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Adaptive control of dynamic balance in human walking

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GENERAL INTRODUCTION

BACKGROUND

Human bipedal walking has intrigued scientists and philosophers for ages. Since Aristotle's first recorded comments (384 – 322 BCE) on vertical oscillations in human walking [1], we have come a long way until Perry's Gait Analysis [2], Winter's Biomechanics and Motor Control of Human Movement [3] and 21st century clinical and experimental gait research and analyses [4]. Humans are one of few mammals to exercise bipedal gait, and research has shown that although human bipedal gait is more energy efficient than quadrupedal gait, it is inherently unstable [5]. To stay upright while walking, humans need to be able to flexibly respond and adapt to (unexpected) changes in the environment, for instance when walking over uneven or slippery terrain, or on a rocking boat. In other words, humans need to be able to adaptively control dynamic balance to remain stable [6]. The role of adaptive control of dynamic balance in human walking becomes clear following natural ageing, disease or impairment, when people have trouble to control their balance and as a result become less mobile or more prone to falling [7-9]. However, to improve adaptive control of dynamic balance in prevention of mobility decline and gait rehabilitation, we first need to understand it. Therefore, the aim of this thesis is to increase our understanding of adaptive control of dynamic balance in human walking.

NEUROMUSCULAR CONTROL OF HUMAN WALKING

Human bipedal gait is produced by activation of muscles through the central nervous system, i.e. through neuromuscular control [10]. On many levels of human movement control, e.g. end-point control, joint angle configurations, or neuromuscular control, more degrees of freedom are available than necessary to perform a certain movement, as described in Bernstein's degrees of freedom problem. Specifically, in neuromuscular control of human walking, an almost infinite number of combinations of muscles is available to produce the same gait pattern [11]. This control problem of redundancy in available muscles for human movement can be solved by the idea that a small set of control signals, i.e. muscle synergies, can control the muscles involved in a specific task, forming functional muscle groups [12-14]. To reduce ambiguity due to different definitions of muscle synergies that are used in the literature, in this thesis we follow a definition given by Turvey (2007) [15]: *'It has been hypothesized that particular patterns of muscular activities could form a base set analogous to the concept of basis in the theory of vector spaces: a minimal number of (linearly independent) elements that under specific operations generate all members of a given set, in this case, the set of all movements' ... 'the synergies-as-basis hypothesis implies that all movement patterns share the same synergies'*. If such a synergistic structure controls all movements in human walking, by definition the same structure should be able to adaptively respond to perturbations of dynamic balance during walking. In other words, a synergistic structure for neuromuscular control of human walking needs to be flexible or adaptive, otherwise we would need a new set of synergies for each gait task, which would result in a virtually infinite instead of limited library of muscle synergies.

One of the most fundamental and frequently performed adaptations in human walking is the change of walking speed. For example, when people walk over a crowded marketplace, they continuously adapt their walking speed to avoid other pedestrians or obstacles, or to slow down before making a turn to the next stall. If neuromuscular control of human walking is regulated by a single synergistic organization, it should be able to control such speed modulations during human walking, without altering the synergistic organization itself. To test this concept and increase our understanding of adaptive neuromuscular control in human walking, we assess whether a synergistic structure can control the speed dependent modulation of muscle activity in healthy human walking in chapter 2 of this thesis.

DYNAMIC BALANCE CONTROL

Dynamic balance control is necessary to remain stable during bipedal locomotion [16]. Consider how hard it would be for one to balance a two-legged wooden stool with a 65 kg weight on top. As that task would be nearly impossible, it is amazing how healthy human adults manage to remain stable during stance [17], let alone while making over a million steps every year [18]. However, when dynamic balance control fails for even a single step in that million, the consequences can be severe. Fall related incidents in healthy adults lead to injuries, reduced quality of life, increased risk of social isolation and an estimated annual cost of 873 million euros in the Netherlands alone [19,20]. Therefore, maintaining or improving dynamic balance control is an important part of both healthy ageing and rehabilitation.

Although falling can be a serious problem in human walking, it is also a key component of normal human walking [17,21]. Dynamic balance control in human bipedal walking can be modelled after the falling movement of an inverted pendulum with a point mass on top [17,21]. In this model, the inverted pendulum represents the weightless stance leg and the point mass on top represents the body center of mass. The falling motion of the inverted pendulum during the stance phase of walking is terminated by the next step, after which the inverted pendulum motion repeats itself in the other, contralateral, stance leg. The inverted pendulum model was extended by the work of Pai & Patton (1997) [22] and Hof et al. (2005) [23], who added a center of mass velocity component to the model, improving it for dynamic situations such as walking. This led to the extrapolated center of mass concept [24], which states that stable gait can be achieved through a simple rule. As long as a step is made a minimum lateral distance from the extrapolated center of mass position, termed the mediolateral margin of stability, a person will stay upright. The margin of stability and extrapolated center of mass concept brought understanding of stepping and balance control in human gait, and inspired many studies on reactive and adaptive stepping in human walking [25-28]. In chapters 3, 4 and 6 of this thesis the margin of stability will be assessed to quantify dynamic balance control in the context of locomotor adaptation.

LOCOMOTOR ADAPTATION AND LEARNING ON A SPLIT-BELT TREADMILL

Motor adaptation is suggested to underlie motor learning, and can be seen as the basis of locomotor rehabilitation and training. Motor adaptation occurs when the intended movement and performed movement do not match, but learning occurs only when an adaptation becomes more permanent [29]. An indicator of actual motor adaptation in response to perturbations of movement in experimental settings is the emergence of after-effects once the perturbation is removed, i.e. after adaptation. Typically, these after-effects occur in the opposite direction of the adapted movement and the after-effects wash out after multiple movement repetitions in absence of the adaptation stimulus [30,31]. However, once a new movement is fully learned, after-effects no longer occur, as one is able to switch effortlessly between the different movements, without any after-effects of the adapted movement [32].

Locomotor adaptation and learning can be studied in a controlled experimental setting with split-belt treadmill walking. A split-belt treadmill is equipped with two parallel belts, the speed of which can be controlled independently. By speeding up one of the belts, it is possible to make people walk faster with one leg than the other, provoking an asymmetric gait pattern [30]. Previously, it was found that an asymmetric overground gait pattern is related to lower scores on clinical balance tests [33]. Furthermore, split-belt walking leads to a reduced frontal inclination angle [34], increased mediolateral ground reaction forces, and increased fast-leg hip moment impulse [35]. These findings indicate that, while split-belt walking is a perturbation of gait in the sagittal plane, it also challenges dynamic balance control in the frontal plane. This makes split-belt treadmill walking a suitable task to study the adaptive control of dynamic balance in reaction to a sustained perturbation of human walking.

In this thesis we utilize a common split-belt adaptation protocol to study locomotor adaptation and learning in human walking. This protocol starts with a tied-belt baseline phase, in which both belts move at the same speed, to assess baseline-walking performance. After the baseline phase, one of the belts is set at a higher speed than the other belt, called the split-belt adaptation phase. In the beginning of this phase, i.e. during early adaptation, people typically show large inter-limb asymmetries in step lengths and double support times [30]. During adaptation, these spatiotemporal asymmetries progress towards a more symmetric level over time, until late adaptation. After ten to fifteen minutes, the belts are set at tied speeds again, to wash out the adapted movement. At the start of the washout phase, after-effects are seen in the opposite direction of the spatiotemporal asymmetries in early adaptation. After-effects generally wash out within two minutes, and indicate that the spatiotemporal control of stepping was altered during split-belt adaptation [36,37]. In chapters 3, 4 and 5 a split-belt treadmill is used for continuous perturbations of dynamic balance, to study adaptive control of dynamic balance and assess the effects of external support on locomotor learning in healthy young adults.

A split-belt treadmill can be used for adaptation studies, but also to apply short and discrete perturbations during human walking. By briefly accelerating or decelerating one of the belts, a

person walking on the treadmill will slip or trip [38], resulting in a reactive stepping response. The ability to precisely control the acceleration and velocity of both treadmill belts during such perturbations makes split-belt treadmills very useful to study reactive balance control in a controlled setting in both able-bodied and impaired populations. In chapter 6 a split-belt treadmill is used to selectively perturb the paretic or non-paretic leg at heel-strike during treadmill walking in people post-stroke.

ADAPTIVE CONTROL OF DYNAMIC BALANCE IN PEOPLE POST-STROKE

Approximately 43,000 people in the Netherlands suffer from a stroke annually [39]. Stroke survivors who remain ambulant often have trouble to maintain dynamic stability [40], which can lead to falls or fear of falling [8,9]. The abnormal coordination [41-45], reduced paretic leg force production [46,47], and delays in reflexes [48], that are typically seen in people post-stroke, may lead to the impaired paretic stepping responses [49], i.e. the diminished reactive and proactive balance control, that underlies these falls. During normal walking, people post-stroke unload their paretic leg, while they stabilize and propel themselves with the non-paretic leg [46,47,50], leading to asymmetric anteroposterior and mediolateral margins of stability [26]. Research has shown that people post-stroke increase their mediolateral margin of stability and decrease their anteroposterior margin of stability in response to lateral perturbations of gait, such as a push at the hip [25]. However, it is unclear how exactly reactive stepping is controlled in response to perturbations in the sagittal plane during walking post-stroke, for instance following slips or trips.

Hypothetically, an increase in the anteroposterior margin of stability in reactive stepping may come with a decrease in mediolateral margin of stability [51,52], i.e. a covariation may exist between the anteroposterior and mediolateral margins of stability. Arguably, if such a relation exists and given that people post-stroke walk with asymmetric margins of stability [26], the step length asymmetry seen in people post-stroke [46,53] could be a mechanism to improve dynamic balance on the paretic side. Therefore, to increase our understanding of adaptive control of dynamic balance in people post-stroke, we will test this hypothesis and study covariation of anteroposterior and mediolateral margins of stability in reactive balance control during walking post-stroke in chapter 6 of this thesis.

AIM AND OUTLINE OF THE THESIS

The aim of this thesis is to increase our understanding of adaptive control of dynamic balance in human walking. In all studies treadmills are used to assess human walking, in which changes in treadmill belt speed are applied to perturb participants. First, to study adaptive neuromuscular control of human walking, a synergistic structure to control the speed dependent modulation of muscle activity in human walking is assessed in **chapter 2**. Then, in

chapter 3, the adaptation of mediolateral dynamic balance control to walking with asymmetric belt speeds on a split-belt treadmill, i.e. a sustained perturbation of gait, is studied. Based on the findings in chapter 3, bilateral temporal control of stepping is proposed as a mechanism that controls mediolateral dynamic balance during symmetric, asymmetric and adaptive human walking in **chapter 4**. In chapters 3 and 4 the adaptation of dynamic balance in split-belt walking is studied, but the question remains what happens with adaptation to split-belt walking, once control of dynamic balance is no longer a problem. As adaptive control of dynamic balance was prominent in split-belt adaptation (chapters 3 and 4), we hypothesize that once the balance control problem is eliminated through external support, adaptation effects will be reduced. Therefore, in **chapter 5** the effect of external balance support, by holding on to handrails, on locomotor adaptation and learning in a split-belt walking task is assessed. We expect that chapter 5 will give more insight in the role of dynamic balance control in locomotor adaptation and learning. In **chapter 6**, the knowledge on margins of stability gained in chapters 3 and 4 is exploited to increase our understanding of impaired reactive balance control in people post-stroke. In this chapter, the covariation of anteroposterior and mediolateral stepping strategies in response to short perturbations of gait in people post-stroke is studied. Finally, a general discussion and conclusion of the findings and implications of this thesis will be provided in **chapter 7**.

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