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Augmented feedback of COM and COP modulates the regulation of quiet human standing relative to the stability boundary

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ABSTRACT

The experiment manipulated real-time kinematic feedback of the motion of the whole body center of mass (COM) and center of pressure (COP) in anterior-posterior (AP) and medial-lateral (ML) directions to investigate the variables actively controlled in quiet standing of young adults. The feedback reflected the current 2D postural positions within the 2D functional stability boundary that was scaled to 75%, 30% and 12% of its original size. The findings showed that the distance of both COP and COM to the respective stability boundary was greater during the feedback trials compared to a no feedback condition. However, the temporal safety margin of the COP, that is, the virtual time-to-contact (VTC), was higher without feedback. The coupling relation of COP–COM showed stable in-phase synchronization over all of the feedback conditions for frequencies below 1 Hz. For higher frequencies (up to 5 Hz), there was progressive reduction of COP–COM synchronization and local adaptation under the presence of augmented feedback. The findings show that the augmented feedback of COM and COP motion differentially and adaptively influences spatial and temporal properties of postural motion relative to the stability boundary while preserving the organization of the COM–COP coupling in postural control.

1. Introduction

Human upright quiet standing has been characterized by the motion of the body center of mass (COM) and particularly that of the center of pressure (COP) – the point of application of the vertical ground reaction force at the surface of support. The traditional view has been that of a single-link inverted-pendulum model of the fundamental relation of COP and COM [1,2]. The single link model of upright standing posture has been challenged by the finding that there is motion at joints other than the ankle including the knee, hip and neck [3–5], reflecting that posture like movement tasks in general is a many degree of freedom (DOF) problem [6].

A more recently developed interpretation of the COP–COM coupling relation originates from a dynamical system's framework [3,7,8]. In this view, the dominant in-phase AP motion of COP–COM has been interpreted as a candidate collective variable that preserves the stability of the many DOF of the postural system. In contrast, the motions of joints and synergies are viewed as adaptive components that regulate the system on faster time scales to postural challenges. In the framework of coordination dynamics [9], there are complex interactions between joint motions, synergies and collective variables in the form of a reciprocal causality of influence in the preservation of a coordination mode, such as quiet standing.

Here we tested whether on-line augmented feedback control of either the COP or COM influences the COP–COM synchronization and selected kinematic properties of postural motion. A related focus was a contrast of the control of posture from both the view of a fixed point in an inverted pendulum model and COM and COP motion to a central stability point [10] and motion to the postural stability boundary as reflected in measures of virtual time-to-contact (VTC) [11,12]. Previous studies have shown that COP real-time feedback did not alter postural control mechanisms across participants even though some participants showed increased postural motion [13–16].

Freitas and Duarte [17] found that COP dispersion even increased for older people as a result of COP feedback. These findings imply that feedback of COP may have an *adverse* effect on postural stability in that exploratory or corrective motions may increase particularly in the high frequency time scales of control [16,18]. Therefore, augmented information about the COP position

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or the motion of the COM which we also test here appears to be less beneficial to improve the control of upright stance compared to feedback that relates to the intrinsic frequency structure of body sway [19]. In contrast, in a range of movement task contexts, kinematic and kinetic augmented feedback has been shown to facilitate the acquisition of a variety of movement tasks [20–22].

The purpose of the study here was to investigate the active mechanisms of postural control by contrasting the effect of 2D COP and COM feedback with natural postural sway under no augmented feedback control. The 2D functional stability boundary served as visual feedback of the task goal. The task instruction was to minimize the postural motion toward the stability boundary through centering the COP or COM position within the stability region. The visual feedback display was also manipulated through scaling in independent conditions the functional stability boundary to 75%, 30% and 12% of its original size resulting in a gain of feedback resolution as well as a minimization of the available workspace [18,23]. The experiment allowed a test of the effect of the different augmented feedback conditions on the spatial and temporal constraints on the motion of COM and COP.

Given the above theoretical framework it was hypothesized that: (1) both COP or COM augmented information feedback control would not change the COP–COM coupling relation in the lower frequencies below 1 Hz [3,18], given its projected role as a collective variable and the constraint that the participants did not take a step or fall, but that the adaptation would occur in the faster frequency bands; (2) that augmented feedback of the COP and COM would be reflected by a significant increase in the motion of either the COP or COM which ever was not displayed in the feedback [19]; (3) the amount of postural motion of COP and COM would increase and VTC would decrease due to the subjects exploiting a shorter potential contact time with the virtual boundary [12]; and (4) augmented feedback would change the selected scaling of individual joint and synergy properties of postural stability with postural motion occurring less frequently in direct spatial proximity to the limits of the stability boundary [24].

2. Methods

2.1. Participants

Fifteen healthy adults (9 males, 6 females) with a mean age of 27 ± 5.2 (SD) years participated in the study. All participants signed the approved consent form of the University of Georgia Institutional Review Board.

2.2. Experimental set-up

Eight VICON (VICON Industries Ltd., Hampshire, United Kingdom) Bonita cameras were spatial-temporally synchronized with one AMTI (American Mechanical Technology, Inc., Watertown, MA) force platform and tracked the positions of 39 reflective markers. Data were collected at 100 Hz and the VICON Nexus software was used to process the data.

VICON's DataStream SDK 1.5 was used to stream the data in real-time from Nexus into MATLAB (MathWorks, Natick, MA). Custom-written MATLAB code processed the incoming data stream and displayed the postural kinematic data as augmented information feedback on a 58 cm widescreen computer screen. The computer screen was positioned at eye level approximately 1.5 m in front of the participant.

2.3. Tasks and procedures

Participants were asked to assume a two-legged side-by-side standing posture on the force platform with their feet being a comfortable distance apart. Their visual attention was centered at the computer screen in front of them. At the beginning of the experiment we marked the foot placement on the platform. After this procedure one dynamic trial (circular sway about ankle joint) was recorded to model the 2D functional stability boundary [11,12].

There was one baseline condition where no feedback was presented although participants were asked to look at the black computer screen. During the remaining conditions we manipulated two aspects of the augmented visual feedback simultaneously. One manipulation was the type of feedback where we displayed either the COP or COM position. The current position (no past history) of the COP or COM (yellow dot on black background) was given in 2D space (AP and ML dimensions). The second manipulation displayed the functional stability boundary ellipse (in red) that was scaled to 75%, 30% and 12% of its original size. However, it was always amplified to match the borders of the screen, therefore, achieving a visual gain in addition to the smaller spatial stability area. In total, there were 7 experimental conditions (no feedback, COP feedback for each of the 3 boundary sizes and COM feedback for each of the 3 boundary sizes).

Three postural trials that lasted for 35 s in each condition were collected. All experimental conditions including the no feedback condition were randomized in their blocked presentation order. The task goal during the feedback conditions was the instruction to center postural motion within the functional stability boundary. During the no feedback condition participants were asked to fixate their gaze at the black computer screen.

2.4. Data analysis

Data analysis was performed in MATLAB (MathWorks, Natick, MA). Raw data were low-pass filtered (4th order Butterworth low-pass filter) at a cutoff frequency of 10 Hz. Subsequently, the COP was derived from the forces and moments recorded by the force platform and the COM was calculated as the weighted sum of all body segments [1]. We calculated the average velocity of both the COP and COM as traditional indicators of the degree of postural motion [10].

The VTC was computed as the boundary-relevant stability index [11,12,25,26]. VTC quantifies the temporal proximity to the stability boundary and smaller VTC values indicate decreased instantaneous stability. Here VTC was based on the dynamics of the COP or COM in AP and ML directions and computed with reference to the 2D functional stability boundary [11,12]. After extracting the VTC time series the mean values were computed. In addition, the shortest linear distance to the stability boundary and the distance to the boundary based on the VTC direction were computed as additional boundary-relevant stability metrics [24].

Of particular interest in this study was the COP–COM coupling. Three previously used analysis techniques in movement coupling were implemented, namely, the relative phase using the Hilbert transform, given the non-cyclic postural sway [27] and the spectral coherence and co-phase between the two signals [28]. The latter measure was computed over 8 frequency bins covering a frequency spectrum of 0.02–4.88 Hz and the average coherence and average absolute co-phase for each frequency bin was derived. We implemented a multi-taper spectral analysis. As opposed to ensemble averaging, the multi-taper technique reduces the spectrum estimation bias by obtaining multiple independent estimates from the same time series [3]. Time-bandwidth was set to 3 and the number of tapers to 5.

2.5. Statistics

To analyze the general statistical effects of feedback compared to no feedback (eyes open, black computer screen), we implemented a feedback (3 levels: no feedback, COP fb and COM fb) one-way