CHAPTER I

General Introduction
1. General introduction

Comparing human walking with analogous-legged robots from the early 2000s illustrates the complexity of bipedal locomotion vividly. While such biped robots could readily locomote from point A to point B (e.g., see [1]), their movements often looked clumsy, did not seem to correspond to human walking, and they would fall at the slightest disturbance. These observations highlight several of the complex problems humans must deal with daily to locomote on two feet.

Walking (gait) on two feet involves, for instance, biomechanical problems that the balance control system must solve. Humans alternate between having one (single/uni-) or two (double/bi-) feet (stance/pedal) in contact with the ground when walking. During the single stance phase, the body’s centre of mass (COM) moves forward and outside the base of support (BOS). Since this induces an impending forward fall caught by contralateral foot contact [2,3], bipedal gait is often considered a sequence of controlled falls. In fact, the English word cadence (steps/min) is derived from the Latin cadere, which literally means falling. The unstable biomechanical situation in which the vertical projection of the COM is outside the BOS constitutes approximately 80% of the gait cycle [2].

Another problem is the many variations occurring in task demands (e.g., changes in the environment or body) while walking. In daily life environments, the paths people walk on can be slippery, inclined, or uneven, while in the body, muscle properties, such as strength and mass, could structurally change throughout the lifespan due to natural ageing or pathology [4] and even at a younger age due to injury or fatigue [5,6]. Therefore, walking needs to be flexible to transition between different tasks quickly and safely (i.e., the ability to respond quickly to unexpected changes in task demands), but also needs to be adaptable over time so that more structural and efficient solutions can be generated when the change in task demands persists.

The adaptability of gait may explain why humans hardly ever fall while walking—healthy humans are successfully falling (i.e., walking on two legs) without falls (i.e., losing balance) despite the biomechanical challenges of bipedal gait and the environmental changes. Since age-related changes occur in the sensory and neuromotor systems [4,7], it is conceivable that older adults implement different adaptive strategies to cope with external perturbations. If and how (older) adults achieve these locomotor adaptations is important to understand because potential consequences (e.g., hospitalization) of a fall will be more severe at an older age due to, e.g., osteoporosis. Therefore, there is a need to understand the underlying mechanisms of locomotor adaptation and how this changes with age. The overarching aim of this thesis is to assess (i) the adaptive strategies people use in response to external perturbations and (ii) how these strategies are affected by age.
1.1. Locomotor adaptation

Anyone with sneakers and Oxford shoes in the closet may have experienced locomotor adaptation first-hand (Fig. 1, Oxford shoes in black, sneakers in orange and green). Suddenly switching to sneakers after walking in Oxford shoes for a while can provoke the feeling of thudding the heel into the ground for a few steps. This phenomenon occurs because Oxford shoes have heels, while sneakers do not. What is expected (i.e., the shoe to have heels) thus no longer matches what is experienced (i.e., the shoe has no heels) once switching from Oxford to sneakers shoes. After a while, however, the thudding feeling disappears because the walking pattern is recalibrated to accommodate this change in shoe-ware. This is called motor adaptation, which is defined as “(...) a behavioural change that involves adjusting how an already well-practiced action is executed to maintain performance in response to a change in the environment or the body (...) by (...) modifying how the current action is executed”, p. 616, [8].

Locomotor adaptation can be studied in a controlled experimental setting using a split-belt treadmill. Figure 1 shows a representative adaptation curve (i.e., the adaptation of step length asymmetry) of a single participant from the cohort studied in Chapter III. This task is not unlike switching from Oxford (baseline) to sneaker shoes (split-belt adaptation). The split-belt treadmill has two separate belts that can be controlled independently. During the adaptation phase, a continuous perturbation is imposed by setting the belts to asymmetrical speeds (e.g., 0.7 vs. 1.4 m/s). Following the abrupt introduction of this new set of task constraints (i.e., the asymmetry in belt speeds), flexibility is required to ensure a consistent task performance (Fig. 1 highlight flexibility in orange) [9], while adaptability is required to implement structural changes in the task-performance when the change in task constraints persists (Fig. 1 highlight adaptability in green) [8]. Initially, subjects respond with feedback adjustments to the split-belt configuration by walking with asymmetric step length and step times [10,11]. Since this asymmetry is metabolically and mechanically inefficient [12,13], subjects gradually re-establish symmetry after prolonged exposure to the asymmetrical speeds. This is achieved by incorporating the expected effects of the split-belt perturbation into the execution of upcoming steps through feedforward control [10,11]. These feedforward changes persist when the belts are set to symmetrical speeds again during the washout phase [14]. As a result, the asymmetry re-occurs during washout (i.e., an aftereffect), but now in the opposite direction of adaptation [10]—this asymmetry quickly returns to baseline values throughout the washout phase. The aftereffects reflect the extent to which gait was recalibrated during split-belt adaptation [15].
1.2. Quantifying changes in locomotor adaptation at older age

To better understand how age affects the ability to quickly switch to a new task context and the ability adapt to over time, locomotor flexibility and adaptability were assessed across different ages in Chapter III. The initial level in step length asymmetry (SLA) immediately after exposure to the split-belt conditions is suggested to reflect locomotor flexibility, whereas the final level in SLA at the end of adaptation and how this is achieved (i.e., the rate of adaptation)
is suggested to reflect locomotor adaptability. To gain insights into these critical aspects of adaptation, studies often fit non-linear models, such as a single exponential, to the SLA data [16–21]. While this implies that every subject adapts step lengths following a single-exponential pattern, that is rarely the case in practice (Fig 1, adaptation may follow a sigmoid pattern). The use of these analytical approaches could hamper the detection and quantification of critical aspects of the adaptation curve, such as locomotor flexibility, because assumptions about the course of adaptation must be made a priori. Therefore, a non-parametric method that estimates the adaptation trend accurately regardless of the adaptation curve’s course is required to detect and quantify its critical aspects. As such, the thesis starts in Chapter II by presenting and testing a data-driven method called Singular Spectrum Analysis (SSA) to quantify the adaptation trends accurately. With SSA, the original time series is decomposed into its underlying components [22]. A subset of these components is then identified with spectral analysis [23] and used to reconstruct the trend. SSA has been successfully applied in the areas of climatology and econometrics to estimate trends from idiosyncratic time series [24].

1.3. Dynamic balance control—the inverted pendulum model

Dynamic balance control is needed to remain stable in response to continuous or discrete perturbations, such as slips or trips. As bipedal gait is essentially a sequence of controlled falls, dynamic balance control can be modelled after the falling motions of an inverted pendulum. In this model, the pendulum represents the weightless stance leg, while the point-mass on top of the pendulum represents the body’s COM [2]. The pendulum is stable when the vertical projection of the COM is above the point of application, such as in a standing stationary position. However, since walking is a dynamic activity, the COM velocity must be accounted for as well [25,26]. This is done by incorporating both the position and the velocity of the COM—a concept known as the extrapolated centre of mass (XCOM) [26]. It is now possible to determine how “resistant” an individual is to balance loss in a certain direction by calculating the margin of stability, i.e., the distance between the BOS and XCOM [26]. Since external perturbations disrupt this margin (e.g., a slip perturbation moves the foot or BOS anteriorly relative to the body’s COM), it is important to explore the possibilities of recovering or safeguarding dynamic balance.

1.4. Reactive balance control

Dynamic balance can be recovered through reactive balance control, which involves motor adjustments following perturbation onset to recover the perturbation-induced instability [27]. To prevent a fall following perturbation onset, recovery must be achieved within a short time—recovering the distance between BOS and (X)COM may no longer be feasible when too much time is taken. There are different relevant mechanisms, including arm movements [28], generating joint moments [29], and foot placement to bring the body back into equilibrium.
during recovery. Arms movements following trip events, for instance, are used to move the body in a more favourable orientation for balance recovery in the transverse plane [28]. But foot placement is arguably one of the most important mechanisms in reactive balance control [30] as that directly determines the BOS. Together these findings show that, next to the time-criticality, the actual recovery reaction needed following perturbation onset is very complex—it requires a reorganization of the entire body configuration, including the arms and torso. As complex and time-critical reactions are prone to error, it makes sense to have strategies that can avoid this complex and time-critical—or afford a greater margin for error in the—recovery when it is obvious a perturbing stimulus is imminent.

1.5. Anticipatory balance control

Indeed, as a first line of defence against potential balance loss, people can rely on anticipatory balance control to safeguard dynamic balance. By identifying potential threats to balance, anticipatory motor adjustments in the walking pattern can be made to accommodate these threats proactively [31]. From previous experience, it is known that ice is slippery (front cover). As a result, when people need to walk across the ice the next time, they will cross it more slowly and cautiously by taking wider-and-shorter steps (back cover) [32]. Such spatiotemporal step adjustments in the face of potential threats to balance serve two important functions. On the one hand, anticipatory control can safeguard dynamic balance proactively to prevent the need for a reactive response [31], while on the other hand, anticipatory control may afford a greater margin for error in the reactive aspect of the recovery response [33].

Anticipatory control can be experimentally provoked by letting people step on a movable platform embedded in the walkway (as if stepping on a skateboard) or, alternatively, letting people walk on a treadmill and briefly accelerating the belts in the forward direction (as if someone pulls the carpet from under your feet) at foot contact (see [34] for a visual overview of these perturbation methods). Previous studies have shown that repeated exposure promotes improvements in both anticipatory (i.e., the final unilateral step preceding a perturbation) and reactive control in the lab [33–37]. Throughout repeated exposure to the same perturbation, the reliance on anticipatory increases, while the reliance on reactive control decreases [27]. This illustrates that anticipatory control could reduce the ‘pressure’ on reactive control and underscores its significance in dynamic balance control. However, as the vast majority of slip studies aim at the prevention of falls, the focus has primarily been on reactive balance control, and anticipatory control has perhaps not been appreciated as a phenomenon worth studying on its own. As such, it is not fully understood how anticipatory control develops of multiple (left/right) steps when repeatedly exposed to simulated slips.

Therefore, an uninterrupted protocol of treadmill walking was created (i.e., the belts are not stopped) to study spontaneous anticipatory strategies in more detail (Chapters IV and V). Subjects were exposed repeatedly to simulated slip after a randomized number of steps. By
filtering the recovery steps after each perturbation, numerous (unperturbed) anticipatory steps in between the perturbations could be assessed. Using this approach, it was assessed in Chapter IV if and how young adults develop anticipatory strategies spontaneously over multiple left and right steps to accommodate the requirements of slip-like perturbations with predictable and unpredictable magnitudes (i.e., the duration of the slip).

1.6. Effects of older age on anticipatory balance control

Studies suggest that anticipatory control is an important adaptive mechanism when perturbing stimuli are expected. For instance, when the support surface is translated predictably during quiet stance, both young and older adults use anticipatory control to minimize the perturbation impact by shifting the centre of pressure (COP) proactively in the anticipated perturbation direction [38]. As older adults may experience more difficulties recovering from perturbation during walking [39], it is important to understand the anticipatory adjustments older adults use in anticipation of predictable perturbations during walking. Therefore, we examined in Chapter V whether the way and extent to which healthy older adults utilize anticipatory control when exposed repeatedly to expected slip perturbations differed from young adults.

1.7. Thesis aim and outline

The overarching aim of this thesis is to gain a better understanding of the adaptive strategies used in response to external perturbations and how these strategies are affected by age. To accurately quantify changes in locomotor flexibility, adaptability, and the effects of age, the applicability of SSA to accurately derive adaptation curves was tested in Chapter II. Subsequently, the effects of age on locomotor flexibility and adaptability were assessed in Chapter III using SSA. Then, in Chapter IV, it was assessed how young adults proactively adjust their gait to accommodate simulated slips with (un)predictable magnitudes. Finally, in Chapter V, it was assessed if healthy older adults utilize anticipatory adjustments to predictable slip perturbations in the same way and to the same extent as younger adults.

1.8. Framework summary

Figure 2 presents the completed falling without falls framework, in which the different experimental studies are framed. Motor adaptations through feedback and feedforward mechanisms (Fig. 2, purple) are needed to ensure a consistent task-performance following the abrupt introduction of a continuous perturbation (Fig. 2, orange) and to implement structural changes in task performance when the perturbation persist (Fig. 2, green). Motor adjustments through anticipatory and reactive mechanisms (Fig. 2, gold) are needed for safeguarding and recovering dynamic balance when exposed to discrete slip perturbations. While anticipatory balance control can be used when the slip is expected (Fig. 2, blue, *),
people may be forced to rely solely on reactive balance control when the slip is unexpected (Fig. 2, red, **). In addition, anticipatory control is also utilized when a perturbation is expected but not presented (e.g., following a slip warning) (Fig. 2, dotted lines, #) [40–42]. Together, the experimental studies may increase our understanding of how (older) age affects various functions of gait adaptability.

**Figure 2: Falling without falls framework.** In Chapter II, the applicability of Singular Spectrum Analysis was tested to quantify critical aspects of locomotor adaptation (scale symbols). In Chapter III, a continuous perturbation is used to determine how age affects locomotor flexibility (through feedback mechanisms) and adaptability (through feedforward mechanisms). In Chapters IV, discrete slip perturbations are used to study locomotor adjustments in anticipatory control when the perturbation magnitude is predictable and unpredictable. The effects of older age on anticipatory locomotor adjustments are studied in Chapter V. Single symbols (*, #) reflect conditions in which the slip is expected (e.g., through slip warning), while double symbols (**) reflect unexpected slips. Coloured terms were explained in more detail and highlighted in bold throughout the introduction text.
References


