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Do kinematic metrics of walking balance adapt to perturbed optical flow?

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ABSTRACT

Visual (i.e., optical flow) perturbations can be used to study balance control and balance deficits. However, it remains unclear whether walking balance control adapts to such perturbations over time. Our purpose was to investigate the propensity for visuomotor adaptation in walking balance control using prolonged exposure to optical flow perturbations. Ten subjects (age: 25.4 ± 3.8 years) walked on a treadmill while watching a speed-matched virtual hallway with and without continuous mediolateral optical flow perturbations of three different amplitudes. Each of three perturbation trials consisted of 8 min of prolonged exposure followed by 1 min of unperturbed walking. Using 3D motion capture, we analyzed changes in foot placement kinematics and mediolateral sacrum motion. At their onset, perturbations elicited wider and shorter steps, alluding to a more cautious, general anticipatory balance control strategy. As perturbations continued, foot placement tended toward values seen during unperturbed walking while step width variability and mediolateral sacrum motion concurrently increased. Our findings suggest that subjects progressively shifted from a general anticipatory balance control strategy to a reactive, task-specific strategy using step-to-step adjustments. Prolonged exposure to optical flow perturbations may have clinical utility to reinforce reactive, task-specific balance control through training.

1. Introduction

Walking balance control depends on integrating reliable sensory feedback and on planning and executing appropriate motor responses (O'Connor and Kuo, 2009). Accordingly, sensory perturbations are increasingly used to study balance control mechanisms in walking. Visual (i.e., optical flow) perturbations in particular can elicit strong and acute motor responses to regulate balance from step to step (O'Connor and Kuo, 2009; Terry, Sinitski, Dingwell, & Wilken, 2012). Moreover, these acute motor responses are remarkably more intense in subjects with sensorimotor deficits, such as those due to advancing age (Franz, Francis, Allen, O'Connor, & Thelen, 2015). These results forecast the promising potential of optical flow perturbations applied during walking in the diagnosis of people at risk of falls. However, some evidence from the postural control of standing suggests that subjects may adapt to such perturbations, effectively adjusting their sensitivity to visual feedback over time (Jeka, Allison, & Kiemel, 2010). Although highly relevant to their translational potential, it remains unclear whether walking balance exhibits this time-dependent behavior, which we refer to as visuomotor adaptation.

Multisensory reweighting, the central process that determines the relative priority placed on somatosensory, visual, and vestibular feedback, is considered an essential component of balance control (Horak, Shupert, & Mirka, 1989; Jeka et al., 2010; Oie,

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Kiemel, & Jeka, 2002). However, to the best of our knowledge, this adaptive sensorimotor process has been exclusively studied in the context of postural sway during standing. For example, Jeka et al. (2010) used anterior-posterior (AP) optical flow perturbations to reveal that the relative priority placed on visual feedback in regulating standing balance is reduced when perturbation amplitudes are larger, and that this dynamic response is tuned over prolonged durations. Indeed, depending on environmental conditions, one would expect sensory feedback modalities deemed more reliable to be those prioritized in balance control. Although optical flow perturbations have been used in studies of walking, these studies have not been designed to investigate the propensity for visuomotor adaptation, with trial durations limited to between 30 s and 3 min and time-averaged outcome measures generally reported.

How would visuomotor adaptation manifest in the control of walking balance? Foremost, walking balance is governed via highly coordinated adjustments in whole-body center of mass (CoM) motion and foot placement from step to step. Adjustments in foot placement in response to optical flow perturbations can be well characterized via step-to-step variability (O'Connor and Kuo, 2009). Step width variability in particular has emerged as a robust metric of dynamic balance in walking and is uniquely compromised in the presence of perturbations (O'Connor and Kuo, 2009). Indeed, although AP balance in standing is highly susceptible to optical flow perturbations, mediolateral (ML) balance is more susceptible in walking and is governed in part by step-to-step adjustments in lateral foot placement (i.e., step width variability) (Bauby & Kuo, 2000; Collins & Kuo, 2013; Donelan, Shipman, Kram, & Kuo, 2004; O'Connor and Kuo, 2009; O'Connor, Xu, & Kuo, 2012). In addition, we and others have used the spectrum of ML CoM motion to provide insight into the relative priority placed on visual feedback for walking balance control (Franz, Francis, Allen, O'Connor, & Thelen, 2015; Latt, Menz, Fung, & Lord, 2008). Specifically, human walking exhibits naturally emerging entrainment to frequencies directly present in ML optical flow perturbations, and the strength of this entrainment can be interpreted to signify one's sensitivity to visual stimuli (Franz, Francis, Allen, O'Connor, & Thelen, 2015; Franz, Francis, Allen, & Thelen, in press). However, time-dependent changes in foot placement variability and ML CoM motion following exposure to perturbations in walking have yet to be investigated. A return of these metrics of walking balance control toward values seen during normal, unperturbed walking despite ongoing perturbations may allude to the occurrence of visuomotor adaptation.

The purpose of this study was to investigate the propensity for visuomotor adaptation in walking balance control using prolonged exposure to optical flow perturbations of different amplitudes. We used a virtual reality environment to apply continuous ML optical flow perturbations during treadmill walking and recorded the time course of effects on measures of balance control. We first hypothesized that subjects would exhibit visuomotor adaptation, such that the effect of perturbations on walking balance would decrease with walking duration. We also hypothesized that this adaptation would scale with perturbation amplitude, with larger perturbations exhibiting more persistent effects on walking balance.

2. Methods

Ten healthy, young adult subjects (mean ± standard deviation; age: 25.4 ± 3.8 years, height: 1.75 ± 0.10 m, weight: 74.4 ± 16.7 kg, 4 female) participated in this study. Before testing, all subjects provided written informed consent according to the University of Wisconsin Health Sciences Institutional Review Board.

2.1. Experimental Procedures and measurements

Subjects first walked down a 10 m walkway at their self-selected comfortable speed. We calculated subjects' preferred overground walking speed as the average of two times taken to traverse the middle 4 m of the walkway (1.38 ± 0.13 m/s). Subjects then

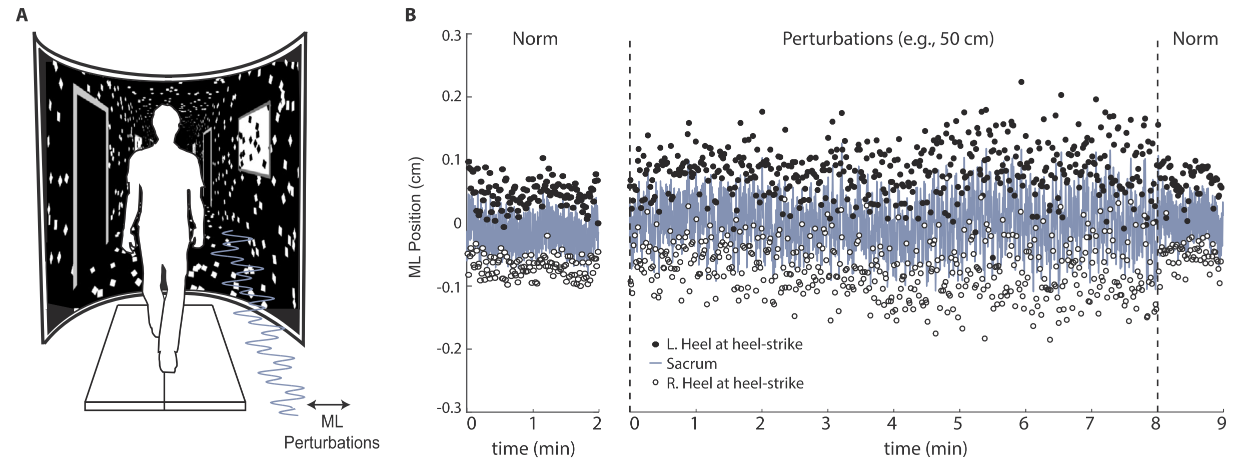

Fig. 1. (A) Subjects walked on a treadmill while watching a speed-matched, immersive virtual hallway with and without continuous mediolateral optical flow perturbations of different amplitudes. (B) Mediolateral (ML) sacrum motion and lateral step placement during normal walking ("Norm") and walking with the largest amplitude visual perturbation for a representative subject. Perturbation trials consisted of 8 min of prolonged exposure followed by 1 min of normal, unperturbed walking. L.heel and R.heel refer to the mediolateral locations of markers placed on the left and right heels at the instant of heel-strike, respectively.