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Anti-phase action between the angular accelerations of trunk and leg is reduced in the elderly

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ABSTRACT

Quiet standing posture in humans has often been modeled as a single inverted pendulum pivoting around the ankle joint. However, recent studies have suggested that anti-phase action between leg and trunk segments plays a significant role in stabilizing posture by reducing the acceleration of the center of mass (COM) of the body. The aim of this study is to test the hypothesis that anti-phase action is attenuated in the elderly compared to the young. The anterior–posterior movements of leg and trunk segments were measured using 4 laser displacement sensors from 22 healthy young subjects (age range, 20–35 years) and 38 healthy elderly subjects (age range, 57–80 years) standing quietly for 30 s twice. To focus on the segmental action between trunk and legs, we applied constraints (i.e., wooden splints) on each segment. We found that the velocity and acceleration of the COM (standard deviation of the time series was evaluated) were significantly higher for the elderly subjects than for young subjects. The increase in the acceleration of the COM resulted not only from an increase in the angular acceleration of the segments but also from the reduction of their anti-phase relationship, as demonstrated by an index that quantifies the degree of cancelation between both segments. We conclude that the degree of anti-phase action between trunk and leg segments during quiet standing is smaller for elderly subjects than for young subjects, and that this change of the anti-phase action due to aging resulted in increased COM acceleration in the elderly subjects.

1. Introduction

Human bipedal stance is inherently unstable due to its configuration as an inverted pendulum. This instability is compensated by meticulous cooperative functions of visual, vestibular, and somatosensory systems [1]. Hence, the impairment of these functions due to aging should significantly affect the postural control in the elderly [2,3]. One of the most well known symptoms experienced by the elderly is an increased body sway during quiet standing, compared to young person [4–6].

Quiet standing posture is often approximated as a single-link inverted pendulum [7]. However, recent studies have pointed out that hip joint plays a significant role in postural maintenance even during quiet standing [8–11]. For example, Aramaki et al. [8] demonstrated that the hip-joint movement is larger than the ankle joint movement during quiet standing. Therefore, it is necessary to analyze the coordination of the two segments when we investigate the aging of postural control during quiet standing. Indeed, Accornero et al. [12] demonstrated the change of coordination due to aging, i.e., the link between trunk and leg segments is enhanced in the elderly compared to the young.

Aramaki et al. [8] also demonstrated that, although the hip-joint action is considerable, its angular acceleration is in an anti-phase relationship with the ankle-joint's angular acceleration, which contributes to reducing the center of mass (COM) acceleration. This

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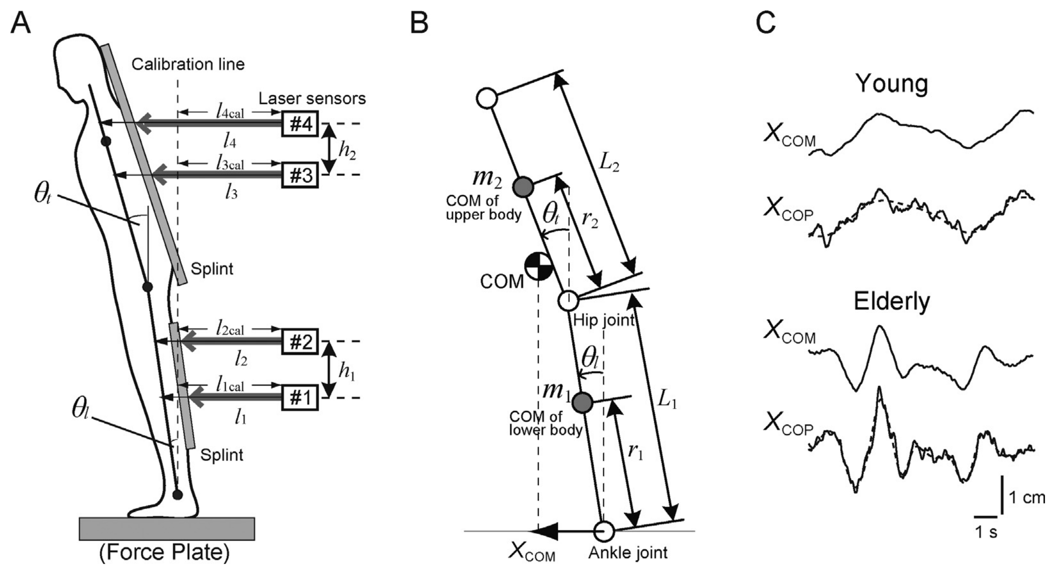

Fig. 1. Schematic diagram of the experimental setup and definition of angular displacement of leg (θ_l) and trunk (θ_t) segments. (A) The CCD sensors were used to measure the distance between splint and sensor. Using a tape measure, the distance between the splint and the central line of the body was also measured. Adding the distance to the data from sensors yielded l_1, l_2, l_3 and l_4. (B) Two link model was used to obtain the relationship between the anterior–posterior position of center of body mass (X_{COM}) and θ_l and θ_t. The L, r, and m represent, respectively, the length of segment, the length between the joint and the center of mass of segment, and mass. (C) Representative examples of estimated X_{COM} and X_{COP} (anterior–posterior position of center of pressure). The broken lines in X_{COP} indicate the X_{COM} obtained by low-pass filtering X_{COP} according to [19].

mechanism is thought to work by the anti-phase action between trunk and leg segments canceling out each other's acceleration. Such tightly controlled segmental action is widely seen in various human movements and it is intensively studied. The segmental action in human movements is theorized as the Minimum Intervention Principle [13] and is similarly conceptualized in the UnControlled Manifold concept (UCM) [14]. The UCM has revealed that body segments are coordinated to stabilize the COM position during standing [14]. The uniqueness of the finding by Aramaki et al. [8] was that the anti-phase action between trunk and leg segments was seen in their angular accelerations, and that such coordinated segmental action was mathematically proven to reduce the COM acceleration. Recently, Hsu et al. [15] investigated the aging effect on the recovery from an unexpected perturbation during standing using UCM, and found that the elderly reduce the coordination of trunk and leg segments. Considering that the COM acceleration is higher in the elderly [6], we can hypothesize that the anti-phase relationship between the accelerations of trunk and leg segments is attenuated in the elderly, and that the COM acceleration is larger in the elderly than the young due to this aging in the segmental coordination.

Therefore, the purpose of this study was to test this hypothesis by investigating trunk and leg segmental motions during quiet unperturbed standing for the elderly and the young. We introduced an index to quantify the anti-phase action based on a comparison of variability of COM acceleration between empirical data and theoretical data eliminating covariance of segmental motions. To focus on the segmental action between trunk and leg, we applied constraints, i.e., wooden splints, on each segment.

2. Methods

2.1. Subjects

Twenty-two healthy young (age range, 20–35 years; 13 male and 9 female) and 38 healthy elderly (age range, 57–80 years; 2 male and 36 female) subjects participated in the experiment with informed consent. They had no medical history or signs of neurological disorders. The experimental procedure was approved by the ethical committee of our research institute. As the result of recruitment, there was an unequal gender distribution in each age group.

2.2. Experimental protocol

The barefoot subjects were asked to stand quietly for 30 s with their eyes open either on a force plate (9281B, Kistler, Switzerland) or on a floor. Two trials were performed for each subject. Note that the force plate recording was added in the later phase of data collection for 16 young and 21 elderly subjects for the purpose of measuring the center of pressure (COP). In order to focus the analysis on the motion in the sagittal plane, the intermalleolar distance was set to 10 cm, because narrow stance width (<8 cm) increases lateral sway [16]. We also used 3 wooden splints that were strapped to the back of the subjects at the forehead and pelvis for the upper body, and above and below each knee for the legs (Fig. 1A) so that motion was restricted to only the hip and ankle joints. Four CCD laser sensors (LK-2500, Keyence, Japan) were used to measure the anterior–posterior displacement at 4 locations of the body ($l_1 - l_4$ in Fig. 1A), and the anterior–posterior position of the COP (X_{COP}) was simultaneously recorded using the force plate (only for the subjects who stood on the force platform).

2.3. Data processing

The signals were A/D converted with a sampling frequency of 100 Hz (WE7251, Yokogawa Electric, Japan) and then low-pass filtered with a cut off frequency = 5 Hz using a fourth-ordered Butterworth filter with zero phase lag [17]. Each of the two trials was analyzed separately, and the average values were used to represent the subject's outcome.

The displacement measured by the laser sensors was then converted into angular displacements with an approximation as (Fig. 1A): $\theta_l \approx \{(l_2 - l_{2cal}) - (l_1 - l_{1cal})\}/h_1$ and $\theta_t \approx \{(l_4 - l_{4cal}) - (l_3 - l_{3cal})\}/h_2$, where θ_l and θ_t represent, respectively, the angles of trunk and leg segments, l_{1-4} represent the distances from splints to each sensor surface, l_{1-4cal} represent the distances from the