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Review

Inter-foot coordination dynamics of quiet standing postures

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ABSTRACT

It has long been held that the net center of pressure (COP_{NET}) is the controlling variable to human stance that indirectly represents postural sway. The formation of the COP_{NET} trajectory emerges from an active control of transporting the body weight from one foot to the other and the self-organized coordination of the COP of each individual foot – properties that cannot be determined from the typical single force platform protocol. The findings of recent studies, with the application of the two-force platform paradigm, have revealed the coordination properties of the lower limbs in regulating COP_{NET}. In this article, we review these new findings and insights into the control of postural stability within the framework of a dynamic systems approach. The issues include: (1) the active asymmetrical body weight distribution and transportation process during both short- and long-term stances; (2) the spatial and temporal characteristics of the inter- and intra-foot COP coupling dynamics; (3) the influence of mechanical constraints (e.g., foot position, foot orientation, etc.) on the inter-foot and intra-foot COP coordination dynamics; and (4) the role of the specificity of task context to the functional asymmetry of the feet and its relation to footedness. The findings from foot coordination dynamics reveal subtle regulation of stability and instability in postural control that needs to be mapped to the coordination dynamics of the multi-link postural control system.

Contents

1. Introduction

To preserve postural stability, it is essential for individuals to actively align their trunk and head position relative to gravity (postural orientation), and to maintain the projection of the center of mass (COM) within the base of support boundaries (postural equilibrium) (Massion, 1998; Horak, 2006). Postural equilibrium incorporates multiple movement strategies to stabilize the COM against gravity during both self-initiated and externally triggered perturbations (Hof, 2007; Hsu et al., 2007; Wang et al., 2014a). In this view, postural equilibrium does not represent a motionless body configuration or a fixed steady state (fixed point) as the traditional literature held. Instead, it is a set of dynamically

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Abbreviations: COM, center of mass; COP_{NET}, the net center of pressure derived from a single force platform; COP_L, the center of pressure of the left foot derived from the two-force platform paradigm; COP_R, the center of pressure of the right foot derived from the two-force paradigm; Fz_L, the ground reaction force acting on the left foot; Fz_R, the ground reaction force acting on the right foot; SS, side-by-side stance; Staggered-L/R, staggered stance with the left/right foot forward; Tandem-L/R, tandem stance with the left/right foot forward; AP, anterior–posterior; ML, medial–lateral.

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and instantaneously varied equilibrium states migrating within the support area (e.g., “instant equilibrium” by Zatsiorsky and Duarte, 2000; “multistable states” by Wang and Newell, 2012a). This control of posture for healthy adults is typically conducted subconsciously and takes little effort or attention (for a review see Woollacott and Shumway-Cook, 2002).

Given the infinite number of degrees of freedom of the human body that are available at each level of analysis (e.g., limbs, joints, muscles, motor neurons, etc.), a central question is how the postural control system coordinates and controls one solution or a set of solutions out of the infinite to sustain postural equilibrium (Bernstein, 1996; Massion, 1998; Hof, 2007; Hsu et al., 2007; Wang et al., 2014a). It has long been held that the net center of pressure (COP_{NET}: the COP trajectory typically derived from a single force platform) is the controlling variable to human upright quiet stance that indirectly relates to postural sway (Horak, 2006; Hof, 2007). There have been several proposed coordination solutions that parse the COP_{NET} generation from the possible solutions of the redundant system. For example, the coordination solutions may utilize the ankle joint alone (inverted pendulum model) (Winter et al., 1996; Peterka, 2002), ankle–hip coordination (double inverted pendulum model) (Horak and Nashner, 1986) or multi-joint synergy (multi-linkage model) (Hof, 2007; Hsu et al., 2007; Wang et al., 2014a).

In quiet postural stances, that is stances where the participant is trying to stand still within an environment that is not changing, the COP_{NET} is determined by the collective average of the COP of each foot (COP_L and COP_R) and the body weight distribution over the feet (Fig. 1). The COP_L and COP_R can be acquired by having the participant stand with each foot on a separate force platform (i.e., two-force platform paradigm) during the postural tasks (Winter et al., 1996; Wang et al., 2012; Kinsella-Shaw et al., 2013):

$$COP_{Net} = COP_L \cdot \frac{Fz_L}{Fz_L + Fz_R} + COP_R \cdot \frac{Fz_R}{Fz_L + Fz_R} \tag{1}$$

where Fz_L and Fz_R are the ground reaction force from each foot separately.

The COP_{NET} variability and complexity in both the sagittal (anterior–posterior, AP) and frontal (medial–lateral, ML) planes have been comprehensively documented, especially in the side-by-side quiet postural stance (Powell and Dzendolet, 1984; Goldie et al., 1989; Collins and De Luca, 1993; Newell et al., 1997). However, little is known about the coupling/coordination of COP_L and COP_R, body weight distribution and their time-dependent characteristics as a function of mechanical task constraints (e.g., foot position, dimension of the base of support, etc.). This is because it is only through the use of two-force platforms that the COP_L and COP_R foot coordination properties can be investigated (Winter et al., 1996; Wang and Newell, 2012a; Wang et al., 2012; Kinsella-Shaw et al., 2011, 2013). In this article, we show through recent investigations of upright stance with two-force platforms: (1) the interactive effect of body weight distribution to postural stability; (2) the time evolutionary properties of the inter- and intra-foot COP coupling dynamics; (3) the influence of mechanical constraints on the foot COP coordination in quiet stance; and (4) expressions of footedness – the functional asymmetry of the lower limbs.

2. Body weight distribution asymmetry during quiet stance

Upright quiet stance in most previous studies has been examined with the side-by-side foot position (Fig. 1), in which the lower limbs are aligned in parallel about hip or shoulder width apart and it is typically assumed that they are anatomically and functionally symmetrical. In the past, though, the identification and quantification of asymmetrical body weight distribution of healthy individuals has received limited attention. In quiet natural stance, the asymmetrical body weight distribution or transfer is an active process that has been observed in both short-term and long-term postural stances.

The asymmetrical body weight distribution has been attributed as an index of an aging-related decline in balance control (Maki et al., 2003). During a 120 s side-by-side natural stance, Blaszczyk et al. (2000) observed that older participants (72.3 ± 4.0 yr) tended to load their body weight asymmetrically as compared with the young adults. This asymmetrical weight distribution preference was more significant with eyes closed. They concluded that unloading one limb during natural stance is a “preselected protective strategy” reducing the time necessary to complete a step initiation in case balance was challenged.

On the contrary, in a prolonged (30 min) unconstrained standing task, Prado et al. (2011) found that the older adults (65–80 years) produced less active weight transfer than young adults. They quantified the participants’ performance according to the percentage of body weight transferred from one lower limb to the other. For example, a large amplitude transfer was defined when >50% body weight was actively transferred from side to side whereas a small amplitude transfer was determined when 10–50% body weight was relocated. During the long-term stance, older adults’ large amplitude transfer was 4 times less than young adults indicating a loss of mobility in the frontal plane.

It has been suggested that the effect of aging on postural stability in the ML direction has a strong correlation with older adults’ falling history, fear of falling and future falling (Maki et al., 2003). Accordingly, aging also plays a significant role in body weight distribution/transfer over the feet in postural stance. Due to increased fear of falling and reduced level of mobility, older adults either adopt a stiffness strategy to constrain their postural equilibrium in order to avoid the projection of the COM further migrating toward the base of support boundary or endorse an asymmetrical weight loading strategy prepared for step initiation depending on the duration of stance.

In postural control, two types of asymmetries are evidenced: anatomical and functional (Peters, 1988; Sadeghi et al., 2000). Functional asymmetry arises from the confluence of task, environmental and organism constraints (Newell, 1986; Latash, 2008). Thus, the postural control strategy can be significantly different under altered task instructions. For example, consider the contrasting instructions of “preserving standing posture” and “maintaining balance”. The former implies “not moving your feet at any account” so that taking a step forward is not an allowable solution for the task. Younger adults prefer ankle, hip or ankle–hip strategies in the face of perturbations whereas older adults usually initiate multiple steps to catch up balance due to their reduced ability of estimating postural boundaries and their increased COP_{NET} motion when it closes to the boundaries (Blaszczyk et al., 1994; Horak, 2006). Environmental factors such as the availability of a handrail, texture of the floor and lightening conditions of a room also play a significant role affecting older adults’ postural control strategy.

A growing body of evidence has shown increased lower limb functional asymmetry with aging such as the above mentioned asymmetrical body weight distribution (Blaszczyk et al., 2000; Prado et al., 2011; Kinsella-Shaw et al., 2013), asymmetrical COP maximum excursion with forward and lateral body leaning (Blaszczyk et al., 1994), asymmetrical lower limb reflex (Welgampola and Colebatch, 2002), proprioception (Kristinsdottir et al., 2001) and muscle activation (Perry et al., 2007). Future investigations are required to examine the linkage between aging related lower limb asymmetry and lateral postural instability to further reveal neurophysiological mechanisms of aging related fall.

Fig. 2A shows the findings from 12 right-footed young adult participants’ body weight distribution in 60 s quiet standing as a function of foot position and the availability of vision. In