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Sagittal plane momentum control during walking in elderly fallers

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ABSTRACT

Objective: The purpose of this study was to examine sagittal plane momentum control during walking with the use of center of mass (COM) velocity and acceleration.

Methods: COM control in the antero-posterior direction during walking of healthy young and elderly adults, and elderly fallers (n = 15/group) was examined. Using a single-link-plus-foot inverted pendulum model, boundaries for the region of stability were determined based on the COM position at toe-off and its instantaneous velocity or the peak acceleration prior to toe-off (ROSv or ROSa, respectively).

Results: Although no significant difference in forward COM velocity was detected between healthy young and elderly subjects, the peak forward COM acceleration differed significantly, suggesting age-related differences in momentum control during walking. Elderly fallers demonstrated significantly slower forward COM velocities and accelerations and placed their COM significantly more anterior than healthy young and elderly subjects at toe-off, which resulted in their COM position-velocity combination located within the ROSv. Similar results were obtained in the ROSa, where elderly fallers demonstrated a larger stability margin than healthy young and elderly subjects.

Interpretations: Significantly slower peak COM accelerations could be indicative of a poor momentum control ability, which was more pronounced in elderly fallers. Examining COM acceleration, in addition to its velocity, would provide a greater understanding of person's momentum control, which would allow us to better reveal underlying mechanisms of gait imbalance or falls.

1. Introduction

Most falls resulting in fatal physical injuries in the elderly occur while walking [1]. A better understanding of the mechanisms underlying gait imbalance would enhance impairment assessment and implementation of fall prevention intervention. The occurrence of imbalance has been traditionally regarded as a consequence of the whole body center of mass (COM) going outside the boundaries of the base of support (BOS). The BOS boundaries have been considered as stability limits since the BOS provides a possible area for center of pressure (COP) movement, where balance is maintained by regulating the COP to keep the COM within the BOS [2–4].

The COM-BOS position relationship alone, however, has been demonstrated to inadequately describe the control of whole body dynamic equilibrium during movements [3]. The instantaneous COM velocity needs to be considered when examining dynamic balance maintenance, where success of protective steps to avoid falling depends on locations of the BOS and COM as well as COM velocity [3,5,6]. Time-to-Contact, which uses the COM instantaneous velocity to predict when the COM will reach the BOS boundary, has been used to characterize dynamic stability [7]. Pai and Patton [6] used a biomechanical model to determine the allowable range of COM velocities at a given COM position that would permit successful movement termination [6,8,9]. Hof et al. also suggested the importance of COM velocity in the examination of gait stability and derived the extrapolated center of mass that accounts for the COM velocity [2,10]. Many studies have utilized such position–velocity relationship between COM and BOS to quantify dynamic stability during gait [2,3,6,11].

Although COM velocity, which reflects momentum, describes an instantaneous state of motion, it does not provide information on how such a momentum is controlled by skeletal muscles to maintain balance. As muscle forces produce joint torques and accelerations, the COM acceleration is directly regulated and therefore reflects active control of COM momentum. Elderly adults may exhibit difficulties in the regulation of COM momentum due

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to age-related declines in muscle functions [12–15]. Poor momentum control due to an inappropriate COM acceleration generation could lead to gait imbalance. However, it remains unclear how the COM acceleration is generated to regulate momentum and maintain gait stability, and whether elderly adults, especially those who experienced falls, would differ from young adults in such control. Thus, an examination of COM acceleration, in addition to its velocity, could enhance our understanding on how balance is controlled during gait, which could better reveal the mechanisms underlying falls during walking.

We have recently proposed that examining COM acceleration could provide further insights into balance control during sit-to-stand movement and established the region of stability using COM position and its acceleration [16,17]. Our findings demonstrated that COM acceleration could more sensitively differentiate individuals with different balance control abilities, as COM acceleration differed significantly between young and elderly adults although no detectable differences in COM velocity were found. The objective of this study was, therefore, to expand our investigation to COM acceleration during walking to examine differences in dynamic momentum control in the antero-posterior (AP) direction during walking among healthy young and elderly adults, and elderly fallers. It was hypothesized that elderly fallers would adapt a strategy with a slower forward COM velocity and acceleration, indicating their reduced momentum control ability.

2. Methods

2.1. Derivation of regions of stability

The regions of stability in the AP direction were derived in two ways: one using COM velocity (ROSv), and the other using COM acceleration (ROSa). A single-link-plus-foot inverted pendulum model in the sagittal plane was used to define stability boundaries at toe-off (TO), which is the beginning of the single-limb support phase (Fig. 1a). Detailed derivation of the boundaries is presented in Appendix A.

2.1.1. ROSv

The boundaries of the ROSv were defined using the following equation derived based on the concept of XcoM [2].

$$-\tilde{X}_{TO} \le \tilde{\dot{X}}_{TO} \le 1 - \tilde{X}_{TO} \tag{1}$$

where $\tilde{X}_{TO}$ and $\tilde{\dot{X}}_{TO}$ are normalized COM position and velocity at TO, defined as $\tilde{X}_{TO} = (X_{TO} - X_h)/L_f$, $\tilde{\dot{X}}_{TO} = \dot{X}_{TO}/(L_f\omega_0)$ $\left(\omega_0 = \sqrt{g/l},\right.$ $L_f = X_t - X_h$: foot length).

2.1.2. ROSa

The ROSa was defined as the region confined by peak COM acceleration needed to be generated prior to TO. The COM acceleration was modeled as a triangle-shape prior to TO. The initial conditions of COM position and velocity **were** obtained when the COM velocity reached its minimum prior to TO (Fig. 1b). The boundaries of the ROSa were derived using the following equation:

$$\frac{(\tilde{X}_{TO} + \dot{X}_i/(\omega_0 L_f))(\tilde{X}_{TO} - \dot{X}_i/(\omega_0 L_f))}{\tilde{X}_{TO} - \tilde{X}_i} < \tilde{\ddot{X}}_p < \frac{(1 - \tilde{X}_{TO} + \dot{X}_i/(\omega_0 L_f))(1 - \tilde{X}_{TO} - \dot{X}_i/(\omega_0 L_f))}{\tilde{X}_{TO} - \tilde{X}_i} \tag{2}$$

where $\tilde{X}_{TO}$ and $\tilde{X}_i$ are the normalized COM position at TO and initial COM position defined as $\tilde{X}_{TO} = X_{TO}/L_f$ and $\tilde{X}_i = X_i/L_f$, respectively $\tilde{\ddot{X}}_p$ is the normalized peak COM acceleration prior to TO defined as $\tilde{\ddot{X}}_p = \ddot{X}_p/\omega_0^2 L_f$.

2.2. Experimental protocol

Fifteen healthy young adults [Young: 7 men; mean age 22.1 ± 1.9 years, mean height 170.4 ± 11.0 cm, mean mass 68.2 ± 14.6 kg], 15 healthy elderly adults [Elderly: 6 men; mean age 70.0 ± 3.2 years, mean height 170.1 ± 8.7 cm, mean mass 79.1 ± 18.3 kg], and 15 elderly adults with a history of falls [Fallers: 3 men; mean age 71.9 ± 4.3 years, mean height 164.2 ± 8.6 cm, mean mass 83.1 ± 20.1 kg] participated in this study. The criterion for inclusion in the Fallers group was a self-report of two or more falls

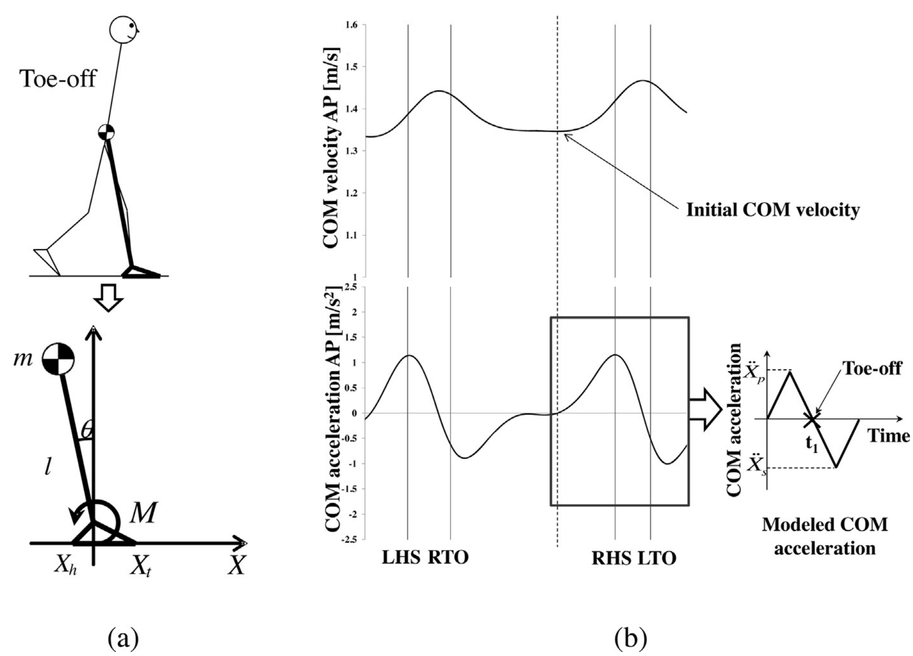

Fig. 1. (a) A single-link-plus-foot inverted pendulum model in the sagittal plane. X indicates the COM position in the AP direction. X_h and X_t indicate the heel and toe positions. m, l and M are whole body mass, pendulum length (distance from the ankle to the COM), and ankle joint moment. (b) Representative time–history plot of COM velocity and acceleration with modeled COM acceleration profile. LHS/RHS and LTO/RTO indicate left/right heel-strike and toe-off instants.