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Altered center of mass control during sit-to-walk in elderly adults with and without history of falling

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ABSTRACT

Sit-to-walk (STW) is a commonly performed activity of daily living that requires a precise coordination between momentum generation and balance control. However, there is a lack of biomechanical data demonstrating how the center of mass (COM) momentum and balance control interact. This study examines COM kinetic energy distribution in three movement directions and COM-Ankle inclination angles during STW among 15 healthy young adults, 15 elderly non-fallers, and 15 elderly fallers. We found that elderly adults, especially elderly fallers, chose a COM control strategy that provided more stability than mobility to perform STW. A smaller forward COM velocity, a more upward COM momentum distribution, and a smaller anterior–posterior COM-Ankle angle characterize this strategy. Healthy elderly adults modified their STW movement around seat-off so that they achieved a more upright position before walking. Elderly fallers not only altered COM control around seat-off but also showed limitation in COM control during gait initiation. Furthermore, their COM control in the medial-lateral direction might be perturbed at swing-off due to an increased distribution of kinetic energy. Examining COM momentum distribution in different movement directions and the relationship between positions of the COM and supporting foot during STW could enhance our ability to identify elderly adults who are at risk of falling.

1. Introduction

Falls are a serious public health problem affecting elderly adults. Approximately one-third of older adults (65 years or older) are reported to have fallen annually [1–3]. Most falls in elderly adults occur during daily activities [2,4]. Many of these activities require successful movement transitions such as from sitting to walking. During daily activities, sit-to-stand (STS) and gait initiation are commonly merged into the sit-to-walk (STW) motion.

The Timed Up and Go test (TUG) is a routinely used clinical fall risk assessment, and it includes a STW transition [5–7]. Studies have demonstrated that the amount of time required to complete TUG correlates with the Berg balance scale, gait speed, and the Barthel index [8], and that elderly adults with a higher risk of falling take a longer time to complete the TUG [7]. While timing the STW phase during TUG can serve as an initial screening tool to detect fallers [9], biomechanical analyses of the STW phase could examine the underlying mechanisms of such functional decline and provide clinicians more insightful interpretations of the TUG results.

STW was reported to impose greater challenges on dynamic balance control than STS alone due to its requirement of a greater horizontal momentum for gait initiation and a simultaneous narrowing of the base of support [10]. Moreover, STW is not a sequential arrangement of two individual tasks but requires a smooth transition from STS to gait initiation at seat-off. However, such a smooth transition is not observed in elderly adults [11–13]. Elderly adults were reported to generate a less horizontal center of mass (COM) momentum at seat-off when compared to young adults [12,13]. Although many factors could contribute to this age-related reduction in COM forward momentum [14,15], such a reduction may be related to an altered COM control strategy to maintain a more stable upright posture prior to gait initiation during STW [13]. However, there is a lack of biomechanical data demonstrating how COM momentum and balance control interact during STW.

Instantaneous positioning of the COM with respect to the center of pressure (COP) during gait could detect elderly individuals with impaired balance control [16–18]. When the COP is not available, the COM-Ankle inclination angle during the single stance phase provides an alternative assessment to clinical populations [19]. Elderly adults with balance impairments demonstrated a greater

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frontal plane and smaller sagittal plane COM-Ankle angles than healthy elderly adults during walking. Assessing the COM-Ankle angles during STW would reveal how the COM is positioned in relation to the supporting foot and provide an objective quantification of balance control.

Elderly adults who are at risk of falling also showed a movement hesitancy during STW with a significant decrease in COM forward velocity after seat-off [11]. While this might be regarded as a safer movement strategy, elderly adults with fear of falling were also reported to demonstrate a disproportionately higher sideways velocity during STW when compared to the forward velocity [20]. This indicates that an excessive reduction in COM forward velocity (or momentum) during STW could perturb COM motion in the medio-lateral direction. Examining the distribution of COM momentum in different movement directions during STW could provide us further insights on dynamic balance control and enhance our ability to identify elderly adults who are at risk of falling.

In this study, we examined the distribution of COM linear kinetic energy in different movement directions as well as the COM position in relation to the base of support (BOS) during STW among three groups: healthy young adults, healthy elderly adults, and elderly adults with a fall history. As age-related movement hesitancy has been shown in STW, it was hypothesized that, when compared to young adults, elderly adults would demonstrate smaller forward COM velocity, altered distributions of COM kinetic energy in different movement directions, and a smaller anterior–posterior COM-Ankle angle. We further hypothesized that these changes in COM motion control could be different between elderly fallers and non-fallers.

2. Methods

Fifteen healthy elderly adults (EA; 9 women/6 men; mean age: 76.2 ± 4.2 years, mean height: 163.9 ± 10.5 cm, mean mass: 72.0 ± 16.4 kg), 15 elderly adults with a fall history (EF; 11 women/4 men; mean age: 77.7 ± 7.7 years, mean height: 162.5 ± 9.5 cm, mean mass: 77.2 ± 23.2 kg) over the age of 70 and 15 healthy young adults (YA; 8 women/7 men; mean age: 26.0 ± 3.4 years, mean height: 167.6 ± 6.4 cm, mean mass: 63.1 ± 9.7 kg) were recruited from the community. An a priori power analysis was performed, using the horizontal COM velocity collected from 4 subjects in each group, which indicated that a minimum of eleven subjects per group were required to achieve a power of 0.95 with an alpha level of 0.05.

Inclusion criteria for all participants were individuals who (1) could walk without the use of an assistive device; (2) had no history of neurological or musculoskeletal deficits that might contribute to gait instability or falls, such as amputation, stroke, significant head trauma or Parkinson's disease; (3) had no uncorrectable visual impairment, vestibular dysfunction, or dementia. The EF was determined as elderly individuals who had fallen twice or more in the year prior to study participation. A fall was defined as "an unexpected event where a person falls to the ground from an upper level or the same level" [21]. Furthermore, only falls that occurred during activities of daily living were included, so that falls due to major intrinsic events, such as syncope, were excluded. An average of 3.1 ($\pm$1.0) falls were reported by the EF. A Fullerton Advanced Balance (FAB) scale of 30 or lower was required to target fallers with balance impairments [22]. The FAB scale is a performance-based measure specifically designed for independently functioning elderly adults [23]. FAB scores were 33.6 ($\pm$2.7) and 21.4 ($\pm$8.4) for EA and EF, respectively. Prior to testing, all participants agreed to the experimental procedure approved by the Institutional Review Board and signed consent forms.

Participants performed TUG while barefoot and were asked to stand up from the bench, walk 3 meters, turn around, return to the bench and sit down. A total of 4 trials were performed, including one practice trial. A rest period was provided between trials as needed. The following instructions were provided to all subjects: "please complete the whole task at your comfortable speed, and we will time you." A height-adjustable bench was set at each participant's knee height.

Twenty-nine markers were placed on selected bony landmarks of the subject [24]. Whole body motion data were captured with a 10-camera motion system (Motion Analysis Corp., Santa Rosa, CA). Marker trajectories were sampled at rate of 60 Hz and then smoothed using a fourth-order Butterworth filter with a cutoff frequency of 8 Hz While seated, participants placed both feet on a force plate (AMTI, Watertown, MA) in order to detect the instant of seat-off [15]. Ground reaction forces were sampled at 960 Hz Anthropometric reference data for both sexes were adapted from Dempster [25]. Whole body COM position was calculated as the weighted sum of a 13-segment model [24].

The overall time used to complete the TUG was recorded. In order to present the contribution of COM velocity in each direction, the linear COM kinetic energy was calculated as $½ \times m \times v^2$ (m = body mass, v = velocity). Total COM kinetic energy was the sum of the kinetic energy in all three directions, $½ \times m \times v_x^2 + ½ \times m \times v_y^2 + ½ \times m \times v_z^2$. The COM kinetic energy in each direction was then normalized with the total COM kinetic energy to yield a ratio of kinetic energy distribution. COM-Ankle angles were calculated as the inclination angles of the line formed by the COM and lateral ankle malleolus marker in the sagittal plane [19].

Data from onset, seat-off, swing leg toe-off (swing-off), stance leg toe-off (stance-off) during STW were extracted for analysis. Onset was identified as the instant of initial COM forward position change [15]. Seat-off was identified as the time of the peak vertical ground reaction force [26]. Swing-off and stance-off were identified as the time when the leading foot toe marker and trailing foot moved forward, respectively [15]. The duration of STW was calculated from onset to stance-off. Distances between two lateral malleolus ankle markers in the frontal (step width) and the sagittal plane (step length) were examined at stance-off (the first step during STW).

Differences among three subject groups were assessed using one-way multivariate analysis of variance with an alpha level of 0.05. In order to control for the possible effect of speed, STW duration was included as a covariance in the analysis for COM-Ankle angles. Follow up analyses were performed using Bonferroni adjustment. SPSS version 19.0 (IBM SPSS Inc., Chicago, IL) was used for all statistical analyses.

3. Results

No significant differences were found between the groups in body mass and height ($p \geq 0.092$). No significant age differences were found between the two elderly groups ($p = 0.521$). EA had significantly higher FAB scores than EF ($p < 0.001$).

Significant group main effects were detected in TUG duration, STW duration and step length at stance-off (Table 1). EF took a longer time to complete the TUG task than YA or EA. When compared to YA, STW duration was notably longer for EF. At stance-off, YA took a significantly larger step than both EA and EF. Additionally, the EA had a larger step length at stance-off than EF. No significant differences were found between groups in the step width during STW.

Young adults demonstrated a faster COM forward velocity throughout the STW than either EA or EF (Fig. 1a). When compared to EA and EF, YA demonstrated significantly higher forward COM velocities at seat-off, swing-off and stance-off (Fig. 2a). EA demonstrated significantly faster forward COM velocities than EF at seat-off and stance-off (Fig. 2a). In the vertical direction, YA reached a greater peak velocity than either EA or EF (Fig. 1b). Furthermore, significant group main effects were found in upward velocity at swing-off and stance-off. YA had a significantly greater

Table 1
Timed get up and go test and sit-to-walk duration, step length and step width at stance-off for three groups [mean (SD)].

	YA	EA	EF	p-Value	p-Value (* ‡ #)
TUG duration (s)	7.93 (1.18)	10.18 (1.54)	14.78 (6.41)	<.001	.359* <.001‡ .007#
STW duration (s)	1.31 (0.18)	1.60 (0.34)	2.29 (1.45)	.01	1.00* .010‡ .102#
Step length (m)	0.59 (0.06)	0.52 (0.08)	0.42 (0.06)	< .001	.045* <.001‡ <.001#
Step width (m)	0.21 (0.08)	0.21 (0.07)	0.23 (0.07)	.714	N/A

* Differences between YA and EA.
‡ Differences between YA and EF.
# Differences between EA and EF.