Human Movement Science 59 (2018) 178–192

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Full Length Article

Coordinative structuring of gait kinematics during adaptation to variable and asymmetric split-belt treadmill walking – A principal component analysis approach

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ARTICLE INFO

Keywords:
Split-belt
Motor learning
Variable practice
Principal component analysis
Gait

ABSTRACT

Gait adaptation is a task that requires fine-tuned coordination of all degrees of freedom in the lower limbs by the central nervous system. However, when individuals change their gait it is unknown how this coordination is organized, and how it can be influenced by contextual interference during practice. Such knowledge could provide information about measurement of gait adaptation during rehabilitation. Able-bodied individuals completed an acute bout of asymmetric split-belt treadmill walking, where one limb was driven at a constant velocity and the other according to one of three designed practice paradigms: serial practice, where the variable limb belt velocity increased over time; random blocked practice, where every 20 strides the variable limb belt velocity changed randomly; random practice, where every stride the variable limb belt velocity changed randomly. On the second day, subjects completed one of two different transfer tests; one with a belt asymmetry close to that experienced on the acquisition day (transfer 1; 1.5:1), and one with a greater asymmetry (transfer 2; 2:1) . To reduce this inherently high-dimensional dataset, principal component analyses were used for kinematic data collected throughout the acquisition and transfer phases; resulting in extraction of the first two principal components (PCs). For acquisition, PC1 and PC2 were related to sagittal and frontal plane control. For transfer 1, PC1 and PC2 were related to frontal plane control of the base of support and whole-body center of mass. For transfer 2, PC1 did not have any variables with high enough coefficients deemed to be relevant, and PC2 was related to sagittal plane control. Observations of principal component scores indicate that variance structuring differs among practice groups during acquisition and transfer 1, but not transfer 2. These results demonstrate the main kinematic coordinative structures that exist during gait adaptation, and that control of sagittal plane and frontal plane motion are perhaps a trade-off during acquisition of a novel asymmetric gait pattern.

1. Introduction

Human locomotion requires coordinative flexibility to accommodate changing environmental demands while maintaining balance. In acute situations, such as a rapidly applied resistance to the leg (Noble & Prentice, 2006; Reisman, Bastian, & Morton, 2010), the human central nervous system (CNS) must quickly implement a new lower-limb coordination pattern. This phenomenon has been

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https://doi.org/10.1016/j.humov.2018.04.009
Received 17 August 2017; Received in revised form 12 April 2018; Accepted 22 April 2018

reported as evidence of gait adaptation (Bastian, 2008), which can become more permanent following musculoskeletal injury (Wexler, Hurwitz, Bush-Joseph, Andriacchi, & Bach, 1998), neurological injury (Chen et al., 2003), or following repeated bouts of gait rehabilitation (Reisman et al., 2010). As repeated exposure to an environmental condition occurs, individuals become more capable of switching to that adapted pattern, and re-organizing limb coordination back to the original pattern when the stimulus is removed (Bastian, 2008).

Experimentally, gait adaptations can be studied using an asymmetric split-belt treadmill walking (SBW) protocol. This protocol involves driving the two belts of a split-belt treadmill at different velocities, effectively inducing a limp. In recent decades, researchers have used this paradigm to describe gait adaptation in altered lower-limb mechanics over time. Dietz, Zijlstra, and Duysens (1994), Reisman, Block, and Bastian (2005), and Morton and Bastian (2006) noted that when able-bodied individuals are given a novel gait asymmetry, they alter step length, time spent in double support, and interlimb coordination even when belt velocities do not change. Feed-forward adaptations such as these are likely mediated in the cerebellum, since individuals with cerebellar damage do not exhibit changes when given an asymmetric SBW paradigm (Morton & Bastian, 2006).

Other recent work has sought to fine-tune asymmetric SBW exposure to maximize the magnitude and duration of specific mechanical adaptations. This idea stemmed from the previously noted role of sensory prediction errors in motor learning, where a discrepancy between predicted and actual sensory feedback drives a correction process to mechanical limb output (Miall & Wolpert, 1996; Tseng, Diedrichsen, Krakauer, Shadmehr, & Bastian, 2007). In the case of gait adaptation, repeated exposure to sensory prediction errors over time induces changes in mechanical gait parameters to find a coordination solution that minimizes sensory discrepancies (Bastian, 2008; Tseng et al., 2007). A recent study by Torres-Oviedo and Bastian (2012) reported that subjects who experience large sensory prediction errors often attribute those errors to environmental conditions rather than internal errors. It was postulated that large sensory prediction errors impact how the new asymmetry is learned. These findings have been generally supported by recent demonstration that a gradual introduction of small errors during an acute bout of asymmetric SBW leads to improved retention and transfer of frontal (Sawers, Kelly, Kartin, & Hahn, 2013) and sagittal plane (Sawers & Hahn, 2013) balance compared to a sudden introduction of large errors.

In parallel with this fine-tuning, there remains a need to clarify which outcome measures are most demonstrative of the underlying coordination strategy implemented by the CNS. One way to clarify the most demonstrative measures of coordination strategy is to make use of the large amount of kinematic information available during a gait analysis through isolation of the coordinative features which indicate the underlying motor control of the system. Because the CNS affects many degrees of freedom leading to a coordinated solution during walking, a reduction of available kinematic data to a set that helps explain more important coordination patterns among these variables would allow more targeted research measuring gait adaptation outcomes. Other studies have used principal component analyses (PCA) for data reduction to answer clinical gait analysis questions (Deluzio & Astephen, 2007; Olney, Griffin, & McBride, 1998). For each of these studies, a list of underlying coordinative structures were extracted to explain the overall gait strategy adopted.

Therefore, there were two main purposes of this study. First, this study sought to identify the underlying kinematic coordination patterns during acquisition, and two levels of transfer difficulty for a novel bout of asymmetric SBW in able-bodied individuals. Previous work has highlighted hip (Hinkel-Lipsker & Hahn, 2016b) and ankle (Selgrade, Toney, & Chang, 2017) sagittal plane kinetics as primary sites of gait adaptation. Thus, we hypothesized that across groups, some of the most relevant kinematic features of this locomotor adaptation would be related to their kinetic equivalents: adaptive changes (i.e. variance) in sagittal plane hip and ankle joint motion (including thigh and foot segment kinematics). We also expected that these adaptations would generalize to the two different transfer tasks in this study. The second purpose was to observe whether sensory prediction error variance through contextual interference during acquisition had an influence on how individuals structure those patterns, and if it affects structuring during transfer. We hypothesized that the group with the largest amount of contextual interference during acquisition, a random practice group, would demonstrate different structuring of coordination patterns compared to the other two practice groups in this study. Such information would help to clarify the relationship between sensory prediction errors and gait adaptation, and explain the most important coordinative structures implemented as a response to those errors.

2. Methods

2.1. Recruitment

Forty-eight able-bodied individuals were asked to participate in this study. Inclusion criteria for participation required subjects to be between 18 and 50 years of age and be able to walk unassisted on a treadmill for up to 30 min. Exclusion criteria were any self-reported musculoskeletal, cardiopulmonary, or neurological injuries, as well as any experience walking asymmetrically on a split-belt treadmill. The university Institutional Review Board approved all study protocols, and all subjects provided written informed consent prior to enrollment in this study.

2.2. Study design and experimental protocol

Subjects attended two days of testing separated by exactly 24 h. On the first day of testing, subject's self-selected walking speed (SSWS) was measured by calculating the average of 4 times walking across a 20 m walkway. During this process, subjects were instructed to walk as naturally as possible. Subjects were then given a 15-min acclimation phase where both belts on an instrumented split-belt treadmill (Bertec, Columbus, OH) were driven at SSWS to promote gait consistency (Zeni & Higginson, 2010). Following this