair height was a constant proportion of leg length across people with different leg lengths. The maximum height of a stair or surface height that was still perceived as 'step-on-able' was 0.88 times the person's leg length. Similarly, in another study on aperture passibility found that participants only walked frontally through apertures when the ratio between the aperture and their shoulder width was larger than 1.4 (Warren & Whang, 1987). These studies showed that the

individual action capabilities in relation to an object might be described as an invariant proportion of the individual body.

Importantly, other studies showed that these invariant relationships between individuals and the environment did not transfer across different age groups (Konczak et al., 1992; Snapp-Childs & Bingham, 2009). For example, in older adults, Konczak and colleagues (1992) found a lower ratio between leg length and stepping height, which was 0.62 and 0.73 for short and tall older adults. Similarly, Snapp-Childs and Bingham (2009) tried to apply this approach to a study of stepping onto or over a barrier performed by children of different ages and adults. Their study found that age-related differences in scaling actions corresponded to different levels of movement variability. For example, 4-year old children were more variable in their actions than adults, but sensitive to their constraints and thus able to scale their actions accordingly. These studies revealed that affordances not only depend on the *invariant relationships* between intrinsic individual properties, like leg length, but also on the dynamics of the developing perception-action system, such as the biomechanical constraints and the variability of the action itself.

1.2.3 Recalibration

As a result of learning, perception and action become coupled into a relatively stable system (see also chapter 2). When the stability of this system is disturbed, rendering the perception-action link inaccurate, it initiates the process of *recalibration* (Franchak, 2017; Withagen & Michaels, 2004, 2007; see also Chapter 2). The process of recalibration is thought to be necessary to cope with different environments, using different tools, and also coping with acute and long-term changes within the musculoskeletal system. For example, in a short period, fatigue or environmental conditions such as a strong wind can change affordances. Over a longer period, changes in body dimensions like height or width (Franchak & Adolph, 2014), but also changes in strength, flexibility and balance (Konczak et al., 1992) can change the action capabilities. Our literature review showed that young adults could (quickly) recalibrate to changes in their action capabilities (Mark, 1987; Mark et al., 1990; Scott & Gray, 2010; see also Chapter 2). However, no research has focussed on recalibration to action disturbances in older adults. The only study on recalibration in older adults manipulated perceptual information using prism glasses and found that older adults recalibrate slower than younger adults (Fernández-Ruiz, Hall, Vergara, & Diaz, 2000). Following this, we aimed to explore whether older adults also recalibrate slower than young adults to disturbances in their action system.

1.3 The thesis in a nutshell

Recalibration is the rescaling of the perceptual-motor system which happens after there is a disturbance to the system. The concept has its roots in the ecological approach to perception and action, but not much is known about the recalibration process, what factors influence it, or how long it takes. Recalibration is thought to be necessary to cope with acute and long-term changes within the perceptual and musculoskeletal systems, which is important because about a third of adults aged over 65 years fall each year (Public Health England, 2018). More specifically, 32% of falls in the elderly can be accounted for by tripping, stumbling, hitting or bumping into objects or stairs (Robinovitch & Cronin, 1999). In this thesis, we are interested to see whether a poor link between perception and action due to a slower or faulty recalibration could potentially be at the root of falls in the elderly. Therefore, the main *aim of the thesis* is to explore whether there are age-related effects in the recalibration to action disturbances. More specifically, the studies reported in this thesis were designed to unravel how long young and older adults take to recalibrate, which is perhaps the most important aspect of the process of recalibration in terms of practical application. As literature has shown that older adults recalibrate slower to a perceptual disturbance (Fernández-Ruiz et al., 2000), we *hypothesise* that older adults also recalibrate slower than young adults to action disturbances.

Chapter 2 aims to review the current literature on recalibration in functional perceptual-motor tasks and analyses how recalibration can and has been measured. Five databases were systematically screened to identify literature that reported experiments where a disturbance was applied to the perceptual-motor system in functional perceptual-motor tasks. Each of the 91 experiments reported the immediate effects of a disturbance and/or the effects of removing that disturbance after recalibration.

This is followed by *Chapter 3*, which provides a detailed overview of the methodology used to measure and analyse recalibration in the current thesis. We started with an operational definition of recalibration by describing the disturbance used in the experimental chapters. In addition, we described an innovative methodology that we used for the first time to identify the point of recalibration. Finally, we gave an overview of the biomechanical methods used in the latter experimental studies.

The first experimental study, *Chapter 4*, aims to investigate whether young and older adults recalibrate their affordance perception after their action boundaries have been disturbed. In this study, participants were asked to judge the maximum height at which they were able to climb a step without using their hands. After the baseline judgements,

the participants were fitted with very heavy ankle weights and asked to judge their maximum stepping height again in several sets of judgements. Participants were allowed to walk and explore the weights in between each set of judgements.

The second experimental study, *Chapter 5,* aims to investigate how long young and older adults take to recalibrate to disturbances of different magnitudes while climbing stairs. In this study, participants were asked to repeatedly climb a 2-step staircase. After the baseline condition, participants were fitted with light, medium or heavy ankle weights that disturbed their actions, and asked to climb the staircase again. This procedure was then repeated using the two other sets of weights. As it is important to know when participants reached complete recalibration on the task, we used a trial-by-trial analysis to apply a new methodology to find the point of recalibration.

The third experimental study, *Chapter 6,* aims to investigate how long young and older adults take to recalibrate when crossing varying obstacles. This required participants to recalibrate to the weight disturbance in an unpredictable environment, which was more challenging than the set of stairs in Chapter 5. In this study, participants repeatedly walked from one end of the runway to the other to touch a button on the tripod and crossed the obstacle when they encountered it. First, participants performed the task without any ankle weights. Then, we disturbed participants' movements with heavy ankle weights and measured recalibration. Finally, the ankle weights were removed, and we captured the aftereffects of recalibration.

Finally, the last chapter, *Chapter 7,* discusses the main results of this thesis in light of the merits and pitfalls of the methodology. It focussed on the theoretical implications of our results in relation to the existing literature on recalibration. Finally, we addressed our contribution to knowledge, the practical significance of the results, and implications for future research.

Chapter 2

Recalibration in functional perceptual-motor tasks: a systematic review

Abstract

Skilled actions are the result of a perceptual-motor system being well-calibrated to the appropriate information variables. Changes to the perceptual or motor system initiate recalibration, which is the rescaling of the perceptual-motor system to informational variables. For example, a professional baseball player may need to rescale their throws due to fatigue. The aim of this systematic review was to analyse how recalibration can and has been measured and also to evaluate the literature on recalibration. Five databases were systematically screened to identify literature that reported experiments where a disturbance was applied to the perceptual-motor system in functional perceptual-motor tasks. Each of the 91 experiments reported the immediate effects of a disturbance and/or the effects of removing that disturbance after recalibration. The results showed that experiments applied disturbances to either perception or action and used either direct or indirect measures of recalibration. In contrast with previous conclusions, active exploration was only sufficient for fast recalibration when the relevant information source was available. Further research into recalibration mechanisms should include the study of information sources as well as skill expertise.

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2.1 Introduction

Mrs Poorthuis' son is a major league baseball pitcher, who is expected to throw a strike ball each time he pitches the ball. Halfway through the game, his arm is getting slightly fatigued, but he is expected to keep throwing his pitches. Even though his next throw may be a little off or outside the strike zone, but he will soon find the right adjustments and throw the ball accurately again. "Getting used to the fatigue" includes the rescaling of both the perceptual and the motor system and this process is known as *recalibration* (Withagen & Michaels, 2004, 2007). The aim of this systematic review is to analyse how recalibration can and has been measured and also to evaluate the literature on recalibration.

In the present review, recalibration has been defined in the context of the ecological approach. According to this approach, people directly detect the useful information available in the environment to guide their actions (J. J. Gibson, 1979). The proposal is that people do not detect the intrinsic properties of objects, but rather the informational variables that are specified by actions. That is to say, the information that is available in the environment is directly useful to guide the actions performed. In the context of ecological psychology, the accuracy of actions can be improved using attunement, calibration, and recalibration which we will define next (Jacobs, Vaz, & Michaels, 2012; Michaels & Carello, 1981; Withagen & Michaels, 2004).

From an ecological perspective, it has been proposed that during attunement, the person converges onto the most useful informational variable(s) that are available and can guide a successful action. Actions can be inaccurate because the person converged onto variables that are not optimal, meaning that they are not sufficiently specifying for a given action (Jacobs et al., 2012). However, through exploration, they may attune to those variables which result in a consistently good performance (Michaels & Carello, 1981). For example, throwing to a target can be specified by variables that relate directly to the distance to the target such as the angle of elevation or declination (de Oliveira, Oudejans, & Beek, 2009; Ooi, Wu, & He, 2001). The attunement process by which people gradually change from detecting less useful to more specifying variables is also referred to as education of attention (E.J. Gibson, 1963; J.J. Gibson & E.J. Gibson, 1955; Jacobs et al., 2012). Attunement, on its own, may not always be sufficient because calibration is also required for actions to be successful (Withagen & Michaels, 2004).

Calibration is the second process involved in improving the accuracy of actions. From an ecological perspective, calibration is defined as the scaling of action to the perceptual information (Withagen & Michaels, 2004). Having attuned to using certain informational variables the person needs, subsequently, to scale their perception-action link to these informational variables. This calibration is only possible through practice, and it is what maintains the appropriate relationship between the informational variable and the perception or action (e.g., Jacobs & Michaels, 2006; Withagen & Michaels, 2002, 2004). Despite important differences, the term calibration has often been used interchangeably with recalibration, including the only review on [re]calibration by van Andel, Cole, and Pepping (2017). Calibration and recalibration may have been used interchangeably because they are thought to be similar processes of scaling information to perception and action. However, the distinction is important, because they differ in terms of a) what may elicit these processes; b) how long they may take to complete the process; c) what methods should be used to investigate them; and d) practical implications when calibration or recalibration are thought to underlie poor performance.

Recalibration happens only after a *disturbance* in either perception or action renders the perception-action link inaccurate, thereby initiating the rescaling of that link (rearrangement). For example, when a player's throwing requires an updated scaling of the perceptual-motor coupling due to fatigue. Recalibration is necessary to cope with different environments, using different tools, and coping with acute and long-term changes within the musculoskeletal system. Recalibration has been thought to largely depend on exploration (Withagen & Michaels, 2004, 2007) and a recent review concluded that even minimal movements might be sufficient for recalibration (van Andel et al., 2017). The authors stated that recalibration occurred rapidly when there was a good match between the action that required recalibration and the movements that participants were allowed to make during exploration (e.g., when exploring maximal braking capabilities by experiencing braking in a car). On the other hand, when movements were restricted recalibration took longer. These conclusions were based on four articles and applied only to changes in action capabilities, so it is unclear whether the authors' generalisation is warranted. Another review studied only changes in perception and consequent recalibration using prism glasses (Redding, Rossetti, & Wallace, 2005). They studied recalibration in a three-step process: a pre-exposure baseline, an active exposure to the prism glasses, and a post-exposure after-effect. In the present systematic review, we will review recalibration by including experiments that studied changes in both perception and action, and we also include all the stages relevant for the study of recalibration.

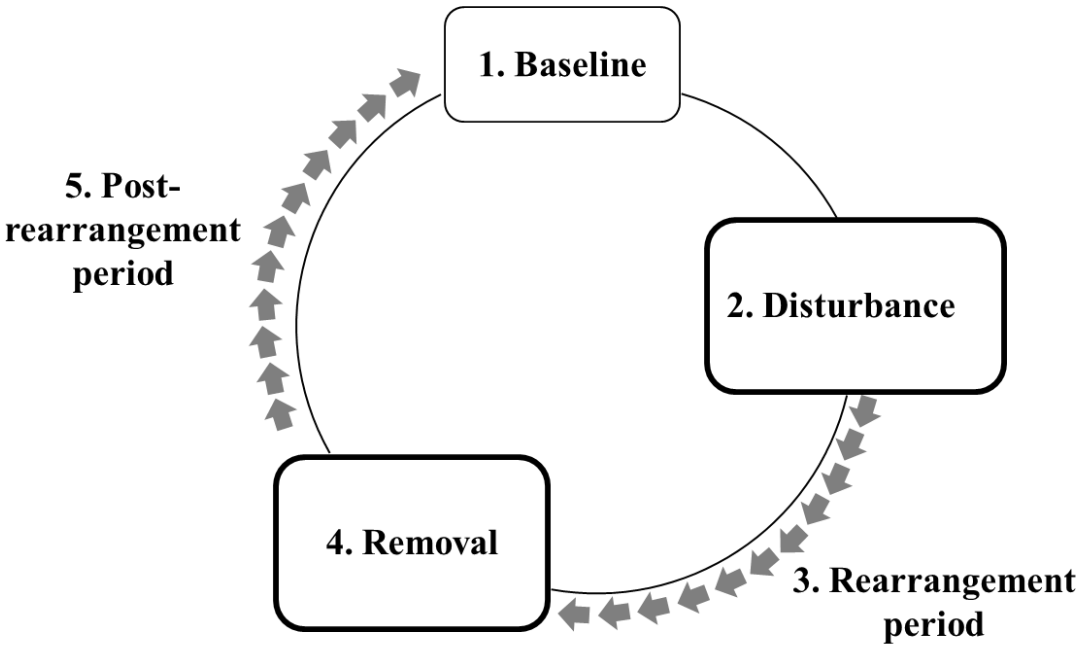


Figure 2.1 A schematic illustration of strategies to measure recalibration. At (1) baseline, the perceptual-motor system is calibrated; (2) represents a disturbance to the perceptual-motor system; (3) in the rearrangement period each of the grey arrows represents a trial or measurement of recalibration; (4) represents the removal of the disturbance and (5) in the post-rearrangement period each of the grey arrows represents a trial or measurement of recalibration. Direct measures of recalibration include measures at (2) and (3) capturing both the disturbance and the rearrangement period. On the other hand, indirect measures of recalibration include measures at (1) and (4) capturing the baseline and the effects upon removal of the disturbance.

Recalibration is a dynamic process that can be captured and measured at different points in time. Schematically, recalibration consists of five different measurable stages that can be useful to guide research into the process of recalibration. We propose figure 2.1 as an illustration of the recalibration process (extended from Redding et al., 2005). It includes a (1) *baseline* where the perception-action coupling is calibrated for a given task. Measurement at baseline is crucial to establish that the skill is well-calibrated. A (2) *disturbance* in the perception-action coupling, where performance is affected. This can be a disturbance directed at the action system or the perceptual system. After this, the (3) *rearrangement* period consists of rescaling perception and action to information. During this period, performance can be measured trial-by-trial to capture, for example, whether recalibration is gradual or sudden. At (4) *removal,* the disturbance is withdrawn, and performance is affected again (often known as after-effect). The (5) *post-rearrangement* period consists of rescaling perception and action back to baseline levels. Again, trial-by-trial measurements can ascertain the time course of this stage. Different studies have

measured different stages of this model. For example, Scott and Gray (2010) focused on measuring the *disturbance* and *rearrangement* of perception-action to study recalibration. In their study, participants used either a standard, lighter or heavier bat to swing at a simulated approaching baseball. During the first couple of trials, significant differences were found in baseball swings between the three bat conditions (*disturbance*). The lighter group *rearranged* within five pitches, and the heavier group *rearranged* within 10 pitches. After 30 trials, differences between the three groups were not significant, hence rearrangement was complete. Alternatively, Kunz, Creem-Regehr, and Thompson (2015) took measurements at the *baseline* and *removal* to study recalibration. Participants walked through a visually faster or a visually slower hallway (*disturbance*). After *removal* of this visual disturbance, they measured an after-effect whereby participants overshot distance in the visually slower condition and undershot distance in the visually faster condition.

An additional strategy used to study the concept of recalibration is to investigate whether the rearrangement of the perception-action coupling for one action transfers to another action. In studying how the transfer of recalibration is organised, Rieser, Pick Jr, Ashmead, and Garing (1995) found that the rearrangement of walking transferred to side-stepping which served the same functional goal but did not transfer to throwing. The authors argued that this type of functional organisation is most efficient because recalibrating one action to a particular environmental situation generalises to other actions which may be used to accomplish the same goal (Rieser et al., 1995). On the other hand, Bingham, Pan, and Mon-Williams (2014) studied anatomical recalibration, which had also been proposed by Rieser et al. (1995). Bingham et al. (2014) argued that the transfer of recalibration should also be anatomical because there are often anatomical differences between limbs (e.g., one arm shorter than the other). They proposed that where the anatomy of limbs is different, the recalibration of actions by one limb should affect the other limb (Bingham et al., 2014).

The aim of this systematic review is to analyse how recalibration can and has been measured and also to evaluate the literature on perceptual-motor recalibration. Although previous reviews have been published on the topic of recalibration, they have not 1) addressed the methodological strategies used in those studies and 2) have been restrictive in terms of the type of disturbance included. In this connection, there are two reviews worth mentioning. The first is a recent review by Van Andel et al. (2017) who studied disturbances to action capabilities only; they concluded that active exploration was necessary for [re]calibration and that there was no research on older populations. The second review, by Redding et al. (2005), studied only disturbances to perception using

prism glasses. Currently, no review has focused on experiments that included disturbances applied to both the perceptual and the motor systems. This is important because the concept of recalibration entails the recoupling of perception and action based on information. Therefore, if we find that recalibration is essentially different depending on which system is primarily affected by the disturbance, this has implications for the concept of recalibration. In addition, there is no information available regarding the methods, measures and results across these disturbances. Therefore, this systematic review studies disturbances that are applied to both the perceptual and the motor systems in functional perceptual-motor tasks. The analysis of these experiments focusses on how recalibration can and has been measured, and on evaluating the literature on recalibration.

2.2 Methods

2.2.1 Search strategy

An extensive literature search was performed using the following electronic databases: Medline, Web of Science, Scopus, SportDiscus and PsycInfo. The following search terms were used: [perceptual-motor OR ecological psychology] AND [movement OR locomotion OR exercise OR action] AND [calibrat* OR recalibrat* OR adapt* OR readapt* OR scale OR rescale OR scaling]. The search was performed on all available literature up to December 2016 and limited to experimental articles written in English. The authors also manually screened the literature for additional relevant articles.

2.2.2 Inclusion and exclusion criteria

The literature was screened based on titles, abstracts and full-texts to include relevant articles. For inclusion, articles had to report on experiments where a disturbance was applied to the perceptual-motor system in a task that involved functional perceptual-motor tasks. Articles had to report data on the immediate effect of a disturbance or removal as well as include an additional data point to compare it against. For example, this could be data on disturbance and rearrangement, or baseline and removal (see figure 2.1). Articles had to report on participants who were healthy and with normal or corrected-to-normal vision. Articles were excluded if their focus was on attunement (or learning) instead of recalibration, if the task involved pacing to an external rhythm, or if it was based on eye-movement data only. Articles were also excluded if their focus was on sensorimotor adaptation, or the disturbance was to proprioception. Both authors reviewed the search results independently in three phases; first, the titles, then abstracts,

and then full texts. For each phase, in case of disagreement, the conflicting article was discussed until a consensus was reached over its inclusion or exclusion.

Figure 2.2 shows the results of the review phases in a flow diagram (PRISMA; Moher, Liberati, Tetzlaff, & Altman, 2009). The database search resulted in the retrieval of 1773 journal articles, of which 192 duplicates were removed. The remaining 1581 articles were screened for their titles, and subsequently, 467 titles were selected for abstract screening. There were 86 articles identified as potentially relevant based on their abstracts, and their full-text articles were reviewed. In addition, the authors screened the literature and included 4 articles for full-text review. A final list of 44 articles was identified as suitable for inclusion in the systematic review; these articles included a total of 91 experiments.

2.2.3 Quality assessment

Table 2.1 shows the scale for the quality assessment of the experiments. We used a scale with items from both the Quality Index (Downs & Black, 1998) and the Crowe Critical Appraisal Tool (Crowe & Sheppard, 2011), and added two relevant items for assessing recalibration experiments (adaptations have been used before, e.g., Uiga, Cheng, Wilson, Masters, & Capio, 2015; Van Andel et al., 2017). The scores for each of the items on the scale ranged from 0 = no information, 1 = unclear or incomplete, and 2 = clear and detailed. The maximum score available for the quality assessment was 24.

The mean score for the methodological quality of the experiments was 73 % (SD = 10 %) with a range of 46-92 % (see Table 2.2). More than 92 % of the experiments clearly described their study design, procedure, tasks, data collection and results. Detailed information on participants' characteristics and the inclusion of a control group was only found, respectively, in 49 % and 11 % of the experiments.

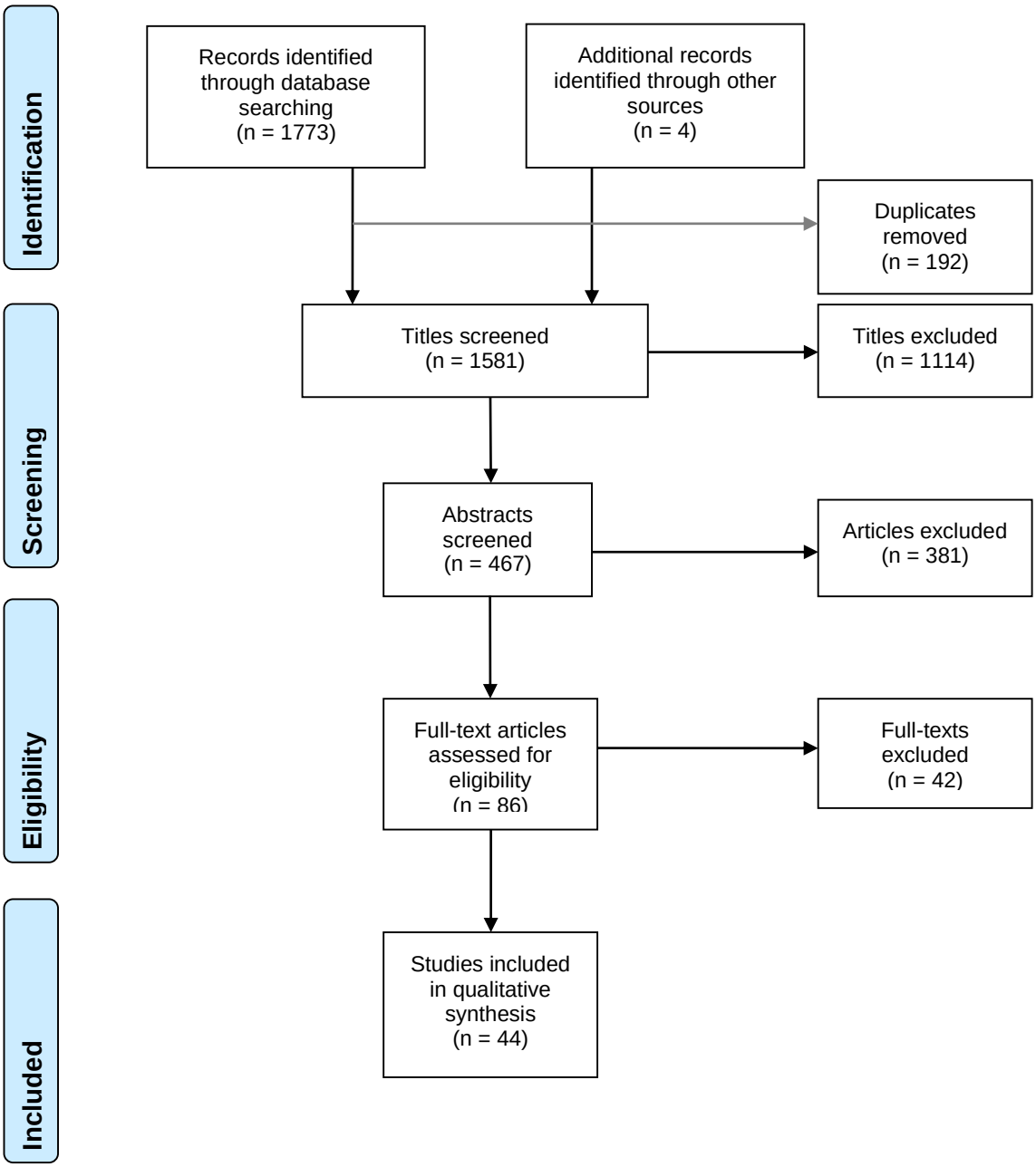


Figure 2.2 PRISMA flowchart of literature search results. From top to bottom the flowchart shows the identification of 1777 articles, the screening of 1581 titles and 467 abstracts, the further screening for eligibility of 86 full-text articles, and the inclusion of 44 articles.

Table 2.1 The quality assessment items and their origin. Experiments were assessed on a scale of 0 to 2.

	Quality assessment items	Origin
1	Are the hypothesis, aims, objectives clearly described?	Downs and Black, 1998; CCAT*
2	Is the design clearly described?	CCAT
3	Is the procedure of the experiment clearly described?	Downs and Black, 1998; CCAT
4	Are the tasks clearly defined?	Downs and Black, 1998
5	Are the data collection methods clearly described?	CCAT
6	Was the data processing clearly defined?	Uiga et al., 2015
7	Were the outcome measures clearly defined?	Downs and Black, 1998; CCAT
8	Are the main findings of the study clearly described?	Downs and Black, 1998; CCAT
9	Does the study provide estimates of random variability in the data?	Downs and Black, 1998
10	Were participants representative of the population under study?	Downs and Black, 1998; CCAT
11	Are the characteristics of participants clearly described?	Downs and Black, 1998; CCAT
12	Was there a control group?	Uiga et al., 2015

*CCAT by Crowe and Sheppard, 2011.

Table 2.2 Quality assessment scores of the included experiments

	Items												
Included experiments	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
Bingham (2005)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Bingham and Mon-Williams (2013)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Bingham and Pagano (1998 - exp.1)	2	2	2	2	2	2	2	2	2	0	1	0	79%
Bingham and Pagano (1998 - exp.2)	2	2	2	2	2	2	2	2	2	0	1	0	79%
Bingham and Pagano (1998 - exp.3)	2	2	2	2	2	2	2	2	2	0	1	0	79%
Bingham and Pagano (1998 - exp.4)	2	2	2	2	2	2	2	2	2	0	1	0	79%
Bingham and Romack (1999)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Bingham et al. (2014 - exp.1)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Bingham et al. (2014 - exp.2)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Brennan et al. (2012)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Bruggeman et al. (2005 - exp.1)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Bruggeman et al. (2005 - exp.3)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Bruggeman et al. (2005 - exp.4)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Coats et al. (2014 - exp.1)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Coats et al. (2014 - exp.2)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Coats et al. (2014 - exp.3)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Dotov et al. (2013)	2	1	2	2	2	2	2	2	2	0	2	2	88%
Durgin et al. (2005 - exp.2)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Durgin et al. (2005 - exp.3)	2	2	2	2	2	1	2	2	0	0	1	0	67%
Durgin et al. (2005 - exp.1)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Durgin et al. (2005 - exp.5)	2	2	2	2	2	1	2	2	2	0	1	0	75%
Durgin et al. (2005 - exp.6)	2	2	2	1	0	0	0	2	1	0	1	0	46%
Fernandez-Ruiz and Diaz (1999 - exp.1)	0	2	2	2	1	2	2	1	0	0	0	0	50%
Fernandez-Ruiz and Diaz (1999 - exp.2)	0	2	2	2	1	2	2	1	0	0	0	0	50%
Fernandez-Ruiz and Diaz (1999 - exp.3)	0	2	2	2	1	2	2	1	0	0	0	0	50%
Fortis et al. (2013)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Franchak and Adolph (2014 - exp.3)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Hackney et al. (2014)	2	2	2	2	2	2	2	2	1	0	2	0	79%
Higuchi et al. (2004 - exp.1)	2	2	2	2	2	2	2	2	0	0	2	2	83%

Higuchi et al. (2004 - exp.2)	2	2	2	2	2	2	2	2	0	0	2	2	83%
Hirose and Nishio (2001)	2	2	2	2	2	2	2	2	1	0	2	0	79%
Kunz et al. (2009 - exp.5)	2	2	2	2	2	2	2	2	1	0	2	0	79%
Kunz et al. (2013 - exp.1)	2	2	2	2	2	2	2	2	1	0	1	0	75%
Kunz et al. (2013 - exp.2)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Kunz et al. (2013 - exp.3)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Kunz et al. (2013 - exp.4)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Kunz et al. (2015)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Marcilly and Luyat (2008)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Mark (1987 - exp.2)	2	2	2	2	2	2	2	2	1	0	2	0	79%
Mark (1987 - exp.3)	2	0	2	2	2	2	2	2	0	0	0	0	58%
Mark et al. (1990 - exp.1)	2	2	2	2	2	2	2	2	0	0	0	0	67%
Mark et al. (1990 - exp.2)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mark et al. (1990 - exp.3)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mark et al. (1990 - exp.4)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mark et al. (1990 - exp.5)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Mark et al. (1990 - exp.6)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Mohler et al. (2007 - exp.1)	2	2	2	2	0	0	0	2	2	0	0	0	50%
Mohler et al. (2007 - exp.2)	2	2	2	2	0	0	0	2	1	0	0	0	46%
Mon-Williams and Bingham (2007 - exp.1)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mon-Williams and Bingham (2007 - exp.2)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mon-Williams and Bingham (2007 - exp.3)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Mon-Williams and Bingham (2007 - exp.4)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Morton and Bastian (2004)	2	2	2	2	2	2	2	1	0	0	2	0	71%
Pagano and Bingham (1998)	2	2	2	2	2	2	2	2	2	0	1	0	79%
Pan et al. (2014 - exp.3)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Redding and Wallace (1985 - exp.1)	2	2	2	2	2	2	2	1	0	0	0	0	63%
Redding and Wallace (1985 - exp.2)	2	2	2	2	2	2	2	1	0	0	0	0	63%
Redding and Wallace (1985 - exp.3)	2	2	2	2	2	2	2	1	0	0	0	0	63%
Redding and Wallace (1987)	2	1	2	2	2	2	2	1	0	0	0	0	58%
Richter et al. (2002)	2	2	2	2	1	2	1	2	1	0	2	2	79%
Rieser et al. (1995 - exp.1)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Rieser et al. (1995 - exp.10)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 - exp.2)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 - exp.3)	2	2	2	2	2	2	2	2	2	0	0	0	75%

Rieser et al. (1995 - exp.4)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 - exp.5)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 - exp.6)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 - exp.7)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 - exp.8)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Rieser et al. (1995 - exp.9)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Saunders and Durgin (2011)	2	0	2	2	2	0	0	2	1	0	1	0	50%
Scott and Gray 2010 - exp.1)	2	2	2	2	2	2	2	2	1	0	2	2	88%
Scott and Gray 2010 - exp.2)	2	2	2	2	2	2	2	2	1	0	2	2	88%
Stefanucci and Geuss (2010 - exp.3)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Stefanucci and Geuss (2010 - exp.4)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Stefanucci and Geuss (2010 - exp.4b)	2	2	2	2	2	2	2	2	2	0	0	0	75%
Stoffregen et al. (2005 - exp.1)	2	0	2	2	2	0	0	2	1	0	1	0	50%
Stoffregen et al. (2005 - exp.2)	2	0	2	2	2	0	0	2	2	0	1	0	54%
Turchet et al. (2014)	2	2	2	2	2	2	2	2	1	0	2	0	79%
van Hedel and Dietz (2004)	2	0	2	2	2	2	2	2	2	0	1	0	71%
Wagman and Abney (2012 - exp.3)	2	2	2	2	2	2	2	2	1	0	0	0	71%
Waller and Richardson (2008 - exp.1)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Waller and Richardson (2008 - exp.2)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Waller and Richardson (2008 - exp.3)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Withagen and Michaels (2002)	2	2	2	2	2	2	2	2	2	0	2	0	83%
Withagen and Michaels (2007 - exp.1)	2	2	2	2	2	2	1	2	1	0	1	0	71%
Withagen and Michaels (2007 - exp.2)	2	2	2	2	2	2	1	2	1	0	1	0	71%
Yasuda et al. (2014 - exp.1)	2	2	2	2	2	2	2	2	2	0	2	2	92%
Yasuda et al. (2014 - exp.2)	2	2	2	2	2	2	2	2	2	0	2	2	92%
Yu and Stoffregen (2012)	2	2	2	2	2	2	2	2	0	0	2	2	83%
Yu et al. (2011)	2	2	2	2	2	2	2	2	1	0	2	2	88%

2.3 Results

2.3.1 Descriptive statistics

The number of studies on recalibration has steadily grown over the years after the first articles were published in 1985. Most recalibration studies were published in the Journal of Experimental Psychology: Human Perception and Performance (39 %), followed by Experimental Brain Research (17 %) and Ecological Psychology (16 %). Half of the recalibration articles reported multi-experimental articles (55 %) with two or more experiments. Only 29 % of the studies measured recalibration at 3 or more points during the recalibration process. The 38 % of experiments that reported participants' characteristics recruited mainly university students. Overall, the age range in the studies was 18-52 years.

2.3.2 Disturbances to perception or action and related measures

Direct measures of recalibration are those where data is collected throughout the rearrangement period. These experiments (n = 50 out of 91) provided information on how long it took participants to rearrange and/or whether participants fully recalibrated to the disturbance. From these, half of the experiments (n = 25) applied a disturbance to the action capabilities of participants, for example by altering body dimensions and/or joint kinematics (e.g., attaching blocks underneath feet, holding wide objects, or being seated in a wheelchair; Franchak & Adolph, 2014; Hackney, Cinelli, & Frank, 2014; Higuchi, Takada, Matsuura, & Imanaka, 2004; Hirose & Nishio, 2001; Mark, 1987; Mark, Balliett, Craver, Douglas, & Fox, 1990; Scott & Gray, 2010; Stefanucci & Geuss, 2010; Stoffregen, Yang, & Bardy, 2005; Van Hedel & Dietz, 2004; Yasuda, Wagman, & Higuchi, 2014; Yu, Bardy, & Stoffregen, 2011; Yu & Stoffregen, 2012). For example, Van Hedel and Dietz (2004) measured gait pattern on 50 trials after attaching an orthosis to participants' left foot. The other half of the experiments (n = 25) took direct measures of recalibration after applying a disturbance to perception (Bingham & Mon-Williams, 2013; Bingham & Romack, 1999; Bingham, Pan, & Mon-Williams, 2014; Bingham, 2005; Bingham & Pagano, 1998; Coats, Pan, & Bingham, 2014; Fernández-Ruiz & Díaz, 1999; Fortis, Ronchi, Calzolari, Gallucci, & Vallar, 2013; Mon-Williams & Bingham, 2007; Pagano & Bingham, 1998; Richter et al., 2002; Saunders & Durgin, 2011; Turchet, Camponogara, & Cesari, 2014). These experiments used prism glasses, restrictive monocular apparatus, virtual reality, or auditory information to disturb the participants'

perception. For example, Saunders and Durgin (2011) measured mean heading errors on 20 trials after disturbing visual heading through virtual reality.

Indirect measures of recalibration are those where data is collected before and after, but not during, the rearrangement period. These experiments (n = 41 out of 91) typically informed on the after-effects as a proxy to the preceding rearrangement period. The majority of experiments (n = 27) applied a disturbance to perception by manipulating optic flow, using prism glasses, or giving distorted feedback during the rearrangement period, and subsequently measuring effects upon removal of the disturbance (Bruggeman, Pick, & Rieser, 2005; Dotov, Frank, & Turvey, 2013; Kunz, Creem-Regehr, & Thompson, 2009, 2013; Kunz et al., 2015; Marcilly & Luyat, 2008; Mohler, Thompson, Creem-Regehr, & Willemsen, 2007; Redding & Wallace, 1985, 1987; Rieser et al., 1995; Wagman & Abney, 2012; Waller & Richardson, 2008; Withagen & Michaels, 2002, 2007). For example, Kunz, Creem-Regehr, & Thompson (2009) found that participants overshot distance by 15 % after walking in a visually slower environment and undershot distance by 14 % after walking in a visually faster environment. Fewer experiments (n = 7) took indirect measures of recalibration after manipulating action (Brennan, Bakdash, & Proffitt, 2012; Durgin et al., 2005; Rieser et al., 1995). These experiments disturbed different components of locomotion on a treadmill, such as duration and speed. For example, results showed that blind-walking distance significantly increased after only 20 seconds of treadmill blind-running (Durgin et al., 2005, exp. 6).

2.3.3 The analysis of rearrangement phase

Some experiments studied the rearrangement phase using a regression analysis where the slope and intercepts of these regression lines to show offset and inform about the scaling and offset of errors (n = 27; Bingham, 2005; Bingham & Pagano, 1998; Bingham & Romack, 1999; Coats et al., 2014; Mark, 1987; Mark et al., 1990; Mon-Williams & Bingham, 2007; Stoffregen et al., 2005; Wagman & Abney, 2012; Withagen & Michaels, 2007; Yu & Stoffregen, 2012). The intercept indicates an offset error; a constant underestimation or overestimation, for example of the actual distance. The slope indicates the scaling error, for example, between perceived to actual distance. Bingham's studies used slopes and intercepts to analyse the effect of distorted feedback on reaching movements (Bingham, 2005; Bingham & Pagano, 1998; Bingham & Romack, 1999; Coats et al., 2014; Mon-Williams & Bingham, 2007). These studies plotted reached distances against actual target distances and analysed the resulting slopes. Withagen and Michaels (2007) analysed the intercepts and slopes of the regression lines between

perceived and actual length judgements. They used this pre-test slope to manipulate the feedback distortion and then tested whether recalibration transferred from length perception to sweet-spot perception. Similar methods were used by Wagman and Abney (2012) who compared intercepts and slopes in pre-test and post-test to evaluate the effects of distorted feedback. Other experiments also used slopes to indicate the change of judgement error over blocks or trials (Mark, 1987; Mark et al., 1990; Yu & Stoffregen, 2012).

2.3.4 Quality and duration of the rearrangement period

Results showed that active exploration was the most effective way to recalibrate to changes in perception or action capabilities (n = 15), as shown in Table 2.3. From these experiments, seven showed that a small number of rearrangement trials (5 to 12 trials) was sufficient for complete or near-complete recalibration using a trial-by-trial rearrangement analysis. For example, Scott and Gray (2010, exp. 1) showed that participants recalibrated within five pitches to a lighter baseball bat, while participants using heavier bats recalibrated within 10 pitches. Bruggeman et al. (2005) found that participants throwing beanbags while rotating on a carousel recalibrated after 10 throws. Similarly, Bingham and Romack (1999) showed that participants placing an object in a target hole while wearing 10-diopter prism glasses recalibrated as their movement times gradually decreased over trials within each block. They also found that the initial effect of the disturbance gradually decreased over three days as recalibration took 10.2 trials on day 1 and was reduced to 5.6 trials on day 3. Other experiments also found that participants required a small number of rearrangement trials before recalibrating (Mark, 1987; Mark et al., 1990; Saunders & Durgin, 2011; Scott & Gray, 2010).

From the 15 experiments, five also showed that participants recalibrated within 20-50 trials by setting a fixed amount of rearrangement trials for participants to rearrange. Note that shorter periods might have been sufficient, but there was no trial-by-trial analysis of the rearrangement period. For example, 20 rearrangement trials squeezing through doorways while wearing a pregnancy pack dramatically reduced judgement errors of passibility (Franchak & Adolph, 2014, exp. 3). In another experiment, judgments also improved after 21 rearrangement trials during which participants walked through apertures with a 69-cm horizontal bar (Yasuda et al., 2014, exp.1). Other experiments also used a fixed amount of rearrangement trials during which recalibration occurred (Fortis et al., 2013; Hackney et al., 2014; Richter et al., 2002; Van Hedel & Dietz, 2004).

Interestingly, incomplete recalibration using active exploration was found in 8

experiments. The pattern seems to show that restricted availability of information during exploration resulted in a reduced ability to recalibrate. These experiments (n=5; Bingham, 2005; Bingham & Pagano, 1998) restricted visual perception in different conditions but allowed participants to actively reach to a target. Their results showed that normal binocular vision resulted in an accurate perception of distance while monocular vision resulted in incomplete recalibration even with feedback (Bingham, 2005; Bingham & Pagano, 1998, exp.4). Furthermore, when participants viewed through a restrictive camera, they were unable to use the haptic feedback of reaching to improve performance (Bingham & Pagano, 1998, exp.3).

Secondly, incomplete recalibration was also found in experiments that used a wheelchair for locomotion (n=3, Higuchi et al., 2004, exp. 1-2; Yasuda et al., 2014). These experiments asked participants to make judgements about the person-plus-wheelchair passibility through apertures. Yasuda et al. (2014, exp.2) found that 21 rearrangement trials propelling a wheelchair through apertures were not sufficient to accurately judge passibility through apertures, and Higuchi et al. (2004, exp. 1) found that 20-28 rearrangement trials were also not sufficient. A longer period of rearrangement over eight days was effective in reducing participants' underestimations after wheelchair-use on four separate days (Higuchi et al., 2004, exp. 2). It is noteworthy that although participants had normal locomotion and passibility experience, they had no prior experience with wheelchairs. Therefore, it is likely that the lack of experience or skill in the specific task of wheelchair passibility led to incomplete recalibration.

Recalibration without active exploration was not impossible, but it depended on the amount of restriction that was applied during the rearrangement period (n = 9; Mark, 1987; Mark et al., 1990; Stoffregen et al., 2005; Yu et al., 2011; Yu & Stoffregen, 2012). For example, when participants were allowed body sway during rearrangement but were not allowed to walk with blocks under their feet, they still recalibrated within 12 trials in a judgement task that depended heavily on eye-height as an information source (Mark, 1987, exp.3; Mark et al., 1990, exp.2; Stoffregen et al. 2005). In contrast, experiments where the movement was severely restricted in a way that the restricted the availability of relevant information sources for the task, showed that participants did not recalibrate (Mark et al. 1990, exp. 3, 4, 5). Even when participants were allowed to move (e.g., by sitting 2-3 times) before performing a perceptual task under severe restrictions, participants did not recalibrate (Mark et al., 1990, exp. 6). In addition, experiments found that judgments about minimum lintel height when participants were allowed to move their head unrestrained were more accurate than when their heads were restrained during

rearrangement (Yu et al., 2011; Yu & Stoffregen, 2012). These experiments indicate that the availability of information rather than the ability to move during the rearrangement is the crucial factor for rearrangement to be successful.

2.3.5 The effects of disturbances on rearrangement

Results suggest there may be a positive link between the disturbance effect and the time required to rearrange (n = 2). One experiment found that rearrangement was longer for glasses of 30 prism diopter compared to glasses of 10 or 20 prism diopter (Fernández-Ruiz & Díaz, 1999, exp. 1). While participants reached maximum rearrangement with 30 diopter glasses within 12 throws, with 10 and 20 diopter glasses they only required 6 and 9 throws. Similarly, Van Hedel and Dietz (2004) found that more restrictive orthoses required longer rearrangement periods. Their experiment showed that participants fitted with an ankle-foot orthosis rearranged within 50 trials, but this was not sufficient for participants fitted with a knee orthosis or knee-ankle-foot orthosis.

There is also some evidence (n=2) that longer rearrangement periods lead to longer post-rearrangement periods. Fernández-Ruiz and Díaz (1999, exp. 3) had two groups wearing 30 diopter prism glasses. One group had a rearrangement period of 25 throws at a target and the second group had a rearrangement period of 50 throws at a target. Although the after-effect upon removal of the prism glasses was similar in both groups, the post-rearrangement period required was longer for the group which had experienced a longer rearrangement period. Similarly, Bingham and Mon-Williams (2013) asked participants to reach and grasp a virtual target over 14-blocks or 24-blocks of distorted feedback. After removal of the (distorted) haptic feedback, the 24-block group continued to show distorted reaches for another 6 blocks whereas the 14-block group immediately started reaching closer to the actual (undistorted) target.

There is contradictory evidence regarding the effect of the rearrangement period on the after-effect upon removal. While Fernández-Ruiz and Díaz (1999, exp. 3) used different rearrangement periods but found similar after-effects, Durgin et al. (2005, exp. 3, 6) also used different rearrangement periods but found different after-effects. Durgin et al. (2005, exp. 6) found that after 20 s of blind treadmill walking participants overshot a target during blind-walking by 12 %, and with an additional 40 s, 60 s, 80 s, and 100 s this increased to 18 %, 17 %, 22 %, and 21 % (Durgin et al., 2005, exp. 6). In another experiment, they found that the forward drift after-effect of blind running-in-place was significantly larger after two minutes blind treadmill running than after one minute blind-treadmill running (Durgin et al., 2005, exp.2)

Table 2.3 Quality of the rearrangement period. Experiments 1-7 showed rearrangement after a small number of trials with active exploration, experiments 8-12 showed rearrangement after a fixed amount of trials with active exploration, experiments 13-17 showed incomplete recalibration using active exploration due to restricted availability of information, experiments 18-21 showed incomplete recalibration using active exploration due to a lack of experience, and experiments 22-30 restricted exploration.

No.	Author (year)	Participants	Task	Disturbance to baseline calibration	Activity and duration of rearrangement period	Amount of trials needed for recalibration
1	Bingham and Romack (1999)	5 total, 2 female and 3 male (18-28 yrs)	Participants reached from launch platform next to the participant to place a stylus in a target hole in the front (varied: continued until participant reached the criterion within a max. of 4 blocks)	10-degree displacement prism glasses	Reaching to place a stylus in a target hole in the front with alternating clear goggles and 10-degree displacement goggles	The number of trials per block decreased over 3 days: 10.2 trials on day 1, 5.2 on day 2, and 5.6 on day 3. The rate of decrease was the same each day (.30 trials per block)
2	Bruggeman, et al. (2005 - exp.4)	12 right-handed undergraduate students (20 ± 4 yr.)	Participants made underhand throws to targets (12 blocks of 5 throws)	Throws on a rotating beam to hit the target on the other end of the beam	Made underhand throws for 60 throws	75 % of the beanbags landed on the platform within 10 throws
3	Mark (1987, exp.2)	12 female undergraduate students	Participants judged their maximum climbable riser height or maximum seat height (6 blocks of height-judgments)	10-cm high blocks underneath their feet	Walked around after each block of judgment series	6 judgement trials

4	Mark et al. (1990, exp.1)	12 total, 6 female and 6 male undergraduate students	Participants judged their maximum sitting height (12 blocks of height-judgments)	10-cm high blocks underneath their feet	Walked around after each block of judgment series	6 judgement trials
5	Saunders and Durgin (2011)	12 undergraduate students	Participants walked to a visible target on the ground (20 trials)	Participants were shown environments that either provided target-motion or ground-flow motion with a 10 degrees offset	Walked to a target for 20 trials	Within 10 trials mean heading errors decreased
6	Scott and Gray 2010, exp.1)	30 total, 19 male and 11 female (23.4 ± 0.8 yr.)	Participants swung a baseball bat at a simulated approaching baseball	Lighter or heavier bat weight	Made baseball swings for 2 training blocks of 15 trials	The lighter group within 5 pitches; Heavier group within 10 pitches
7	Scott and Gray 2010, exp.2)	20 total, 14 male and 6 female (24.1 ± 0.6 yr.)	Participants swung a baseball bat at a simulated approaching baseball	Heavier bat weight	Made baseball swings for 2 training blocks of 15 trials	Within 15 pitches
8	Fortis et al. (2013)	48 total - young group: 24 total (24 ± 2.67 yrs), old group: 24 total (68 ± 5.74 yrs)	Participants made pointing movements to a target	Prisms displacing the visual field 10 degrees horizontally to the right	Pointing movements to a target	90 pointing movements

9	Franchak and Adolph (2014, exp.3)	12 total (18 - 22 yr., M=20.6 yr.)	Participants made judgements whether they would fit through doorways (30 judgements)	Wearing a pregnancy pack	Walked through apertures for 20 walking trials	20 practice trials
10	Hackney et al. (2014)	22 total, 13 women and 9 men (22.8 ± 1.5 yr.)	Participants walked at a natural pace toward the goal and avoided colliding with the two obstacles (4 tray size blocks: 3 trials × 4 apertures widths)	No-tray (always first block) vs tray (1.2-, 1.4- and 1.6-times shoulder-width)	Walked while avoiding obstacles for 36 judgements	3 blocks of 12 trials
11	Richter et al. (2002)	14 total - experimental group (7 male: (25 ± 2.3 yr.) and control group (7 male: 27 ± 4.9 yr.)	Participants threw arrows at a dartboard or ambulated forward or sideways through a narrow obstacle course	Binocular prism glasses inverted visual field (180 degrees)	Played darts, or ambulated forward, or sideways through an obstacle course for 7 days	All tasks improved over the 7 days
12	van Hedel and Dietz (2004)	18 young volunteers	Participants walked on a treadmill, with reduced vision and auditory feedback, and stepped over a randomly approaching obstacle	An AFO (ankle-foot), KO (knee) or KAFO (ankle and knee) orthosis attached to their left leg	Walked on a treadmill for 50 steps	AFO within 50 trials, but KO and KAFO need a longer rearrangement for similar recalibration

13	Bingham and Pagano (1998 - exp.1)	4 total, 1 female and 3 male (29-39 yrs)	Participants reached from launch platform next to the participant to place a stylus in a target hole	A verbal judgement, headcam reach, static-camera reach, headcam-ballistic reach, restricted-field monocular reach or monocular reach	Reaching to place a stylus in a target hole (25 trials each)	Moving headcam, headcam-ballistic: no ability for recalibration. Some participants slightly recalibrated in restricted-field viewing.
14	Bingham and Pagano (1998 - exp.2)	8 total, 3 female and 5 male (18-39 yrs)	Participants reached from launch platform next to the participant to place a stylus in a target hole	A restricted field or monocular viewing	Reaching to place a stylus in a target hole (25 trials each)	The restricted-field viewing: recalibration using feedback from reaching. Monocular: no recalibration.
15	Bingham and Pagano (1998 - exp.3)	2 total	Participants reached to place a stylus under a target surface to align the stylus	Headcam or monocular viewing	Reaching to align a stylus in a target surface (25 trials each)	Headcam and monocular viewing: no recalibration
16	Bingham and Pagano (1998 - exp.4)	4 total, 2 female and 2 male (18-21 yrs)	Participants reached from launch platform next to the participant to place a stylus in a target hole	Monocular or binocular viewing	Reaching to place a stylus in a target hole (25 trials each)	Binocular: more accurate than monocular viewing (no recalibration)
17	Bingham (2005)	22 total, 8 female and 14 men, 19-30 yrs. 9 monocular, 6 binocular and 7 dynamic binocular group	Participants reached to touch the front, back and sides of a virtual target with a hand-held stylus	Monocular viewing restriction and dynamic conditions (participant first moved head and torso while counter-rotating the head)	Participants reached to touch a virtual target (5 blocks of 20 trials)	The performance was better when using binocular vision

18	Yasuda et al. (2014, exp.1)	49 total, 27 female and 22 male (23.6 ± 5 yr.)	Participants reported whether apertures of various widths were passable (6 trials)	Holding a 69-cm horizontal bar (not allowed to turn shoulders)	Walked through apertures holding a horizontal bar for 21 trials	21 practice trials
19	Higuchi et al. (2004, exp.1)	12 male college students (23 ± 4.2 yr.)	Participants estimated whether they could pass through the aperture without rotating shoulders and touching it.	Sitting in a wheelchair (free to move the head, body and arms but had to remain seated)	Rolled their wheelchair through apertures for 20-28 rearrangement trials	No differences pre- and post-practice
20	Higuchi et al. (2004, exp.2)	8 male college students (23.6 ± 3.7 yr.)	Participants estimated whether they could pass through the aperture without rotating shoulders and touching it	Sitting in a wheelchair - free to move the head, body and arms but had to remain seated.	Rolled their wheelchair through apertures. They performed 3 blocks of 5 trials with different widths for 8-days within 4 weeks.	A slight improvement over the practice sessions, but the perceptual boundary was still less than 1.0 in the 8th-day session
21	Yasuda et al. (2014, exp.2)	37 total, 19 female and 18 male (22.8 ± 5.9 years)	Participants reported whether apertures of various widths were passable	Sitting in a wheelchair	Rolled their wheelchair through apertures for 21 trials	No improvement of the perception of passibility after the practice
22	Mark (1987, exp.3)	8 female undergraduate students	Participants judged their maximum climbable riser height or maximum seat height	10-cm high blocks underneath their feet (body sway only)	Usage of body sway for 12 judgement trials	9 judgement trials

23	Mark et al. (1990, exp.2)	12 total, 6 female and 6 male undergraduate students	Participants judged their maximum seat height	10-cm high blocks underneath their feet (body sway only)	Usage of body sway for 12 judgement trials	12 judgement trials
24	Mark et al. (1990, exp.3)	12 total, 6 female and 6 male undergraduate students	Participants judged their maximum seat height	10-cm high blocks underneath their feet (while looking through a monocular peephole)	Usage of limited body sway for 12 judgement trials	No recalibration
25	Mark et al. (1990, exp.4)	12 total, 6 female and 6 male undergraduate students	Participants judged their maximum seat height	10-cm high blocks underneath their feet (in an awkward stance position)	Usage of limited body sway for 12 judgement trials	No recalibration
26	Mark et al. (1990, exp.5)	12 total, 6 female and 6 male undergraduate students	Participants judged their maximum seat height	10-cm high blocks underneath their feet (without body sway)	Made judgements for 12 trials	No recalibration (only a few observers improved their judgements)
27	Mark et al. (1990, exp.6)	24 total, 12 female and 12 male undergraduate students	Participants judged their maximum seat height	10-cm high blocks underneath their feet (restriction as in experiments normal stance or peephole condition)	Practised sitting on the apparatus 2-3x before the perceptual task for 12 judgement trials	No recalibration

28	Stoffregen et al. (2005, exp.1)	12 undergraduate students, 5 men and 7 women (18 - 35 years)	Participants made judgments of their maximum seat height	10-cm high blocks underneath their feet (body sway only)	Usage of body sway for 12 judgement trials	12 judgement trials
29	Yu & Stoffregen (2012)	48 total, 20 men and 28 women (18 - 52 years)	Participants judged the lowest lintel under which they could roll in the wheelchair	Sitting in a wheelchair (active or passive movement & unrestrained or restrained head movement).	Rolled a wheelchair up and down a 25 m hallway for 2 minutes	The accuracy of the judgments improved only for actively controlled wheelchair locomotion (head restrained or non-restrained)
30	Yu et al. (2011)	48 total, 18 men and 30 women (18-32 years)	Participants judged the lowest lintel under which they could roll in the wheelchair	Sitting in a wheelchair (with restrained or unrestrained head movement during practice and/or judgments)	Rolled a wheelchair up and down a 25 m hallway for 2 minutes	Judgments were more accurate when the head movement was unrestrained rather than restrained

2.3.6 Transfer of recalibration

In total, 12 experiments studied whether the transfer of recalibration is functional, anatomical or both. In their experiment, Bingham, Pan, and Mon-Williams (2014, exp. 2) showed an example of *anatomical* or limb-specific recalibration. The results showed that after 26 feedback blocks of reaching and grasping to a distorted virtual target simultaneously for both hands, the left hand overreached the target compared to the right hand after the feedback was removed. This indicated that although the arms must be recalibrated relative to one another in the context of action, the anatomical properties of the individual limbs also contribute to the recalibration of the action.

The remaining 11 experiments showed that the recalibration of action transferred to actions with a similar *functional* goal (Durgin et al., 2005; Kunz et al., 2013; Rieser et al., 1995; Withagen & Michaels, 2002). For example, Withagen and Michaels (2002) found that walking transferred to crawling, which also has the functional goal of locomotion. After walking on a treadmill for 15 minutes in a virtual environment, they found a similar effect of recalibration for both walking and crawling. Since the effect of recalibration was similar for both actions, this indicated a transfer of the recalibration completed for walking into the new task of crawling. Similarly, a significant transfer from treadmill walking to side-stepping was found after treadmill walking with a visual disturbance (Rieser et al., 1995, exp. 8). Bingham, Pan, & Mon-Williams (2014, exp.1) found that recalibration transfers between limbs (e.g., from right to the left hand) as limbs are functionally specific to the action. The results showed that the distorted feedback transferred from the right to the left hand.

Interestingly, of the 11 experiments that studied functional transfer, the 3 experiments mentioned above found a stronger transfer effect while the remaining 8 found a weaker effect of the transfer. When analysing these in more detail, it seems that the skilfulness of participants in a given task may have been an important factor in the transfer of recalibration. Actions that had similar functional goals, but where participants seemed less skilled, found a no transfer or a weak transfer of recalibration (n=8, Durgin et al., 2005; Kunz et al., 2013; Morton & Bastian, 2004; Rieser et al., 1995). For example, Kunz et al. (2013, exp. 3, 4) found a weak transfer from walking to blind wheel-chairing after participants walked through a virtual hallway for 5-7 minutes (participants were not regular wheelchair users). They also found no transfer of recalibration of wheelchair locomotion to blind-walking after participants wheel-

chaired through a virtual hallway. Results also showed that a weak transfer of recalibration from forward walking to sidestepping when the after-effect was measured (Durgin et al., 2005, exp. 5). In addition, Rieser et al. (1995, exp. 9) found that recalibration of turning in place did not transfer to forward walking and vice-versa (Rieser et al., 1995, exp. 10). These experiments used actions that are not commonly practised and are probably less skilled. It could indicate that a transfer is not possible where skills are not already well-calibrated (i.e., skilful actions imply appropriate calibration).

2.4 Discussion

The aim of this systematic review was to analyse how recalibration can and has been measured and also to evaluate the literature on recalibration. In summary, our results showed that participants recalibrated to disturbances in both perception and action in similar ways. Active exploration was sufficient for fast recalibration only when the relevant information source was available, and the skill had been well-learned. When information was restricted, this resulted in slower or incomplete recalibration. This is in contrast with Van Andel et al. (2017), who concluded that when the movement itself is explored [re]calibration occurs rapidly. Using a broader article selection, we showed that 1) it is not the movement but instead the perceptual information which needs to be explored in order for recalibration to occur; and 2) recalibration time seems to depend on the magnitude of the disturbance effect and skill rather than simply on exploration.

It is critical that the informational variables that guide a particular action or judgement remain available throughout exploration. For example, sitting quietly after rearrangement does not elicit post-rearrangement (Bruggeman et al., 2005, exp. 4) and informational restriction during rearrangement results in slower or incomplete recalibration (Mark et al. 1990, exp. 3, 4, 5). During recalibration, the perceptual-motor system, which is linked via relevant informational variables, is required to rescale to disturbances in the perceptual or the motor system (Withagen & Michaels, 2004, 2007). This is also shown in Henriques and Cressman's (2012) review, who found that both active or passive exploration resulted in recalibration of hand proprioception (i.e., reaching their hand along a channel versus having the hand passively moved). Importantly, it is often the case that relevant information is made available through action; hence, the broadly accepted conclusion that active exploration is required.

Future studies should look closer into active exploration for recalibration. Specifically, they should investigate the availability of information (cf., Bingham & Pagano, 1998) and the duration of exploration. Firstly, the availability of information is important to directly test which informational variables are relied upon during recalibration. This line of research would be best informed by ecological psychology, given its strong tradition in attempting to uncover information sources that guide perceptual-motor actions. Secondly, the duration of exploration is important to understand how much active exploration is needed for recalibration and whether this duration is indeed dependent on the skill level and use of appropriate information.

Incomplete recalibration using active exploration was found when the task was not well-learned and calibrated. Participants, who were new to wheelchairs made judgements about the person-plus-wheelchair passibility through apertures (Higuchi et al., 2004; Withagen & Michaels, 2007; Yasuda et al., 2014). The novelty of the wheelchair task might be the reason why participants did not show complete rearrangement over the trials, even if participants were supposedly attuned to (walking) passibility through apertures. A longer period of rearrangement over eight days was more effective in reducing participants' underestimations after wheelchair-use for four separate days (Higuchi et al., 2004, exp. 2). Results of these experiments indicate that the participants were probably not attuned and calibrated to wheelchair locomotion at the start of the experiment. This is in accordance with results showing that American Football players were better than Rugby players at running through apertures while wearing shoulder pads (Higuchi et al., 2011). Although both groups had extensive experience in judging passibility through apertures, only the American Football players were already calibrated to locomotion wearing shoulder pads. Future studies should ensure that the task is well-learned and calibrated before applying disturbances; in practice, this means that studies should always take a baseline measure to ascertain calibration before applying a disturbance.

Results suggest that recalibration is an iterative process, whereby each time the perception-action coupling is used; it updates the informational link between perception and action. There is some evidence to argue that larger disturbances result in longer rearrangement periods (Fernández-Ruiz & Díaz, 1999; Van Hedel & Dietz, 2004). In other words, when the disturbance causes a greater or more obvious error, the rearrangement is slower. For smaller disturbances, a couple of trials are sufficient to re-scale the perception-action coupling, while for larger disturbances multiple trials are

needed. In addition, Bingham and Romack (1999) found that as participants went through multiple disturbances-rearrangement-removal over several days, the amount of error at disturbance gradually decreased. This would indicate that expert athletes, for example, who may have experienced disturbances more often, will take fewer attempts before they are fully recalibrated. More research is necessary to confirm these effects, so research strategies should be carefully employed to tease apart the different stages of recalibration.

This review showed that recalibration is studied using either direct or indirect measures of recalibration and that these measures have been constraining which type of disturbance is used. Direct measures have been used to study both disturbances in perception and action, whereas indirect measures have mainly been used to study disturbances in perception. When analysing the differences between the tasks and the disturbances used in each of these experiments, it was noted that certain disturbances allowed for direct measures while others allowed only for indirect measures of recalibration. On the one hand, experiments using direct measures of recalibration applied a disturbance and measured its direct effect. For example, attaching blocks underneath the feet disturbed action (i.e., error) and allowed for continuous data collection in the rearrangement period to show recalibration (i.e., error reduction). On the other hand, experiments using indirect measures of recalibration applied a disturbance that only shows the effects of rearrangement after its removal. For example, when manipulating optic flow using virtual reality, the effects of the optic flow disturbance is only observable upon removal of the optic flow disturbance. These types of disturbances only allow for data collection before and after but not during rearrangement. Since direct measures of recalibration provide a full overview of the recalibration process, future studies are advised to use direct measures with either perception or action disturbances to inform on the trial-by-trial rearrangement process.

The ecological approach was mentioned in the majority of studies reviewed, and therefore, it is appropriate to discuss how the results relate to this approach both in terms of methods used and results found. In terms of results, some of the studies lend support to the ecological approach to visual perception. For example, the most effective way to recalibrate is through active exploration of the perceptual information, as only a few trials of rearrangement were sufficient for (fast) recalibration (Bingham & Romack, 1999; Bruggeman et al., 2005; Mark, 1987; Mark et al., 1990; Saunders & Durgin, 2011; Scott & Gray, 2010). Also, according to the ecological definition of

recalibration, actors need to be attuned and well-calibrated (to the appropriate information source) before recalibration can take place. Our results showed that the skilfulness of participants in a given task might be an important factor in both recalibration and its functional transfer (Durgin et al., 2005; Kunz et al., 2013; Morton & Bastian, 2004; Rieser et al., 1995).

In terms of methods, studies using direct measures that capture the trial-by-trial rearrangement period were more informative than those using indirect measures where recalibration was inferred from two discreet moments in time. The emphasis on trial-by-trial changes is in the tradition of the ecological approach as it would not expect the rescaling of perception and action to be accomplished in one error-comparison and error-correction attempt (cf., Desmurget & Grafton, 2000; Henriques & Cressman, 2012). Another methodological point worth mentioning was the use of verbal judgements versus actions as measures of recalibration. An ecological approach would argue against conscious analytical responses because they are far removed from the perceptual-motor task and might 'recalibrate' very differently (Heft, 1993; Pagano & Isenhower, 2008). This was what Pagano and Bingham (1998) found when using a very analytical judgement task (i.e., the judgement was done in units of arm length). The remaining 22 articles in this review, which also used judgements, asked participants about reachability or passibility. This type of judgement is much closer to the perceptual-motor task and hence closer to units of action. Perhaps, for this reason, our results did not show a pattern of poorer results in judgement studies.

Also consistent with the ecological approach, Bingham and Pagano (1998) state that recalibration is an intrinsic component of perception-action that generates accurately targeted actions. Several of Bingham's studies suggest that *what* is recalibrated is the mapping between intrinsic units of perception and intrinsic units of action (Bingham et al., 2014; Coats et al., 2014; J. S. Pan, Coats, & Bingham, 2014). These studies found that the recalibration of actions was guided by different informational variables. For example, Coats et al. (2014, exp.3) showed that matching target distance was still accurate after participants' eye-height (EH) was disturbed. The recalibration of matching target distance used inter-pupillary distance (IPD) as an informational variable instead of EH, because the undistorted IPD was considered a more stable informational variable. The concern with uncovering information sources which guide perception-action as well as its recalibration is a central tenet of the ecological approach.

2.4.1 Conclusions

Overall, we conclude that active exploration is only sufficient for fast recalibration when the relevant information source is available. Very few trials are sufficient to fully recalibrate provided perceptual information is unrestricted. Recalibration is similar after disturbances to both perception and action. Research lines worth pursuing when studying the mechanisms of recalibration include the study of information sources and skill expertise.

2.4.2 Relevance for the following chapters

Chapter 2 showed that while young adults only needed 5-12 rearrangement trials for (fast) recalibration, no research had yet focussed on recalibration in older adults. Therefore, the aim of this thesis is to explore age-related differences in recalibration to action disturbances. Chapter 2 also showed that only a limited amount of studies had measured and reported on recalibration throughout the rearrangement period, and as a result, little is known about recalibration duration. Following these results, all experimental studies will apply direct measures and use a trial-by-trial recording and analysis of the rearrangement process. Next, Chapter 3 will explain the methodology used to measure and analyse recalibration in the current thesis.

Chapter 3
General methods

Mrs Poorthuis enjoys cooking and is particularly keen on following the detailed methods described in her cooking books. Likewise, this chapter will provide a detailed overview of the methodology used to measure and analyse recalibration in the following experimental chapters. The chapter starts outlining general participant information and will then provide an operational definition of recalibration by describing the disturbance used in the experimental chapters. Subsequently, we describe an innovative methodology that we use for the first time to identify the point of recalibration. Finally, we give an overview of the biomechanical methods used in Chapters 5 and 6.

3.1 Participants' characteristics

All studies included male and female healthy adults, aged 18-45 years (young adult group) and over 65 years old (older adult group; World Health Organization, 2010). Sample size calculations for individual chapters will be discussed later. Before the start of each study, participants completed a health questionnaire. Participants with orthopaedic, neuromuscular, cardiovascular diseases or balance impairments were excluded from the studies. Participants had to have a self-reported normal or corrected-to-normal vision. Furthermore, older adults were asked to perform the 'Timed Up and Go' test to determine their fall risk (Podsiadlo & Richardson, 1991; Shumway-Cook, 2000).

<u>Timed-Up and Go test</u>

The 'Timed Up and Go' (TUG) test is a simple, quick and commonly used clinical tool for assessing lower extremity function, dynamic mobility, and fall risk. Research has shown that the TUG can identify otherwise healthy older adults who are prone to falls, as it correctly classified 13/15 fallers (87% sensitivity) and 13/15 non-fallers (87% specificity; Shumway-Cook, 2000). The TUG test is a fairly simple and quick test to conduct. The participant starts the test in a seated position on a standard chair (seat height between 44 and 47 cm) and is then asked to stand up on command, walk 3 meters

at a comfortable pace, turn around, walk back to the chair and sit down. The chronometer time starts on command and stops when the participant is seated again in the chair. A shorter time on the TUG is considered as better performance. In general, it has been suggested that 13.5 seconds is the optimal threshold for identifying participants with an increased risk of falling (Lundebjerg, 2001; Shumway-Cook, 2000). Subsequently, older adults were included in our studies if they were able to complete the TUG within 13.5 seconds.

3.2 The operational definition of recalibration

As the literature review described in more depth, recalibration happens after a *disturbance* in either perception or action renders the perception-action coupling inaccurate, thereby initiating the rescaling of that link (*rearrangement*, see Chapter 2). In the following section, we will first explain the disturbance that has been used, followed by the methodology used to capture the rearrangement period.

3.2.1 Disturbance

Previous studies have used different strategies have been used to provoke disturbances to participants' actions, such as blocks fitted under shoes, holding trays, seated in wheelchairs, and weighted baseball bats (see Chapter 2). In Chapters 4, 5, and 6, ankle weights were used as a disturbance to the participants' action capabilities. The weights consisted of larger sets of ankle weights of 1 or 2 kg along with a smaller empty ankle weight holder which was adjusted up to 100 grams accuracy (using fishing leads; see figure 3.1). Next, we will justify the usage of ankle weights as a disturbance and explain how weights were scaled for individual participants.

Figure 3.1 An example of a mass of 3.7 kg fitted around the participant's ankle. Seven fishing leads of 100 grams were embedded into smaller ankle weight holder and together with larger ankle weights of 1 and 2 kg fitted around the ankle.

Ankle weights as a disturbance

Ankle weights have often been used to disturb participant's action capabilities (Byrne et al., 2002; Mukherjee, Siu, Katsavelis, Fayad, & Stergiou, 2011; Nessler, Gutierrez, Werner, & Punsalan, 2015; Ramenzoni, Riley, Shockley, & Davis, 2008; Smith & Martin, 2007). For example, Ramenzoni et al. (2008) used ankle weights to reduce participants' jumping capability. The weights were approximately 5% of the participant's body mass and reduced their jumping ability on average by 6 cm. Ankle weights were between 0.91 and 3.63 kg and were adjustable up to 10-gram accuracy by adding or removing the mass. Similarly, Smith and Martin (2007) fitted an ankle weight of 1.95 kilograms around one of the participants' lower legs during the adaptation part of their experiment. They found an increase in swing time and a reduced stance time for the loaded limb when participants walked on the treadmill with the ankle weight. The studies outlined above used only young and healthy participants and fitted weights that were either a fixed mass or a percentage of their body mass. As the experimental studies in this thesis included both young and older adults, we aimed to scale the ankle weights to a more specific variable that entailed the age-related differences in action capabilities for stepping tasks.

Scaling to knee extensor muscle strength

In stair climbing, it is important that enough force is generated to pull the leading foot onto the first stair. This force is mainly generated by the quadriceps in the supporting leg to overcome the gravitational forces and is accompanied by active hip flexion in the swing leg (Konczak et al., 1992). Knee extensor muscle strength is, therefore, critical during the pull-up phase. Research has shown that knee extensor muscle strength is a strong predictor of the performance in both stair ascent and descent, explaining more than 1/3 of the variance in the overall performance (Ploutz-Snyder, Manini, Ploutz-Snyder, & Wolf, 2002; Salem, Wang, Young, Marion, & Greendale, 2000; Tiedemann, Sherrington, & Lord, 2007). Differences in ascending stairs between young and older adults are characterised by changes in the contraction of the quadriceps femoris, hamstrings, soleus, and gluteus maximum during the support phase as shown in an electromyography (EMG) study (McFadyen & Winter, 1988; Watanabe, Kouzaki, & Moritani, 2017). These muscles are used to generate maximum torque around the knee joint, which is used to extend the supporting leg (e.g. Hortobágyi, Mizelle, Beam, & DeVita, 2003; McFadyen & Winter, 1988). Studies have also shown that the knee extensor muscles were active for a longer period than the flexor muscles during the stair ascent (Andriacchi, Andersson, Fermier, Stern, & Galante, 1980; McFadyen & Winter, 1988). Since reduced lower-limb muscle strength is considered one of the main factors causing age-related differences in stair climbing, the disturbance was scaled to the participant's knee extensor muscle strength.

Measuring knee extensor muscle strength

Three maximum isometric voluntary contractions (MVC) were performed for each leg on an isokinetic dynamometer chair system (Kin-Com, Chattanoga Group, Inc., TN, USA) to measure knee extensor muscle strength. Participants were asked to sit in the chair of with their hip and knee joints fixed at a 90° angle (Araki et al., 2016; Christou, Yang, & Rosengren, 2003; Larsson, Grimby, & Karlsson, 1978; Mebes et al., 2008). Participants were secured in the chair using straps diagonal across their chest and another strap over their thigh. The straps were secured to ensure stability and prevent movement. The shin pad of the dynamometer was adjusted for leg length, and the lower edge of the pad was 2 cm proximal of the malleoli and secured with a strap around the lower leg. Each participant was instructed to perform an MVC during knee extension for 3 s (Mebes et al., 2008; Ploutz-Snyder et al., 2002; Tracy & Enoka, 2006) with one-

minute rest in between each of the MVCs in which participants were free to move their leg (Christou et al., 2003; De Salles et al., 2009; Hooten, Rosenberg, Eldrige, & Qu, 2013; Nordin, Nyberg, & Sandberg, 2019; Nunn & Mayhew, 2013). Individual knee extensor muscle strength was measured as the peak knee extensor muscle strength per leg in Newtons.

Pilot study

A pilot study was conducted to determine the magnitude of the disturbance needed to effectively disturb the participants' maximum action capabilities or action boundaries. Eight participants (30.6 ± 6.21 years) participated in this pilot study that examined how heavy the weights needed to be to significantly reduce participants' action boundaries in a stepping task. First, participants were asked to step onto a platform to measure the maximum platform height participants could step on without support. After measuring their maximum stepping height without weights, participants were fitted with 1 kg ankle weights and asked to step onto the same platform again. The mass of the weights was gradually increased with 1 kg increments until the point where participants were not able to step on the same platform anymore (i.e. their action boundaries were effectively reduced). From this data, the ratio between the mass of the weights and the corresponding leg strength for each participant was calculated. Results showed that participants' average leg strength was 499 ± 123N and that a mass of approximately 2.00 ± 0.756 kg was sufficient to lower their action boundaries. The corresponding ratio to calculate for the mass of the ankle weight was 4.27 ± 0.899% of the participant's leg strength (Newton converted to kg). These results indicated that a mass that was 5% of knee extensor muscle strength was heavy enough to prevent participants to reduce their maximum stepping height. Ankle weights of 5% of knee extensor muscle strength were equal to a mass of 2.5 kg per leg for young adults (average leg strength 500N) and a mass of 1.2 kg for older adults (average knee extensor muscle strength 240N).

From these results, we determined the heaviness of the ankle weights for Chapter 4, 5, and 6. In Chapter 4, participants judged whether or not they were able to step onto a platform and were essentially judging their action boundaries in a stepping task. Therefore, the mass of the ankle weights was set at 10% of the participant's leg strength (very heavy weights) to ensure participants' maximum stepping height was significantly lowered. For Chapters 5 and 6, participants' actions were disturbed as they climbed a small set of stairs or crossed an obstacle. Both Chapters 5 and 6 used heavy

ankle weights, which were set at 5% of the participant's knee extensor muscle strength. For Chapter 5, the medium and light weight conditions were calculated from the heavy weight and were set at 2.5% and 1% of the participant's knee extensor muscle strength.

3.2.2 Analysis of the rearrangement period

In the next section, we will describe how the rearrangement period was analysed in Chapters 5 and 6. In addition, we will explain the innovative methodology using piecewise regressions, which allowed for automatic identification of the point of recalibration.

Several studies have used a regression analysis in various forms to analyse recalibration (Bingham, 2005; Mark, 1987; Mark et al., 1990; Mon-Williams & Bingham, 2007; Stoffregen, Yang, Giveans, Flanagan, & Bardy, 2009; Wagman & Abney, 2012; Withagen & Michaels, 2007; Yu & Stoffregen, 2012). Generally, these studies used the slopes and intercepts of regressions to inform on the scaling and offset of recalibration error. For example, Bingham's studies used linear regressions to analyse the effect of distorted feedback on reaching distance (Bingham, 2005; Mon-Williams & Bingham, 2007). They plotted reached distances against actual target distances and analysed the resulting regression slopes. Results showed that, without feedback, the level of performance in the binocular condition (slope of 0.86, the intercept of 0.11) was better than the monocular condition (slope of 0.65 and intercept of 0.30; Bingham, 2005). In addition, other studies used the slopes of regressions to indicate recalibration over blocks or trials (Mark, 1987; Mark et al., 1990; Yu & Stoffregen, 2012). In these studies, for recalibration to be visible, slopes in the experimental condition would have to be significantly different from zero and lead to a reduced judgement error. In comparison, regression slopes in the control condition would have to be close to zero (Mark, 1987; Mark et al., 1990; Yu & Stoffregen, 2012).

When reviewing the recalibration literature, we found that the process of recalibration is visible over time and that the perceptual-motor rearrangement period can be divided into two parts. The rearrangement period generally consists of an initial rearrangement immediately after a disturbance, followed by a final rearrangement period when recalibration is complete. The two parts of rearrangement can be seen as two separate linear regressions. In other words, the initial rearrangement is characterised by a steep slope, and the final rearrangement is characterised by a slope close to zero. This also denoted that the point where participants have recalibrated was

generally visible in the data as the point where the initial rearrangement levelled off into the final rearrangement. In this thesis, we used an innovative methodology using piecewise regressions to derive this point of recalibration from the data (see Chapters 5 and 6).

Point of recalibration

The point of recalibration was determined using Matlab 2016b and by using a piecewise regression (The MathWorks, Natick, MA, USA). The regression analysis breaks the independent variable, such as trials, into intervals and fits a separate linear regression to each interval. The linear regressions are separated by a breakpoint, which is generally used to quantify an 'abrupt' change in a signal or response function. The breakpoint is calculated using the least squares method, which is applied separately to each of the two segments. The two regression lines are made to fit the data set as closely as possible while minimising the sum of squares of the differences (SSD). The breakpoint is varied until it ensures that the sum of the residual (squared) error of each segment is as small as possible. So, if x is a variable with *N* number of elements, then the breakpoint partitions x into two parts, x (1: breakpoint - 1) and x (breakpoint: N). In our case, the piecewise regression portions the data of a specific kinematic variable measured over a number of trials into two separate linear regressions (see figure 3.2). The breakpoint, also known as *the point of recalibration*, is the point where the initial rearrangement is split from the final rearrangement and classified as the point when recalibration is completed. The point of recalibration is calculated separately for each disturbance/group condition for each kinematic variable in Chapters 5 and 6. When recalibration was not visible, the piecewise regression returned similarly sloped regressions and/or unreasonable breakpoints.

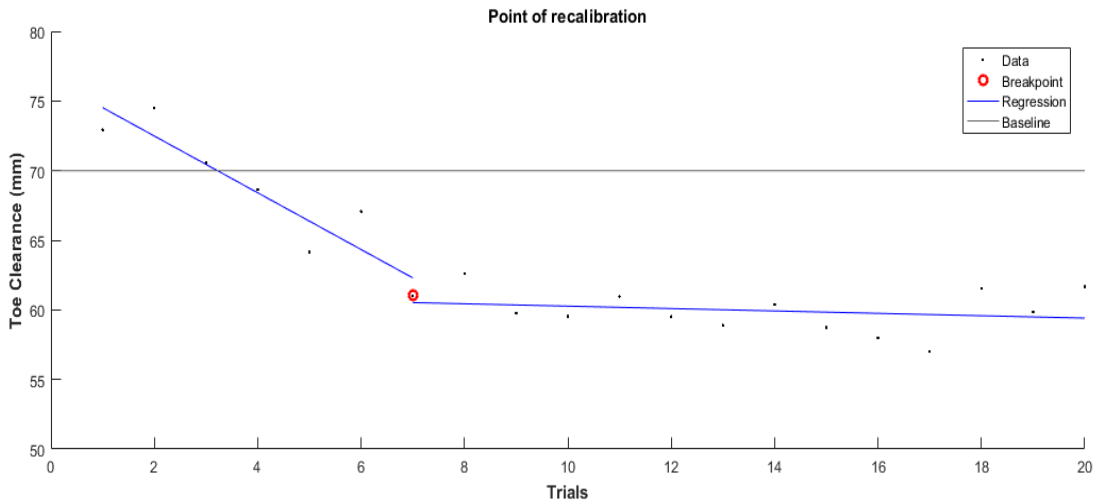


Figure 3.2 An example of the piecewise regression and identification of the breakpoint for toe clearance. The black dots represent the data of the average toe clearance over 20 trials. The piecewise regression portioned the toe clearance data into two separate linear regressions while minimising SSD. The breakpoint is the point where the two linear regressions are split and classified as the point when recalibration is completed. The point of recalibration, or breakpoint, is the red circle around trial 7. The two blue lines are the two regression curves that represent the slopes of the initial and final rearrangement.

3.3 Biomechanical methods

Here, we will discuss the biomechanical methods that were used in Chapter 5 and 6. We will discuss the marker set, the justification for the extraction of the action-specific kinematic variables, and the validity of the measures.

<u>Laboratory calibration</u>

The laboratory was calibrated using a 600 mm calibration wand and an L-shaped reference structure on the ground. The calibration wand had two markers attached at a fixed distance from each other. The reference structure had four markers attached to it and was used to define the global coordinate system. It was placed in the laboratory in such a way that the long arm of the L-shape represented the y-axis, and the short arm represented the x-axis. During the 60 sec calibration of the laboratory, the x, y, z positions of the calibration wand were tracked and compared to the x, y, z positions of the four markers on the reference structure. For each camera, residual calibration errors smaller than 1.00 mm were accepted.

3.3.1 Marker set

In general, studies on stair climbing have used lower-body marker sets to measure differences between young and older adults while climbing stairs (Alcock, O'Brien, & Vanicek, 2014; Alcock, Vanicek, & O'Brien, 2013; Begg & Sparrow, 2000; Benedetti, Berti, Maselli, Mariani, & Giannini, 2007). Most studies used either a lower-limb Helen Hayes (Davis III, Ounpuu, Tyburski, & Gage, 1991) or a six-degrees of freedom marker set (Cappozzo, Catani, Della Croce, & Leardini, 1995) to track the movements. The Helen Hayes marker set fits markers directly onto anatomical landmarks to model the participant's body. The six-degrees of freedom marker set uses a combination of anatomical and tracking markers to model the body. Its tracking markers are generally clustered in what is known as the calibrated anatomical systems technique (CAST; Cappozzo et al., 1995). The two techniques are comparable, but the CAST technique overcomes the biggest theoretical limitation of the Helen Hayes marker set: soft tissue artefact (Collins, Ghoussayni, Ewins, & Kent, 2009). There is less movement between the bone and the markers because the tracking markers are not mounted directly onto the joints. Instead, the CAST technique uses clusters of markers mounted on a rigid structure, which are attached to each segment to track movements. This means that the markers move relative to each other and not independent of each other. Therefore, in Chapters 5 and 6, a six-degrees of freedom lower-body marker set with a combination of anatomical and CAST cluster markers was used to track the participant's movements.

More specifically, the marker set as used in Chapters 5 and 6 was a lower-body marker set derived from the whole-body marker set as used by Jones, James, Thacker, and Green (2016, see figure 3.3). The marker set consisted of 7 segments: pelvis, thighs, shanks and feet. The anatomical coordinate systems for each body segment and joint centre locations were based on Ren et al. (2008) except the hip joint centre, which was based on the CODA pelvis (Bell, Brand, & Pedersen, 1989). A combination of static and tracking markers was used to model the lower-body in a static trial (Ren et al., 2008, see table 3.1). In the static trial, participants were asked to hold the anatomical position to take a 5-second capture of all markers. The static anatomical markers were then removed, and only the tracking markers were used for the subsequent dynamic movement trials (see table 3.1).

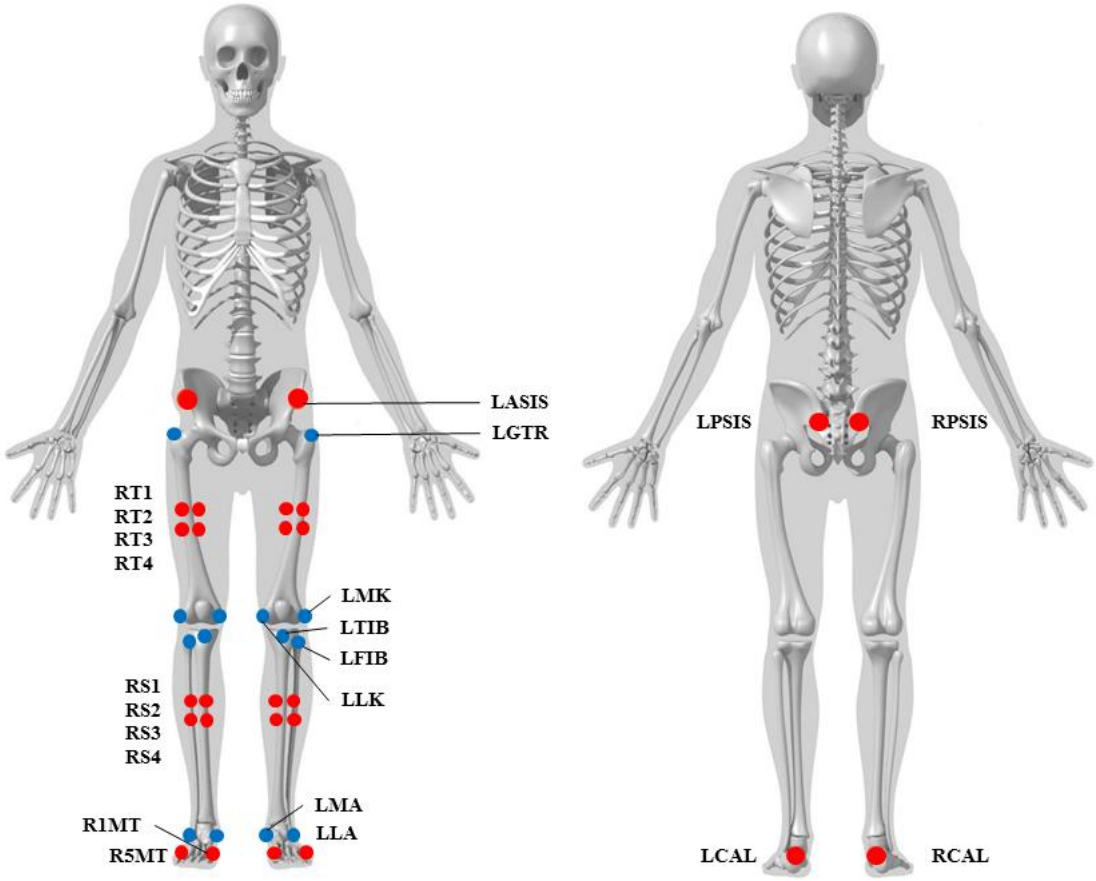


Figure 3.3 A schematic illustration of the lower-body marker set. The red dots indicate the tracking markers, and the blue dots indicate the static markers for lower-body modelling only. Figures were adapted from C-motion wiki.

Table 3.1 Specific information on the lower-body marker placement

Segment	Anatomical or cluster	Static	Tracking	Label	Landmark
Pelvis	A	X	X	ASIS	Anterior superior iliac spine
	A	X	X	PSIS	Posterior superior iliac spine
	A	X	-	GTR	Greater trochanter
Thigh	A	X	-	LK	Lateral femoral epicondyle
	A	X	-	MK	Medial femoral epicondyle
	C	X	X	T1	Thigh tracking marker 1
	C	X	X	T2	Thigh tracking marker 2
	C	X	X	T3	Thigh tracking marker 3
	C	X	X	T4	Thigh tracking marker 4
Shank	A	X	-	TIB	Tibia tuberosity
	A	X	-	FIB	Fibula head
	A	X	-	LA	Lateral malleolus
	A	X	-	MA	Medial malleolus
	C	X	X	S1	Shank tracking marker 1
	C	X	X	S2	Shank tracking marker 2
	C	X	X	S3	Shank tracking marker 3
	C	X	X	S4	Shank tracking marker 4
Feet	A	X	X	CAL	Upper ridge of calcaneus
	A	X	X	1MT	First metatarsal
	A	X	X	5MT	Fifth metatarsal
Total:		40	26		

Notes: All markers in the table were placed both on the left and the right side of the body. This means that the ASIS hip marker consisted of a LASIS and RASIS marker on respectively the left and right side of the body.

Table 3.2 Anatomical coordinate reference system definitions for the lower body

Segment	Origin	Axes X	Y	Z
Foot	The upper ridge of the calcaneus (CAL)	Oriented from the midpoint between 1MT and 5MT to CAL, pointing forward	Mutually perpendicular to both x- and z-axis, pointing upwards	Perpendicular to the x-axis in the plane defined by CAL, 1MT and 5MT, pointing right
Shank	The midpoint between medial and lateral malleolus (MA and LA)	Mutually perpendicular to both y- and z-axis, pointing forward	Coincides with the intersection between the plane defined by fibula head (FIB), MA and LA, and its perpendicular plane containing tibia tuberosity (TIB) and midpoint between MA and LA, pointing upwards	Perpendicular to y-axis defined by FIB, MA and LA, pointing right
Thigh	The midpoint between medial and lateral epicondyles (MK and LK)	Mutually perpendicular to both y- and z-axis, pointing forward	Oriented from the midpoint between LK and MK to hip joint centre, pointing upwards	Perpendicular to the y-axis in plane defines by LK, MK and hip joint centre, pointing right
Pelvis	The midpoint between the left and right anterior and posterior iliac spine (ASIS and PSIS)	Perpendicular to the z-axis in the plane defined by LASIS, RASIS and midpoint between LPSIS and RPSIS	Mutually perpendicular both x- and z-axis, pointing upwards	Oriented from LASIS to RASIS, pointing right

Deriving kinematic variables

The anatomical coordinate systems for each body segment and joint centre locations were based mainly on Ren et al. (2008) with adaptations to the CODA pelvis which was based on Bell et al., (1989, see table 3.2). The kinematic variables were derived using a distal anatomical frame of reference. Joint rotations were calculated using an X (sagittal), Y (frontal), and Z (transverse) Cardan rotation sequence. The kinematic parameters were sagittal plane joint rotations: ankle dorsiflexion and plantarflexion, knee flexion and extension, and hip flexion and extension. Positive rotations were ankle dorsiflexion, knee extension, and hip flexion.

3.3.2 Kinematic variables

One of the earliest studies divided stair climbing into a stance and swing phase, which consisted again of five phases (McFadyen & Winter, 1988). In the *stance phase*, three sub-phases were described: weight acceptance, pull-up, and forward continuance phase (see figure 3.4). The weight acceptance phase initiates with moving the weight from the middle to the front portion of the leading foot to prepare an optimal position for the body to be pulled up to the next step. The pull-up phase, when the person is climbing from step to the next, is from toe-off to mid-swing of the trailing leg. In the forward continuance phase, which starts mid-swing of the trailing leg, the person has fully ascended one step and continues forward to the next step. The *swing phase* had two sub-phases again, including a swing through of the leg (leg pull-through) and preparation for foot placement. Similar phases can be detected in obstacle crossing: first, a person steps over the obstacle with their leading foot, shifts their weight to that foot, and then swings their trailing foot over the obstacle.

We reviewed stair ascent literature to find kinematic variables that showed age-related differences when ascending stairs and crossing obstacles, and these variables were used to analyse recalibration in Chapters 5 and 6. Next, each of these kinematic variables are described and discussed in relation to climbing stairs and crossing obstacles. As some variables were used for both tasks, and thus, both experimental studies, we start explaining these variables first and subsequently move onto the variables that are specific to crossing obstacles.

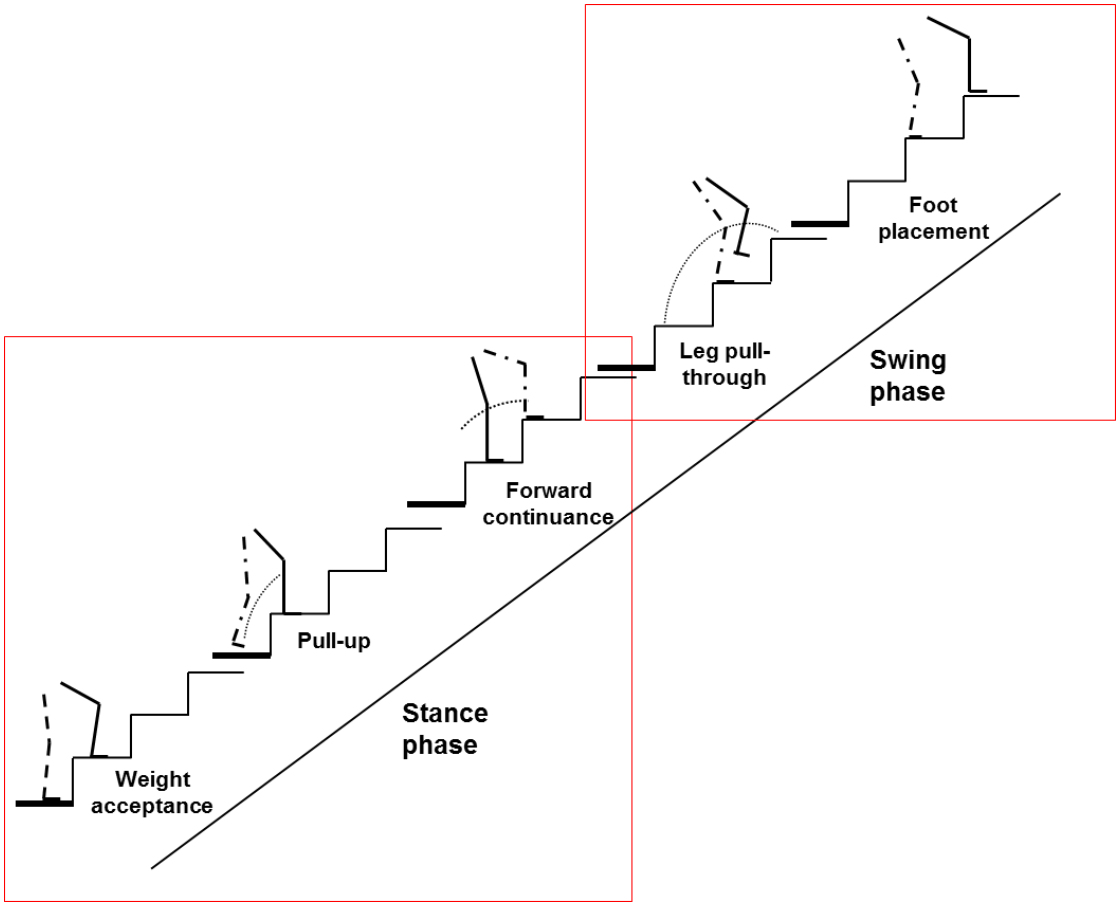


Figure 3.4 An illustration of the stair climbing phases as described by McFadyen and Winter (1988): weight acceptance, pull-up, forward continuance, leg pull-through, foot placement phase. The stance and swing phase are visualised regarding the separate sub-phases in the leading leg. The leading leg is the solid line, and the trailing leg is the dotted line.

Toe clearance is measured as the vertical distance between the metatarsal foot joints and the step or obstacle during swing phase (Andriacchi et al., 1980; Austin, Garrett, & Bohannon, 1999; Begg & Sparrow, 2000; Chen, Lu, Wang, & Huang, 2008; Chou & Draganich, 1997; Johnson, Buckley, Scally, & Elliott, 2007; Loverro, Mueske, & Hamel, 2013; H.-F. Pan, Hsu, Chang, Renn, & Wu, 2016; Patla, Prentice, & Gobbi, 1996; Pijnappels, Bobbert, & Van Dieën, 2001; Snapp-Childs & Bingham, 2009). In stair climbing, several studies have shown that older adults have lower toe clearance than young adults (Begg & Sparrow, 2000; Elliott, Vale, Whitaker, & Buckley, 2009). It is likely caused by a reduced muscle strength of the knee extensors and hip flexors, especially in high risk older adults (Johnson et al., 2007). On the other hand, in obstacle crossing, studies have shown that toe clearance was higher for older adults, indicating a larger margin of safety (Chen et al., 2008;

Pan et al., 2016). In both tasks, difficulties arise when toe clearance reduces and a safe crossing of the step or obstacle is no longer possible.

Swing time is measured as the time from the toe-off of the leading foot on the ground to heel strike on the first step or the landing of the leading foot on the other side of the obstacle (Alcock et al., 2014; Begg & Sparrow, 2000; Benedetti et al., 2007; Chen et al., 2008; Foster, Whitaker, Scally, Buckley, & Elliott, 2015). In stair climbing, studies have shown that older participants tend to walk slower than young adults and have larger swing times when stepping onto stairs (Begg & Sparrow, 2000; Benedetti et al., 2007). Similarly, in obstacle crossing, research has shown that older adults had a longer swing time (Pan et al., 2016). In both tasks, a longer swing time indicates that participants required more time to prepare the leading limb for toe clearance and landing, which could cause instability and lead to falls.

A variety of studies have looked at the *joint kinematics* of the lower limbs while climbing stairs or crossing obstacles (Alcock et al., 2014; Andriacchi et al., 1980; Austin et al., 1999; Benedetti et al., 2007; Chen et al., 2008; Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2009). Most studies have calculated maximum ankle, knee and hip flexion angles from the joint kinematic data. In stair climbing, results showed that older adults had an increased hip flexion during the swing phase compared to young adults, which could suggest a proximal hip strategy of limb control during postural change (Benedetti et al., 2007). The same study also showed that older adults used less dorsiflexion in maximum ankle angle during the swing phase (Benedetti et al., 2007). Reduced dorsiflexion indicates that there was an increased plantarflexion during the negotiation of the step, which could be dangerous because it could lead to contact with the edge of the step. In obstacle crossing, research had shown that older adults had greater hip abduction, knee flexion, and ankle eversion when the trailing foot was above the obstacle (Chen et al., 2008).

Obstacle crossing studies have usually focused on other kinematic variables. For example, research has shown that older adults not only crossed obstacles more slowly but also placed their feet closer to the obstacle before crossing it (Austin et al., 1999; Chen et al., 2008; Pan et al., 2016; Patla et al., 1996). The *toe-off distance* is measured as the horizontal distance between the leading foot and obstacle. It is an important measure for the preparation of a safe crossing because placing the foot closer to the obstacle means less time to clear the edge of the obstacle and could suggest an increased risk of tripping.

3.3.3 The validity of the measurements

CalTester

Any errors in the parameter settings or calibration measurements of the laboratory can lead to incorrect values of kinetic data that are calculated from force plate data. To ensure this, the laboratory where research is conducted needs to be properly calibrated. This includes an accurate calibration of the positions of force platforms and cameras within the laboratory coordinate system, as well as the correct setting of the force platforms. Holden, Selbie, and Stanhope (2003) developed a test to ensure accurate spatial synchronisation by recording the position and orientation of a mechanical testing device (MTD-2 CalTester rod) via the motion capture system. This mechanical testing device is used to apply forces to the individual force plates. The device includes spherical reflective targets attached to a heavy rod with a pointed tip at each end. The CalTester software used a computational method based on static equilibrium that combines and evaluates the data from the motion capture system and the force plates in four different test variables: 1) the force orientation error and 2) differences in the three coordinates of the Center of Pressure (CoP) location (x, y, z). The force orientation error is the difference in spatial orientation (angle) of the rod determined from the individual force plate measures and kinematic measures of the rod. The CoP is the difference between the x, y, or z component of the displacement vector between the CoP location from the force plate and the tip of the testing rod as determined from the motion capture system.

To evaluate the validity of the laboratory set-up in Chapters 5 and 6, we used the mechanical device to apply ten trials of dynamic loading to each of the force plate positions (see figure 3.5). For the dynamic loading, the experimenter applied a force that exceeded 200N on the end of the rod and moved the upper part of the rod 30 degrees from vertical and back into the other direction in the sagittal plane. From this data, the CalTester program in Visual3D then calculated the four different test variables. In general, the results showed that the force orientation errors were smaller than 5 mm for the laboratory set-ups in Chapters 5 and 6 (see tables 3.3 and 3.4). This indicated that the axial component of the applied force and the orientation of the long axis of the device were aligned. These findings are in line with Holden et al. (2003), who also reported small force orientation and CoP errors. However, our results also showed that the magnitude of CoP errors on the force plates varied with the location of the applied force. Some locations showed CoPx,y errors that were larger than 5 mm and could be up to 20mm. For example, results showed a displacement error of 13 mm between the CoPy location measured by the force platform and the endpoint of the calibration testing device in one of the force platform corners in the set-up of Chapter 5. Since the results showed some

large displacement errors in the CoPx and CoPy, we decided not to use the force plate data to calculate the margin of stability and joint moments through inverse dynamics. Instead, the force plate data were only used to determine toe-off and heel strike on the step or each side of the obstacle.

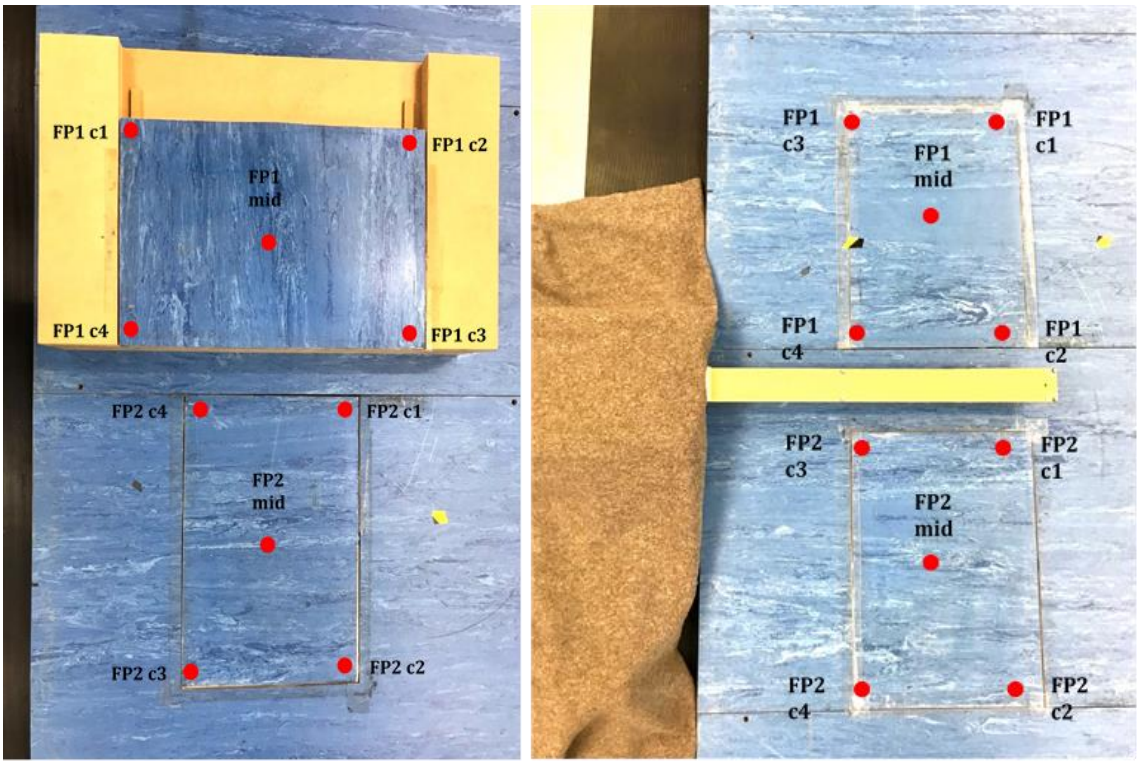


Figure 3.5 an illustration of each of the five locations on the force plates embedded in the experimental set-up in Chapter 5 (left) and 6 (right).

Table 3.3 Results of the CalTester device for the experimental set-up of Chapter 5

	Force Orientation Error (°)	**CoP x (mm)**	**CoP y (mm)**	**CoP z (mm)**
FP1 mid	0.4 ± 0.4	-2.1 ± 2.4	-2.1 ± 2.4	-0.4 ± 0.8
c1	1.7 ± 1.3	-9.6 ± 8.2	-1.6 ± 3.9	-0.5 ± 0.6
c2	1.0 ± 0.5	-10.1 ± 3.4	4.9 ± 3.4	0.3 ± 0.6
c3	0.8 ± 0.6	-6.1 ± 3.6	-0.5 ± 1.6	0.1 ± 0.6
c4	1.7 ± 1.5	-5.0 ± 9.1	-13.9 ± 3.2	-0.6 ± 0.8
FP2 mid	3.3 ± 2.5	9.3 ± 6.1	-7.4 ± 2.5	0.3 ± 0.8
c1	3.2 ± 1.7	0.4 ± 7.5	11.1 ± 4.1	1.0 ± 1.0
c2	5.4 ± 3.3	17.7 ± 5.8	0.6 ± 3.3	0.4 ± 0.8
c3	5.3 ± 3.9	10.5 ± 5.6	-3.9 ± 3.2	0.4 ± 0.8
c4	3.5 ± 2.4	-10.7 ± 6.7	-7.1 ± 6.6	0.4 ± 0.8

Table 3.4 Results of the CalTester device for the experimental set-up of Chapter 6

	Force Orientation Error (°)	**CoPx (mm)**	**CoPy (mm)**	**CoPz (mm)**
FP1 mid	5.4 ± 4.6	-1.8 ± 6.1	1.1 ± 1.9	-4.0 ± 0.2
c1	4.9 ± 4.7	-2.6 ± 4.8	-7.3 ± 3.0	-3.5 ± 0.3
c2	5.8 ± 3.2	-12.2 ± 6.6	7.7 ± 4.1	-3.9 ± 0.3
c3	6.3 ± 5.6	7.5 ± 6.2	-5.2 ± 3.4	-3.3 ± 0.1
c4	5.9 ± 5.8	5.0 ± 5.0	20.0 ± 5.0	-3.7 ± 0.3
FP2 mid	4.9 ± 3.9	2.5 ± 5.6	-2.4 ± 1.5	-3.7 ± 0.3
c1	4.3 ± 3.1	2.0 ± 5.7	-11.6 ± 4.0	-3.9 ± 0.2
c2	3.2 ± 2.0	-7.4 ± 7.2	2.6 ± 2.8	-3.3 ± 0.2
c3	5.9 ± 6.3	7.1 ± 5.4	-2.5 ± 3.9	-3.8 ± 0.2
c4	5.2 ± 4.6	2.5 ± 5.5	10.3 ± 1.6	-3.6 ± 0.2

3.4 Relevance for the following chapters

Chapter 3 showed that ankle weights, scaled to knee extensor muscle strength, will be used as a disturbance in this thesis. Furthermore, it described an innovative methodology to measure recalibration using piecewise regressions that we will use for the first time to identify the point of recalibration in Chapter 5 and 6. It also described the lower-limb marker set that will be used to track participants' movements in these chapters. Next, Chapter 4 will be the first experimental study of this thesis to measure recalibration using ankle weights as a disturbance.

Chapter 4

Exploring age-related differences in the recalibration of affordance perception

Abstract

In older age, declines in physical functioning or fatigue can lead to changes in action boundaries and therefore, making correct judgements is crucial to avoid potential falls. The aim of this study was to investigate whether young and older adults recalibrate their affordance perception after their action boundaries have been disturbed. A total of 28 participants consisting of 14 young (*M* = 29.7, *SD* = 5.2 years; 7 females) and 14 healthy older adults (*M* = 69.9, *SD* = 6.1 years; 7 females) participated in this study. Throughout the experiment, participants were asked to judge the maximum height at which they were able to climb the step without using their hands. After the baseline judgements, the participants were fitted with very heavy ankle weights and asked to judge their maximum stepping height again for a total of 10 sets of judgements. After each set of judgments, participants walked 15 meters with the weights. Results showed that although participants were accurate at baseline and were affected by the disturbance, they did not improve their accuracy over trials. Results showed no effect of recalibration for both young and older adults. Therefore, it is suggested that walking with the weights did not provide the right information source to recalibrate affordance perception. Investigating recalibration remains relevant, but experimental designs should incorporate kinematic measures, everyday activities, and a more ecologically-grounded and informative rearrangement period relevant to the movement.

4.1 Introduction

To make sure performance is successful, information about action capabilities is necessary to distinguish possible from impossible actions. Inaccurate judgements of maximum action capabilities, or action boundaries, could lead to risky behaviour or the needless avoidance of actions. For example, when Mrs Poorthuis goes skiing with her family, she needs to recalibrate to the ski boots. The ski boots are sturdy and a lot heavier than her normal boots and disturb her action boundaries. If she does not recalibrate to the ski boots quickly, she might misjudge and try to leap over a semi-frozen puddle, slip, and fall. Especially in older age, declines in physical functioning or fatigue lead to changes in action boundaries and therefore, making correct judgements is crucial to avoid potential falls. Therefore, it is relevant to investigate whether some of those falls are a result of poor recalibration to changes in action boundaries.

Gibson's theory of direct perception states that the information available in the environment can be directly perceived to guide actions. That is to say, people or other animals perceive the environment in terms of their ability to act in it. These action possibilities are defined in ecological psychology as *affordances* (Gibson, 1979; see Chapter 1). The term affordance has received considerable attention in the literature. For Michaels and Carello (1981) affordances are what the environment offers the animal, while later discussions view affordances as invitations for action (Withagen et al., 2012). In developing Gibson's ecological approach to affordances, research has shown that the relationship between intrinsic individual properties and the environment can be described by invariants (e.g. Warren, 1984; Warren & Whang, 1987). For example, Warren (1984)'s study showed that maximum stepping height corresponded to 88% of leg length across a variety of young participants. Later, Konczak and colleagues (1992) investigated maximum stepping height in older adults. They found a lower ratio between leg length and stepping height of 62% and 73% for short and tall older adults, indicating that the action boundary may also depend on biomechanical constraints such as knee extensor muscle strength and hip flexibility. As the action boundaries for young and older adults in that task were different, these results concur that the actions afforded by the environment depend on the actor's intrinsic properties.

From infancy to older age, action boundaries change depending on body size, morphology, and physical functioning over small and long timescales (Adolph, 2008; Franchak & Adolph, 2014). For example, when pregnant women gain abdominal girth their action boundaries for squeezing through doorways change (Franchak & Adolph, 2014). Disturbances, like a fast-growing belly in pregnant women, render the perception-action link inaccurate and

trigger recalibration (Franchak, 2017). Recalibration then rescales the perception-action link which is necessary to judge action boundaries correctly. This means that pregnant women need to recalibrate to changes in body size and compression to accurately judge possibilities for squeezing through doorways (Franchak & Adolph, 2014). Similarly, changes in older age are thought to trigger recalibration, although this has not been investigated before.

In young participants, recalibration of action capabilities has been investigated by asking participants to judge their action boundaries following a disturbance (Franchak & Adolph, 2014; Hackney, Cinelli, & Frank, 2014; Higuchi, Takada, Matsuura, & Imanaka, 2004; Hirose & Nishio, 2001; Mark, 1987; Mark, Balliett, Craver, Douglas, & Fox, 1990; Stoffregen, Yang, Giveans, Flanagan, & Bardy, 2009; Yu & Stoffregen, 2012; see Chapter 2). For example, Mark (1987) investigated recalibration to 10-cm high blocks underneath participants' feet in a study about affordances to sitting and stair climbing. Participants were asked to judge their maximum seat height and maximum stepping height for 12 trials after being fitted with the blocks. They initially underestimated their action boundaries for sitting, but recalibrated their affordance perception after some walking with the blocks (i.e., from 0.460 to 0.496 of seat/eye height ratio; Mark, 1987). Similarly, other studies have used judgements to measure the recalibration of affordance perception in tasks such as fitting through an aperture while carrying wide objects or while sitting in a wheelchair (Hackney et al., 2014; Higuchi et al., 2004).

In this body of literature, judgements are discrete cognitive assessments of affordances, or in other words, they are used as a proxy to affordance perception. Research has applied disturbances to the action system and used judgements to measure affordance perception both before and during rearrangement (see Chapter 2). Reduced judgement errors serve as evidence of successful recalibration while failure to reduce judgement errors indicates incomplete recalibration (e.g., Franchak, 2017). To improve recalibration, active exploration of relevant information sources is essential in young participants and should also apply to older age (cf. Fernández-Ruiz, Hall, Vergara, & Diaz, 2000), but this has not been investigated before (see Chapter 2).

The aim of this study was to investigate whether young and older adults recalibrate their affordance perception after their action boundaries have been disturbed. To explore possible age-related differences in recalibration, participants were asked to judge their maximum stepping height, a task that is known to be impacted by ageing (Konczak et al., 1992) and is also well-used in the field of ecological psychology (Hirose & Nishio, 2001; Mark, 1987; Warren, 1984, also see Chapter 2). Participants wore ankle weights to disturb and reduce their

action boundaries (Ramenzoni, Riley, Shockley, & Davis, 2008; see Chapter 3). After each judgement trial, the participants walked several steps to allow them to explore the information available (Mark et al., 1990). Participants' judgement errors were expected to be larger immediately after the disturbance but reduce over several trials. In addition, older adults were expected to take longer than young adults to fully recalibrate their affordance perception (Fernández-Ruiz et al., 2000).

4.2 Methods

4.2.1 Participants

A total of 28 participants consisting of 14 young (*M* = 29.7, *SD* = 5.2 years; 7 females) and 14 healthy older adults (*M* = 69.9, *SD* = 6.1 years; 7 females) volunteered to participate in this study. The young and older group were significantly different in age, height, knee extensor muscle strength, hip flexibility, and maximum stepping height (Table 4.1; see later for assessment of participants' action capabilities procedure). The sample size was informed by a sample-size calculation based on a previous study by Mark and colleagues (1990). We estimated the sample-size based on their first experiment (effect size of the difference between actual and perceived seat height; *d* = 1.22). It showed that a sample size of 2 groups of 12 would have a power of 0.8. For inclusion, participants had to have self-reported normal or corrected-to-normal vision. Before the start of the experiment, all participants completed a health questionnaire and were excluded if they reported orthopaedic, neuromuscular, cardiac problems, or balance impairments. Older adults were also asked to perform the Timed Up and Go test (TUG; Podsiadlo & Richardson, 1991; see Chapter 3). If they were not able to complete the TUG test within 13.5 seconds or had been advised not to participate in exercise, they were excluded from further testing. Study procedures were approved by the London South Bank University's ethics committee (SAS1627a).

Table 4.1 Mean and SD of participants' characteristics and their action capabilities.

Variables (units)	Young	Older
Age (years)	29.7 ± 5.22	69.9*** ± 6.13
Height (cm)	173 ± 12.3	165* ± 7.52
Weight (kg)	69.6 ± 10.5	72.4 ± 15.6
Knee extensor muscle strength (N)	475 ± 141	307** ± 147
Hip flexibility (degrees)	63.7 ± 11.3	88.4*** ± 14.1
Maximum stepping height (cm)	87.1 ± 10.4	55.8*** ± 12.5
Maximum stepping height with weights (cm)	80.4 ± 9.83	51.1*** ± 12.4

Notes: Significant differences between older and young groups are indicated by * $p < .05$, ** $p < .01$ ***$p < .001$. The older group showed significantly less strength, flexibility and stepping height than the young group. Maximum stepping height with weights was measured after the experiment.

4.2.2 Procedure

When participants arrived at the lab, the study was explained, and they signed the informed consent. Subsequently, participants' height, weight, knee extensor muscle strength, hip flexibility and maximum stepping height without ankle weights were measured to characterise individual action capabilities.

Then, for each trial, participants stood 30 cm in front of an apparatus that allowed them to raise and lower a step using a cord (see figure 4.1). Participants were able to make small adjustments until they were happy with the height. The apparatus was placed against a grey background and on a black carpet to minimise visual cues. Throughout the experiment, participants were asked to judge the maximum height at which they would be able to climb the step of the apparatus without using their hands. A measuring tape was fixed to the back of the apparatus for the experimenter to read and record the height of each judgement. Subsequently, the experimenter moved the step back to an extreme position, so the step was either at the bottom (18 cm) or top of the apparatus for each new judgement (180 cm). On each trial, participants were asked for two judgements: one judgment where the participant raised the step and one where the participant lowered it to their maximum stepping height (cf., method of limits; Kluft, Bruijn, Weijer, Diee, & Pijnappels, 2017; Mark, 1987; Mark et al., 1990; Stoffregen et al., 2009). Participants were asked to judge both ascending and descending trials

to prevent an effect of direction on their judgements, as commonly observed before (Hirose & Nishio, 2001; Pufall & Dunbar, 1992).

After the baseline judgements, the participants were fitted with very heavy ankle weights. The ankle weights were 10% of peak knee extensor muscle strength for each leg (see Chapter 3 for more details). Participants were asked not to sway or move after being fitted with the weights but to judge their maximum stepping height immediately. After this set of judgments, participants walked 15 meters wearing the same weights and judged their maximum stepping height again. The participants completed a total of 10 sets of two judgments wearing ankle weights. At the end of the experiment, participants' maximum stepping height wearing ankle weights was measured.

Participants were asked to rate the fatigue in their legs before, in the middle and after the experiment by indicating a value on the Borg rating of perceived exertion scale (RPE) which ranges from 6 (very very light) to 20 (extremely fatigued; Borg, 1982). Results showed a slight but significant increase in fatigue over the course of the experiment for young adults (see table 4.2).

Table 4.2 Rate of perceived exertion scores over the course of the experiment (mean and SD) to assess fatigue in participants' legs. There were significant differences between scores before and after the experiment for young adults (*p <. 05).

	Before	**Middle**	**After**
Young	9.75 ± 3.04	10.5 ± 2.44	11.7* ± 2.03
	Fairly light	Fairly light	Somewhat hard
Older	7.00 ± 1.96	7.93 ± 3.47	8.00 ± 3.66
	Very very light	Very light	Very light

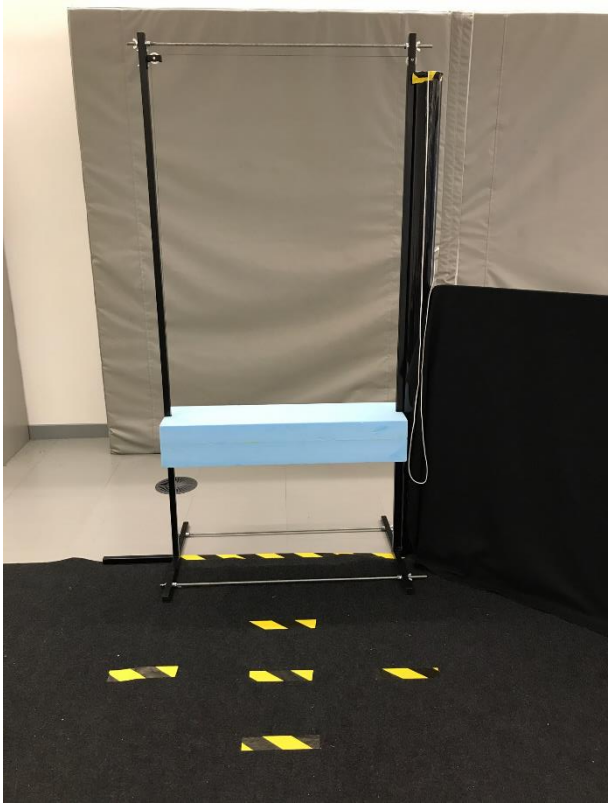


Figure 4.1 Photo of the apparatus used to measure the perceived maximum stepping height. The participants moved the step (18 x 27 x 90 cm) up and down using the cord visible on the right-hand side of the apparatus. The step was held in place using a counterweight, which was covered and out of sight. The apparatus was set against a grey background and on a dark carpet to minimise visual cues. Also, for this reason, the experimenter stood behind the screen on the right. This apparatus was designed and built by Anderson and Brand.

4.2.3 Assessment of participant's action capabilities

Maximum stepping height

Participants were asked to step onto a platform with their preferred leg without support or using their arms (see figure 4.2). The platform was gradually raised until the point where participants were not able to step onto it anymore. Maximum stepping height, with a 1-cm level of accuracy, was recorded as the highest platform height participants could still step onto without support (Konczak et al., 1992). Maximum stepping height was the action boundary.

Hip flexibility

Participants were asked to raise their leg three times as high as possible while standing unsupported. Reflective markers for motion capture were placed on the shoulder (acromion), hip (greater trochanter) and knee (lateral epicondyle) to measure hip flexibility, calculated as the minimum trunk-thigh angle during active flexion in an upright position for each leg (Konczak et al., 1992).

Knee extensor muscle strength

Three maximum isometric voluntary contractions (MVC) were performed for each leg on an isokinetic dynamometer chair system while participants' hip and knee joints were fixed at a 90° angle (Kin-Com, Chattanoga Group, Inc., TN, USA). Each participant was instructed to perform an MVC during knee extension for 3 s with 1-minute rest in between each of the MVCs (Konczak et al., 1992). Individual knee extensor muscle strength was measured as the peak knee extensor muscle strength per leg (in Newtons; see Chapter 3).

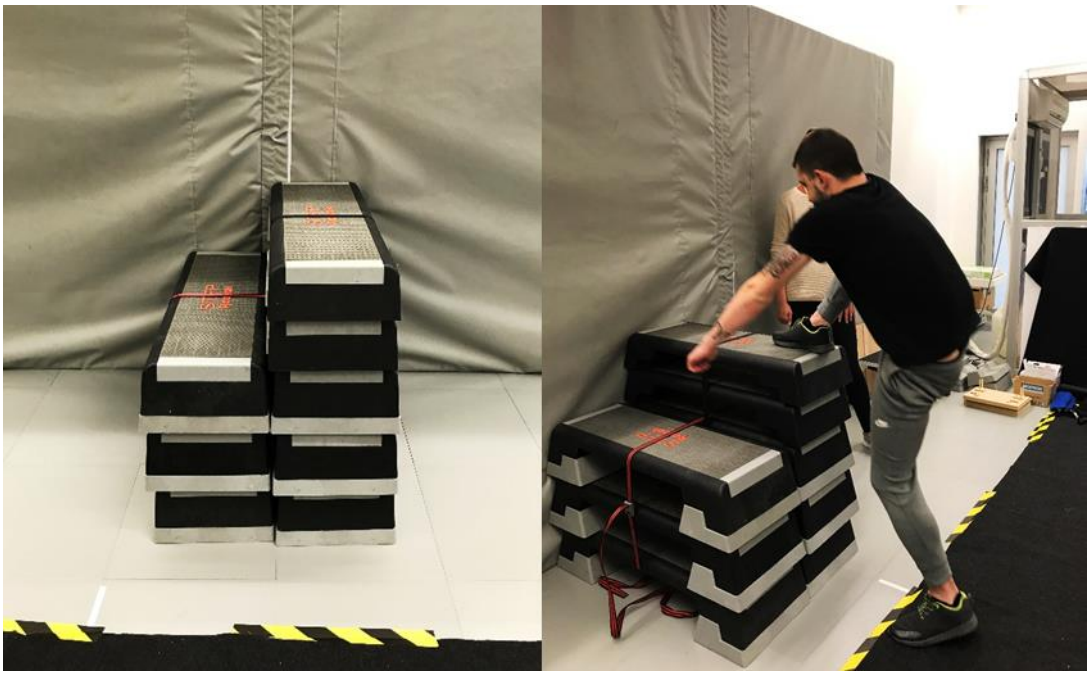


Figure 4.2 The instrument used to test the participant's maximum stepping height (action boundary). Participants were asked to step onto a platform with their preferred leg without support. The instrument consisted of several stackable gym steps and several stackable wooden planks. The steps could be 10 or 15 cm (visible on the figure), and the wooden planks were adjustable from 1 to 6 cm with 1-cm increments.

4.2.4 Dependent variables

Each set of judgements, or judgement trial, consisted of the participant making an ascending judgment and a descending judgment of maximum stepping height. Consequently, this perceptual boundary was calculated as the mean of these two judgments for each trial (e.g. Mark et al. 1990; Mark 1987; Stoffregen et al. 2005). To determine under or overestimation of action boundary, *relative judgement error* was calculated by subtracting the action boundary from the perceptual boundary. For example, if the maximum stepping height was 80 cm (action boundary), this was then subtracted from the mean of the two judgements of 70 cm (perceptual boundary), which resulted in a relative judgement error of -10 cm. A negative value indicated an underestimation, and a positive value indicated an overestimation of the action boundary. In addition, to see whether judgements got more accurate over time, a *judgement accuracy ratio* was calculated by dividing the perceptual boundary by action boundary. A judgement accuracy ratio of 1.0 indicated a perfect judgement of action boundary.

4.2.5 Statistical analysis

Relative judgement errors were submitted to a one-way mixed ANOVA with within-subjects factor Trial (11 levels) and between-subjects factor Group (2 levels: young vs old). Similarly, judgement accuracy ratios were submitted to a one-way mixed ANOVA with within-subjects factor Trial (11 levels) and between-subjects factor Group (2 levels: young vs old). Normality was confirmed using the Shapiro-Wilk test and homogeneity of variance was confirmed using the Levene's test. Where a violation of sphericity was found in Mauchly's test, a Greenhouse-Geisser correction was applied. Post-hoc tests with Least Significant Difference (LSD) correction were applied to significant main effects. Also, to assess the effect of judgement direction, relative judgement errors were submitted to a paired samples t-test comparing ascending and descending judgements. Throughout the analysis of the results, a significance level (alpha) of 5% was used, and all data were statistically analysed using SPSS 21.0.

4.3 Results

4.3.1 Relative judgement errors

Results showed that there was a significant effect of judgement trial for relative judgement error, $F(4.50, 117) = 5.43$, $p < .001$, $\eta^2 = 0.211$. Within-subject contrasts showed a significant linear effect over trials, $F(1, 26) = 10.0$, $p = .004$, $\eta^2 = 0.388$. There was no effects of group, $F(1, 26) = 0.384$, $p = .541$, or interaction effects, $F(4.50, 117) = 0.266$, $p = .988$). Pairwise

comparisons revealed no significant difference between the judgement error at baseline and after the disturbance trial (p = .166). However, significant differences were found between baseline and each of the subsequent trials (p < .05). No significant differences were found within the subsequent trials (p > .05). As shown in figure 4.3, participants were accurate judging their action boundary without ankle weights at baseline (NW: M = -0.02, SD = 5.95 cm). Once weights were fitted, participants started underestimating their action boundary (W1: M = -2.00, SD = 7.41 cm), which they underestimated further after having the opportunity to walk with the weights (e.g., W2: M = -4.91, SD = 8.01 cm) and continued to do so until the end of the experiment.

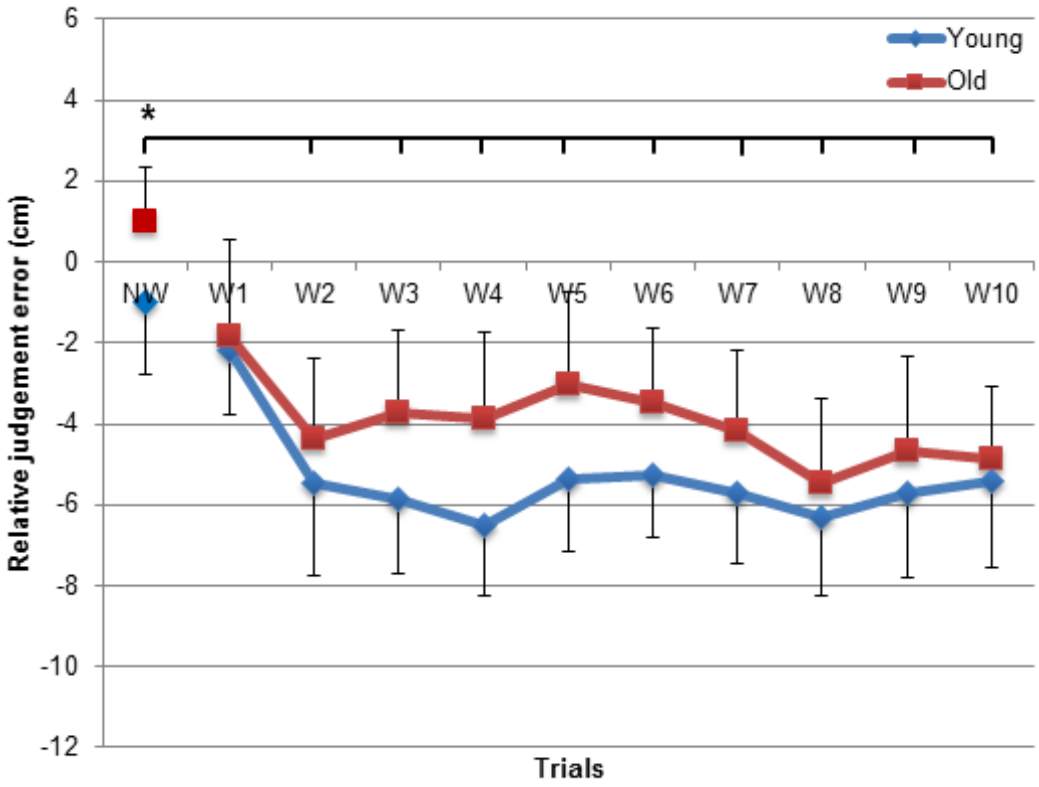


Figure 4.3 Average relative judgement error across trials for the young and old groups. The relative judgement error is the difference between perceptual and action boundary. Baseline was recorded without weights (NW); the disturbance trial was the first with ankle weights fitted (W1), trials W1 to W10 were all with the same ankle weights fitted. Bars represent standard errors of the mean. *p < .05.

Since results suggest that older adults underestimated their action boundaries less than young adults, a further analysis looked at participants' individual judgements. This analysis showed that 71 % of the young and older adults underestimated their action boundaries, while 29 % of the young and older adults overestimated them (figure 4.4). For the participants who consistently underestimated, there was a significant effect of judgement trial, $F(3.93, 70.81) = 7.92$, $p < .001$, $\eta^2 = .44$, because judgement errors differed between baseline and disturbance trial ($p = .004$) and between baseline and trials W2-W10 ($p < .001$) which did not differ between them ($p > .05$). No effects of group, $F(1, 18) = 0.130$, $p = .723$, or interaction effects, $F(3.93, 70.8) = 0.279$, $p = .888$, were found. For the one–third of the participants who overestimated their action boundary, there was no significant effect of judgement trial, $F(3.01, 18.1) = 1.10$, $p = .375$, and no interaction effect, $F(3.01, 48.1) = 0.649$, $p = .594$. A significant group effect, $F(1, 6) = 20.3$, $p = .004$, $\eta^2 = 3.38$, showed that these 4 older adults overestimated significantly more than the 4 young adults. Overall, results showed that both groups were accurate judging their action boundary without the ankle weights but did not significantly reduce their judgement error once the disturbance was applied.

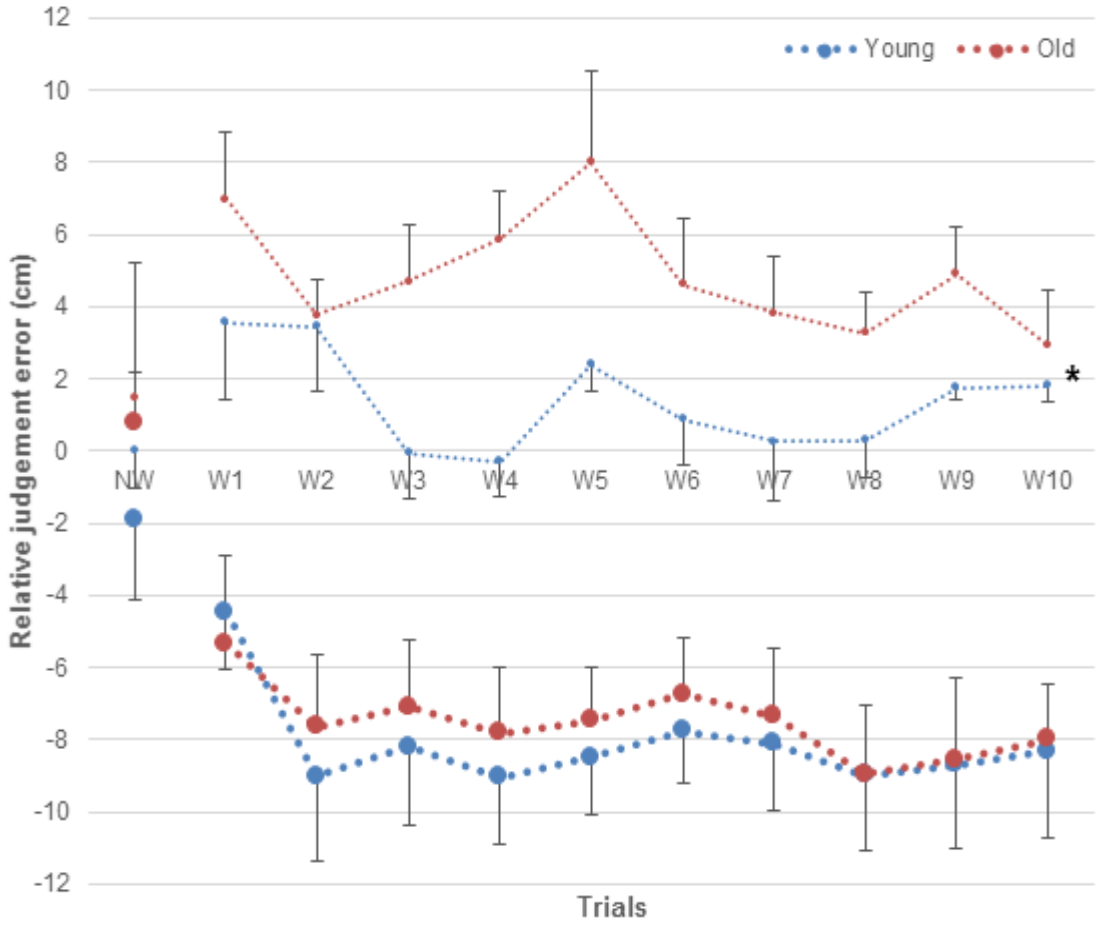


Figure 4.4 Relative judgement error across the trials for the young and old groups divided into under- and overestimators. The relative judgement error is the difference between the perceptual boundary and their action boundary. Baseline was recorded without weights (NW); the disturbance trial was the first with ankle weights fitted (W1), trials W1 to W10 were all with the same ankle weights fitted. Bars represent standard errors of the mean. The number of participants is represented by symbol size: overestimators (n = 4) and underestimators (n = 10) for both groups.

4.3.2 Judgement accuracy ratio

Results showed that there was a significant effect of trial on judgement accuracy ratio, $F(4.48, 117) = 4.10$, $p = .003$, $\eta^2 = 0.164$. Within-subject contrasts showed a significant linear effect over trials, $F(1, 26) = 7.38$, $p = .012$, $\eta^2 = 0.282$. Pairwise comparisons revealed no significant difference between baseline (NW) and the disturbance trial (W1; $p = .159$), but significant differences were found between baseline (NW) and trials W2-W10 ($p < .05$) which were not different between them ($p > .05$). Because participants were accurate at baseline but never regained accuracy after the disturbance, results showed no signs of recalibration. No effects of group, $F(1, 26) = 0.011$, $p = .917$, or interaction effects, $F(4.48, 117) = 0.332$, $p = .875$, were found. As shown in figure 4.5, participants were accurate judging their action boundary at baseline ($M = 1.00$, $SD = 0.017$) but became significantly less accurate after having the opportunity to walk with the weights (W2: $M = 0.927$, $SD = 0.025$), and their judgements remained inaccurate until the end of the experiment (W10: $M = 0.926$, $SD = 0.023$).

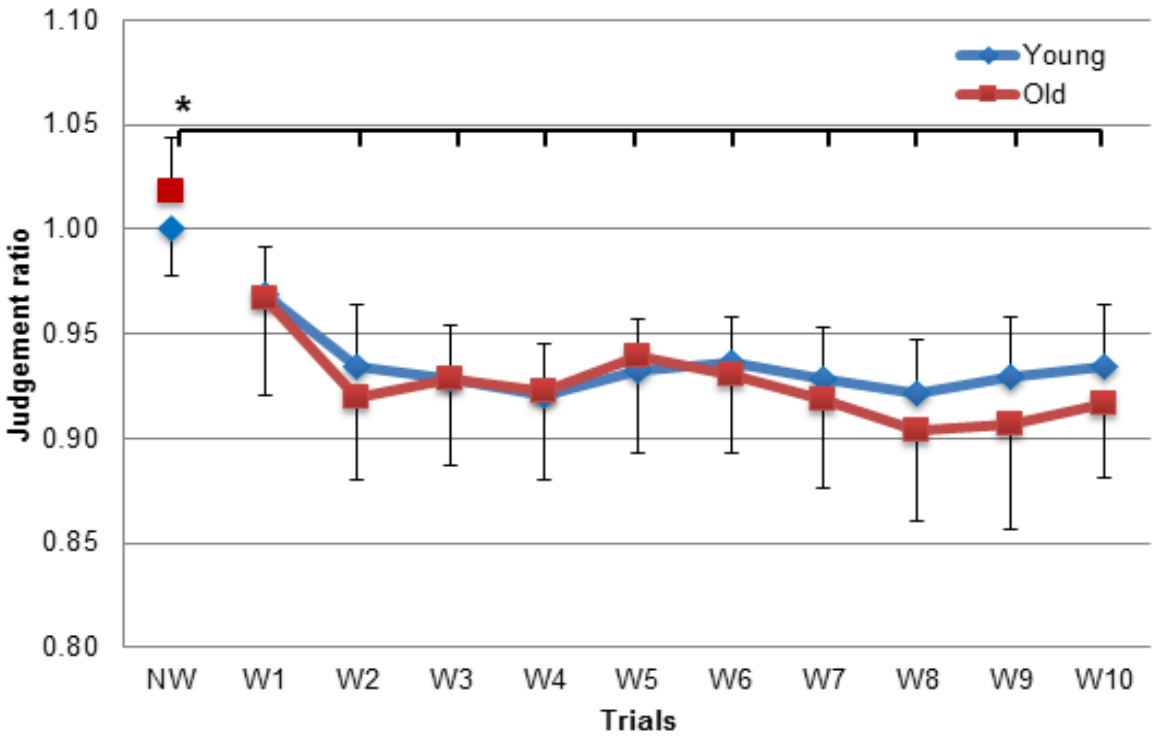


Figure 4.5 Average judgement accuracy ratio across the trials for the young and old groups. The judgement accuracy ratio is each participant's perceptual boundary divided by their action boundary. Baseline was recorded without weights (NW); the disturbance trial was the first with ankle weights fitted (W1), trials W1 to W10 were all with the same ankle weights fitted. Bars represent standard errors of the mean. *$p < .05$.

4.3.3 Effect of judgement direction

On each trial, participants were asked for two judgements (ascending and descending) to account for possible differences in judgements due to direction. Results showed a significant effect of direction, $t(27) = 4.91$, $p < .001$, $d = 0.261$. Ascending judgements were lower than descending judgements (respectively, $M = -4.93$, $SD = 6.22$ cm; $M = -3.28$, $SD = 6.58$ cm).

4.4 Discussion

The aim of this study was to investigate whether young and older adults recalibrate their affordance perception after their action boundaries have been disturbed. Similar to Konczak et al. (1992), results showed that older adults had significantly lower maximum stepping heights than young adults. Although participants were accurate at baseline and were affected by the disturbance, results showed that they did not regain accuracy during the rearrangement period. This indicates there was no recalibration within the ten experimental trials for either group. In the following, we discuss the results in relation to each of the stages in the recalibration process.

Judgements were accurate at *baseline*, indicating that the task of judging maximum stepping height was well-learned and calibrated. Stepping to maximum height is an unusual action, and therefore, it was not warranted that judgements would be accurate. For this reason, the study procedure allowed participants to engage in maximum stepping before they engaged in judgements, which must have been sufficient to calibrate judgements to action before the baseline trials. Whether or not the order of testing affected, the baseline accuracy could easily be tested by measuring judgements first and maximum stepping height later, but this was not done here.

The *disturbance* used in this experiment was successful because the heaviness of the weights did affect judgements in a significant way. We expected judgements to be significantly disturbed immediately after having weights fitted, but results showed only half of the disturbance effect on the first trial and the remaining effect on the second trial. We think this happened because participants needed the opportunity to walk in order to pick up information about the disturbance. On the first trial, participants were asked not to move, so the half-effect observed was probably influenced by the general feeling of being encumbered by the weights. On the second trial, there was active exploration, which is known to be crucial for picking up information for perception and action (E.J. Gibson, 1988; J.J. Gibson, 1979; see Chapter 1).

Our results indicate that, in this case, active exploration is also necessary to pick up information about the disturbance itself.

During the *rearrangement* period, judgements did not become more accurate despite the opportunity to walk between judgement trials. The fact that no recalibration happened was unexpected but may be interpreted regarding three limitations related to study design. First, it is possible that ten opportunities for exploration were not sufficient for recalibration to occur, although previous studies found complete recalibration at the end of five to twelve trials (see Chapter 2). Second, it is possible that the instrument used in the judgement task was rather different from that used to measure the participant's maximum stepping height (recall figures 4.1 and 4.2). The instrument used for making judgements did not allow for actual stepping on and this could have limited participants in their ability to correctly judge their maximum stepping height. Third, it is possible that the opportunities for exploration did not provide the right information source to recalibrate to the new action boundaries. It is known that judgements become more accurate when participants have ample opportunity to actively explore their new action capabilities (see Chapter 2). Also, walking has been used by several other studies as a means of exploration (Mark, 1987; Mark et al., 1990; Ramenzoni et al., 2008). For example, walking 16 meters with the ankle weights resulted in changes to participants' judgements on maximum jumping capability for themselves and others (Ramenzoni et al., 2008), and walking to six different locations allowed participants to explore and recalibrate their altered eye height (Mark, 1987). However, walking was not sufficient to recalibrate maximum stepping height in our study and therefore, may not have provided sufficient information for recalibration to occur. Other studies also provide a similar interpretation (Mark et al., 1990; Stoffregen et al., 2005, 2009; Yu et al., 2011). It is possible that another action, for example, climbing up the stairs, would have provided better information about the heaviness of the weights upon leg lifting.

The results of the present study support the idea that relevant perceptual information through active exploration can be insufficient for successful recalibration (Franchak, 2017; Franchak & Somoano, 2018; Labinger et al., 2018). Their work suggests that although many affordances can be recalibrated by exploring the relevant perceptual information about the new action boundaries, some other affordances need information on whether or not the action was possible to recalibrate successfully (Franchak, 2017). In their study, participants wore a backpack which changed their doorway squeezing-ability. They did not recalibrate their affordance perception just by walking or squeezing the backpack to explore their new action boundaries or the properties of the backpack. Instead, recalibration only occurred after

participants squeezed through doorways wearing the backpack. This was confirmed in another study by Franchak and Somoano (2018), who found that successful recalibration in a doorway-squeezing task required feedback from actually attempting the task. Participants did not recalibrate if they only experienced success or if they only experienced failure. Instead, they needed both types of experiences for a complete recalibration of their affordance perception. Taken together, it seems that recalibration of affordance perception depends on action-specific information about the animal–environment relationship. This means that future research should use exploration actions which are closer to the actions being disturbed (see Chapter 5 and 6).

Results showed that of the one-third of participants who overestimated their action boundaries, older adults made significantly larger overestimations than young adults. Similar results were found by other studies that showed that while older adults tend to overestimate their action capabilities, young adults tend to underestimate (Robinovitch & Cronin, 1999; Sakurai et al., 2013). A study by Kluft et al. (2017) investigated whether these under- and overestimations are task-specific or an inherent trait of the participant. Their results showed that the degree of misjudgement did not transfer between tasks, which suggests that the over- or underestimations may be task-specific. This could be one of the reasons why in our study about two-thirds of young and older participants consistently underestimated their action boundaries. It is likely that the very heavy ankle weights in combination with limited information for recalibration led to conservative judgements. Also, conservative judgements make sense in the face of a disturbance to which the perceptual-motor system has not yet recalibrated. Especially in testing older populations, asking people to judge and perform actions around their action boundaries is not always feasible and by no means an activity that people perform every day. Therefore, it remains relevant to investigate age-related differences in recalibration, and future studies should investigate recalibration using kinematic measures in everyday activities (see Chapters 5 and 6).

4.4.1 Conclusions

This study examined whether young and older adults recalibrated their affordance perception after their action boundaries were disturbed. At baseline, the judgements accurately reflected maximum stepping height. After fitting very heavy ankle weights, which imposed a large disturbance on their perceptual-motor system, participants systematically underestimated their action boundaries and did not improve their accuracy over trials. Results showed no effect of recalibration for both young and older adults. Therefore, it is suggested that walking with the

weights did not provide the right information source to recalibrate affordance perception. Investigating recalibration remains relevant but should incorporate kinematic measures, everyday activities, and a more informative rearrangement period.

4.4.2 Relevance for the following chapter

Chapter 4 showed that participants did not regain accuracy, which suggests no recalibration occurred within the ten experimental trials for either group. It is suggested that walking with the weights did not provide the right information source to recalibrate affordance perception for maximum stepping height. We concluded that investigating age-related differences in recalibration remains relevant, but that kinematic measures may be more useful to investigate recalibration in everyday activities. Therefore, Chapter 5 and 6 will investigate age-related differences in recalibration but will use kinematic measures to measure everyday activities.

Chapter 5

Exploring age-related differences in the speed of recalibration in stair climbing

Abstract

During everyday activities, people are frequently required to step onto surfaces, for instance, when stepping onto a curb or climbing the stairs. The aim of this study is to investigate how long young and older adults take to recalibrate to disturbances of different magnitudes while climbing the stairs. A total of 26 participants consisting of 14 young adults (*M* = 25.0, *SD* = 5.4 years) and 12 older adults (*M* = 70.3, *SD* = 3.8 years) volunteered to participate in the study. Participants' step pattern was motion-tracked using a lower-body marker set while they climbed a small set of stairs. After climbing the stairs 5 times in the baseline condition without weights, participants were fitted with light, medium or heavy ankle weights that disturbed their actions (small, medium, and large disturbances, respectively), and asked to climb the staircase again for 20 consecutive trials. This procedure was then repeated using the two other sets of weights. To determine whether recalibration occurred, we analysed the data in three steps. First, piecewise regressions were applied to each of the kinematic variables to find the breakpoint. Next, using that breakpoint, we fitted two regressions to the individual data. Finally, the two regression slopes were submitted to a two-way mixed ANOVA with within-subjects factors Condition (3 levels: light vs medium vs heavy), Time (2 levels: initial vs final rearrangement), and between-subjects factor Group (2 levels: young vs old). In general, results showed that while young adults took 3-7 trials, the older adults took 6-8 trials across weight conditions for toe clearance. In addition, results showed that while young adults recalibrated faster to smaller disturbances, older adults showed a similar point of recalibration across disturbances. We discuss whether older adults used an over-compensation strategy to deal with all disturbances.

5.1 Introduction

During everyday activities, people are frequently required to step onto surfaces, for instance, when stepping onto a curb or climbing the stairs. Climbing stairs plenty of times before, Mrs Poorthuis is familiar with this action and automatically picks up the right information to safely climb the stairs. Today, however, she visited a footcare specialist and was fitted with orthotic shoes to ease the pain on her feet. Her new shoes are less flexible and have a much thicker sole than her old shoes, which could lead to a destabilising effect in short term (Hijmans, Geertzen, Dijkstra, & Postema, 2007). So, whenever she starts climbing stairs with the shoes, it will take her some time to get used to the new shoes, which is the process of *recalibration*. Recalibration, or the rescaling of the perception-action link, is necessary to ensure safe locomotion for Mrs Poorthuis as she climbs the stairs (Franchak, 2017).

Several biomechanical studies have indicated that older adults were slower adapting to environmental perturbations, such as unstable floors and tripping (respectively, Bierbaum, Peper, Karamanidis, & Arampatzis, 2011; McCrum et al., 2016). For example, McCrum and colleagues (2016) disturbed participants' treadmill walking by applying a perturbation to participants' ankle during the swing phase of their gait cycle in successive cycles. Their study showed that older adults adapted slower compared to young adults. While these studies applied a non-continuous disturbance repeatedly, recalibration studies applied a continuous disturbance and measured the rearrangement over time (Franchak & Adolph, 2014; Mark, Balliett, Craver, Douglas, & Fox, 1990; Scott & Gray, 2010; Stoffregen, Yang, & Bardy, 2005; see Chapter 2). So far, it is unknown how long older adults require to recalibrate to action disturbances, and that is what this study sought to investigate.

Although judgements have been used extensively to study recalibration, results in Chapter 4 found no recalibration within the ten experimental trials for either group. We suggested that walking with the weights did not provide the right information source to recalibrate affordance perception for maximum stepping height. It was suggested that recalibration studies should use exploration actions that are closer to the actions that were disturbed. However, especially in testing older populations, it is not always feasible to ask them to repeatedly perform actions around their action boundaries. Alternatively, studies should measure recalibration to a disturbance in participants' action capabilities in everyday activities, which also provides more insight into the process of recalibration for practical significance. As older adults are more likely to trip over a raised surface, we used stair climbing as our everyday task (Startzell, Owens, Mulfinger, & Cavanagh, 2000).

Up to date, only two studies have used kinematic measures to investigate recalibration (Scott & Gray, 2010; Van Hedel & Dietz, 2004). For example, Van Hedel and Dietz (2004) disturbed young adults' obstacle crossing on a treadmill by fitting an ankle-foot, knee, or knee-ankle-foot orthosis on their left leg. They measured leg muscle activity, swing phase duration and toe clearance to investigate recalibration. Results showed that after 50 trials, only participants with an ankle-foot orthosis recalibrated. Similarly, Scott and Gray (2010) measured temporal swing error, swing onset time, and bat velocity to investigate recalibration after switching to differently weighted baseball bats. For their study, Scott and Gray reviewed the current literature on baseball swings to distinguish between relevant performance measures and other action-specific kinematic measures. They used mean temporal swing error as a performance measure to see whether participants recalibrated their perceptual-motor system and whether they improved their accuracy and precision. The other action-specific kinematic measures informed them about whether participants changed swing onset or velocity that led to the recalibration of their perceptual-motor system. Their results showed that participants recalibrated their swing accuracy to a heavier bat within ten trials by altering their swing on-set time, whereas the lighter bat group recalibrated their swing accuracy within five trials by changing their swing velocity.

Similarly, for the present study, the stair ascent literature was reviewed for relevant performance and action-specific kinematic measures to find potential age-related differences in recalibration. Climbing stairs is a complex movement that requires people to raise their leading foot onto the first step, shift their centre of gravity towards that foot, pull themselves up and carry the trailing foot forward to the next step (see Chapter 3). An important performance measure in stair climbing is toe clearance because a smaller safety margin to clear the step can result in tripping and might lead to falls on stairs (Begg & Sparrow, 2000; Elliott et al., 2009). Other studies have also shown that older adults tend to have a longer swing time when stepping onto a step (Begg & Sparrow, 2000; Benedetti et al., 2007). In addition, a variety of studies have looked at the joint kinematics of the lower limbs while ascending stairs, and found that older adults generally have a more plantarflexed ankle compared to young adults (Alcock et al., 2014; Andriacchi et al., 1980; Benedetti et al., 2007; Reeves et al., 2009). Hence, toe clearance will be used as the performance measure that informs on recalibration after the disturbance, and the other action-specific kinematic measures, like swing time and lower-limb joint kinematics, will inform on differences in the step pattern that led to this recalibration.

Previously, some studies reported on the duration of recalibration by indicating that participants had recalibrated after performing the task in a number of blocks (Bingham &

Romack, 1999; Bruggeman et al., 2005; Scott & Gray, 2010). For example, Bruggeman et al. (2005) found that participants throwing beanbags while rotating on a carousel recalibrated after two blocks of 5 throws. Although these studies give an estimated range of time needed for recalibration, knowing when participants reached complete recalibration (e.g. the point of recalibration) on a particular task is important because it provides better accuracy allowing for group comparisons. To our knowledge, only very recently a few studies have tried to identify a timeframe for recalibration, and they did this by visually inspecting the data (Day et al., 2019; Franchak & Somoano, 2018; Wang & Bingham, 2019). The current study, therefore, will use a trial-by-trial analysis and use a new methodology which allows for automatic identification of the point of recalibration.

To investigate the process of recalibration, previous studies generally compared the results of their disturbance condition to a control condition without disturbance. A regression slope over the control condition would have to be close to zero, and the slope over the experimental condition would have to be significantly different from zero to indicate a recalibration effect (Mark, 1987; Mark et al., 1990; Yu & Stoffregen, 2012). To date, only a few studies measured the immediate effect of disturbances (Fernández-Ruiz & Díaz, 1999; Scott & Gray, 2010; see Chapter 2). For example, Fernández-Ruiz and Díaz (1999) found that the accuracy of hitting a target with balls significantly decreased by 20-60 cm immediately after wearing prism glasses as a direct effect of the perceptual disturbance. Similarly, Scott and Gray (2010)'s results showed that participants' swing accuracy significantly decreased immediately after switching to bats of different weights (i.e., disturbance of action). It seems logical that the effect of the disturbance is visibly different from baseline, although it is unclear whether it is necessary for the process of recalibration. Hence, this study will also assess whether the process of recalibration is preceded by a significant effect of disturbance.

The main aim of this study is to investigate how long young and older adults take to recalibrate to disturbances of different magnitudes. We predicted that there would be a decline in stepping performance for the first few steps after each disturbance, followed by a fast rearrangement of the perceptual-motor system. We were also interested to see whether recalibration was preceded by a significant effect of disturbance. Although no previous research has examined age-related effects on recalibration to disturbances of their action capabilities, we expected older adults to recalibrate slower than young adults (cf., Bierbaum et al., 2011; Bruijn, Van Impe, Duysens, & Swinnen, 2012; Fernández-Ruiz et al., 2000; McCrum et al., 2016). In addition, we expected this effect to be more pronounced for larger disturbances (Durgin et al., 2005; Van Hedel & Dietz, 2004; Chapter 2).

5.2 Methods

5.2.1 Participants

A total of 26 participants consisting of 14 young adults (*M* = 25.0, *SD* = 5.4 years; 9 females) and 12 older adults (*M* = 70.3, *SD* = 3.8 years; 9 females) volunteered to participate in the study (although 30 participants were tested, 4 were excluded due to poor quality of the motion capture data). The young and older group were significantly different in age, height, knee extensor muscle strength, and hip flexibility (Table 5.1). The assessment of participants' action capabilities is described in detail in Chapter 4. The sample size was informed by previous studies (Mark et al., 1990; Reeves et al., 2009; Scott & Gray, 2010). We also did a sample-size estimation based on Reeves et al. (2009) who measured differences in stair ascent between young and older adults (difference in maximum ankle moment; d = 0.99, two groups, 32 participants). It showed that a sample size of 2 groups of 12 would have a power of 0.8. Participants included were healthy and had a self-reported normal or corrected-to-normal vision. Before the start of the experiment, all participants completed a health questionnaire and were excluded if they reported orthopaedic, neuromuscular, cardiac problems, or balance impairments. Furthermore, older adults were asked to perform the Timed Up and Go Test, which is a measure of mobility (Podsiadlo & Richardson, 1991, see also Chapter 3). If participants were not able to complete the Timed up and Go Test within 13.5 seconds or had been advised not to participate in exercise, they were excluded from further testing. Study procedures were approved by London South Bank University's ethics committee (SAS1715).

Table 5.1 Mean and SD of participants' characteristics and their action capabilities.

Variables (units)	**Young**	**Older**
Age (years)	25.0 ± 5.4	70.3*** ± 3.8
Height (m)	1.75 ± 0.11	1.63** ± 0.06
Weight (kg)	77.0 ± 16.2	63.9 ± 19.2
Knee extensor muscle strength (N)	478 ± 194	275** ± 49.8
Hip flexibility (degrees)	64.0 ± 12.3	82.6** ± 14.3

Notes: Significant differences between older and young groups are indicated by ** $p < .01$ ***$p < .001$. The older group showed less strength and flexibility than the young group.

5.2.2 Set-up

A two-step staircase was designed according to standard guidelines for stair construction (Roys, 2001). A stair construction can be described using three terms: rise, going, and pitch. The rise is the vertical distance between two consecutive treads or between the landing and tread of the stairs. The going is the horizontal distance between two consecutive stair edges. The pitch is the angle between the rise of the second step and the going of the first step. The standard guidelines for stair construction recommend the following dimensions for public stairs: a rise between 100 and 190 mm, a going between 250 and 350 mm, and a pitch of maximal 38 degrees. In addition, the minimum width of a normal public staircase should be 1000 mm. In this study, the two-step staircase had a riser of 180 mm, a going of 270 mm, and a pitch of 31 degrees (see figure 5.1). The set-up also included two force plates (9281E, Kistler Instruments Ltd., UK); the first was placed directly in front of the staircase, and the second force plate was mounted into the first step. A stack of gym steps was placed behind the staircase for safety when participants turned around to walk down the stairs.

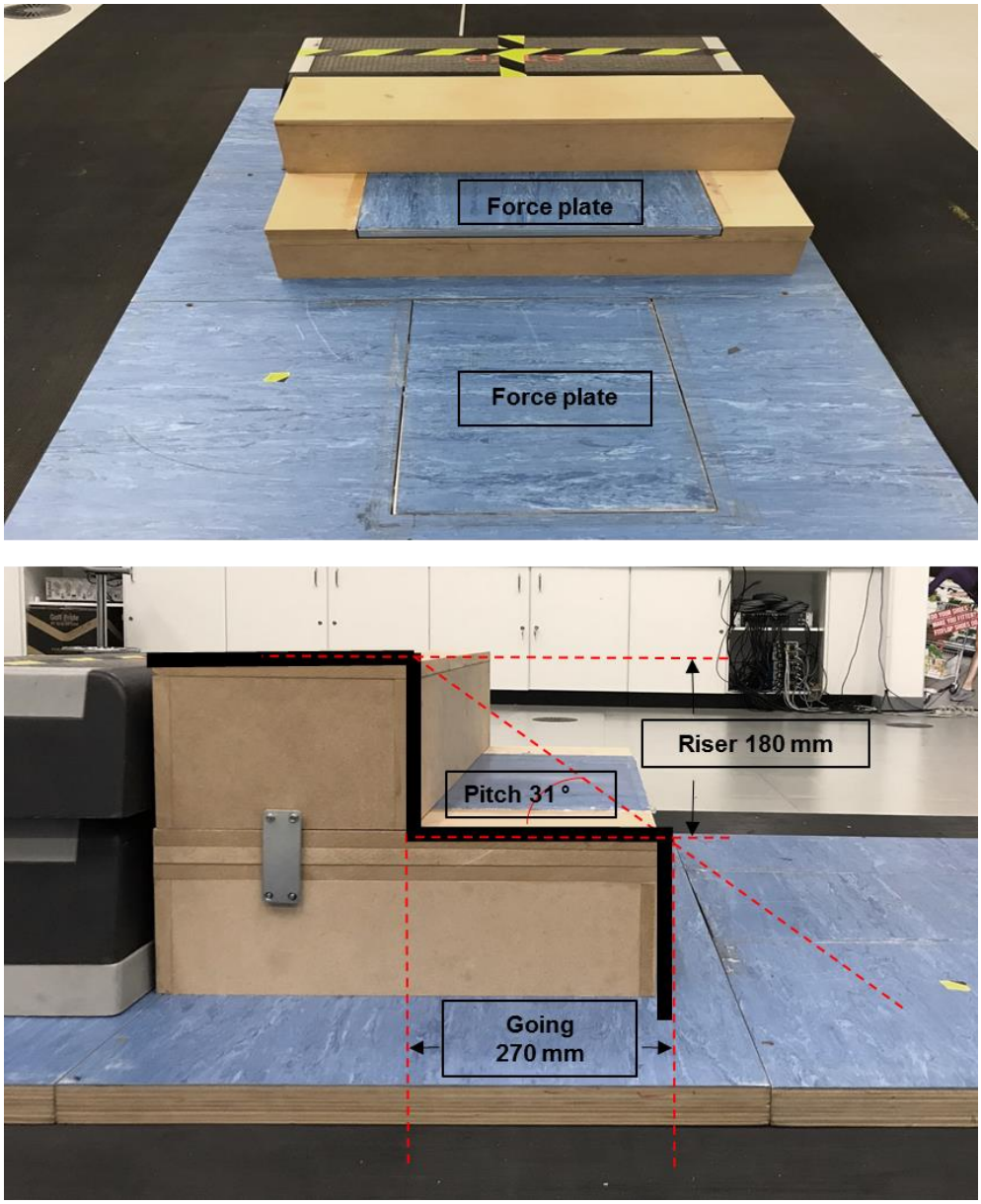


Figure 5.1 A photo of the two-step staircase apparatus. Top) the set-up including two force plates mounted in front and on the first step of the staircase. Bottom) specifications of the staircase construction. This apparatus was designed and built at LSBU by Anderson and Brand.

5.2.3 Procedure

When participants arrived at the lab, the procedures of the study were explained, and consent was obtained. Participants' knee extensor muscle strength, hip flexibility, height and weight were measured to characterise individual action capabilities (see Chapter 4 for assessment of participants' action capabilities). Participants were then fitted with a lower-body marker set which tracked their lower limbs while climbing stairs. For the task, participants were instructed to start with both feet on the first force plate and to climb the staircase using a step-over-step pattern. First, participants were asked to climb the staircase five times without any ankle weights (baseline condition). After the baseline condition, participants were fitted with ankle weights and asked to climb the staircase again for 20 consecutive trials. After 20 trials, the ankle weights were removed, and participants were asked to walk back and forth along a 15 m area for about 3 min to ensure that the effects of the weights were no longer present (i.e., post-recalibration). The second set of weights was then fitted, and the procedure repeated, followed by the last set of weights. The three sets of ankle weights were calculated as a percentage of the individual peak knee extensor muscle strength as measured by maximum voluntary contraction (MVC in Newtons; see Chapter 3). The three weight conditions, which were counterbalanced between participants, were light (1.25% of MVC), medium (2.5% of MVC) and heavy (5% of MVC).

5.2.4 Data acquisition

Individual stepping actions were recorded using 3D motion capture (Qualisys AB, Sweden). A lower-limb model was defined by placing 40 reflective markers which included 26 tracking markers (Jones, James, Thacker, & Green, 2016; Ren, Jones, & Howard, 2008; also see Chapter 3). All markers were used to model the lower-body in the static trial in which participants were asked to hold the anatomical position to take a 5-second capture. The static markers were then removed, and only the tracking markers were used for the subsequent movement trials (see Chapter 3). Marker data were recorded using eight infrared cameras sampled at 100 Hz. This data was synchronously recorded with the analogue input from the two force plates at 1000 Hz (9281E, Kistler Instruments Ltd., UK).

5.2.5 Data analysis

Raw marker and analogue data were imported into Visual3D (C-Motion Inc., USA). Marker data was then filtered with a 4th-order 6Hz low-pass Butterworth filter and force plate data was filtered using a 4th-order 25Hz low-pass Butterworth filter (Alcock et al., 2014, 2013; Jones et al., 2016). After filtering the raw data and calculating the relevant joint angles, the filtered position and kinematic data were exported from Visual3D. Further analyses to calculate and extract the relevant kinematic variables for this study were completed in Matlab 2016b (The MathWorks, Natick, MA, USA).

Step pattern was analysed from the toe-off of the leading foot in the starting position until it landed on the first step. Since participants started each trial standing on the first force plate, this did not allow us to determine toe-off from force plate data. Therefore, similar to Pijnappels et al. (2001), toe-off was detected from the kinematic data as the maximum vertical velocity of the leading foot's calcaneus marker. The landing was determined from the data of the force plate which was mounted in the first step; the first frame where the vertical ground reaction force was consistently over 20N determined foot landing (Zeni, Richards, & Higginson, 2008).

5.2.6 Dependent variables

Using the kinematic data, the following performance variable was calculated from the trajectory of the leading foot for each participant: (1) toe clearance defined as the maximum vertical distance between the first metatarsal marker and the horizontal surface of the step (Alcock et al., 2013; Begg & Sparrow, 2000; Patla & Rietdyk, 1993; Snapp-Childs & Bingham, 2009). The following other action-specific kinematic variables were calculated at the point of toe clearance for the leading and trailing leg (Pijnappels et al., 2001). Joint angles were calculated in the sagittal plane (see Chapter 3): (2) ankle angle (cf., Alcock et al., 2014; Andriacchi et al., 1980; Benedetti et al., 2007; Reeves et al., 2009); (3) knee angle (cf., Alcock et al., 2014; Andriacchi, Andersson, Fermier, Stern, & Galante, 1980; Benedetti et al., 2007; Reeves et al., 2009); (4) hip angle (cf., Alcock et al., 2014; Andriacchi et al., 1980; Benedetti et al., 2007; Reeves et al., 2009); and (5) swing time defined as the difference in time between toe-off and landing of the leading foot on the first step (Benedetti et al., 2007; Sparrow & Tirosh, 2005; Stacoff, Diezi, Luder, Stüssi, & Kramers-De Quervain, 2005).

5.2.7 Statistical analysis

Recalibration should be visible over time and can be measured by investigating whether a disturbance was followed by a visible perceptual-motor rearrangement. For each kinematic variable, we assessed the different markers of the process of recalibration (i.e., disturbance and rearrangement) using linear regressions. To evaluate the effect of the *disturbance*, we fitted linear regressions over the average of the last three baseline trials and the first trial for each group/condition. These slopes were submitted to a one-sample t-test to test against a slope of 0. Significant differences indicate an effect of the disturbance. Normality was confirmed using the Shapiro-Wilk test.

To determine whether *recalibration* occurred, we first fitted a piecewise regression over trials 1 to 20 (see Chapter 3) for each group and condition. This regression analysis method, which has not been applied to recalibration before, partitioned the data into two intervals and fitted a separate regression to each interval. The boundary between the two intervals is known as breakpoint. Next, we fitted two regressions to the data of each participant and condition using breakpoint previously found for the group. For example, if the breakpoint in the light weight condition for young adults was identified at trial 7, then linear regressions were fitted over trials 1-7 and trials 7-20 for each participant in that group/condition. The piecewise regression method was applied to each of the kinematic variables. The slopes of the two individual regressions were submitted to a two-way mixed ANOVA with within-subjects factors Condition (3 levels: light vs medium vs heavy), Time (2 levels: initial vs final), and between-subjects factor Group (2 levels: young vs old). Homogeneity of variance was confirmed using the Levene's test. Where a violation of sphericity was found in Mauchly's test, a Greenhouse-Geisser correction was applied. Post-hoc tests with Least Significant Difference (LSD) correction were applied on significant main effects. The *point of recalibration* was recorded as the breakpoint found during the piecewise regression, where the previous analysis showed an effect of recalibration. Throughout the analysis of the results, a significance level (alpha) of 5% was used. All statistical data were analysed using SPSS 21.0.

5.3 Results

In this section, the results for each kinematic variable will be presented in regards to disturbance effects and recalibration effects. Where recalibration effects are found, we also present data on the point of recalibration.

5.3.1 Toe clearance

The light weight disturbance had a significant effect on toe clearance for the young group only, $t(13) = 3.68$, $p = .003$, $d = 0.982$, increasing it by 18.1 mm ($SE = 4.92$). In the remaining weight conditions toe clearance increased but no significant effects were found for the young group (medium: $t(13) = 2.11$, $p = .055$; heavy: $t(13) = 1.37$, $p = .193$) or the older group (all $t < 1.50$, $p > .100$).

Regarding recalibration, results showed a main effect of time, $F(1, 22) = 18.5$, $p < .001$, $\eta^2 = 0.839$, because the initial rearrangement slope ($M = -3.57$, $SE = 0.749$) was steeper than the final slope ($M = -0.225$, $SE = 0.074$, see figure 5.2). There was no main effect of weight, $F(2, 44) = 2.13$, $p = .131$, $\eta^2 = 0.098$, and no significant group effect, $F(1,22) = 2.41$, $p = .135$, $\eta^2 = 0.109$. No interaction effects were found (all $F < 1.50$, $p > .100$).

Regarding the point of recalibration, the breakpoint analysis showed that while young adults recalibrated within 3-4 trials for the light and medium weight conditions and 7 trials in the heavy weight condition, older adults took between 6 and 8 trials to recalibrate in all weight conditions (see figure 5.2).

5.3.2 Ankle joint angle (leading leg)

Regarding the disturbance, no significant effects were found for the young group (all $t(11) < 1.3$, $p > .100$) or for the older group (all $t(9) < 1.00$, $p > .100$).

Regarding recalibration, results showed a main effect of time, $F(1, 20) = 22.24$, $p < .001$, $\eta^2 = 1.11$, because the initial rearrangement slope ($M = 2.06$, $SE = 0.442$) was steeper than the final slope ($M = -0.018$, $SE = 0.017$; see figure 5.2). No main effects of condition or group were found, respectively, $F(2, 40) = 0.077$, $p = .926$, $\eta^2 = 0.004$, and $F(1, 20) = 0.003$, $p = .864$, $\eta^2 = 0.002$. Also, no interaction effects were found (all $F < 1.00$, $p > .100$).

Regarding the point of recalibration, the breakpoint analysis showed that both groups recalibrated within 2 trials in all weight conditions (see figure 5.2).

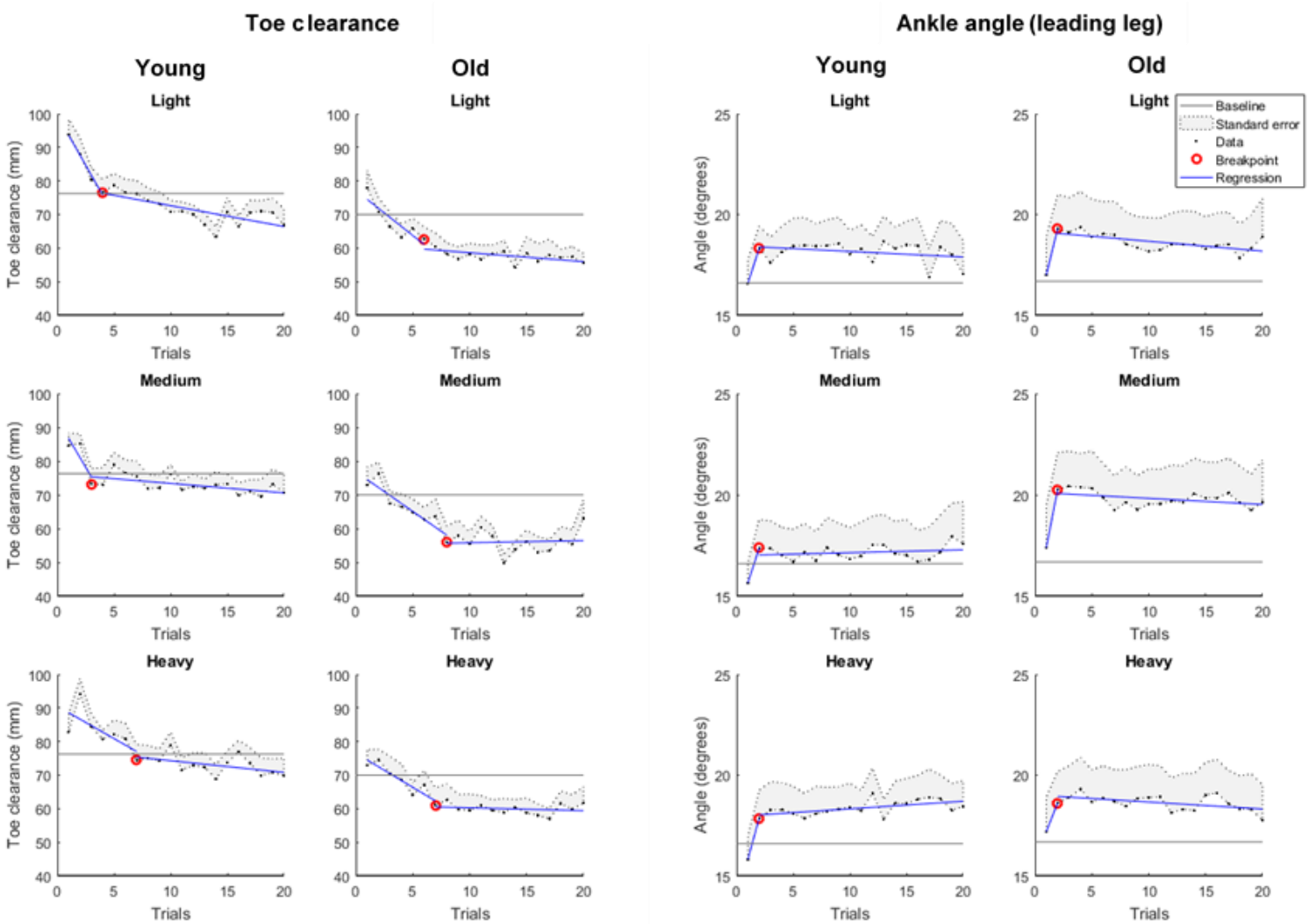


Figure 5.2 An outline of recalibration for both groups in toe clearance and the ankle joint angle of the leading leg. Shaded areas represent the positive standard error of the mean

5.3.3 Knee joint angle (leading leg)

Regarding the disturbance, no significant effects were found for the young, t(12) < 1.5, $p > .100$, or the older group, t(8) < 1.5, $p > .100$.

Regarding recalibration, results showed a main effect of time, $F(1, 19) = 24.8$, $p < .001$, $\eta^2 = 1.31$, because the initial rearrangement slope ($M = -5.42$, $SE = 1.09$) was steeper than the final slope ($M = -0.004$, $SE = 0.039$, see figure 5.3). There were no main effects of condition and group, respectively $F(2, 38) = 1.001$, $p = .377$, $\eta^2 = 0.053$, and $F(1, 19) = 1.05$, $p = .319$, $\eta^2 = 0.055$. There were no interaction effects (all $F < 1.5$, $p > .100$).

Regarding the point of recalibration, the breakpoint analysis showed that young and older adults recalibrated within 2 trials in all weight conditions (see figure 5.3).

5.3.4 Hip joint angle (leading leg)

Regarding the disturbance, no significant effects were found for the young, all t(11) < 1.3, $p > .100$, or the older group, all t(10) < 2.00, $p > .05$).

Regarding recalibration, there was no main effect of time, $F(1, 20) = 3.37$, $p = .081$, $\eta^2 = 0.168$. Results showed a significant effect of group, $F(1, 20) = 7.181$, $p = .014$, $\eta^2 = 0.363$,because the slopes were steeper in the older group ($M = 0.543$, $SE = 0.150$) than in the young group ($M = 0.020$, $SE = 0.125$). No main effect of condition was found, $F(2, 40) = 2.04$, $p = .144$, $\eta^2 = 0.102$. Results showed no Time × Group, $F(1, 20) = 3.56$, $p = .074$, $\eta^2 = 0.177$, and no Condition × Time interaction, $F(1.49, 29.7) = 2.81$, $p = .072$, $\eta^2 = 0.141$. No other interaction effects were found (all $F < 1.00$, $p > .100$). Figure 5.3 shows a large initial slope in the older group for the heavy weight, which an additional *t*-test showed was significantly different from the final slope, t(9) = 2.99, $p = .015$, $d = 1.33$.

Regarding the point of recalibration, the breakpoint analysis showed no evidence of recalibration in young adults, but it seems that older adults in the heavy condition may have recalibrated within 2 trials (see figure 5.3).

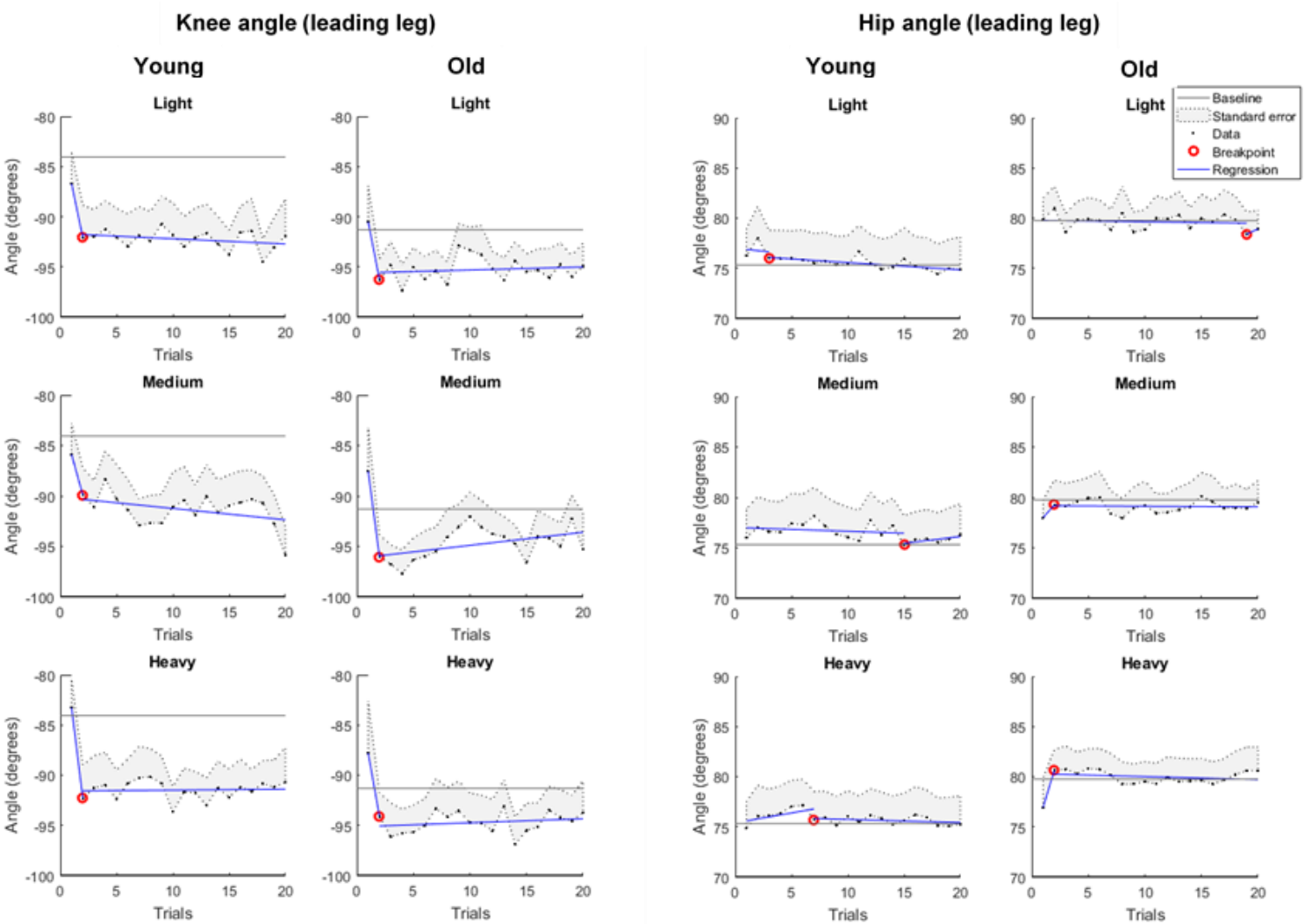


Figure 5.3 An outline of recalibration for both groups in the knee and hip joint angle of the leading leg. Shaded areas represent the positive standard error of the mean.

5.3.5 Swing time

Regarding the disturbance, significant effects were found for all weight and group conditions (all t(12) > 4.91, all $p < .001$, all $d > 0.60$) because swing time increased from baseline to the first disturbance trial (see Table 5.4). For the young group swing times increased by 73.1 ms (*SE* = 13.0), 69.4 ms (*SE* = 14.1), and 97.4 ms (*SE* = 14.5) for the light, medium and heavy conditions respectively. For the older group, swing time increased by 64.8 ms (*SE* = 19.3), 81.8 ms (*SE* = 42.6), and 50.8 ms (*SE* = 29.3) for the light, medium and heavy conditions.

Regarding recalibration, results showed a main effect of time, $F(1, 21) = 28.3$, $p < .001$, $\eta^2 = 1.36$, because the initial rearrangement slope (*M* = -0.058, *SE* = 0.011) was steeper than the final slope (*M* < 0.001, *SE* < 0.001). There were no main effects of condition, $F(2, 42) = 2.19$, $p = .125$, $\eta^2 = 0.107$, or group, $F(1,21) = 0.234$, $p = .634$, $\eta^2 = 0.013$. Results showed no Condition × Group interaction, $F(2, 42) = 2.83$, $p = .070$, $\eta^2 = 0.139$, and no Condition × Time × Group interaction, $F(2, 42) = 2.75$, $p = .075$, $\eta^2 = 0.133$. . No other significant interactions were found (all $F < 3.00$, $p > .05$).

Regarding the point of recalibration, the breakpoint analysis showed that both groups recalibrated within 2 trials across all weight conditions (see figure 5.4).

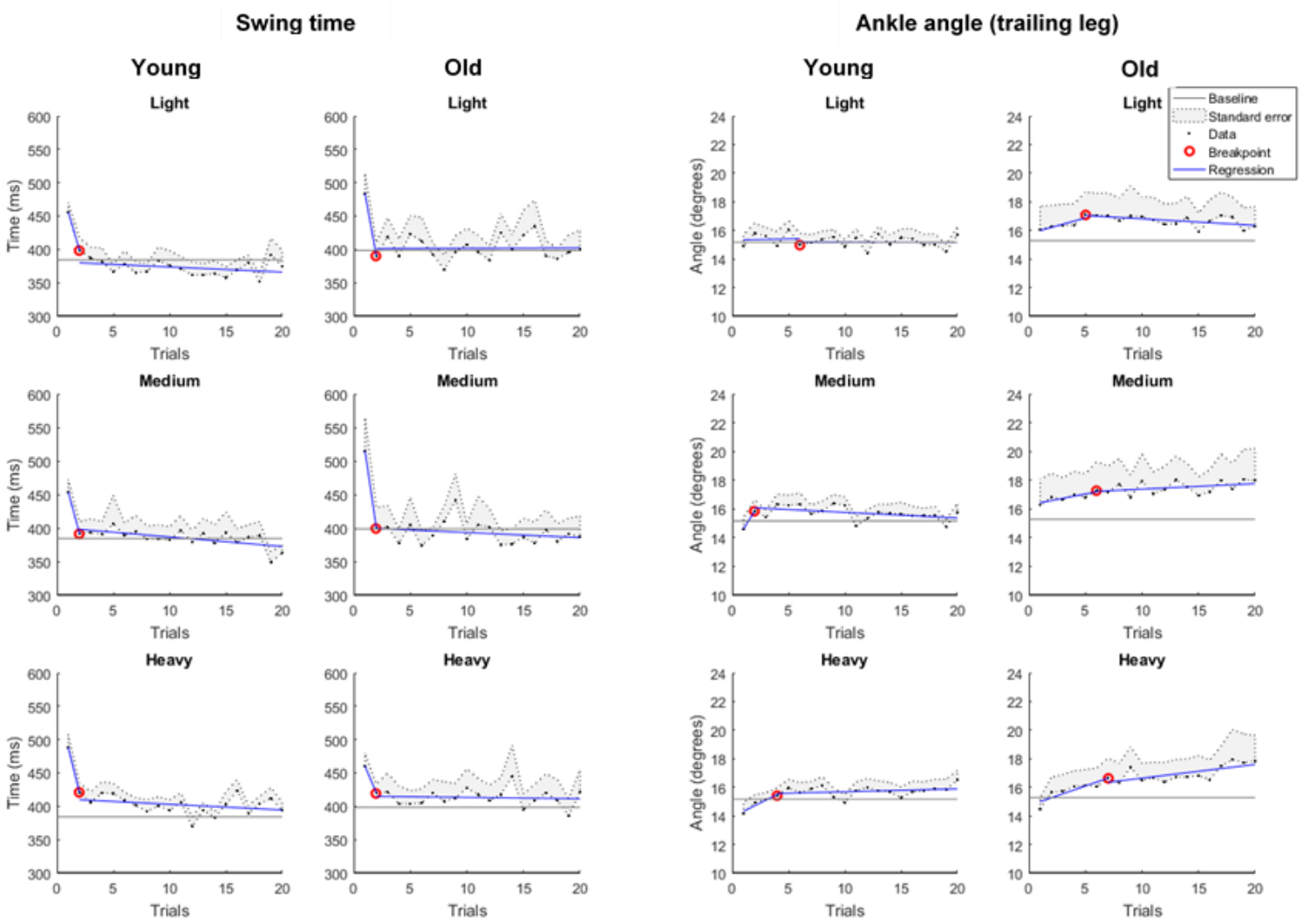


Figure 5.4 An outline of recalibration for both groups in swing time and ankle joint angle of the trailing leg. Shaded areas represent the positive standard error of the mean.

5.3.6 Ankle joint angle (trailing leg)

Regarding the disturbance, no effects were found for all weight conditions for young (all t(12) < .700, $p > .100$) and older groups (all t(11) < 1.1, $p > .100$).

Regarding recalibration, results showed a main effect of time, $F(1, 22) = 4.46$, $p = .046$, $\eta^2 = 0.203$, because the initial rearrangement slope ($M = 0.365$, $SE = 0.165$) was steeper than the final slope ($M = 0.008$, $SE = 0.015$). There was no main effect of condition, $F(1.5, 32.9) = 3.28$, $p = .063$, $\eta^2 = 0.149$. No significant effect of group was found, $F(1,22) = 0.525$, $p = .476$, $\eta^2 = 0.024$. Results showed a significant interaction between Condition × Time × Group, $F(1.64, 36.1 = 3.58$, $p = .047$, $\eta^2 = 0.163$, because the initial rearrangement slopes were steeper for the young group for the medium weight, while the old group had a steeper initial rearrangement slope for the light weight (see figure 5.4). No Condition × Group interaction was found, $F(1.5, 32.9) = 3.18$, $p = .068$, $\eta^2 = 0.145$. No other significant interactions were found (all $F < 2.50$, $p > .100$). Figure 5.4 shows very similar initial and final slopes in the young group for the light weight, which an additional *t*-test showed was not significantly different, t(13) = 0.009, $p = .993$. It also shows that in the older group the initial and final slopes were similar in the medium weight condition, which an additional *t*-test showed was not significantly different, t(10) = 0.716, $p = .490$.

Regarding the point of recalibration, the breakpoint analysis showed that young adults recalibrated within 2 and 4 trials in the medium and heavy weight conditions, whereas older adults recalibrated within 5 and 7 trials in the light and heavy conditions (see figure 5.4).

5.3.7 Knee joint angle (trailing leg)

Regarding the disturbance, no significant effects were found for all weight conditions for the young (all $t(13) < 1.2$, $p > .100$) and older groups (all $t(10) < 1.4$, $p < .100$).

Regarding recalibration, results showed no main effect of time, $F(1, 22) = 2.34$, $p = .140$, $\eta^2 = 0.106$ (see figure 5.5). There were also no main effects of condition, $F(1.09, 23.9) = 1.48$, $p = .238$, $\eta^2 = 0.067$, or group, $F(1, 22) = .008$, $p = .930$, $\eta^2 = 0.0004$. No other significant interactions were found (all $F < 1.00$, $p > .100$).

5.3.8 Hip joint angle (trailing leg)

Regarding the disturbance, no significant effects were found for all weight conditions for the young (all $t(13) < 2.00$, $p > .100$) and older groups (all $t(9) < 1.10$, $p > .100$).

Regarding recalibration, results showed a main effect of time, $F(1, 21) = 21.9$, $p < .001$, $\eta^2 = 1.04$, because the initial rearrangement slope ($M = 1.97$, $SE = 0.416$) was steeper than the final slope ($M = -0.020$, $SE = 0.027$; see figure 5.5). There was no main effect of condition, $F(1.53, 32.2) = 0.865$, $p = .404$, $\eta^2 = 0.041$, or group, $F(1, 21) = 3.04$, $p = .096$, $\eta^2 = 0.145$. No significant interactions were found (all $F < 3.00$, $p > .100$).

Regarding the point of recalibration, the breakpoint analysis showed that both groups recalibrated within 2 trials across all weight conditions (see figure 5.5).

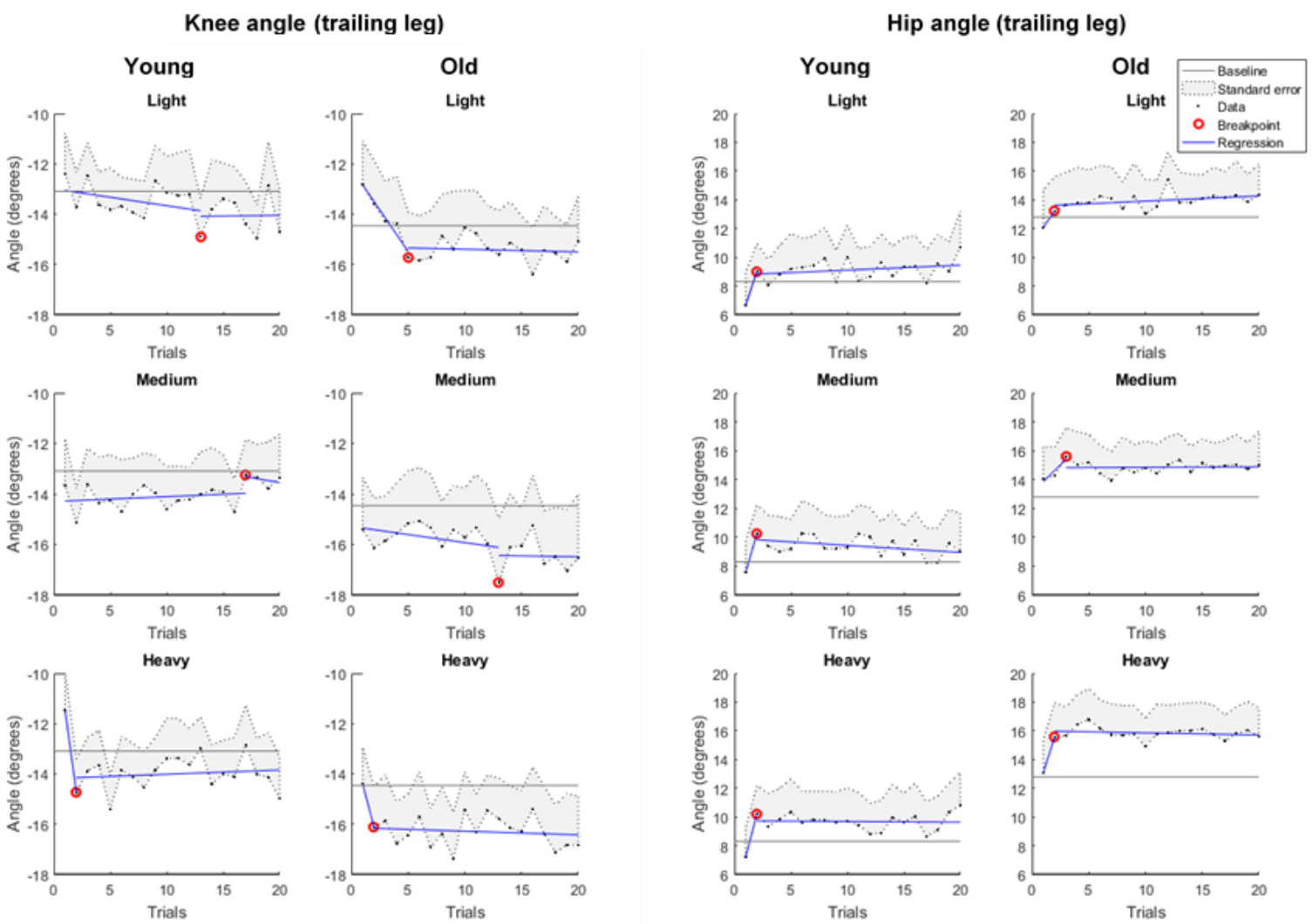


Figure 5.5 An outline of recalibration for both groups in the knee and hip joint angle of the trailing leg at point of toe clearance. Shaded areas represent the positive standard error of the mean.

5.4 Discussion

This study examined the speed of recalibration in stair climbing. Specifically, we investigated how long young and older adults take to recalibrate to disturbances of different magnitudes. As toe clearance is the performance measure that informs on recalibration in this experiment, these results will be discussed accordingly. Results showed that older adults took a few extra trials to recalibrate compared to young adults. While young adults took 3-7 trials, the older adults took 6-8 trials across weight conditions. Results also showed that young adults recalibrated faster for smaller disturbances and slower for large disturbances, but that older adults used a similar recalibration time for all disturbances. In addition, we were interested to see whether recalibration was preceded by a significant effect of disturbance and results showed that this was seldom the case.

Overall, the results confirmed our hypothesis that older adults recalibrate slower than young adults when climbing a set of stairs (cf. Bierbaum et al., 2011; Fernández-Ruiz et al., 2000; McCrum et al., 2016). Although older adults were slower in their recalibration, they did get back into a stable movement pattern and, therefore, it is clear that the ability to recalibrate their perceptual-motor system is not impaired. Similar to Scott and Gray (2010), we measured a variety of action-specific kinematic variables to inform on differences between the two groups that could have led to this slower recalibration. Most kinematic variables showed complete recalibration within two trials except for the trailing ankle angle, which varied across groups/conditions. For this reason, we suggest that older adults may have recalibrated slower into a stable movement pattern due to slower recalibration in the trailing ankle angle. Previous research has shown that wearing a loaded backpack walking up the stairs resulted in a visibly larger trailing ankle dorsiflexion and increased the muscle activation of the gastrocnemius (Yali, Aiguo, Haitao, & Songqing, 2015). However, older adults often use smaller ankle plantarflexion moments when climbing stairs, and therefore rely less on their ankle muscles, such as the gastrocnemius (Novak & Brouwer, 2011; Reeves et al., 2009). The slower recalibration in the ankle angle observed in our results could be the combined result of the added weight and older age.

Unexpectedly, toe clearance results showed that the relationship between weight and recalibration speed was not monotonic. Although our results showed that small and medium disturbances resulted in a faster recalibration than a larger disturbance, this was found only for young adults. Older adults took a similar amount of trials to recalibrate to all of the disturbances. This indicates that older adults responded similarly to small and large

disturbances. In contrast, previous research showed that an increasing amount of trials were needed to recalibrate to larger disturbances compared to small disturbances (Durgin et al., 2005; Fernández-Ruiz & Díaz, 1999; Van Hedel & Dietz, 2004). This non-monotonic relationship between disturbance and recalibration time could indicate that older adults may have overcompensated the initial rearrangement for smaller disturbances. For example, previous research has shown that older adults were more likely to respond to lower perturbation magnitudes than young adults and were more likely to use an extra step to recover their balance after a moving platform was used to disturb their balance (Jensen, Brown, & Woollacott, 2001; Maki, Edmondstone, & McIlroy, 2000). Older adults may have used the overcompensation as a safety mechanism after disturbances, which ultimately led to a similar recalibration across disturbances.

Although it seemed logical that the effect of the disturbance should be significantly different from baseline, our results did not consistently show a significant effect of disturbance. A significant disturbance effect was only found in the light weight condition for the young adults, but not in any other conditions/groups. Especially for the older group, the toe clearance on the first trial was similar to the baseline. This may be because, being aware of the weights attached to their ankles, participants made an effort to maintain or slightly raise their toe clearance but were not able to increase toe clearance as much as young adults due to reduced muscle strength. It is noteworthy that while a lower toe clearance in our study could result in participants painfully bumping their toes into the step, this was not the case in previous studies. For example, the batters in Scott and Gray (2010) study would suffer no major consequence for less accurate swings. It seems possible that, therefore, participants will have tried to maintain their safety margin. After a few trials, their perceptual-motor system may have gathered sufficient information to safely lower toe clearance, thereby recalibrating to a new toe clearance during the final rearrangement. The new lower toe clearance in older adults, may have also been the result of reduced leg muscle strength, which might limit their ability to clear the step with the weights (cf., Chiou, Turner, Zwiener, Weaver, & Haskell, 2012; Johnson, Buckley, Scally, & Elliott, 2007).

The question that arises is whether a significant effect of disturbance in toe clearance is a prerequisite for recalibration or whether visibly disturbing participants' actions (captured in other variables) is enough. Although no significant disturbance was found in toe clearance, results of the piecewise regressions showed that recalibration did occur. Alternative methods were used in previous research in which studies compared the regression slopes of the

experimental and control condition to zero to show whether recalibration occurred or not (Mark, 1987; Mark et al., 1990; Yu & Stoffregen, 2012). This means that a slope significantly different from zero indicates recalibration and a slope close to zero no recalibration. As the present study only had five baseline trials, it was not possible to use this data as a control condition and compare the slope to zero. This is a limitation of the present study, and therefore, future studies are advised to use extended baselines to show that no recalibration occurred in the baseline/control conditions (Chapter 6).

Where previous studies gave an estimated range of time needed for recalibration, our study devised a new methodology to measure recalibration using initial and final rearrangement slopes, which gave us a more precise measure of how long recalibration took. We predicted that there would be a decline in stepping performance for the first few steps after each disturbance, followed by a fast initial rearrangement of the perceptual-motor system. Having derived a broad range of kinematic variables from stair climbing literature, results showed recalibration was visible in many but not all variables. This is important because it seems the methodology is sensitive to instances where recalibration is visible. Where recalibration is not visible, the methodology returns similarly sloped regressions and/or unreasonable breakpoints. Future work can refine the methodology by implementing these errors as constraints on the program syntax to refine and automatically detect the cases where recalibration is not visible. For now, it is important to carefully study the output to evaluate whether the recalibration process is visible. As this is the first study to apply this methodology, and it is important to know the time course of recalibration, further studies should use this methodology investigating other tasks. For example, the methodology used in this study can be replicated by using similar everyday tasks, like crossing an obstacle (see Chapter 6).

In contrast to Chapter 4 and most previous studies that asked participants to judge maximum action boundary, the present study used an everyday and non-maximal stepping task to measure recalibration. This change in approach is an improvement because in non-maximal tasks, the perception of action-scaled affordances is important for the ongoing guidance of actions, because the limits on participants' capabilities to step onto, run, or turn, place critical constraints on successful performance (Fajen, Riley, & Turvey, 2009). Thus, for a successful performance, participants move in such a way that the action is still possible. Fajen referred to this as the affordance-based control framework and proposed that people move in such a way that the ideal state does not cross their action boundary (Fajen, 2005, 2007). This means that,

in the present study, both groups of participants climbed the stairs in such a way that ‘climbing up’ the stairs was always afforded.

5.4.1 Conclusions

This study examined how long young and older adults take to recalibrate to disturbances of different magnitudes. In general, results showed that while young adults took 3-7 trials, the older adults took 6-8 trials across weight conditions for toe clearance. In addition, results showed that while young adults recalibrated faster to smaller disturbances, older adults may have overcompensated the initial rearrangement for smaller disturbances, which resulted in a similar point of recalibration across disturbances. Although it seemed logical that the effect of the disturbance should be visible against the baseline, our results did not consistently show it. Therefore, future studies are advised to use extended baselines conditions. Given how little is known about the time course of recalibration, it is important to continue investigating this topic going forward.

5.4.2 Relevance for the following chapter

Chapter 5 showed that older adults took a few more trials than young adults for toe clearance to be fully recalibrated. Where previous studies gave an estimated range of time needed for recalibration, our study used an innovative methodology to measure recalibration using initial and final rearrangement slopes, which gave us a more precise measure of how long recalibration took. Chapter 6 uses this methodology to investigate recalibration in another everyday activity by asking participants to cross obstacles of varying height.

Chapter 6

Exploring age-related differences in recalibration speed when crossing varying obstacles

Abstract

In everyday life, the environment is unpredictable, which means that it is important to pick up the changing environmental information as well as recalibrate to a disturbance in order to act safely. The aim of this study was to investigate whether there are age-related differences in the speed of recalibration when crossing obstacles of varying height. A total of 24 participants consisting of 12 young (*M* = 28.9, *SD* = 6.2 years; 8 females) and 12 older adults (*M* = 71.6, *SD* = 4.0 years; 7 females) volunteered to participate in the study. Participants' step pattern was motion-tracked using a lower-body marker set while they walked and crossed an obstacle of varying heights. Participants crossed the obstacle for 30 trials without any ankle weights (*baseline*). Then the same procedure was repeated after participants were fitted with heavy ankle weights (*disturbance*) and repeated again after the weights were removed (*removal*). To determine whether recalibration occurred, we analysed the data in three steps. First, piecewise regressions were applied to each of the kinematic variables to find the breakpoint. Next, using that breakpoint, we fitted two regressions to the individual data. Finally, the two individual regression slopes were submitted to two-way mixed ANOVA with within-subjects factors Condition (2 levels: disturbance vs removal) and Time (2 levels: initial vs final rearrangement), and between-subjects factor Group (2 levels: young vs older). Results for toe clearance showed that while young adults took 11 trials to recalibrate older adults only needed 5 trials. No age-related differences were found upon the disturbance removal. It seems that the process of recalibration was intact in both groups but may have been constrained by reduced action capabilities and perceived consequences of the task in the older group.

6.1 Introduction

Mrs Poorthuis likes to stay active, and this morning she has planned to go on a walk through the forest with her granddaughter. After getting out of the car, it is a short walk to the forest path, but her legs are feeling a little stiff and tired. It rained the previous night, so the path is full of twigs and branches, puddles and loose stones. These obstacles are not usually a problem for Mrs Poorthuis if only she could get used to her tired legs faster. The stiffness and fatigue disturbed Mrs Poorthuis' action capabilities prompting the start of the recalibration process. Being faced with a variety of obstacles means that it is important to pick up information about them as well as recalibrate to a disturbance in order to act safely. While Chapter 5 measured recalibration in a predictable environment, in everyday life, the environment is often more unpredictable. A review on falls in older adults has shown that a range of items, such as loose items on the floor, differences in carpet structure, and small steps can lead to falls (Lundebjerg, 2001). Therefore, this chapter will set out to investigate age-related differences in the speed of recalibration in an unpredictable environment (i.e., when crossing varying obstacles).

In general, research has shown that older adults tend to use conservative strategies to cross obstacles in unpredictable environments (Caetano et al., 2016; Lu, Chen, & Chen, 2006; Patla & Rietdyk, 1993; Shin et al., 2015; Yen, Chen, Liu, Liu, & Lu, 2009). For example, Caetano et al. (2016) presented obstacles to participants suddenly and found that older adults significantly slowed down, took more steps and demonstrated poorer stepping accuracy compared to young adults. Patla and Rietdyk (1993) found that older adults crossed obstacles that were 6.7, 13.4, and 26.8 cm with a higher toe clearance than young adults. Other studies also found that older adults crossed obstacles that were 10%, 20% and 30% of leg length with a higher and increasing leading toe clearance compared to young adults (respectively, Yen et al., 2009; Lu et al., 2006). These studies concluded that older adults might use a conservative strategy as a result of an age-related decrease in lower-limb strength. Moreover, previous research reported that in predictable environments with repetitive tasks, older adults recalibrate slower than young adults to motor disturbances, which is also what we also found in Chapter 5 (Bierbaum, Peper, Karamanidis, & Arampatzis, 2011; McCrum et al., 2016). It follows that in unpredictable environments, these effects may be enlarged as older adults adopt a conservative strategy while coping with environmental variability. For this reason, we hypothesise that older adults will recalibrate (even) slower than young adults when crossing obstacles of varying heights.

One feature of the recalibration process that was discussed in Chapter 2 but has not been addressed so far is the removal of the disturbance. Several studies measured the effect of removing the disturbance after the rearrangement period (e.g. Bruggeman, Pick, & Rieser, 2005; Kunz, Creem-Regehr, & Thompson, 2009, 2013, 2015; Rieser, Pick, Ashmead, & Garing, 1995; Withagen & Michaels, 2002, 2007). These studies showed that recalibration had occurred because removing the disturbance (to which they had recalibrated) caused an *aftereffect*. After the removal of a disturbance, a new rearrangement period occurs in which participants get used to their new capabilities and usually recalibrate back to baseline (see figure 2.1, Chapter 2). This has mainly been shown in prism adaptation studies (e.g., Alexander, Flodin, & Marigold, 2011; Dotov et al., 2013; Fernández-Ruiz & Díaz, 1999; Fernández-Ruiz et al., 2000; Redding, 2001; Redding & Wallace, 2002). For example, participants first recalibrated to left-shifting prism glasses when throwing balls at a target, which meant that after removing the glasses, participants threw the ball to the right of the target. Studies have shown that aftereffects are similar for both young and older adults (Bock, 2005; Fortis et al., 2013; McCrum et al., 2016; Roller, Cohen, Kimball, & Bloomberg, 2002; Vervoort et al., 2019). For example, Fortis et al. 2013 found comparable aftereffects for young and older adults after performing a pointing task with prism glasses, and this was replicated in other ecological tasks. Likewise, McCrum et al. (2016) found similar aftereffects for young and older adults. First, they showed that participants recalibrated after resistance was applied to the swing phase while walking on the treadmill. Upon removal of the resistance, the aftereffect was visible as a sudden increase in the base of support. Here we used an experimental design commonly used for prism adaptation experiments which allowed us to gain insight into recalibration to the disturbance and after disturbance removal. This involved testing participants at baseline without disturbance, during the rearrangement of the disturbance, and during the post-rearrangement upon removal of the disturbance.

When crossing obstacles, comparable to stair climbing, a person steps over the obstacle with their leading foot, shifts their weight to that foot and then swings their trailing foot over the obstacle. The risk of stumbling or falling arises from the possible interference of the leading foot with the obstacle in the swing phase, indicating that a person should employ a safety margin when crossing the obstacle. Falls could also arise from instability, which can lead to a loss of balance and stumble (Austin et al., 1999). Obstacle crossing studies have shown that older adults tend to cross obstacles more slowly and place their feet closer to the obstacle before crossing it (Austin et al., 1999; Chen et al., 2008; Pan et al., 2016; Patla et al., 1996). Placing

their feet closer to the obstacle means that they have less time to clear the edge of the obstacle, which could increase the risk of tripping. For the present study, toe clearance, again, will be the performance measure that informs on step accuracy, and the other action-specific kinematic measures, like toe-off distance, and lower-limb joint kinematics, will be used to inform on differences in the step pattern when crossing obstacles (see also Chapter 3).

The aim of this study is to investigate whether there are age-related differences in the speed of recalibration when crossing varying obstacles. This required participants to recalibrate to the weight disturbance in an unpredictable environment., which we predict takes longer older adults than for young adults (i.e., performing several trials before they recalibrate; cf. Lu et al., 2006; Yen et al., 2009). We expect both groups to show a disturbed stepping performance for the first few steps after the disturbance is applied, followed by a fast rearrangement of the perceptual-motor system. We expect to see similar aftereffects for both groups in some of the kinematic variables (Bock, 2005; McCrum et al., 2016; Roller et al., 2002; Vervoort et al., 2019) and are interested to see whether older adults recalibrated slower upon the removal of the disturbance.

6.2 Methods

6.2.1 Participants

A total of 24 participants consisting of 12 young (*M* = 28.9, *SD* = 6.2 years; 8 females) and 12 older adults (*M* = 71.6, *SD* = 4.0 years; 7 females) volunteered to participate in the study. The young and older group were significantly different in age, knee extensor muscle strength, and hip flexibility (Table 6.1). The assessment of participants' action capabilities, which was also used in Chapter 5, is described in detail in Chapter 4. The sample size was informed by a sample-size calculation based on previous studies (Mark, Balliett, Craver, Douglas, & Fox, 1990; Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2009; Scott & Gray, 2010, see Chapter 5 for details of this calculation). All participants included in the study were healthy and had a self-reported normal or corrected-to-normal vision. Before the start of the experiment, all participants completed a health questionnaire and were excluded if they reported orthopaedic, neuromuscular, cardiac problems, or balance impairments. In addition, older adults were asked to perform the Timed Up and Go Test to assess their lower extremity functioning and fall risk (Podsiadlo & Richardson, 1991; see also Chapter 3). If they were not able to complete the test within 13.5 seconds or had been advised not to participate in exercise,

they were excluded from further testing. Study procedures were approved by London South Bank University's ethics committee (SAS1805).

Table 6.1 Mean and SD of participants' characteristics and their action capabilities

Variables (units)	**Young**	**Older**
Age (years)	28.9 ± 6.2	71.6*** ± 4.0
Height (m)	1.69 ± 0.10	1.65 ± 0.06
Weight (kg)	68.1 ± 11.2	70.2 ± 18.0
Knee extensor muscle strength (N)	437 ± 139	312* ± 77.5
Hip flexibility (degrees)	69.9 ± 9.5	86.6** ± 13.9

Notes: Significant differences between young and older groups are indicated by *$p < .05$, **$p < .01$ or ***$p < .001$. The older group showed less strength and flexibility than the young group.

6.2.2 Set-up

As research has shown that obstacles ranging from loose items on the floor to small steps can lead to falls (Lundebjerg, 2001), the obstacle height varied from 90 to 180 mm. The lower limit referred to clutter on the floor, a curb, or a small step, and the upper limit was equal to the stair height used in Chapter 5. The obstacle was a long wooden plank measuring 80 × 750 × 20 mm, which was attached to the top of a mechanical device (see figure 6.2). The mechanical device consisted of an aluminium plate mounted on top of a scissor system that was moved up and down using an electric scissor jack (designed by Lavandeira, LSBU). Four markers were attached to the obstacle monitoring its height and position in space. The experimenter used this information to change obstacle height rapidly using the controller of the mechanical device. The obstacle was positioned in the middle of a runway with a tripod on either end of the runway, and an electrical button switch was attached to the top of each tripod. Force plates (9281E, Kistler Instruments Ltd., UK) were placed on either side of the obstacle, so participants stepped on them before and after crossing the obstacle.

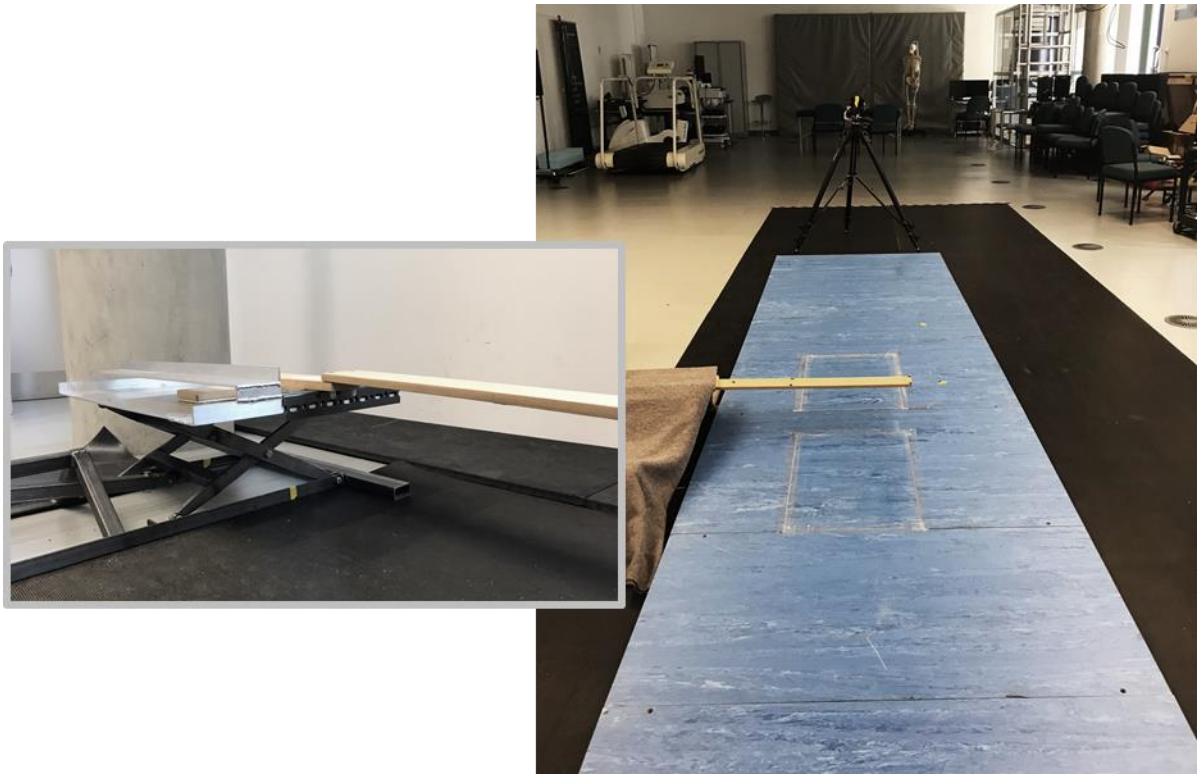


Figure 6.1 A photo of the obstacle apparatus and set-up. The setup consisted of the obstacle apparatus set halfway on a runway between two force-plates. The apparatus consisted of a mechanical device with adjustable height and an obstacle add-on. It was designed and built by Lavandeira of the Engineering Department at LSBU, and the obstacle add-on was designed and built by Hope and Brand. The obstacle apparatus was covered during experiments (photo on the right) but is visible on the left. The obstacle was 80 × 750 × 20 mm, and its height ranged from 90 to 180 mm. Four markers were attached to the obstacle monitoring its height and position in space.

6.2.3 Procedure

When participants arrived at the lab, the procedures of the study were explained. After receiving consent, participants' hip flexibility, knee extensor muscle strength, body weight, and length were measured to characterise their action capabilities. Participants' step pattern was measured using a lower-body marker set (see Chapter 3) while they walked and crossed an obstacle. Participants were instructed that the task was to walk from one end of the runway to the other to touch a button on the tripod, crossing the obstacle when they encountered it. Touching the button served the sole purpose of directing participants' attention away from the obstacle. When they touched the button on the tripod, participants were asked to wait for the experimenter to call them for the next trial; this allowed time for the experimenter to change

obstacle height without participants seeing it. In all conditions, heights were pseudo-randomised and presented to the participants in 3 blocks of 10 heights (ranging from 9 to 18 cm). In the first condition (*baseline*), participants were asked to cross the obstacle for 30 trials without any ankle weights. In the second condition (*disturbance*), participants were asked to perform 30 trials while wearing heavy ankle weights (5% of MVC in Newtons, see Chapter 3). Participants were instructed not to move or sway after having weights fitted around their ankles until they were allowed to walk and cross the obstacle. In the final condition (*removal*), the ankle weights were removed, and participants were asked to perform 30 trials.

6.2.4 Data acquisition

Similar to Chapter 5, step pattern was measured using 3D motion capture; a lower-limb model was defined by placing 40 reflective markers which included 26 tracking markers (Jones, James, Thacker, & Green, 2016; Ren, Jones, & Howard, 2008; also see Chapter 3). Again, all markers were used to model the lower-body in a static trial in which participants were asked to hold the anatomical position to take a 5-second capture. The tracking markers were then used to track the 3D trajectories of the left and right lower extremities with respect to the technical frame of reference established from a static calibration (Cappozzo et al., 1995; Jones et al., 2016). Marker data were recorded using eight infrared cameras sampled at 100 Hz. This data was synchronously recorded with the analogue input from the two force plates at 1000 Hz (9281E, Kistler Instruments Ltd., UK).

6.2.5 Data analysis

Raw marker and analogue data was then imported into Visual3D (C-Motion Inc., USA), and filtered with a 4th-order 6Hz low-pass Butterworth filter and force plate data was filtered using a 4th-order 25Hz low-pass Butterworth filter (Alcock et al., 2014, 2013; Begg & Sparrow, 2000; Jones et al., 2016; Larsen, Sørensen, Puggaard, & Aagaard, 2009). After filtering the raw data and calculating the relevant joint angles in Visual3D, further analyses to extract the kinematic measures were completed in Matlab 2016b (The MathWorks, Natick, MA, USA).

The step pattern was analysed from toe-off of the leading foot on one side of the obstacle to the landing of the leading foot on the other side of the obstacle. Toe-off was detected from kinematic data as the maximum of the vertical velocity component of the calcaneus marker of the leading foot (Pijnappels et al., 2001; see Chapter 5). Landing or heel strike of the

leading foot was determined from the force plate data; an impact over 20N on the force plate after the obstacle determined the foot landing (Zeni et al., 2008).

6.2.6 Dependent variables

From the kinematic data, several kinematic variables were calculated for each participant. Obstacle height and position were derived from the two markers positioned on the side of approach of the participant. First, the performance measure was (1) toe clearance of the leading foot defined as the maximum vertical distance between the first metatarsal marker and the obstacle (Austin et al., 1999; Chen, Lu, Wang, & Huang, 2008; Chou & Draganich, 1997; Loverro, Mueske, & Hamel, 2013; Pan, Hsu, Chang, Renn, & Wu, 2016; Patla, Prentice, & Gobbi, 1996; Snapp-Childs & Bingham, 2009). Second, other action-specific kinematic measures were calculated: (2) swing time: the difference in time between toe-off and landing of the leading foot after the obstacle (Chen et al., 2008; Pan et al., 2016); (3) toe-off distance: the horizontal distance between the first metatarsal marker of the leading foot and the obstacle at the moment of toe-off (Austin et al., 1999; Chen et al., 2008; Pan et al., 2016; Patla et al., 1996). Finally, the following action-specific kinematic variables were calculated at the point of (leading foot) toe clearance for both legs in the sagittal plane (Chen et al., 2008; Pijnappels et al., 2001; Shin et al., 2015): (4) ankle angle; (5) knee angle; (6) hip angle (cf. Austin et al., 1999; Chen et al., 2008).

6.2.7 Statistical analysis

To evaluate the *baseline*, we fitted linear regressions over the 30 baseline trials for each participant. The slopes of these linear regressions were submitted to a one-sample *t*-test against a slope of 0 for each group. Normality was confirmed using the Shapiro-Wilk test. To determine whether *recalibration* after the disturbance (or removal) occurred, we used the same method as in Chapter 5 (also detailed in Chapter 3). Briefly, it consisted of fitting a piecewise regression over trials 1 to 30 for each group and condition. The boundary between the two intervals is known as breakpoint. The piecewise regression method was applied to each of the kinematic variables. The slopes of the two individual regressions were submitted to a two-way mixed ANOVA with within-subjects factors Condition (2 levels: disturbance vs removal of the disturbance) and Time (2 levels: initial vs final rearrangement), and between-subjects factor Group (2 levels: young vs older). When interaction effects were present, paired samples t-tests were run to check whether recalibration was present in both groups/conditions. Homogeneity

of variance was confirmed using the Levene's test. Where a violation of sphericity was found in Mauchly's test, a Greenhouse-Geisser correction was applied. Post-hoc tests with Least Significant Difference (LSD) correction were applied on significant main effects. The *point of recalibration* was recorded as the breakpoint found during the piecewise regression, where the previous analysis showed an effect of recalibration. Throughout the analysis of the results, a significance level (alpha) of 5% was used. All statistical data were analysed using SPSS 25.0.

6.3 Results

In this section, the results for each kinematic variable will be presented regarding the recalibration effects during the disturbance and removal conditions. Where recalibration effects are found, we also present data on the point of recalibration.

6.3.1 Toe clearance

Regarding recalibration, results showed a main effect of time, $F(1, 22) = 5.26$, $p = .032$, $\eta^2 = 0.239$, because the initial rearrangement slope ($M = -3.35$, $SE = 1.47$) was steeper than the final slope ($M = 0.040$, $SE = 0.130$, see figure 6.2. There was no main effect of condition, $F(1, 22) = 0.787$, $p = .385$, $\eta^2 = 0.036$. There was no significant group effect, $F(1, 22) = 0.031$, $p = .862$, $\eta^2 = .001$, and no interactions were found (all $F < 1.50$, $p > .100$).

Regarding the point of recalibration, the breakpoint analysis in the disturbance condition showed that young adults recalibrated within 11 trials and older adults within 5 trials. In the removal condition, both groups recalibrated within 3 trials (see figure 6.2).

6.3.2 Swing time

Regarding recalibration, there was no significant time effect, $F(1, 22) = 2.78$, $p = .110$, $\eta^2 = 0.105$. A main effect of condition was found ($F(1, 22) = 11.903$, $p = .002$, $\eta^2 = 0.545$). There was no significant group effect, $F(1, 22) = 0.957$, $p = .339$, $\eta^2 = 0.053$. Importantly, there was a Condition × Time interaction, $F(1, 22) = 11.748$, $p = .002$, $\eta^2 = 0.545$, because initial rearrangement slopes for the disturbance condition were negative ($M = -0.033$, $SE = 0.011$), whereas initial slopes for the removal condition were positive ($M = 0.012$, $SE = 0.005$, see figure 6.2). Both conditions had similar slopes for the final rearrangement (Disturbance: $M = -0.001$, $SE < 0.001$; Removal: $M < 0.001$, $SE < 0.001$). Additional *t*-tests between initial and final rearrangement slopes were significantly different in the disturbance condition and the removal condition (respectively, $t(23) = 2.88$, $p = .008$, $d = 0.821$, and, $t(23) = 2.40$, $p = .025$, $d = 0.705$), indicating that recalibration occurred in both conditions. No other interaction effects were found (all $F < 1.50$, $p > .100$).

Regarding the point of recalibration, the breakpoint analysis showed that both young and older adults recalibrated within 3 trials in the disturbance condition. In the removal condition, young adults recalibrated within 3 and older adults within 5 trials (see figure 6.2).

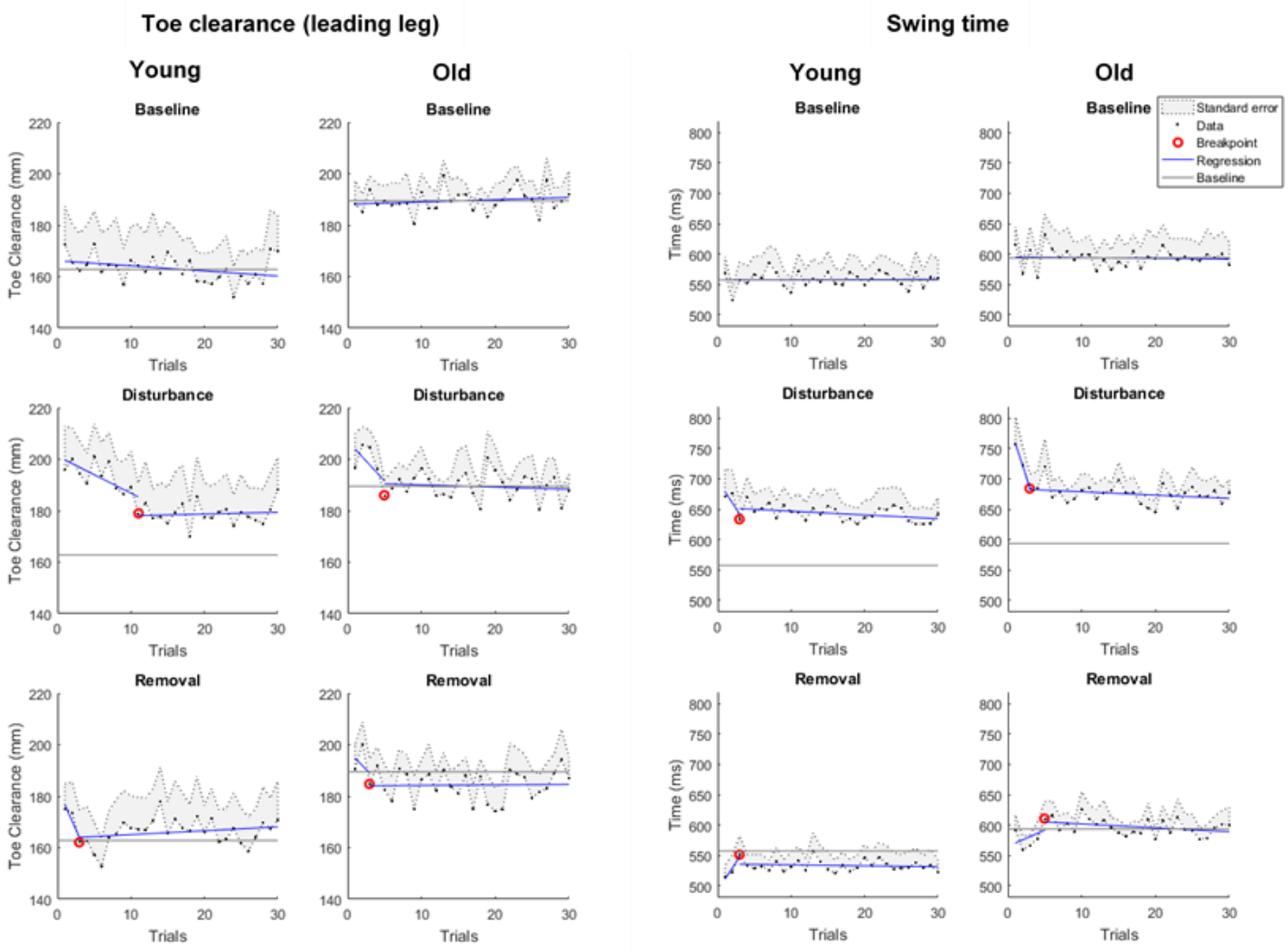


Figure 6.2 An outline of recalibration for both groups in toe clearance and swing time. Shaded areas represent the positive standard error of the mean. Baseline slopes were not significantly different from zero ($p > 0.05$).

6.3.3 Toe-off distance

Regarding recalibration, results showed no main effect of time, $F(1, 22) = 2.11$, $p = .160$, $\eta^2 < 0.001$. There was no main effect of condition, $F(1, 22) = 3.15$, $p = .090$, $\eta^2 < 0.001$, because the initial slopes in the disturbance condition ($M = 0.004$, $SE = 0.002$) were steeper than in the removal condition ($M < 0.001$, $SE = 0.001$, see figure 6.3). There was no significant group effect, $F(1, 22) = 0.014$, $p = .906$, $\eta^2 = 0.068$. There was no Condition × Time interaction, $F(1, 22) = 3.28$, $p = .084$, $\eta^2 < 0.001$. Additional *t*-tests between initial and final rearrangement slopes for the disturbance condition confirmed no significant differences, respectively, young $t(11) = 1.35$, $p = .205$, and, $t(11) = 1.12$, $p = .288$). No interaction effects were found (all $F < 1.00$, $p > .600$).

6.3.4 Ankle joint angle (leading leg)

Regarding recalibration, results showed a main effect of time, $F(1, 20) = 5.41$, $p = .031$, $\eta^2 = .270$, because the initial rearrangement slope ($M = 0.774$, $SE = 0.314$) was steeper than the final slope ($M = 0.045$, $SE = 0.061$, see figure 6.3). There was a significant effect of group, $F(1, 20) = 5.04$, $p = .036$, $\eta^2 = 0.252$, because the slopes were less steep in the young group ($M = 0.044$, $SE = 0.219$) than in the older group ($M = 0.775$, $SE = 0.240$). There was no main effect of condition, $F(1, 20) = .001$, $p = .978$, $\eta^2 < 0.001$. There was a significant Time × Group interaction, $F(1, 20) = 6.84$, $p = .017$, $\eta^2 = 0.342$, because the initial slope was less steep for the young than for the older adults. No other interaction effects were found (all $F < 0.150$, $p > .700$). Figure 6.3 shows large initial and final slopes for the disturbance condition in the young group, an additional *t*-test confirmed no differences between the initial and final rearrangement slopes $t(11) = 1.52$, $p = .158$, indicating no complete recalibration in the disturbance condition for young adults.

Regarding the point of recalibration, the breakpoint analysis showed that older adults recalibrated within 3 trials in the disturbance condition. In the removal condition, the young adults recalibrated within 8 trials and older adults recalibrated within 3 trials (see figure 6.3).

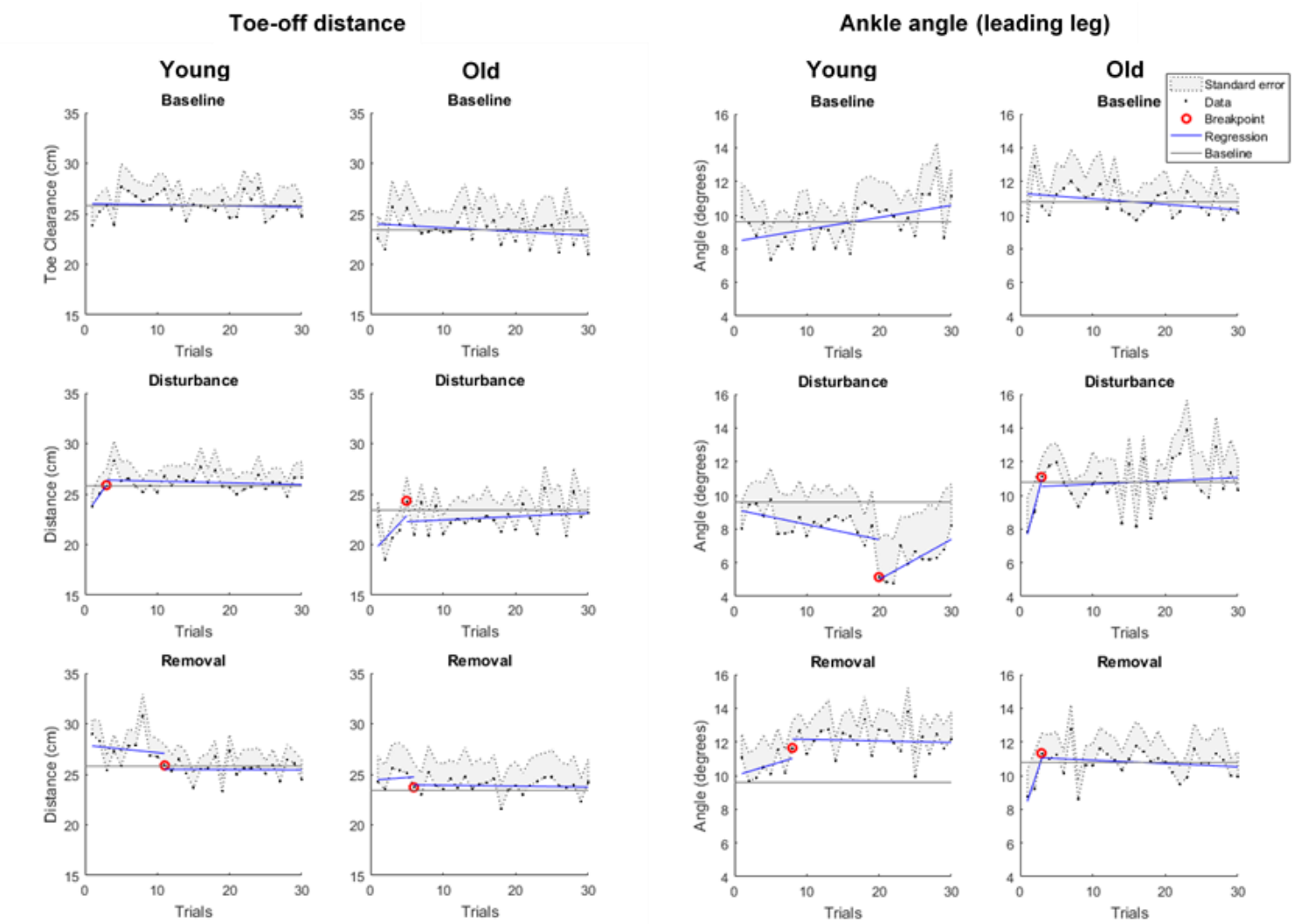


Figure 6.3 An outline of recalibration for both groups in the toe-off distance and the ankle joint angle of the leading leg. Shaded areas represent the positive standard error of the mean. Baseline slopes were not significantly different from zero ($p > 0.05$).

6.3.5 Knee joint angle (leading leg)

Regarding recalibration, results showed no main effect of time, $F(1, 18) = 2.40$, $p = .139$, $\eta^2 = 0.133$, indicating no complete recalibration occurred. There was no main effect of condition or group, respectively $F(1, 18) = 2.23$, $p = .153$, $\eta^2 = 0.124$, and, $F(1, 18) = .033$, $p = .857$, $\eta^2 = 0.002$. Also, no interaction effects were found (all $F < 1.80$, $p > .200$).

6.3.6 Hip joint angle (leading leg)

Regarding recalibration, results showed no main effect of time, $F(1, 18) = 3.77$, $p = .068$, $\eta^2 = 0.210$, see figure 6.4). There was a main effect of condition, $F(1, 18) = 13.9$, $p = .002$, $\eta^2 = 0.772$, because the disturbance slopes ($M = 0.296$, $SE = 0.279$) were less steep than the removal slopes ($M = -1.988$, $SE = 0.713$). There was no significant group effect, $F(1, 18) = 0.156$, $p = .698$, $\eta^2 = 0.009$. There was a significant Condition × Time interaction, $F(1, 18) = 13.4$, $p = .002$, $\eta^2 = 0.746$. This was because the initial slopes of the removal condition ($M = -3.96$, $SE = 1.41$) were steeper than the initial slopes of the disturbance condition ($M = 0.604$, $SE = 0.517$). Figure 6.4 shows a large initial slopes for both groups in the removal condition, and additional *t*-tests confirmed the differences between the initial and final rearrangement slopes, young: $t(11) = 2.42$, $p = .034$, $d = 0.970$, ; and old: $t(9) = 1.90$, $p = .091$, $d = 0.936$, indicating that recalibration occurred in the removal condition for both groups. No other interaction effects were found (all $F < 1.00$, $p > .600$).

Regarding the point of recalibration in the removal condition, the breakpoint analysis showed that both young and older adults recalibrated within 2 trials (see figure 6.4).

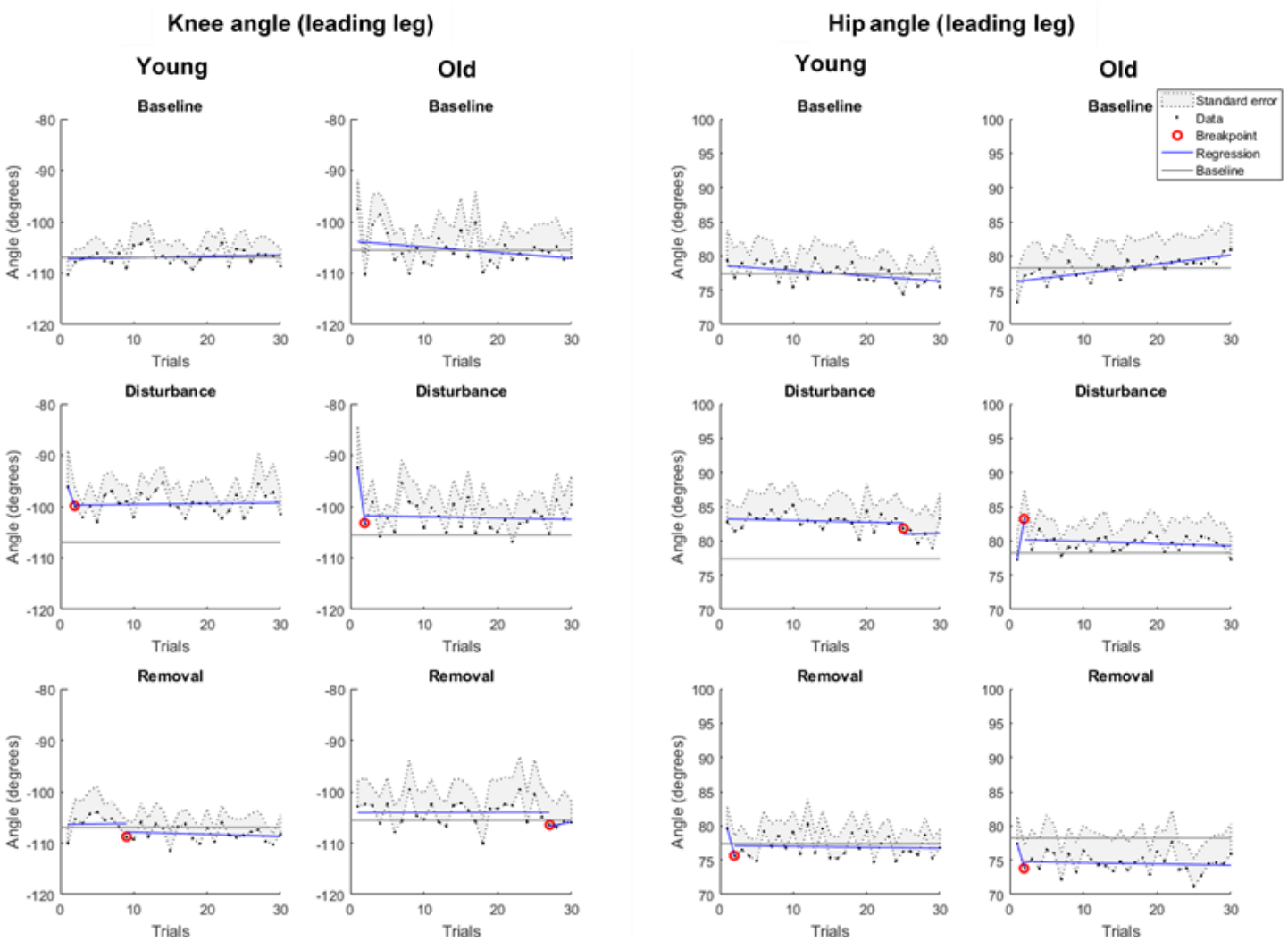


Figure 6.4 An outline of recalibration for both groups in the knee and hip joint angle of the leading leg. Shaded areas represent the positive standard error of the mean. Baseline slopes were not significantly different from zero ($p > 0.05$), except for the leading hip joint angle for the old group ($t(11) = 3.45$, $p = .005$).

6.3.7 Ankle joint angle (trailing leg)

Regarding recalibration, results showed a main effect of time, $F(1, 20) = 9.79$, $p = .005$, $\eta^2 = 0.490$, because the initial rearrangement slope ($M = -1.30$, $SE = 0.417$) was steeper than the final slope ($M = 0.017$, $SE = 0.009$, see figure 6.5). There was a significant group effect, $F(1, 20) = 8.24$, $p = .009$, $\eta^2 = 0.412$, because the slope for the young group ($M = -1.24$, $SE = 0.293$) was steeper than for the older group ($M = -0.046$, $SE = 0.293$). There was no main effect of condition, $F(1, 20) = 1.91$, $p = .182$, $\eta^2 = 0.096$. There was also a significant Time × Group interaction, $F(1, 20) = 7.50$, $p = .013$, $\eta^2 = 0.375$, because the initial slopes for the young group ($M = -2.47$, $SE = 0.590$) were steeper than for the older group ($M = -0.128$, $SE = 0.036$). No other interaction effects were found (all $F < 1.80$, $p > .100$). Figure 6.5 shows shallow initial slopes for the old group in the removal condition, but an additional *t*-test showed no significant differences between the initial and final rearrangement slopes, $t(11) = 1.96$, $p = .077$, $d = 0.677$.

Regarding the point of recalibration, the breakpoint analysis showed that young adults recalibrated within 2 trials and older adults within 6 trials in the disturbance condition. In the removal condition, young adults recalibrated within 2 trials (see figure 6.5).

6.3.8 Knee joint angle (trailing leg)

Regarding recalibration, results showed a main effect of time, $F(1, 21) = 14.1$, $p = .001$, $\eta^2 = 0.670$, because the initial rearrangement slope ($M = 1.69$, $SE = 0.442$) was steeper than the final slope ($M = -0.033$, $SE = 0.052$, see figure 6.6. There was a main effect of condition, $F(1, 21) = 14.4$, $p = .001$, $\eta^2 = 0.685$, because the slopes were steeper for the removal condition ($M = 1.68$, $SE = 0.436$) than for the disturbance condition ($M = -0.017$, $SE = 0.050$). There was no significant group effect, $F(1, 21) = .002$, $p = .961$, $\eta^2 < 0.001$. A significant Condition × Time interaction was found, $F(1, 21) = 15.1$, $p = .001$, $\eta^2 = 0.717$, because the initial slopes were steeper in the removal condition ($M = 3.38$, $SE = 0.878$) than in the disturbance condition ($M = 0.014$, $SE = 0.026$). No other interaction effects were found (all $F < 1.50$, $p > .100$). Figure 6.6 shows shallow initial slopes for both groups in the disturbance condition, and additional *t*-tests confirmed no significant differences between the initial and final rearrangement slopes, young: $t(11) = 0.186$, $p = .856$; and old: $t(10) = 1.12$, $p = .290$.

Regarding the point of recalibration, the breakpoint analysis showed that both groups recalibrated within 2 trials in the removal condition (see figure 6.6)

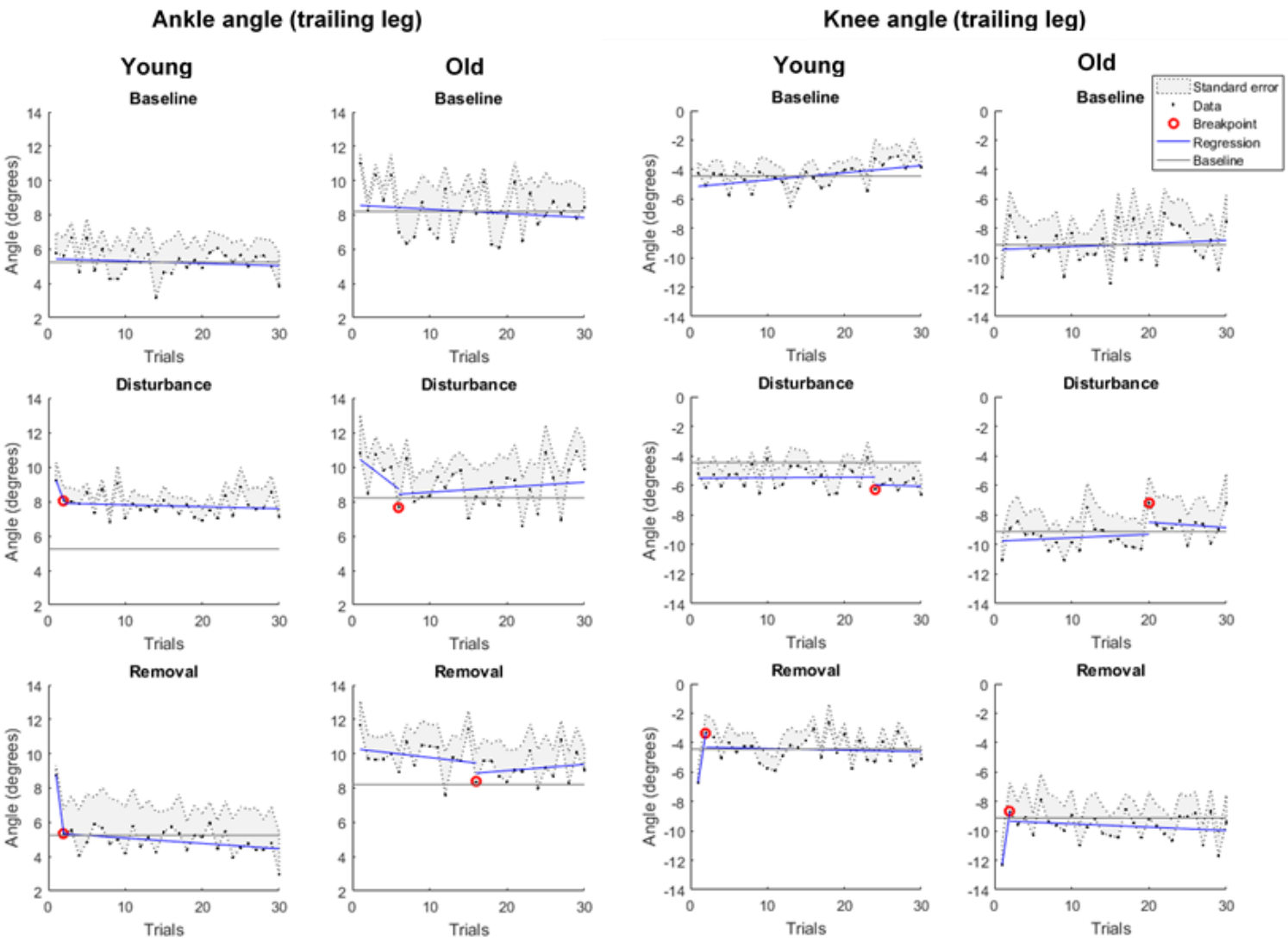


Figure 6.5 An outline of recalibration for both groups in the ankle and knee joint angle of the trailing leg. Shaded areas represent the positive standard error of the mean. Baseline slopes were not significantly different from zero ($p > 0.05$), except the trailing knee joint angle for the young group ($t(11) = 2.77$, $p = .018$).

6.3.9 Hip joint angle (trailing leg)

Regarding recalibration, results showed no main effect of time, $F(1, 19) = 2.83$, $p = .109$, $\eta^2 = 0.149$, indicating no recalibration occurred. The analysis showed other significant results which were not reported as they do not speak to recalibration effects (see figure 6.6).

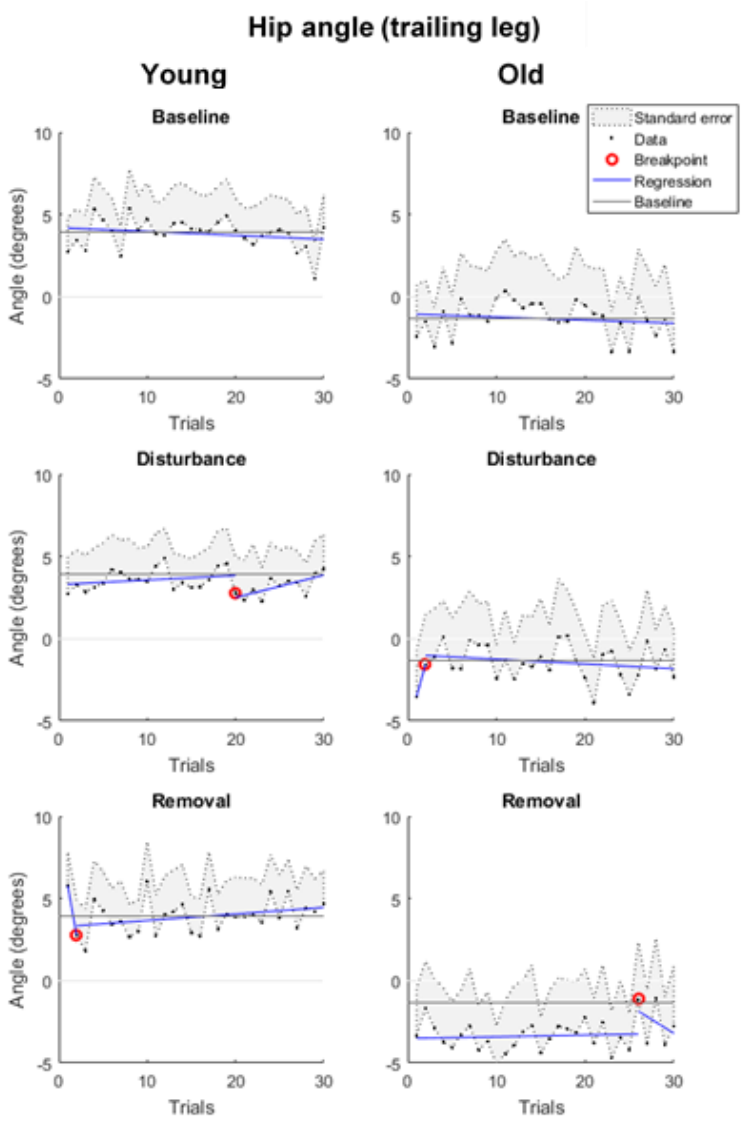


Figure 6.6 An outline of recalibration for both groups in the hip joint angle of the trailing leg. Shaded areas represent the positive standard error of the mean. Baseline slopes were not significantly different from zero ($p > 0.05$).

6.4 Discussion

The aim of this study was to investigate whether there are age-related differences in the speed of recalibration when crossing varying obstacles. This required participants to recalibrate to the weight disturbance in an unpredictable environment. As toe clearance is the performance measure that informs on recalibration in this experiment, results will be discussed accordingly. Surprisingly, results showed that while young adults took 11 trials to recalibrate after the disturbance, older adults only needed 5 trials. Upon removal of the disturbance, both groups recalibrated within 3 trials.

Both groups recalibrated to the weight disturbance, but older adults were faster than young adults to reach recalibration. This is an important result because it shows that older adults recalibrated successfully. A faster recalibration in older adults may have resulted from increased pressure on their perceptual-motor system to recalibrate, given that the consequences of tripping on the obstacle were greater for older than young adults. In addition, previous research in other domains has found that the perceptual-motor system does not strive for optimisation but rather uses good-enough strategies in response to pressure (e.g., Bobbert, Richard Casius, & Kistemaker, 2013; Raab, de Oliveira, Schorer, & Hegele, 2013). Therefore, we suggest that recalibration speed may have been related to perceived consequences in performing this task for both groups. Another explanation is that older adults' reduced action capabilities may have influenced the speed of recalibration. It is well-known that ageing is characterized by declines in neuromuscular, skeletal, and cognitive systems, which affect gait and mobility (Nigam, Knight, Bhattacharya, & Bayer, 2012). For example, in stair climbing, reduced leg strength has been shown to influence older adults' performance (Ploutz-Snyder et al., 2002; Salem et al., 2000; Tiedemann et al., 2007). This decrease in action capabilities might be related to fewer possibilities to successfully perform a task, and therefore, a higher need to recalibrate (cf. van Andel, Cole, & Pepping, 2018). In addition, it could be that older adults explored and performed actions closer to their maximal action capabilities, which may have led to a faster recalibration (cf. Fajen et al., 2009). Taken together, it seems that the process of recalibration was intact in both groups, but may have been constrained by reduced action capabilities and perceived consequences of the task in the older group.

A second result was that both groups increased their toe clearance after the disturbance, but the older group recalibrated to its baseline toe clearance while the young group recalibrated to a toe clearance higher than their baseline. A higher toe clearance

would have been safer for the older group, especially in an unpredictable environment, but a lower toe clearance would have demanded less muscle strength, thereby allowing prolonged muscle recruitment during the experiment. It is also noteworthy that both groups regulated their toe clearance to the trial-by-trial changes in obstacle height while simultaneously recalibrating to the weight disturbance (Appendix A). This indicates an intact perceptual-motor system as changes in the unpredictable environment were perceived and acted upon.

In our study, swing time showed aftereffects upon removal of the disturbance that were in the opposite direction to the effects of disturbance. It is possible that the weight disturbance slowed down participants' movements, which upon removal resulted in faster movements and thus an aftereffect of the recalibration. This is similar to previous studies, which showed that aftereffects have always been reported in the opposite direction to the initial disturbance effect (Bock, 2005; Fernández-Ruiz et al., 2000; McCrum et al., 2016; Roller et al., 2002; Vervoort et al., 2019). In our performance measure toe clearance, the initial aftereffect was in the same direction as the initial disturbance effect. Given that our results show a clear recalibration effect, the question that arises is whether aftereffects can also occur in the same direction of the disturbance effect. We argue that this is the case; the disturbance removal is itself another disturbance, albeit one usually followed by a faster rearrangement (see Chapter 2). It seems that, in obstacle crossing, the principal response to any disturbance (including disturbance removal) is to increase the safety margin, which is accomplished by raising toe clearance. For example, a different disturbance such as fitting an ankle orthosis also led to a higher toe clearance as a first response to the disturbance (Van Hedel & Dietz, 2004). Further, the aftereffect observed in swing time may have itself provoked a raised toe clearance. Previous studies which found aftereffects in the opposite direction used tasks that had a clear direction of recalibration (e.g. Dotov et al., 2013; Fernández-Ruiz & Díaz, 1999; Fernández-Ruiz et al., 2000; Redding, 2001; Redding & Wallace, 2002). For example, wearing left-shifting prism glasses causes a disturbance effect in the motor system to the left. Recalibration recouples vision with the motor system by rescaling the motor system to the disturbed vision. Therefore, after recalibration, the removal of glasses causes a disturbance to the right. This constraint upon the system to recalibrate in one direction probably led to the assumption about the direction of aftereffects (see Chapter 2). However, we propose that the direction of the aftereffect is variable and dependent on the task and disturbance, but

future studies could further explore these aftereffects of recalibration in different everyday activities.

Our results suggest that recalibration can be measured as the recovery of a stable (and safe) movement pattern. The piecewise regressions showed that although participants' movements changed after a disturbance, the perceptual-motor system quickly recalibrated into a stable movement pattern. Some other studies have also focused on movement stability as a requirement for recalibration (Bruijn et al., 2012; Vervoort et al., 2019; Wang & Bingham, 2019). For example, Wang and Bingham (2019) found that participants recalibrated within five trials after their maximum grip was progressively restricted and suggested that this timeframe was sufficient to detect the stability of performance. Similarly, Vervoort et al. (2019) concluded that older adults used a "speed strategy" rather than a "timing strategy" in split-belt walking to recalibrate and restore a stable movement pattern. Other studies, also seemed to equate recalibration to the re-acquisition of a stable performance without detailing the strategies (Chapter 2). Although our results suggest a fast recalibration and recovery of a stable movement pattern for both groups, we did not find any obvious movement strategies that differentiated young and older adults. Although this was not the focus of this study, it could be considered as a limitation of this study because it prevented us from giving a full interpretation of the age-related differences. However, obstacle crossing is a multi-articular movement; different strategies may be suitable to recalibrate toe clearance. In other domains, research has used inter-joint coordination as a measure of stability in multi-articular tasks (de Oliveira, Huys, Oudejans, Van De Langenberg, & Beek, 2007; Yen et al., 2009). These typically compute stability over a number of trials which poses challenges for the study of a dynamic process such as recalibration. However, future studies could go further in their investigation of recalibration by analysing inter-joint coordination patterns between groups.

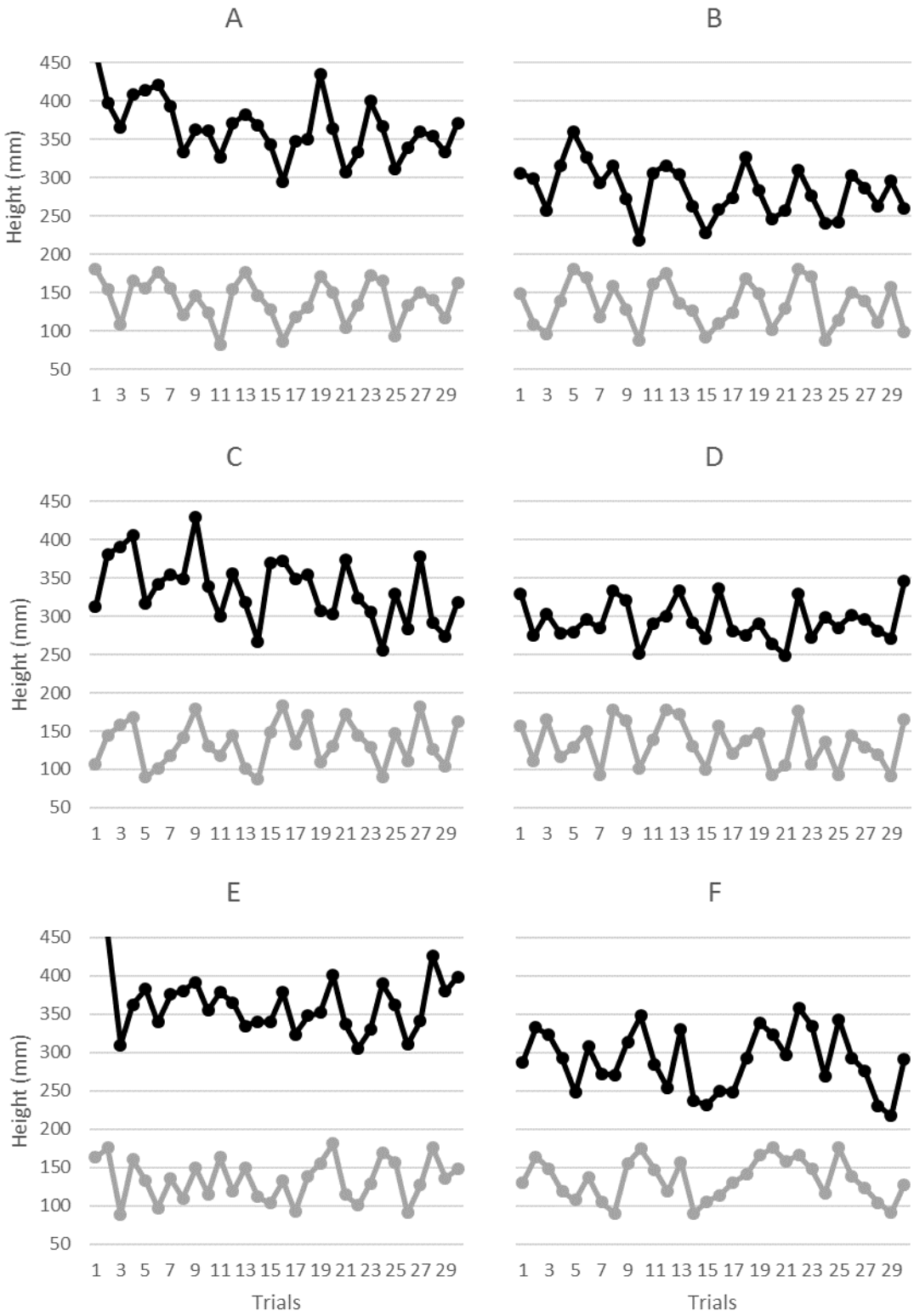
6.4.1 Conclusions

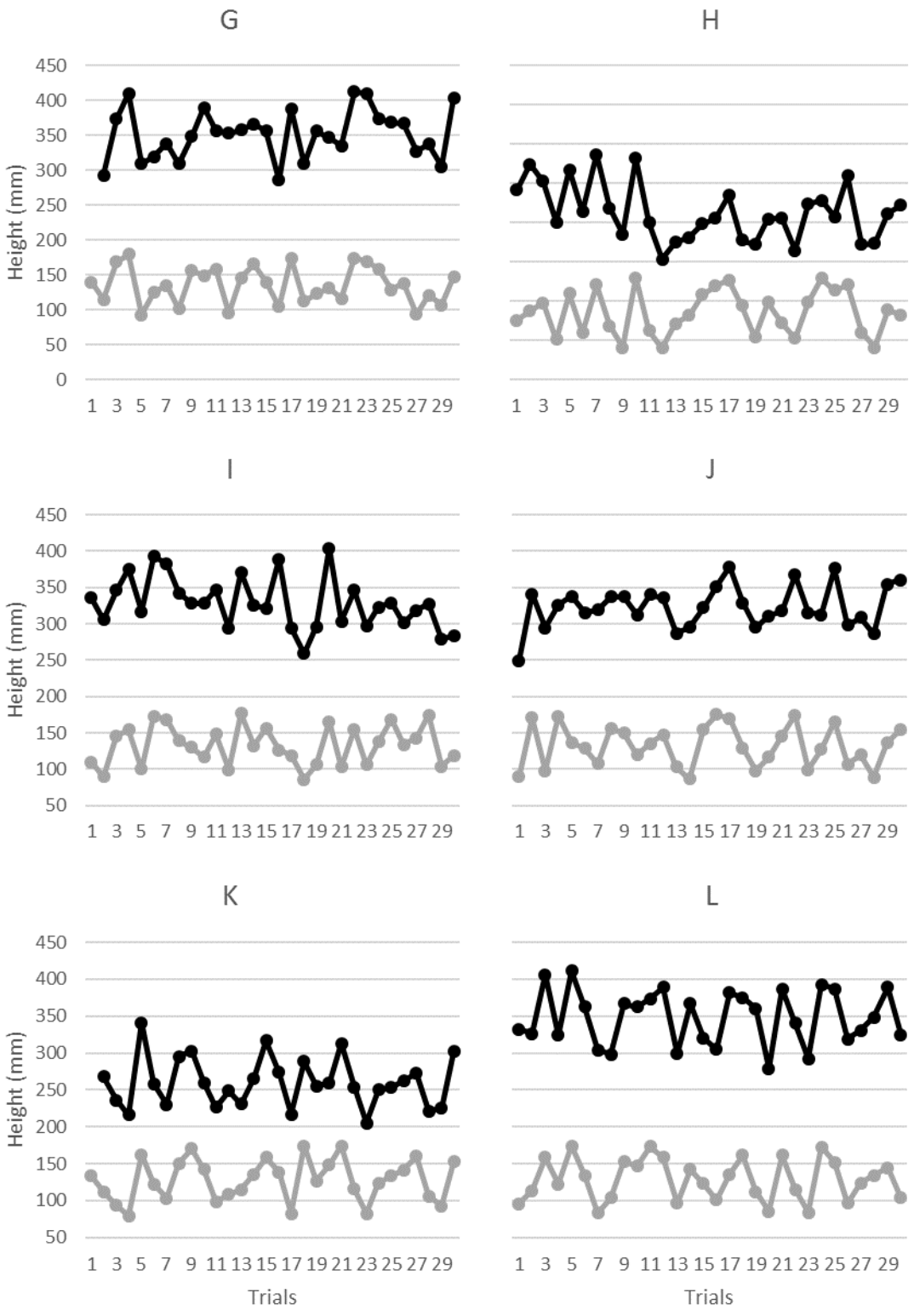
The aim of this study was to investigate whether there are age-related differences in the speed of recalibration when crossing varying obstacles. Results showed that while young adults took eleven trials to recalibrate older adults only needed five trials. It seems that the process of recalibration was intact in both groups but may have been constrained by reduced action capabilities and the perceived consequences of the task in the older group. No age-related differences in recalibration speed were found upon removal of the

disturbance. We propose that the direction of the aftereffect is variable and dependent on the task, but future studies could further explore these aftereffects of recalibration in different everyday activities.

6.5 Appendix A: Individual clearance and obstacle heights

Individual clearance and obstacle heights plotted over 30 trials in the disturbance condition. Each plot is a separate individual: plots A-L represent the young participants and M-X the older participants. The black line shows the height of the first metatarsal at maximum toe clearance. The grey line shows the obstacle height.

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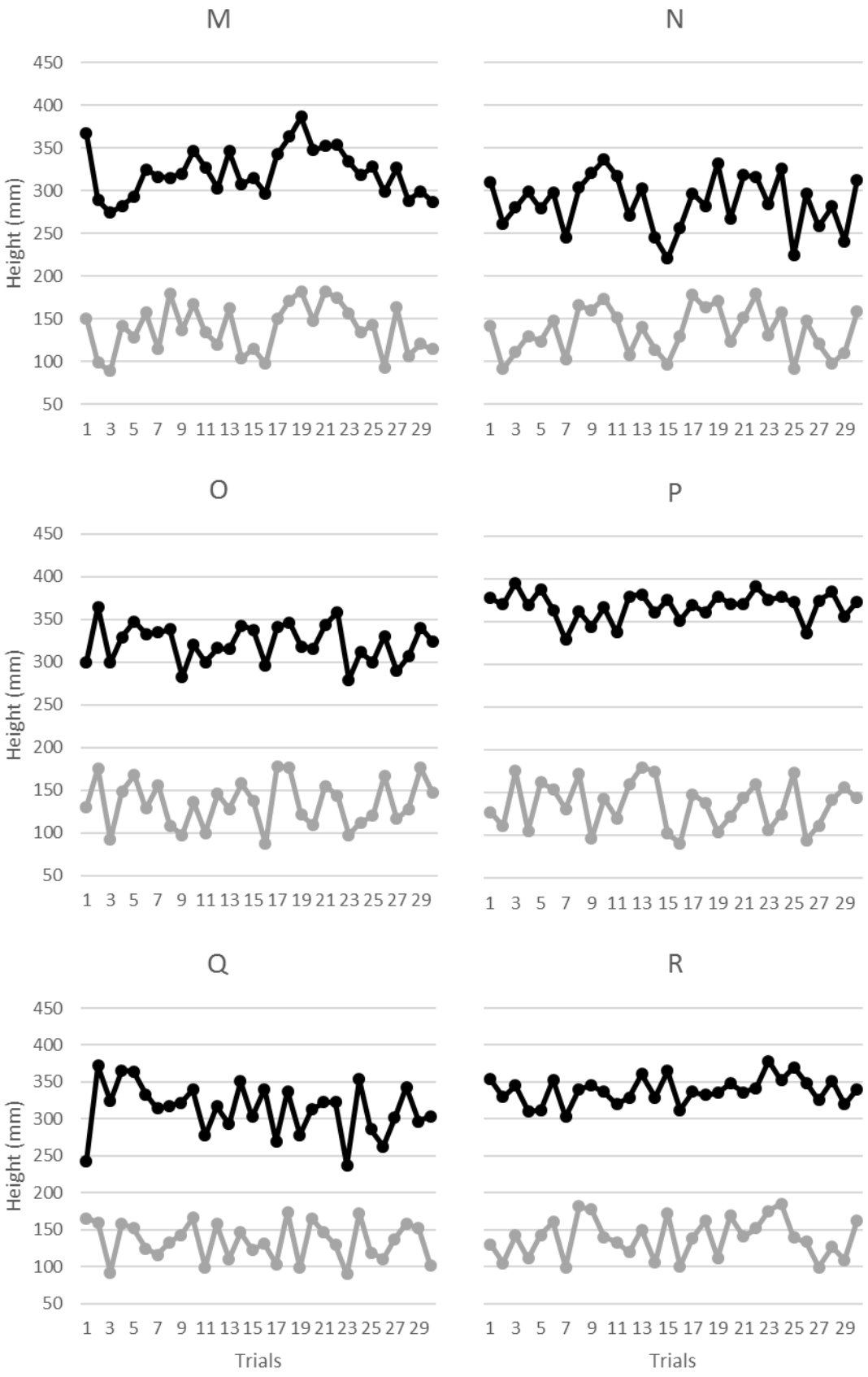
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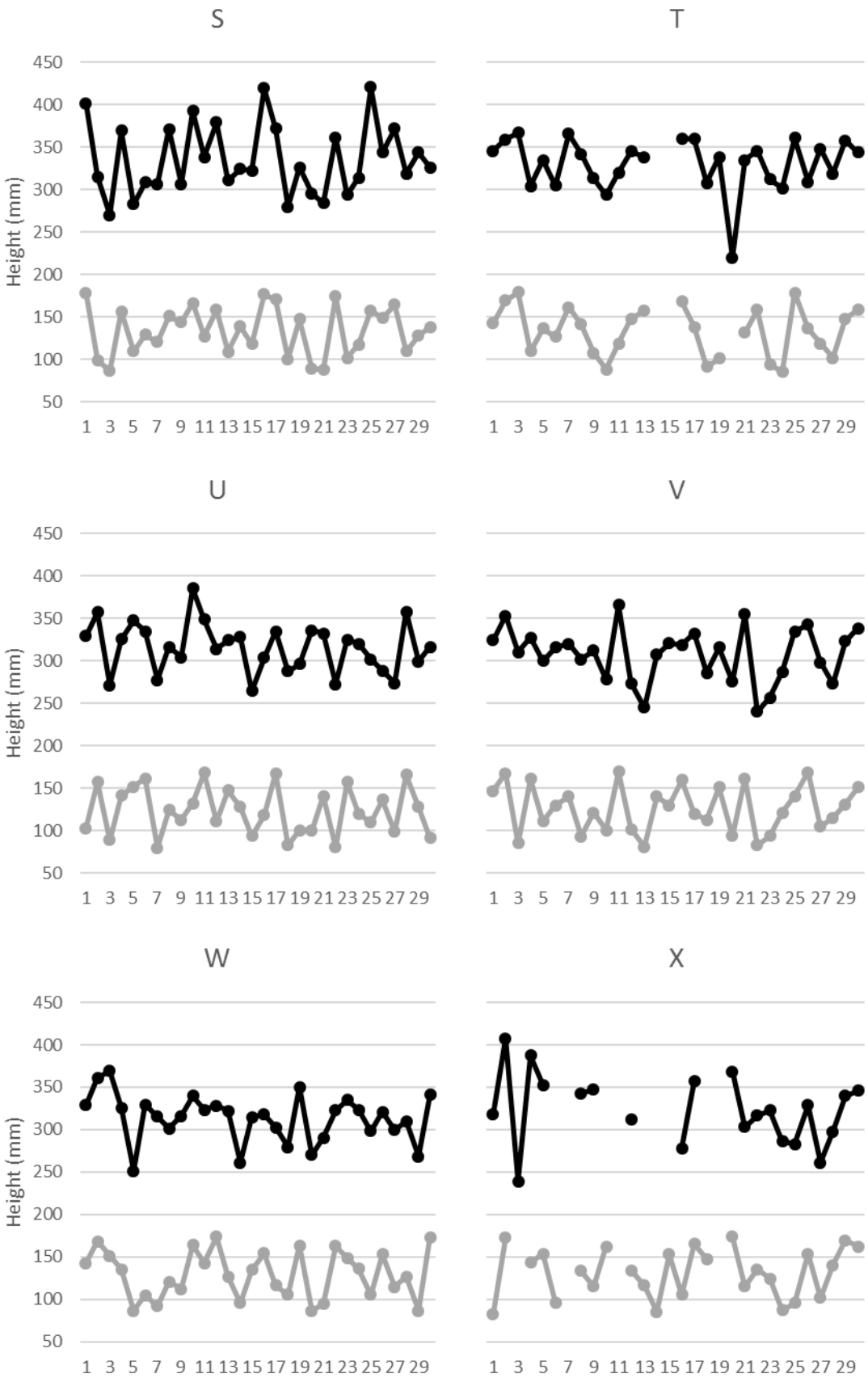
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Chapter 7
General discussion

7.1 Main findings

Mrs Poorthuis has just brewed some tea and is ready for a chat with her friends over the cake she baked earlier; on her coffee table is her granddaughter's PhD thesis. In this thesis, we explored whether there are age-related effects in the recalibration to action disturbances. *Chapter 2* reviewed the current literature on recalibration in functional perceptual-motor tasks and analysed how recalibration can and has been measured. There were four main findings. First, the results showed that experiments applied disturbances to either perception or action and used either direct or indirect measures of recalibration. Second, it showed that only a limited amount of studies had measured and reported on recalibration throughout the rearrangement period. Therefore, little was known about recalibration speed. For this reason, it was important to investigate the rearrangement period using trial-by-trial recording and analysis. Third, results showed that while no research had focussed on recalibration in older adults, young adults only needed 5-12 rearrangement trials for recalibration. Fast recalibration was only possible when the relevant information source was available through active exploration, and the skill was well-learned. When information was restricted, this resulted in slower or incomplete recalibration. Finally, recalibration speed also seemed to depend on the magnitude of the disturbance effect and the skill level.

Following these results, all experimental studies applied direct measures and used trial-by-trial recording and analysis of the rearrangement process. The methods applied in the experimental studies of the thesis were detailed in *Chapter 3*. *Chapter 4* investigated whether young and older adults recalibrate their affordance perception after their action boundaries were disturbed by asking them to judge their maximum stepping height. Results showed that although participants were accurate at baseline and were affected by the disturbance, they did not recalibrate within the ten experimental trials. We suggested that walking with the weights between judgements did not provide the right information source to recalibrate affordance perception for maximum stepping height. We concluded that investigating age-related differences in recalibration remains relevant,

but that using kinematic measures to investigate recalibration and testing everyday activities may be more informative. Therefore, the following experimental studies incorporated kinematic measures rather than judgements and everyday activities rather than maximal tasks.

Chapter 5 investigated how long young and older adults took to recalibrate to disturbances of different magnitudes while climbing stairs. Results showed that while young adults took 3-7 trials, the older adults took 6-8 trials across weight disturbance conditions for toe clearance to be fully recalibrated. In addition, results showed that young adults recalibrated faster to smaller disturbances and longer to larger disturbances. In contrast, older adults used a similar point of recalibration across disturbances possibly because they overcompensated the initial rearrangement for smaller disturbances. In this study, we devised an innovative methodology to measure recalibration using initial and final rearrangement slopes, which gave us a more precise estimate of how long recalibration took. Chapter 6 also used this methodology to investigate a different everyday activity.

Chapter 6 investigated how long young and older adults took to recalibrate when crossing obstacles of varying height. Results showed that while young adults took 11 trials to recalibrate older adults only needed 5 trials. No age-related differences were found upon the disturbance removal. It seems that the process of recalibration was intact in both groups but may have been constrained by reduced action capabilities and perceived consequences of the task in the older group. Before discussing the implications of these results, it is useful first to address some methodological issues that are relevant to a proper evaluation of the present results and those obtained in other studies.

7.2 Methodological limitations and considerations

The first thing to consider is that the older adults who participated in the studies were healthy and active. Although we did not screen participants' fitness level, we excluded anyone that had cardiovascular, orthopaedic, or balance issues for safety reasons. This likely also (self-) excluded frailer older adults. Our results showed that they were not only of older age but also showed significantly worse knee extensor muscle strength and hip flexibility compared to young adults. The results showed that older adults in our studies behaved similarly to those in other research studies. For example, older adults had a lower maximum stepping height (cf. Konczak et al., 1992; see Chapter 4), a lower toe clearance than young adults in stair climbing (cf. Begg & Sparrow, 2000; Elliott et al., 2009; see

Chapter 5), and a higher toe clearance when crossing obstacles (cf. Patla & Rietdyk, 1993; Shin et al., 2015; see Chapter 6). However, when generalising the results of this thesis to the older population, care must be taken as results may not be readily applicable to frail older adults. This is a limitation of the present thesis as important differences exist between frail and healthy older adults which possibly impact the perceptual-motor system and its ability to recalibrate to disturbances.

We did account for some age-related physiological differences by scaling the disturbances to participants' action capabilities. The ankle weights were scaled to knee extensor muscle strength as it is known to cause age-related differences in stepping tasks (Ploutz-Snyder et al., 2002; Salem et al., 2000; Tiedemann et al., 2007). However, measuring knee extensor muscle strength involves an isolated movement, while stepping onto stairs or over an obstacle involves the activation of multiple muscle groups (McFadyen & Winter, 1988; Watanabe et al., 2017). This means that the scaling done in the experimental studies may not have been optimal, and instead, a combination of muscles groups could have been a better scaling factor. For example, a bespoke apparatus where participants lift their leg and push up against a bar with the forefoot would indicate the overall force produced by a combination of relevant muscle groups. A possible limitation in this thesis is that scaling could be optimised to better reflect the age-related differences in muscle strength in a particular task. On the other hand, we have reason to believe that the scaling used was effective because in Chapter 4 the maximum action capabilities were reduced by a similar percentage in both groups when (scaled) weights were applied. Previously, research has used a fixed disturbance for young and older adults (Bierbaum et al., 2011; Fernández-Ruiz et al., 2000; McCrum et al., 2016). For example, McCrum et al. (2016) repeatedly applied the same disturbance to the leg of young and older adults walking on a treadmill. The benefit of using a fixed disturbance is that it is more similar to disturbances that occur in everyday activities. For example, ski boots are heavy regardless of the wearer's age. However, fixed disturbances can represent a small disturbance for young adults, but a large disturbance for older adults. This makes strength a possible confounding variable which needs to be controlled. Therefore, scaling disturbances is useful in investigating the time course of recalibration.

7.3 Theoretical implications

7.3.1 The operational definition of recalibration

Every day people encounter many situations in which the perception-action system needs to recalibrate to perceptual-motor disturbances, such as "getting used to" a different car, fatigue, ski boots, or orthotic shoes. However, a recent study highlighted that the current literature lacks criteria to define exactly whether or not recalibration has occurred (Day et al., 2019). According to them, there are no criteria on what recalibration looks like, and when recalibration is complete. This means that although the concept of recalibration is clear, the operational definition of recalibration is still changing. When reviewing the literature on recalibration (Chapter 2), studies typically reported a reduction in error as indicative that recalibration had taken place. Error can be defined in different ways; for example, in Chapter 4, we measured judgement errors defined as the difference between perceptual and action boundaries. Similarly, studies have reported reductions in throwing errors, swing onset errors, and movement times (respectively, Bruggeman, Pick, & Rieser, 2005; Scott & Gray, 2010; Bingham & Romack, 1999). In contrast, our results in Chapters 5 and 6 suggest that recalibration can also be measured as the recovery of a stable movement pattern. We propose that the way to measuring recalibration depends on the task goal. If the task goal is defined as a target to reach, movement possibilities to this target are limited, and recalibration can be measured as error reduction. On the other hand, if the task goal is a "target to avoid" (e.g., obstacle), the possibilities for action are broader, and recalibration can be measured as the recovery of a stable movement pattern. To address Day et al.'s (2019) concerns, we would suggest that the piecewise regression method applies well to both types of tasks to identify recalibration and also to uncover its time course. Importantly, when participants' action capabilities were not disturbed a stable movement pattern was kept (i.e., not recovered), and where recalibration is not visible, the methodology returns similarly sloped regressions and/or unreasonable breakpoints. This was shown in the baseline condition of Chapter 6, which showed that for most variables, the slopes of the linear regressions were not significantly different from zero. This is similar to previous studies that have found shallow slopes for baseline conditions (Mark, 1987; Mark et al., 1990; Yu & Stoffregen, 2012).

It is also worth noting that for recalibration to be complete, participants did not necessarily have to recalibrate back to their baseline levels. These findings were similar to Scott & Gray (2010), who showed that mean temporal error reduced to a stable pattern although errors were larger than in the control condition. In contrast, other research

studies reported that recalibration was only complete when the error was similar to baseline or control conditions (e.g. Day et al., 2019; Mark et al., 1990). For example, Day et al. (2019) reported that participants took 45 trials to recalibrate to reach an absolute error similar to that of the normal avatar condition. We propose that the disturbance, in combination with the task constraints, may not allow for a recalibration back to baseline levels, but instead, recalibration can be identified through the re-acquisition of a stable pattern. For example, in our studies, having a similar toe clearance with and without heavy ankle weights may not be possible or even desirable. Instead, having a (new) stable pattern would indicate that recalibration was complete.

When recalibration occurred, results still showed movement variability (see Chapters 5 and 6; cf. Mon-Williams & Bingham, 2007; Scott & Gray, 2010). Day et al. (2019) refer to individual movement variability as a persistent movement error in participants' actions. They raised the question of whether one can confidently claim that recalibration has occurred when participants' judgements still show errors or movements still show variability. In our results of Chapter 5 and 6, standard errors show variability even after the point that we determined as complete recalibration. However, the data strongly suggests that a stable movement pattern was acquired by then and the level of variability was similar to that in the baseline condition. Therefore, we suggest that movement variability is an inherent characteristic of movement and that, provided variability is similar to a control/baseline condition, the stability of the movement pattern (e.g., visible in the toe clearance) is a good indicator of recalibration. We propose that the linear regression in the final rearrangement is robust to movement variability by returning a shallow slope when recalibration can be observed to be complete.

*7.3.2 Information *or lack thereof*

The systematic literature review revealed that the timeframe for recalibration is variable. It showed that active exploration or, more specifically, the availability of the relevant information sources is necessary for recalibration. When the information was restricted, this resulted in a slower or incomplete recalibration (Mark et al., 1990; Stoffregen et al., 2005, 2009; Yu, Bardy, & Stoffregen, 2011, see Chapter 2). Our experimental studies supported these conclusions. For example, Chapter 4 found no recalibration probably because walking provided insufficient information for recalibration to occur in the judgement of a maximal task. Another action, like climbing stairs, would have provided better information about the heaviness of the weights upon leg lifting and participants'

action capabilities. Chapters 5 and 6 showed that this was the case. Fast recalibration of 3 to 11 trials occurred after participants had the opportunity to explore the available information, even if that exploration was not conscious but imposed by the nature of the task itself. However, a recent study by Labinger et al. (2018) showed that most participants were spontaneously able to efficiently explore information by approaching and practising fitting through doorways that were near the limit of their abilities. This means that even when active exploration is not imposed, participants naturally sought opportunities to explore the environment in order to recalibrate.

7.4 Summary of significant contributions to knowledge

7.4.1 Recalibration and older age

Our studies have been the first to investigate age-related differences in recalibration. One of the main findings of this thesis was that while both young and older adults recalibrate successfully, recalibration speed seems to change with older age. We argued that the process of recalibration was intact in both groups, but may have been constrained by reduced action capabilities and perceived consequences of the task in the older group. This means that in a predictable environment in which the consequences of tripping were lower, older adults took longer to recalibrate than in an unpredictable environment in which the consequences of tripping were higher. Previous studies have suggested that older adults are less able to adapt and face constraints because ageing leads to a compression of the neuro-behavioural repertoire (Sleimen-Malkoun, Temprado, & Berton, 2013; Sleimen-Malkoun, Temprado, & Hong, 2014; Vernooij, Rao, Berton, Retornaz, & Temprado, 2016). Sleimen-Malkoun et al. (2014) concluded that ageing might also lead to a loss of multi-stability in terms of available movement patterns. For this reason, it could be that the added constraints of environmental variability and increased pressure resulted in a smaller perceptual-motor space with fewer possibilities for action in older adults. While this would have led to a fast recalibration, it may be that older adults adopted a suboptimal movement pattern (our results do not make this clear). On the other hand, in a predictable environment with fewer constraints, older adults took longer to recalibrate but may have adopted a better movement pattern.

7.4.2 Methodological innovation

The experimental studies were designed to unravel how long young and older adults took to recalibrate. Knowing when participants reached complete recalibration, known as the

point of recalibration, on a particular task can have practical implications. Previous studies using direct measures generally indicated that participants had recalibrated after performing the task in a number of blocks (Bingham & Romack, 1999; Bruggeman et al., 2005; Scott & Gray, 2010). Although these studies give an estimated range of time needed for recalibration, a more specific examination of the trial-by-trial analysis fits in the tradition of the ecological approach. To our knowledge, only very recently, a few studies have tried to identify a timeframe for recalibration (Day et al., 2019; Franchak & Somoano, 2018; Wang & Bingham, 2019). Although these studies gave an estimate of the time that is needed for recalibration, their estimates of the point of recalibration were done by visually inspecting the data. Importantly, our innovative methodology using piecewise regressions was able to determine the point of recalibration in an automated fashion, which was also in agreement with a visual inspection. Therefore, we suggest the use of this methodology as the most important methodological contribution that this thesis can offer the field of recalibration.

7.5 Practical significance

In this thesis, we have implemented an ecologically-grounded functional approach to explore age-related differences that occur as a result of healthy ageing. Investigating participants' behaviour in everyday activities is important because the knowledge can be directly applied to make recommendations, in this case, to the activities of older adults. Our research showed that while older adults recalibrated slower than young adults in a predictable environment, they recalibrated faster when faced with an unpredictable environment. This is interesting and suggests that older adults may be more at risk of injury in more familiar environments. In addition to this, older adults may be more distracted in familiar environments or when executing familiar tasks and therefore, less aware of disturbances to their perceptual-motor system. Our results also showed that older adults use a faster recalibration to cope with unpredictable environments, which may have led to a suboptimal movement pattern. In this connection, it seems the best training strategy to cope with perceptual-motor disturbances is to be exposed to them in a controlled environment. For example, McCrum et al. (2016) repeatedly applied the same disturbance to the leg of people walking on a treadmill and found that they adjusted their gait to this disturbance. If such a protocol is modified to integrate an unpredictable task/environment while also applying the disturbances, participants may improve their ability to recalibrate. We suggest that offering a training program which includes

disturbances in a controlled and safe environment for older adults is a fruitful application of recalibration research.

7.6 Future research

In general, it seems that more research into recalibration is necessary. First, our results suggested that recalibration speed may have been constrained by reduced action capabilities and the perceived consequences of the task. However, our studies did not specifically control for action capabilities. One way to do this would be to pair young and older adults on previously assessed action capabilities. Further, our last experimental studies varied both task and predictability, and therefore, it is not clear whether results are attributable to one or the other. Future research should systematically study changes in predictability within a task to assess whether that is a constraint to recalibration. Conversely, keeping predictability and changing task (and consequences of poor performance on that task) would provide insight into whether "fear of tripping" was a constraint to recalibration speed.

Second, because we were interested in a perceptual-motor process, we purposefully excluded cognitive factors from the experiments. However, they can be a powerful constraint in modulating attention and the use of strategies in a given task. It is possible that older adults may be more distracted in familiar environments and therefore, less aware of disturbances to their perceptual-motor system. For this reason, it would be interesting to investigate cognitive factors that might influence the process of recalibration, such as cognitive distractors or multitasking. Many everyday activities demand very little attention from the people performing them (Weerdesteyn, Schillings, Duysens, & Van Galen, 2003). For example, most people can ascend stairs while chatting or texting, without consciously paying attention to their movements. Future research can investigate whether these cognitive distractors interfere with the recalibration process.

Finally, although our results suggest a fast recalibration and recovery of a stable movement pattern for both groups, we did not find any obvious movement patterns that differentiated young and older adults. Although this was not the focus of chapters 5 or 6, future research should investigate changes in movement patterns. This would allow insight into the quality of patterns between groups before and after their perceptual-motor system is disturbed. Previous research has suggested that participants use movement strategies that were within their neuromechanical capabilities to recalibrate successfully (Bruijn et al., 2012; Mecheri et al., 2019). For example, it is suggested that a mild

degradation of cerebral structures in older age led to a decreased ability to use a “timing strategy” (Bruijn et al., 2012). Instead, older adults used a “speed strategy” to recalibrate to the split-belt treadmill. Similarly, a recent study in another domain has found that world-class tennis players were able to adapt their perceptual-motor control based on their individual capabilities to maximise the time before movement initiation (Mecheri et al., 2019). Future research should further investigate whether age-related differences are dependent on participants’ neuromechanical capabilities.

7.7 Conclusion

In this thesis, we explored age-related effects in the recalibration to action disturbances. A systematic review of the literature showed the importance of investigating the timeframe of recalibration using a trial-by-trial analysis of the rearrangement process. Recalibration was not forthcoming in a judgement study of maximal action capabilities and therefore, subsequent studies investigated perceptual-motor everyday activities. An innovative methodology was applied, which identified the timeline of recalibration as the point where a stable movement pattern emerged. By examining two everyday activities, we found that both young and older adults recalibrated quickly, albeit not in the same way. The availability of relevant information appeared essential for such fast recalibration to occur. Age-related differences showed that young adults recalibrated faster than older adults in a predictable environment, but when faced with an unpredictable environment, the young adults recalibrated slower. It seems that the process of recalibration was intact in both groups, but recalibration speed may have been constrained by reduced action capabilities and perceived consequences of the task in the older group. These findings have broader theoretical and practical implications for future research in recalibration.

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