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Original Article

Process of dynamic balance recovery after voluntary perturbation: a time-series data analysis of young and older adults

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Abstract. [Purpose] This study investigated differences in the convergence mode of post-step sway between young and older adults using a step-down task to identify fall causes in older adults and assess consecutive postural adjustments. [Participants and Methods] This study included 15 young and 15 older adults (nine females and six males in each group). The participants stepped down from a standing position to a force platform 10 cm lower and maintained a one-leg standing position. The center-of-pressure total trajectory length was assessed using a force plate and regression equations for time and sway were derived from the associated time-series data for both groups. [Results] An inversely proportional aspect was observed for both groups, with significantly different coefficients and constants. The center-of-pressure total trajectory length per second from foot contact was significantly different between 2–3 s and 4–5 s in the older group but not in the younger group. [Conclusion] The results suggest a difference in the convergence mode of dynamic balance between the two groups, with young adults exhibiting a more rapid balance-sway reduction than older adults. The novel computational approach used in this study may be useful for dynamic balance measurements.

Key words: Online adjustment, Aging, Consecutive postural adjustments

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INTRODUCTION

Human beings acquire postural stability during their developmental stages, starting from infancy. Furthermore, the capacity to regain postural stability following perturbations is gradually acquired. Hay and Redon[1)] revealed distinct qualitative dissimilarities in postural coordination when examining the center of pressure (CoP) shifts between 3–5 and 6–8 year-old groups. More recently, the study of human balance control has increasingly focused on the mechanisms responsible for the recovery of postural stability following perturbation. Zelei et al.[2)] formulated a model comprising three hypotheses for elucidating the recovery dynamics of postural control. According to their model, postural control derives not solely from quicker response times but from a combination of fast response and robustness against sensory perturbations.

CoP serves as a crucial measure of the recovery of postural stability. It represents the central point of forces acting on the contact surface between the body and the floor and is an important outcome measure in assessing balance[3)]. Two experimental systems have been developed to observe postural stability recovery: one employs external disturbances, while the other uses voluntary disturbances[4, 5)]. External disturbances focus on feedback control, and studies employing this approach are influenced by aging, as evidenced in studies on reaction latency[6)]. However, using external disturbances for testing is costly and requires specialized equipment and safety harnesses. Alternatively, studies involving voluntary disturbances are

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less costly and require simple devices. They have focused on feedback and feedforward control mechanisms. These two control mechanisms operate efficiently to restore postural stability following voluntary perturbations, resulting in fewer CoP perturbations. The ability to restore stability after a voluntary perturbation has been termed consecutive postural adjustments (CPA_S)[7]. CPA_S employ transitions from bilateral to unilateral support[8] and have been observed in side-stepping[9], with Huang and Brown[10] also noting CPA_S during reaching tasks.

The capacity to avoid falls after an unexpected trip or slip is impaired in older adults. Fall avoidance ability is considered a function of recovering dynamic postural stability after perturbation and is categorized as CPAs. Previous studies showed that older adults exhibited a high incidence of falls and step errors, with falls occurring more frequently in the forward direction[11]. The one-leg stand test, a kind of voluntary perturbation, has been used to predict falls in older adults[12–14]. Because of these factors, we have chosen to focus on the drop-jump task, commonly used for the evaluation and pre-participation screening of athletes in rehabilitation and sports medicine clinics. This task assesses athletes' high balance ability, identifies potential injury risks, and evaluates muscle strength and neuromuscular control[15–18]. In this study, we proposed modifying the task to reduce its difficulty and using it as a step-down task for assessing dynamic balance in older adults.

The assessment of dynamic balance in older adults comprises various methods, such as postural perturbations[19–21], timed-up-and-go (TUG) test[22], gait speed[23], and step tasks[19, 24–28], and Berg's Balance Scale[29] and the balance evaluation systems test[30]. Each assessment method has distinct elements due to methodological differences. However, TUG and Berg's Balance Scale only identify the presence or absence of balance disorders and are not specific to each balance component. Although the balance evaluation systems test effectively extracts the characteristics of each balance component, it is time-consuming and may not be practical for clinical use. In contrast, the step-down task is a more advanced version of the one-leg test that assesses CPAs and recovery of postural stability with aging. This task is performed quickly, using only a force plate, and includes the abovementioned forward stepping and one-legged standing components essential for dynamic balance assessment.

In previous studies observing CPA_S in older populations, Roemer and Raisbeck[31] compared sway in the anterior/posterior and medial/lateral directions every 1 to 3 seconds (s) in older adults with that in younger adults. Their findings indicated that older adults had significantly greater sway than younger adults. Porter et al.[9] and Huang and Brown[10]'s studies yielded similar results with varying tasks. The observations in these studies were made at arbitrary time points, and the changes in CPA_S over time have yet to be investigated. In this study, we examined the step-down task to observe the changes in postural stability recovery with age, specifically focusing on the CPAs after voluntary perturbations. Furthermore, we compared older and younger adults using the step-down task. To investigate the differences in postural stability recovery with age after voluntary perturbations, we employed a computational approach to observe the time-series changes in CoP. This study aimed to elucidate the influence of age on the dynamic-balance recovery process following a step-down task in both young and older adults and to identify novel aspects not previously reported in the literature.

PARTICIPANTS AND METHODS

The study included 15 young adults (nine females, six males; mean ± standard deviation [SD] age, height, weight, and body mass index [BMI]: 21.3 ± 1.1 years, 164.1 ± 7.7 cm, 54.6 ± 7.7 kg, and 20.2 ± 2.1 kg/m^2, respectively), and 15 older adults (nine females, six males; mean ± SD age, height, weight, and BMI: 66.7 ± 2.2 years, 158.9 ± 7.3 cm, 56.9 ± 8.5 kg, and 22.5 ± 2.4 kg/m^2, respectively). The older adult participants were examined for cognitive impairment using the Mini-Mental State Examination (MMSE); the mean MMSE score was 31.7 ± 0.8. The daily activities undertaken by the older adults exhibited a high degree of self-sufficiency. Furthermore, they sustained a level of physical activity sufficient to enable them to continue gainful employment. After the participant selection, we screened the participants based on their history of falls within the past year to further select participants for the task performance analysis. All group participants did not have orthopedic trauma within the past year that affected their balance ability, and they could understand and perform motor tasks. All participants provided written informed consent, and the study was approved by the research ethics committee of Kawasaki University of Medical Welfare (approval number 16-073).

Participants stood static on a platform 10 cm higher than a force plate with arms folded and the feet in a closed foot position. With a 5-s countdown, participants rapidly took a step with their right leg toward the force plate 10 cm below and maintained a right one-leg standing position for 7 s (Fig. 1). They were instructed to stand on one leg with the other leg off the platform while taking a step onto the force plate to avoid the double support phase and remain stationary. Additionally, they were directed to gaze forward. Each participant performed ten trials. Trials where the double support phase was visually observed, the supporting leg moved after stepping out, the arm left the axilla, or the left toes touched the floor were excluded (discarded and invalid trial: 0–4 times/person).

The force plate (TFP-404011B-A, Sports Sensing Inc., Fukuoka, Japan) is a 40 × 40 × 11 cm strain gauge type and is sufficiently robust to measure up to a 1 t load. The plate measured the ground reaction force data during the step-down task at a sampling frequency of 1,000 Hz. The collected data were stored in a dedicated personal computer (PC) and used for offline data analysis.

CoP total trajectory length (CoP_{length}) was calculated from the measured ground reaction force using MATLAB (The MathWorks, Inc., Version 7.4) for 5,000 ms from foot contact on the force plate. CoPx and CoPy denote the anteroposterior and lateral sway series, respectively. Before each index was calculated, the collected ground reaction force data were filtered using the Butterworth filter method at a low cutoff frequency of 70 Hz. Fz represents the vertical component of the ground reaction force normalized to each participant's weight.

The mean and SD of CoP_{length} were obtained every 50 ms in both groups (Fig. 2). The regression equation was derived from the measured CoP_{length} curve to approximate the time-series change in CoP_{length}. The coefficients and constants obtained were compared between groups to clarify differences in time-series changes in CoP_{length}.

The following equation approximates the change in CoP_{length} over time by applying the reciprocal function at time:

$$F(t) = at^{-1} + b$$

Where "t" is arbitrary time, F(t) is the CoP_{length} at the arbitrary time, and "a" is coefficient, and "b" is constant. The coefficient-a of the regression curve reflects the initial disturbance upon grounding, with a larger value indicating a greater initial disturbance. The constant-b represents the value of convergence of CoP_{length}.

The goodness of fit of the regression equation was evaluated using the coefficient of determination, R-Square. The slope of the regression line represents the speed at which the posture is stable. The coefficients and constants were compared using a t-test. Paired t-tests were performed on constant-b and the measured convergence value (CoP_{length} at 5,000 ms). A time interval of 4,000–5,000 ms was designated as the baseline. The baseline was defined as the mean CoP_{length} at the time of sway convergence. The mean value of CoP_{length} was computed for the baseline and three subsequent segments, namely 0–1,000 ms, 1,000–2,000 ms, and 2,000–3,000 ms, using the techniques described in a previous investigation by Roemer and Raisbeck[31].

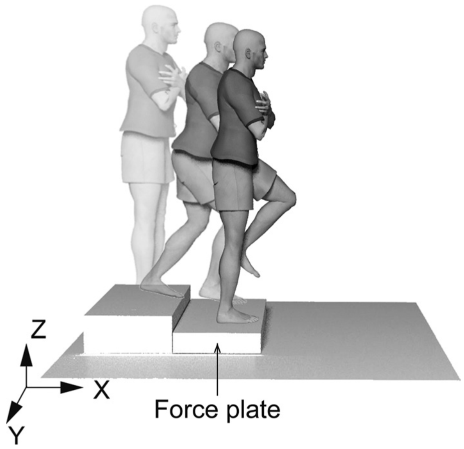

Fig. 1. Step-down task. To a 5-s countdown output from a personal computer (PC), the participant descends from a 10-cm high platform and maintains a one-leg stand.

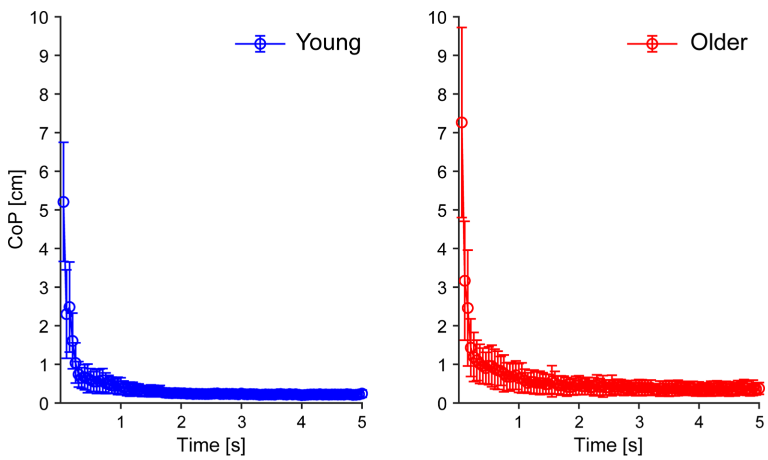

Fig. 2. Time-series variation of center-of-pressure total trajectory length (CoP_{length}). Each point on the Y axis indicates the sum of CoP_{length} every 50 ms. The error bars represent the mean of standard deviation of CoP_{length} over each 50 ms time interval.

Mixed-design two-way analysis of variance (ANOVA; group ×interval: 0–1,000 ms, 1,000–2,000 ms, and 2,000–3,000 ms, baseline) was performed on each dependent variable (mean value of CoP_{length}) to determine the difference in the amount of sway in each group. IBM SPSS Statistics 25 (IBM SPSS Statistics Inc., Tokyo, Japan) was used for statistical processing, and $p<0.05$ was considered statistically significant.

RESULTS

Figure 2 shows the temporal change of CoP-length obtained every 50 ms. The older adult group showed more sway during the early ground contact phase, 0–1,000 ms, than the young adult group. The curves for both groups became plateaued after approximately 1 s. Figure 3 shows the vertical component of the floor reaction force normalized by body weight, which was slightly higher in the young adults immediately after ground contact.

Figure 4 shows the quadratic regression equations obtained from the curves in Fig. 2. For the young adult group, a=0.243 ± 0.002, b=0.152 ± 0.003, and the coefficient of determination=0.962, while for the older adult group, a=0.328 ± 0.020, b=0.272 ± 0.007, and the coefficient of determination=0.983. The coefficient-a and the constant-b were significantly different between groups (coefficient-a: $t_{28}=-2.25$, p=0.03, effect size: d=0.82, power=1; constant-b: $t_{28}=-3.15$, p=0.004, d=0.59, power=0.74) suggesting that young adults had a faster CoP_{length} stabilization rate and a lower final CoP_{length} than older adults. Conversely, Figs. 2 and 4 showed a discrepancy between the convergence value and the constant-b. Therefore, the constant-b was compared with CoP_{length} at 5,000 ms, and a significant difference was observed for each group (young adults: $t_{14}=-7.75$, $p<0.001$, d>1, power=1; older adults: $t_{14}=-3.76$, p=0.002, d=0.87, power=1).

To test the difference in the mean CoP_{length} in the two groups and intervals, a mixed-design two-way ANOVA was performed with the independent variables being group and interval and the dependent variable being mean CoP_{length}. The results indicated a significant difference in the interaction ($F(3,84)=7.39$, $p<0.001$, effect size:$\eta_p^2=0.21$), with the main effects of the group and interval factors being significant (in the following order: group: $F(1,28)=27.73$, $p<0.001$, $\eta_p^2=0.50$ and interval: $F(3,84)=561.47$, $p<0.001$, $\eta_p^2=0.95$).

A simple main effect test of the intervals for the groups showed a significant difference between groups (young adults: $F(1,28)=227.85$, $p<0.001$; older adults: $F(1,28)=508.11$, $p<0.001$). A simple main effect test of the groups in the intervals showed a significant simple main effect at all levels (0–1,000 ms: $F(1,28)=18.63$, $p<0.001$; 1,000–2,000 ms: $F(1,28)=17.94$, $p<0.001$; 2,000–3,000 ms: $F(1,28)=25.62$, $p<0.001$; baseline: $F(1,28)=34.81$, $p<0.001$).

The results of the multiple comparisons indicated that CoP_{length} values of the younger group were consistently smaller than those of the older group across all intervals, including baseline (Table 1). Furthermore, there were significant differences between all intervals in both groups, except for between the baseline and 2,000 ms–3,000 ms intervals in the younger group.

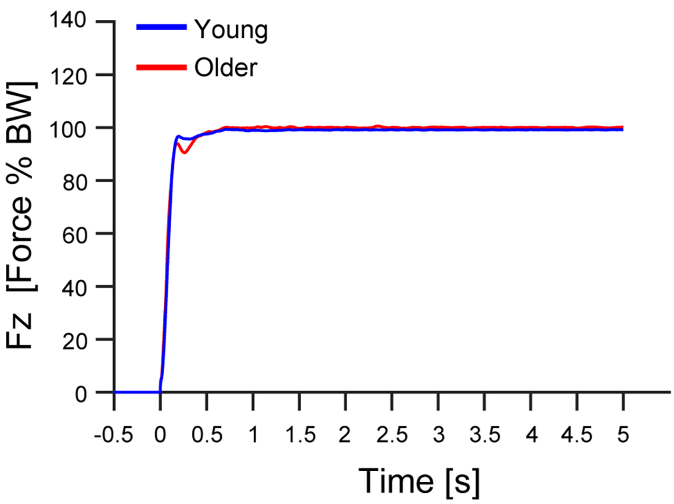

Fig. 3. Mean curves of Fz during the step-down task. The data averages 15 participants after foot placement on the ground. Blue and red lines indicate the young and older adult groups, respectively. Fz: vertical ground reaction force.

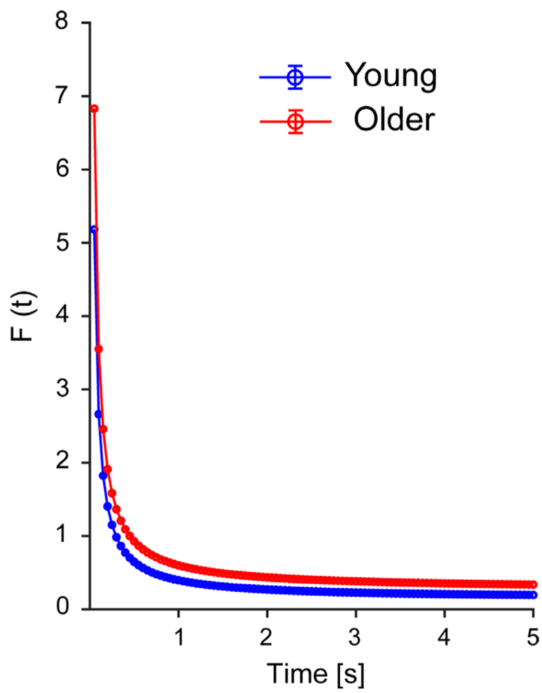

Fig. 4. Curve regression equations for each group. Young adult group: $F(t)=0.243t^{-1} + 0.152$. Older adult group: $F(t)=0.328\, t^{-1}+0.272$.

Table 1. Mean center of pressure total trajectory length before and after stabilization in young and older adults

		0–1 s	1–2 s	2–3 s	Baseline (4–5 s)
CoP (cm)	Young adults (n=15)	20.7 (2.5)*, †, ‡, §	6.1 (1.5)*, ‖, ¶	4.8 (0.8)*	4.3 (0.7)*
	Older adults (n=15)	28.1 (6.2)†, ‡, §	10.0 (3.1)‖, ¶	8.2 (2.5)**	7.4 (1.9)

Center of Puressure (CoP), Mean CoP trajectory length (SD) cm for each duration.
*Significant difference between young and older adults in same duration ($p<0.05$).
†Significant difference between 0–1 s and 1–2 s in same group ($p<0.05$).
‡Significant difference between 0–1 s and 2–3 s in same group ($p<0.05$).
§Significant difference between 0–1 s and 4–5 s in same group ($p<0.05$).
‖ Significant difference between 1–2 s and 2–3 s in same group ($p<0.05$).
¶Significant difference between 1–2 s and 4–5 s in same group ($p<0.05$).
**Significant difference between 2–3 s and 4–5 s in same group ($p<0.05$).

DISCUSSION

This study characterized time-series changes in the CoP_{length} in younger and older adults using the step-down task to focus on CPAs after voluntary perturbations. The regression analysis revealed that the two groups exhibited distinct patterns of convergence in terms of postural sway. Additionally, it was observed that in the younger group, no significant disparity in CoP_{length} was evident between the baseline and the 2–3 s interval. Alternatively, in older adults, a significant divergence in CoP_{length} was still evident between the two aforementioned intervals.

The coefficient-a of the regression curve reflects the initial disturbance upon grounding. For older adults, the coefficient-a and the constant-b were larger than those for younger adults, indicating a more significant disturbance at all times. Table 1 further supports this coefficient, as no significant divergence was identified between 2–3 s and baseline for younger adults. This indicates that CoPlength reduced more swiftly than for older adults, aligning with previous research[31]. “The stability point” denotes the duration it takes for sway to stabilize[32]; however, it is not a sensitive parameter from a comparison of healthy participants and those with ankle instability[8]. The regression curve introduced in this study could be used instead of the stability point to indicate changes in the CPA and aspects of postural stabilization.

The constant-b of the regression curve refers to the group’s ability to maintain CoP_{length} at a constant static level; this ability was reduced in older adults. Possible explanations for the decreased balance after stabilization might include the age-related decline in somatosensory perception[33], muscle strength[23], and sensory information-processing ability[34] in feedback control. The constant-b could not accurately represent the convergence value of CoP_{length}, indicating divergence between CoP_{length} and the regression curves from the middle of the curve. However, significant differences in the values were observed between groups, suggesting that the intercept value may indicate the final stability of CoP_{length}. Both groups expressed the convergence curve during the step-down task as an inversely proportional curve regardless of aging, suggesting that it may represent a common aspect of human balance control.

CPAs are commonly regulated by both feedback and feedforward control[7]. Motor control processes that use information from prior movements to facilitate subsequent movements are identified as online control and coordination. Online control can be segregated into a fast model (automatic adjustments, usually without awareness) and a second model (slow voluntary adjustments, confirmed in the lower extremity)[35]. The second model is affected by aging and displays a delayed response latency[36]. Therefore, the impact of aging on online control would similarly influence the curve.

This study has several limitations. First, we could not measure the movement speed during the step-down task. Ideally, velocity should have been standardized using a high-speed camera or motion capture. The velocity of the descending step impacts the center of pressure of the sway. As depicted in Fig. 3, the maximum value of the Z-component at the time of grounding was approximately equal to or greater than that for both younger and older adults. Second, for a more precise approach, an additional force plate should have been installed on the upper step to calculate the CoP of the pre-step sway and to eliminate the double support phase rigorously. Alternatively, adjusting the height of the step to prevent achieving a double support phase could have been considered. In such a case, adjustments for the future need to consider fall prevention and safety. However, clinically, even a single force plate could provide sufficiently beneficial results, as demonstrated in this study. Conversely, while force plates offer precise measurements, their high cost and limited availability may restrict their widespread use in clinical and research settings.

Ceiling effects are present in the static balance tasks. This assessment may lack sufficient relevance, especially for healthy older adults and those with high motor function who have no history of falls. Compared to standing on one leg, the step-down task is a challenging upper-level task. In preliminary experiments, the step-down task could not be performed by patients with a history of falls. Because comparisons with other balance tests were not conducted in this study, it is as yet being determined whether the step-down task is superior to others, even though it includes elements of forward movement and standing on one leg that capture the characteristics of older adults. In the future, the step-down task could be combined with existing balance tests to provide a more comprehensive assessment of individual abilities.

In summary, we developed the step-down task to assess the dynamic balance of older individuals. By observing stability recovery over time in both young and older adults, we derived regression equations. These equations revealed inverse proportionality in both groups, with coefficient comparisons of the coefficients and the constant indicating faster stability recovery in the younger group. Our computational approach's novelty lies in its depiction of CPAs changes over time, offering a promising new indicator of dynamic balance. Future research should evaluate the applicability of the step-down task and the implications of changes in the regression equations. It is crucial to investigate whether this task can differentiate between individuals who have fallen and those who have not. Additionally, this approach could serve as an effective tool to monitor changes in CPAs performance over time among people with disabilities, assess the effect of rehabilitation interventions, and identify disease-specific balance-control issues in conditions such as Parkinson's disease and stroke.

Author contributions

Daisuke Kimura: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Writing–original draft, Writing–review & editing.

Kosuke Oku: Data curation, Investigation, Visualization Writing–review & editing

Issei Ogasawara: Conceptualization, Methodology, Project administration, Resources, Software Writing–review & editing.

Tomotaka Ito: Data curation, Writing–review & editing.

Ken Nakata: Conceptualization, Methodology, Supervision, Writing–review & editing.

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Conflict of interest

There are no conflicts of interest to declare.

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