Journal of Biomechanics 48 (2015) 3825–3829

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Compensatory mechanisms of balance to the scaling of arm-swing frequency

Ji Hyun Ko [a,*], Zheng Wang [b], John H. Challis [a], Karl M. Newell [c]

[a] Department of Kinesiology, The Pennsylvania State University, University Park, PA 16802, United States
[b] Center for Autism and Developmental Disabilities, University of Texas Southwestern Medical Center, Dallas, TX 75390, United States
[c] Department of Kinesiology, The University of Georgia, Athens, GA 30602, United States

ARTICLE INFO

Article history:
Accepted 14 September 2015

Keywords:
Postural control
Arm-swing
Center of mass
Center of pressure

ABSTRACT

The present study investigated the contribution of the Hof (2007) mechanism 1 (M1-moving the center of pressure (COP) with respect to the vertical projection of the center of mass (COM_{Total})); and mechanism 2 (M2-rotating the trunk and upper limbs around the COM_{Total}) to postural control and the stability of COP–COM_{Total} cophase as a function of lateral arm-swing frequency. Young adults were instructed to stand still on a force platform while alternating their arm swinging from above the head to the side of their thigh to create perturbations to postural control. Scaling the frequency of arm-swing (random step changes of 0.2 Hz within a bandwidth of 0.2 to 1.6 Hz) increased the SD of COP but decreased the SD of COM_{Total}. Increments in arm-swing frequency induced a progressive increase in M1 and decrease in M2 in terms of their relative contribution to postural stability. The cophase between COP and COM_{Total} became more tightly in-phase over increments of arm-swing frequency. These findings show an adaptive compensatory role of M1 and M2 within the stability of COP–COM_{Total} coupling in the regulation of human balance control.

1. Introduction

The maintenance of balance in human upright posture requires the vertical projection of the whole body center of mass (COM_{Total}) to be within the stability region (Duarte and Freitas, 2010; Horak and Macpherson, 1996) that has been defined geometrically (Maki and McIlroy, 2006; Pai and Patton, 1997) and functionally (Kilby et al., 2014). Typically, postural stability has been determined from the dispersion and dynamic properties of the center of pressure (COP) – a variable that has been assumed to regulate the motion of the COM_{Total} (Winter, 1990). This functional role of the relation between the COP and COM_{Total} is predicated on the definition of the COP as the location on the surface of support of the vertical reactive force to the motion of the COM_{Total}.

Arm movements can be used to create internal perturbations to the postural control system. This situation leads the arm movements and postural configuration to become coordinated to realize the dual task demands (Kerr et al., 1985). Carr and Gentile (1994) revealed in a standing task that arm movements were strongly synchronized to lower leg extension and potentiated propulsion of the whole body into an upright position without losing balance. Slobounov and Newell (1994) found that 3- and 5-year-old children introduced compensatory arm movements in balance tasks to increase stability, particularly when visual information was unavailable. Otten (1999) investigated the contribution of arm movements in the medio-lateral (ML) direction to one foot standing on a narrow ridge and found that upper limb motion plays a significant role in balance preservation particularly with reduced based of support.

Hof (2007) presented equations of motion for a standing multi-joint postural model. The model permitted identification of three mechanisms of balance control in standing posture, namely: (M1) moving the COP with respect to the vertical projection of the COM_{Total}; (M2) counter-rotating of segments around the COM_{Total}; and (M3) applying an external force other than the ground reaction force. The role of M1 reflects postural control of upright stance as described by the inverted pendulum model (Winter, 1990). M2 is often enhanced in situations where the reduced base of support limits the motion of the COP to the extent that it fails to

Abbreviations: M1, mechanism 1 (moving the COP with respect to the vertical projection of the COM); M2, mechanism 2 (counter-rotating segments around the whole body COM); M3, mechanism 3 (applying an external force other than the ground reaction force); COP, total whole body center of pressure; COM1, center of mass determined from M1; COM_{Total}, total whole body center of mass; COM_{Seg}, center of mass of a given effector segment; MA1, displacement of the moment arm determined from M1; MA2, displacement of the moment arm determined from M2; MATotal, displacement of the moment arm determined from M1 and M2

* Corresponding author. Tel.: +1 814 863 4037.
E-mail address: cozy1123@gmail.com (J.H. Ko).

http://dx.doi.org/10.1016/j.jbiomech.2015.09.008
0021-9290/

compensate the motion of the COM_{Total}, such as in standing on a tightrope. M3 occurs during actions such as leaning against a wall, or standing holding a cane but it was not examined by Hof (2007), as is also the case in our experiment here.

Hof (2007) reported the contribution of M1 and M2 in several postural conditions (e.g., one leg standing, trunk rocking, standing on a narrow bar, and arm-swing on the side) and subsequently[1] suggested there might be a compensatory effect between M1 and M2 depending on task demands. For example, in the Hof (2007) study the contribution of M1 and M2 was 43% and 57% respectively, for trunk rocking, while that of M1 and M2 was 12% and 87% for standing on a narrow bar. When alternatively swinging the arms sideways at a frequency close to 0.5 Hz, the contribution of M1 was 9%, whereas that of M2 was 91%. However, although this study showed different relative roles of M1 and M2 under different task conditions, it did not examine the effect of scaling the level of perturbations to the postural system to determine the function for the relative contribution of each mechanism to balance control.

The focus of the present study was to investigate whether the relative contribution of each mechanism (M1 and M2) to postural control would change as a function of arm-swing frequency. The relative (%) contribution of M1 and M2 was determined to understand how these mechanisms worked together in postural support. We compared the effect of arm swing frequency on the within condition M1 and M2 mechanical difference through their relative contribution to postural stability. The relative contribution of M1 and M2 as a function of perturbation level provides an index of their respective contribution to postural control under parameter scaling conditions.

We investigated the effect of a random step function change in arm-swing frequency, with the range from 0.2 to 1.6 Hz in steps of 0.2 Hz, on the relative contribution of M1 and M2 to balance control in the ML direction of a stance with feet parallel and close together. It was expected that a faster arm-swing would generate stronger internal perturbations due to increased torque from the shoulders, leading to an increase in the contribution of M1 to postural control consistent with enhancing mechanical stability by stiffening the leg and trunk motion (Hagood et al., 1990; Cholewicki et al., 1997). Moreover, there would be a compensatory effect between the two mechanisms, in that if the relative contribution of M1 increased that of M2 would decrease, and vice versa because it is assumed that the sum of the contribution of both mechanisms is close to 100% (Hof, 2007). We also examined whether the changes in the relative contribution of each mechanism as a function of arm-swing frequency are directly related to the amount of both COP and COM motion. Given that M1 and M2 are related respectively to moving the COP and trunk rotation around COM_{Total} it was expected that there would be a contrasting trend to the COP and COM motions as a function of arm-swing frequency.

Previous studies have provided evidence for a global collective variable within a given postural mode (Ko et al., 2014; Wang et al., 2014) that captures the overarching pattern of interactions among the multiple joints and muscles of the movement system (Kelso, 1995). Wang et al. (2014) found that joint motions and their couplings changed to differing degrees in multiple postural activities whereas the COP–COM_{Total} coordination was maintained close to in-phase at the low frequencies of postural control with a small dispersion of variability. Here it was anticipated that the compensatory mechanisms of M1 and M2 would be scaled with the level of arm frequency but the influence on the macroscopic COP–COM_{Total} coupling would be negligible if the postural coordination was preserved.

In summary, the study examined three related hypotheses: 1) there would be an adaptive compensatory effect between M1 and M2 as a function of arm swing frequency (Hof, 2007); 2) the SD of COP would increase over increments of arm-swing frequency whereas the SD of COM_{Total} would be reduced (Ko et al., 2014); and 3) the COP–COM_{Total} coordination would not change and remain close to in-phase as a function of arm-swing frequency (Ko et al., 2014; Wang et al., 2014).

[1] Hof, A.L., 2014. Personal communication May 31.

2. Methods

2.1. Participants

The participants were 12 young healthy male volunteers from the Pennsylvania State University (age 28.16 ± 3.01 yr; height 175 ± 4.86 cm; weight 75.16 ± 6.73 kg). A written informed consent was administered to each participant before the testing. The study protocol was approved by the Institutional Review Board of the Pennsylvania State University.

2.2. Apparatus

The COP was derived from an AMTI force platform (Advanced Mechanical Technology Inc., OR6-5-1000) positioned on the floor. Prior to testing, 17 reflective markers were attached on the participants' anatomical landmarks (Fig. 1) located at the head (mandible condyle), neck (the spinous process of the 7th cervical vertebra), shoulder (acromion process), elbow (radius head), hand (ulnar styloid), hip (greater trochanter), knee (lateral condyle), ankle (lateral molleolus) and big toe (the 2nd metatarsal). The motions of these markers were captured via the Qualysis Track Manager System (Qualysis AB., Göteborg, Sweden) with 6 Proreflex cameras that were uniformly suspended at the ceiling. To keep the foot position consistent across the different conditions, the participants' footprints for the narrow stance were marked on a tracing paper attached to the surface of the force platform prior to the experiment proper.

The motion capture system and the force platform were synchronized for data collection (sampled at 100 Hz). Prior to data filtering, we checked the frequency component of the raw data using a fast Fourier transform (FFT) and confirmed that the frequencies less than 5 Hz showed high amplitude of the signal, while over 5 Hz it was close to zero. Therefore, a 4th order bidirectional low pass Butterworth filter at a cut-off of 5 Hz was utilized to acquire relevant data for further analyses not losing the frequency information from the arm-swing oscillation (0.2–1.6 Hz).

2.3. Procedures

The participants were requested to stand barefoot on the force platform in a stance with feet parallel and touching each other and their right arm fully extended over the head and the left arm positioned close to their thigh (Fig. 1). The participants were asked to alternate their arm positions by swinging them in the frontal plane in an anti-phasic manner following a metronome beep (Fig. 1). There were 8 metronome frequencies from 0.2 to 1.6 Hz with 0.2 Hz of change that were randomly administered to each participant. Each subject had 2 trials for each arm-swing frequency that created a total of 16 trials (2 trials × 8 frequencies). Each trial was 30 s in duration. During a trial the participants focused their attention on a target attached to the wall at their eye level and that was 2 m away from the force platform.

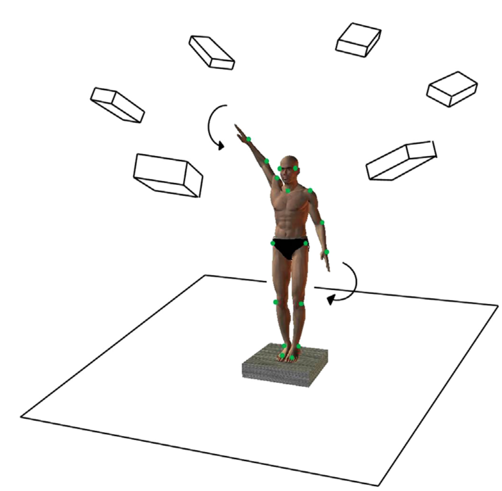

Fig. 1. Experimental setup. Arrows represent the arm-swing motions performed in the frontal plane.