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The effects of predictability on inter-limb postural synchronization prior to bouts of postural instability

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ABSTRACT

Anticipatory balance control optimizes balance reactions to postural perturbations. Predictive control is dependent on the ability of the central nervous system to modulate gain in accordance with specific task demands. Inter-limb synchronization is a sensitive measure of individual limb contributions to balance control and may reflect the coordination of gain modulation in preparation for instability. The purpose of the study was to determine whether gain modulation in advance of predictable bouts of instability was reflected in the extent of inter-limb synchronization. Two adjacent force plates were used to collect center of pressure (COP) data from 12 healthy young adults (27.5 ± 3.4 years). Participants prepared for internal and external balance perturbations using a cueing paradigm with three auditory warning tones followed by an imperative tone. Perturbations were delivered in blocked and randomized conditions with two perturbation magnitudes (small and large). Inter-limb synchrony was calculated using the cross-correlation function of the COP excursions from the left and right foot for three seconds prior to perturbation onset in the anteroposterior (AP) and mediolateral (ML) direction. Inter-limb synchrony decreased in the AP and ML directions as perturbation magnitude became more unpredictable. The need to take a step or not knowing whether a step was required prior to postural instability reduced ML inter-limb synchrony. No differences were found between internal and external perturbations. Modulation of postural set was evident in the extent of inter-limb synchrony.

1. Introduction

Postural control is not an automatic process, but instead requires attentional resources to optimize control [1–5]. Reliance on these resources for generating contextually appropriate postural responses implies that top-down processes likely regulate balance control and are engaged when preparing for balance responses in the event of postural instability. Anticipatory balance control optimizes reactions to perturbations induced by self-generated movements or for externally-generated perturbations whose characteristics are known.

Anticipatory control is dependent on the extent of central nervous system (CNS) readiness, also known as 'central set' [6] and is influenced by prior experience and current context [7]. Prior experience with predictable stimuli enables descending commands to prepare and modify postural responses [6,7]. By anticipating perturbations, postural muscle activity can be initiated prior to perturbation onset and mitigate subsequent instability [8,9]. The role of set modulation is supported by studies characterizing the cortical potentials associated with the factors of central set (i.e. the predictability and amplitude) of the upcoming balance perturbations [10–12].

One important feature of anticipatory control is the extent to which gain modulation affects postural control strategies. Previous work has demonstrated center of pressure (COP) shifts (i.e. early postural adjustments; EPA) prior to self-initiated forward postural sway [13] that were distinct from anticipatory postural adjustments. EPAs optimize postural control in preparation for volitional or reactive instability [13]. Additionally, bilateral activation of postural muscles with comparable magnitude and onset in advance of self-initiated bilateral shoulder-flexion perturbations

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demonstrated a more unilateral activation pattern for unilateral perturbations [14]. These examples illustrate the capacity of the CNS to modulate gain in accordance with task demands by coupling or decoupling between-limb coordination as necessary given current contextual requirements or previous experience (i.e. depending on whether the conditions under which postural instability is experienced are known or familiar) [15]. The extent of inter-limb synchronization of COP displacements reflects the coordination of muscle activation patterns between limbs [16] and is a sensitive measure of balance control [17–19]. Thus, measuring the extent of between-limb coordination in advance of postural instability may enhance understanding of the processes by which humans prepare for and optimize balance-correcting responses.

The purpose of this study was to determine whether changes in inter-limb postural synchronization prior to bouts of postural instability are indicative of modulation in postural set. Consistent with studies identifying modifiability in pre-perturbation cortical activity related to postural set alteration [10] and because high inter-limb synchrony may contribute to optimal balance control in quiet standing [14,16,18,19], we hypothesized that inter-limb synchrony would be highest when perturbation magnitudes were predictable and of low magnitude. Conversely, when the parameters of instability were unpredictable and required the execution of compensatory stepping responses, we expected a reduction in inter-limb synchronization (i.e. decoupling of between-limb synchrony). As volitional movements have an additional level of saliency/predictability due to internal models for the intended movement, we predicted that individuals would demonstrate better control of movement through higher levels of inter-limb synchrony when perturbations were internally generated. Lastly, we expected that inter-limb synchrony would change from the start to the end of repeated exposure to perturbations when perturbation magnitudes were known, but would not differ when magnitudes were unpredictable. Preliminary data has been presented in abstract form [20].

2. Methods

2.1. Participants

Fifteen healthy adults volunteered for the study. Three participants were excluded – two reported to be in the first trimester of their pregnancy, while another participant did not meet our inclusion criteria of normal/corrected visual acuity during testing. Data were collected from twelve participants (seven males, 27.5 $\pm$ 3.4 years, 172.7 $\pm$ 9.6 cm, 68.8 $\pm$ 11.6 kg) who provided written, informed consent prior to the start of study. Participants completed the Waterloo Footedness Questionnaire [21] to determine lower extremity dominance. Dominant limb was defined as the limb used most frequently for manipulation of object and providing support during an activity [22]. The study was approved by the Research Ethics Board at Sunnybrook Research Institute.

2.2. Instrumentation and protocol

Two force plates (Bertec Corp., Columbus, OH, USA) were arranged with the *Y*-axis in parallel and separated by 5 mm. Ground reaction forces and moments from each plate were sampled at 500 Hz using a 16-bit acquisition system (Power 1401 mk2, Spike2 v7.02 software, Cambridge Electronic Design, Cambridge, UK). External perturbations were applied using a 5.5 cm aluminum rod (tipped with a dense rubber cap) attached to a load cell (MLP-300, Transducer Techniques, Temecula, CA, USA). Load cell signals were sampled at 1000 Hz and down-sampled to align to the collection of the force channels for analysis (LVC-U5, A-Tech Instruments Ltd., Toronto, Canada).

Each foot was positioned on a separate force plate. Foot placement was standardized across individuals (medial aspects of each foot 0.185 m apart) at the start of each trial. For baseline measures, one 30-s quiet standing (QS) trial was collected. Participants then were presented with a series of three auditory warning cues (1-s inter-cue interval) while maintaining a fixed gaze on a target approximately 3 m ahead of them. On the presentation of a fourth auditory tone (a different tone for each condition), participants experienced a postural perturbation.

Participants completed two sessions at least one week apart, each consisting of internal or external perturbations. Each session consisted of three conditions: a block of small (BS), a block of large (BL) and a block of randomly presented small (RS) or large (RL) perturbations. Thirty trials of each condition were presented as a block in the S and L conditions and a set of 60 trials was presented in random order for the random condition for a total of 120 trials. Inter-trial duration was 15 s and participants were given a 5-min break in between each condition. Internal perturbations were performed first and the order of BS and BL conditions was randomized among participants. The random condition was always presented last to allow familiarization with the different auditory tones associated with either the S or L conditions for both Internal and External perturbations.

2.2.1. Internal perturbations

For the L conditions, participants were instructed to take a volitional step in the anterior direction with their dominant foot as quickly as possible immediately after hearing the imperative tone. For the S conditions, participants were instructed to not take a step immediately after the imperative tone (i.e. prepare not to step).

2.2.2. External perturbations

External perturbations were delivered manually using an aluminum rod, similar to previous work [23]. Perturbations were applied directly over the spinous processes (approximate location T5) to reduce any torques about the trunk. A rectangular foam pad (15.5 cm $\times$ 20.5 cm $\times$ 1.5 cm) was placed between the two scapulae to reduce the impact of the rod on the spinous processes. Small perturbations associated with the S condition resulted in feet-in-place reactions, while large perturbations associated with the L conditions resulted in stepping responses (see Fig. 1 and Table 1). Force thresholds for each participant were determined by exposing the participant to various levels of force magnitudes in random order (i.e. calibration trials). This allowed the experimenter to determine the force threshold for small and large perturbations, which evoked a feet-in-place and stepping reactions, respectively. The same experimenter performed all perturbations.

Prior to each set of blocked trials, participants were informed about the number and magnitude of the perturbation. For the random trials, participants were informed that they would experience either a small or large perturbation. In all conditions, participants were instructed to "use whatever strategy you need to regain your balance".

2.3. Data analysis

Center of Pressure – Raw data were low-pass filtered using a zero-lag, fourth-order, Butterworth filter with a cut-off frequency of 10 Hz. Anteroposteior (AP) and Mediolateral (ML) COP under each limb were calculated. The cross-correlation function was calculated using the left and right mean-removed AP and ML COP waveforms. Cross-correlation coefficients at zero phase-lag ($R_{xy}(0)$) were calculated at incremental phase-shifts defined by the sampling rate, by iteratively shifting the right limb COP