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ORIGINAL

# Analysis of the Dynamic Balance Recovery Ability by External Perturbation in the Elderly

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**Objective:** The aim of the study was to investigate the age-related ability of dynamic balance recovery through perturbation response during standing.

**Method:** Six older and 6 younger adults participated in this study. External perturbation during standing as pulling force applied at the pelvic level in the anterior direction was provided to the subject. The margin of stability was quantified as a measure of postural stability or dynamic balance recovery, and using principal component analysis (PCA), the regularity of the margin of stability (MoS) was calculated.

**Results:** Our results showed that in the older adult group, 60.99% and 28.63% of the total variance were captured using the first and second principal components (PCs), respectively, and in the younger adult group, 81.95% and 10.71% of the total variance were captured using the first and second PCs, respectively.

**Conclusion:** Ninety percent of the total variance captured using the first two PCs indicates that the older adults had decreased regularity of the MoS than the younger adults. Thus, the results of the present study suggest that aging is associated with non-regularity of dynamic postural stability.

**Keywords:** Perturbation, Aging, Margin of stability, Principal component analysis, Regularity

## INTRODUCTION

Aging-related changes in the nervous system can reduce the balance ability of the elderly by affecting their stimulus response time and nerve conduction velocity (Lee, Lee, & Song, 2014). The ability to maintain balance, which also refers to the ability to continue to maintain stability, is an essential element of performing basic activities of daily living (Cohen, Blatchly, & Gombash, 1993; Wade & Jones, 1997; Woo & Park, 2015). The most frequent accidents that are most closely related to the balance ability of the elderly in daily life are falls, which is defined as an accident where the body unexpectedly ends up on the ground or the posture changes to a low position. Moreover, the occurrence of falls in the elderly tends to continue to increase with the passing of time, which can lead to serious injuries that cause various complications (Kim & Im, 2017). Zecevic, Salmoni, Speechley, & Vandervoort (2006) reported that motor control aspects, such as physical coordination, slow physical response time, low agility, and sudden postural change account for 50% of falls in the elderly and that they occur as a result of deviation from physical balance and other environmental factors, such as unexpected perturbation.

Numerous studies have investigated the dynamic balance abilities of the elderly using perturbation that causes sudden postural change and sudden environmental factors for identifying the dynamic movement of the elderly in relation to falls (Pai, Rogers, Patton, Cain, & Hanke, 1998; Schulz, Ashton-Miller, & Alexander, 2006). In particular, instead of analyzing the center of pressure (CoP) to investigate changes in postural maintenance, quantification of dynamic balance ability in the field of kinematics has involved analyzing the margin of stability (MoS) on the basis of extrapolated center of mass (xCoM), which is known to be more suitable for predicting the direction of movement, as the center of mass (CoM) includes information on velocity at dynamic posture, leg length, and gravitational acceleration (Hasson, Van Emmerik, & Caldwell, 2008; Hof, Gazendam, & Sinke, 2005). Such a method can quantify dynamic stability that allows for spatiotemporal analysis (Bierbaum, Peper, Karamanidis, & Arampatzis, 2010; Barrett, Cronin, Lichtwark, Mills, & Carty, 2012; Jang, Hong, & Jang, 2016).

From a motor control aspect, one of the characteristics of aging is non-regularity where a consistent pattern does not appear when a motion or movement is performed owing to the lack of cognitive and sensory motor resources (Eskofier, Federolf, Kugler, & Nigg, 2013). The claim that regularity is reduced in the elderly can be found in numerous previous studies. Challis (2006) reported that in plantar flexion motion that induces maximal contractile force, reduction in motor units due to aging causes a decline in muscle coordination ability, which leads to reduced regularity in the elderly. Moreover, Verrel, Lövdén, Schellenbach, Schaefer, & Lindenberger (2009) reported that regularity of whole-body CoM change during walking was lower in the elderly than in young people, whereas Eskofier et al. (2013) also reported that gait variability was larger among the elderly than among young people. However, all the aforementioned studies arrived at the same result that regularity decreased or variability increased in the elderly during gait analysis using principal components analysis (PCA). Accordingly, the present study aimed to investigate the changes in dynamic stability of the elderly using PCA to test whether the elderly have a consistent pattern of maintaining dynamic stability or non-regularity where such consistent pattern is lost.

The objective of the present study was to identify the regularity of dynamic balance recovery by the elderly using PCA and MoS analysis with CoM for investigation of the stability that allows recovery of dynamic balance ability when an external stimulation is applied to the elderly.

## METHODS

### 1. Participants

The participants in the present study included 6 elderly (female: 5, male: 1, age: 69.33 ± 2.87 y, height: 160.20 ± 6.10 cm, weight: 63.40 ± 7.31 kg) and 6 young people (female: 6, age: 21.17 ± 6.04 y, height: 160.85 ± 3.38 cm, weight: 51.18 ± 3.65 kg) who did not have any musculoskeletal disorders in the lower extremities. Prior to their participation in the study, all the participants received full explanation, learned all experimental procedures involved, and voluntarily participated in the study after signing an written informed consent form.

### 2. Measurements

The present study used 6 high-speed infrared cameras to capture motion during application of perturbation stimulus (100 fields/sec, 110 shutter speed 1/500, 6 Hz low-pass filter). Nineteen reflective markers were attached throughout each participant's body (head, shoulder, elbow, wrist, finger, thigh, knee, ankle, and big toe) to acquire whole-body positional data.

The experimental procedure involved having the participant maintain a natural standing position and face straight forward while wearing a perturbation belt on the waist. For the boundaries of each participant's base of support (BoS), the shoulder width of each participant was measured and the boundaries were marked accordingly to fit each participant. The perturbation stimulus was applied using the force of the spring connected to a motor to pull the participant forward via the cord connected to the belt worn on the waist and then releasing. The experiment was conducted with 8 different strength conditions, ranging from 2 to 30 kg (Park, Koh, Lee, Shim, & Park, 2016). After application of the perturbation stimulus, the strengths when the CoM of one foot moved completely forward for the first time in each participant were 9, 13, 20, and 24 kg for 1, 5, 4, and 2 participants, respectively. The motion events were set as shown in Figure 1. Event 1 was defined as the ready position with both feet placed on the BoS before application of the perturbation stimulus. Event 2 was defined as the point where one foot was in toe-off position from the CoM moving after application of the perturbation stimulus. Event 3 was defined as the point where the foot that was in toe-off position moved the CoM to assume the heel contact position. Moreover, Phase 1 was defined as the phase between Events 1 and 2, whereas Phase 2 was defined as the phase from Event 2 to Event 3. The analysis interval was from Event 1 to 2 sec later. As each participant has a different heel contact point that corresponds to Event 3, the participant with the slowest time of reaching the heel contact point was used as the reference, and the maximum allowance point of 2 sec was designated for analysis.

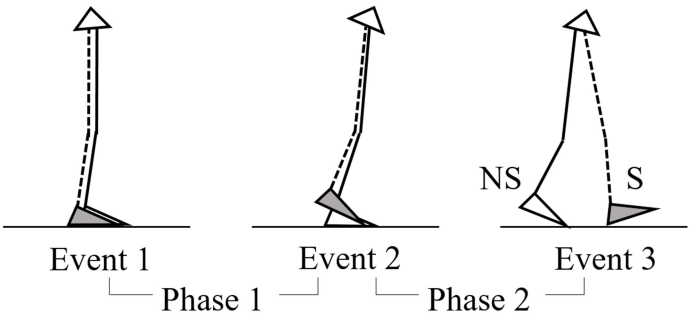



**Figure 1.** Analysis setting during the stepping event. NS: non-stepping leg; S: stepping leg.

### 3. Data processing

CoM data were derived from using the positional data acquired with 6 infrared cameras and analyzed using the Kwon3d XP software. Moreover, MATLAB was used to derive the primary components via PCA.

#### 1) Calculation of margin of stability

Hof et al. (2005) calculated xCoM using the equation given below to predict dynamic CoM:

$$\left( \mathrm{XCoM} = \mathrm{PCoM} + \left( \frac{\mathrm{VCoM}}{\sqrt{\frac{g}{l}}} \right) \right)$$

Here, PCoM represents the position of the CoM; VCoM, the velocity of the CoM;. $l$, the leg length, which was used as the distance from the position of both ankles in ready position to the CoM in the present study; and $g$, the gravitational acceleration. In the present study, the MoS was analyzed using the relationship between xCoM and BoS. For the MoS, the distance (m) from BoS to xCoM was calculated using the following equation:

(MoS=BoS-XCoM) (Hof et al., 2005).

Moreover, for the MoS analysis, BoS was defined as the distance from the marker on the heel of the non-stepping foot (the supporting leg without CoM movement) and the marker on the big toe of the stepping leg after the leg moved forward by one step with complete movement of the CoM after application of perturbation stimulus (Barrett et al., 2012) (Figure 2).

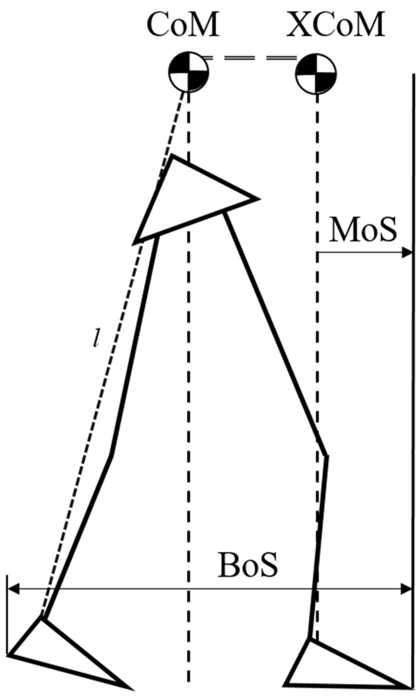



**Figure 2.** Schematic diagram defining the parameters used to compute the margin of stability (MoS). *l*: leg length; XCoM: the extrapolated center of mass; CoM: center of mass; BoS: base of support.

### 2) Principal component analysis

PCA is a linear transformation technique, which condenses data by transforming high dimensional data into low dimensional data (Jolliffe, 2011). Among the observed data, the base vectors of the coordinates transformed by expressing correlated variables in linearly transformed form are referred to as principal components (PC). In PCA, the number of components needed to capture the total variance is an indicator of data regularity. PCA is an analytic method that transforms variables with many possible correlations into fewer uncorrelated variables called PC. In particular, this method has been used primarily for quantifying the kinematic pattern of human movement (Daffertshofer, Lamoth, Meijer, & Beek, 2004) and is known to be a suitable method for analyzing the regularity of movement (Zamparo, Zorzi, Marcantoni, & Cesari, 2015). The MoS values of the elderly and young people analyzed from all phases designated in the present study were analyzed using PCA, and the variance values of the PCs needed to explain the total variance of the MoS in each group were used as indicators of regularity.

### 4. Statistical analysis

Data analysis of the MoS values of the designated events and phases in the two groups was performed using independent samples *t* test. SPSS Statistics 21.0 was used for statistical analysis with the significance level set at 5%.

## RESULTS

### 1. Margin of stability

Table 1 shows the MoS values and statistical results of the two groups when perturbation stimulus was applied. Phase 1 ($t$ = .616), which represents the difference in MoS values from Events 1 and 2, and Phase 2 ($t$ = .378), which represents the difference in MoS values from Events 2 and 3, did not show significant differences between the elderly and young groups.

Figure 3 shows the pattern graphs of the means and standard deviations of the MoS in the elderly and young groups. The results showed that the two groups had large differences in the pattern of the mean graph and range of standard deviation.

**Table 1.** Results of the margin of stability (MoS)

| Event | Groups | Mean ± SD (m) | *t* Value |
|---|---|---|---|
| Phase 1 | Elderly | 0.19 ± 0.08 | .616 |
| | Young | 0.21 ± 0.06 | |
| Phase 2 | Elderly | 0.18 ± 0.02 | .378 |
| | Young | 0.19 ± 0.05 | |

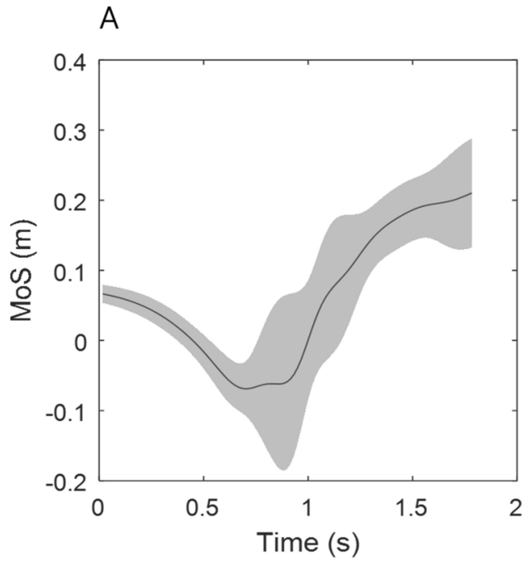
### 2. Regularity of the MoS

To analyze the regularity of the MoS, the present study used the PCA method to analyze the components of the MoS data in the elderly and young groups when perturbation stimulus was applied.

Figure 4 shows the results of the PCA of the MoS results of the elderly and young groups. The first and second PC were respectively 60.99% and 28.63% in the elderly group, and 81.95% and 10.71% in the young group. The young group showed greater regularity than the elderly group.

## DISCUSSION

Among the recent studies that assessed the physical abilities of the elderly, many have attempted to kinematically identify the mechanism



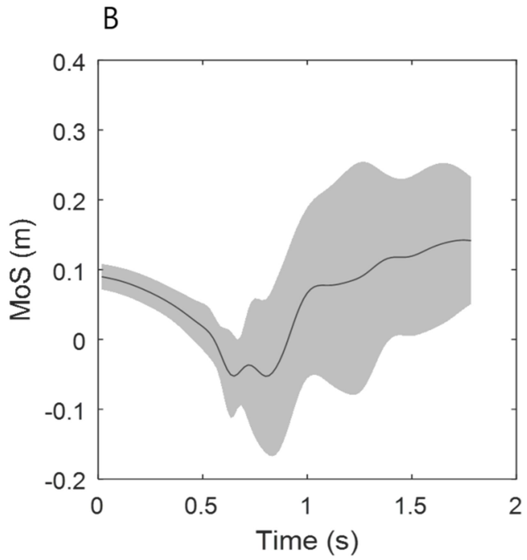




**Figure 3.** Pattern graphs of the mean and standard deviation of the margin of stability (MoS) across the subjects of each group. A: young group; B: elderly group.

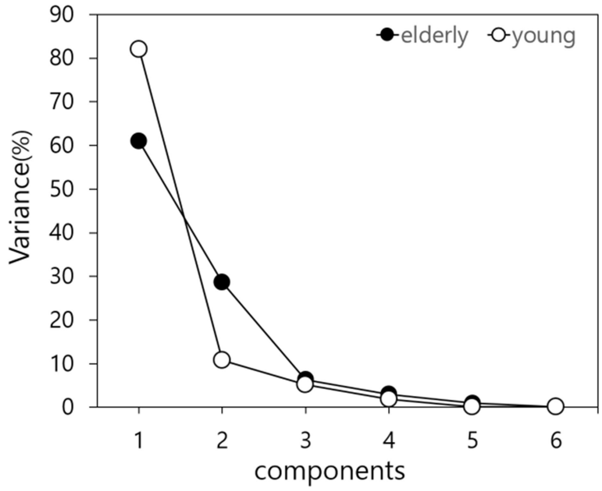



**Figure 4.** The percentage of the total variance explained using each principal component.

behind the ability to recover dynamic balance after artificially inducing the state of dynamic imbalance (Menant et al., 2008; Bierbaum et al., 2010; Barrett et al., 2012). In particular, previous studies quantified the dynamic balance recovery ability of the elderly using a MoS analysis. Barrett et al. (2012) demonstrated the mechanism of recovering dynamic balance in the elderly by quantifying balance recovery ability through a MoS analysis under the condition of repeated perturbation by the tether-release method. Moreover, Bierbaum et al. (2010) examined the ability to recover balance under an imbalanced state and reported that the MoS showed a greater decrease in the elderly group than in the young group when the MoS analysis method used in the present study was applied to a dynamic imbalance situation where the ground changed suddenly while walking.

In the present study, when the elderly group was compared with the young group with respect to Phase 1 and 2 motions covering the point after applying perturbation stimulus and recovering the dynamic stability, the difference in mean values between the groups showed that the elderly group had a shorter MoS than the young group, but the difference was not statistically significant. The pattern graphs shown in Figure 3 indicate that the real-time MoS pattern of the elderly group was more irregular than that of the young group, whereas the range of standard deviation was very large as well. Therefore, the calculated MoS of the two groups in the present study showed that the balance stabilization ability especially of the elderly showed markedly different patterns.

PCA is an analytic method for quantifying the regularity of movements, which has been used in various ways in the fields of kinematics and motor control (Verrel et al., 2009; Jolliffe, 2011; Park, Sun, Zatsiorsky, & Latash, 2011; Eskofier et al., 2013) and was used in the present study to investigate whether regularity appeared during stabilization of dynamic balance by the elderly. As shown in Figure 4, the first and second PC were 60.99% and 28.63%, respectively, in the elderly group, indicating that the distributions of the first and second PC were spread out (with a difference of 32.36% between the first and second PC). In the young group, the first and second PC were 81.95% and 10.71%, respectively (with a difference of 71.24% between the first and second PC). On the basis of these results, the young group showed a MoS with regularity in the first variance, whereas the PC of the elderly group were variable without representativeness, showing greater non-regularity than the young group. Previous studies indicated that one of the characteristics of movements by the elderly was that they showed large variability or non-regularity. A study by Stergiou, Giakas, Byrne, & Pomeroy (2002) analyzed the variability of ground reaction force during walking between the elderly and young groups, and found that although no significant differences in vertical direction was found between the two groups, the inter-subject coefficient of variation of the elderly group was highest, with 11.89 for vertical ground reaction force, indicating that the intra-subject margin of pattern in the elderly group was widely distributed. Moreover, a study by Verrel et al. (2009) used PCA to examine the changes in whole-body CoM in the gait patterns of elderly and young groups when simultaneously occurring cognitive tasks were given while walking on a treadmill. The results showed that the gait pattern of the elderly group was more irregular than the pattern shown by the young group. The results of the aforementioned studies support the findings of the present study, which indicated that the elderly group had non-regularity in MoS, which reflects the ability to stabilize dynamic balance.

Ultimately, when MoS values, which reflect the ability to recover dynamic balance under situations when perturbation causes unexpected imbalance in the elderly, were analyzed, no statistically significant diffeence was found in the movements between the elderly and young groups. However, when the distribution of the MoS was analyzed using PCA, the results showed non-regularity in core stabilization, with each elderly subject showing different patterns of dynamic balance recovery ability during recovery of their dynamic balance. Therefore, we believe that the elderly have no consistency in their ability to recover dynamic balance, with each individual showing different characteristics.

In the present study, the elderly group did not show a consistent pattern of balance ability and showed characteristics of non-regularity. Therefore, we believe that when presenting future exercise programs or training to increase the balance ability of the elderly, more-diverse exercise methods that consider various individualized dynamic balance abilities should be used.

## CONCLUSION

The present study applied external perturbation in 6 elderly and 6 young participants to examine the stability that allows recovery of dynamic balance ability in the elderly, which was performed through a MoS analysis using CoM and regularity of dynamic balance recovery via PCA. On the basis of the findings of the present study, conclusions were derived. No statistically significant differences in MoS based on movements were found between the elderly and young groups. However, when the distribution of MoS was analyzed via PCs, each elderly participant showed different patterns in their ability to maintain stability during the process of recovering dynamic balance, which indicated non-regularity in core stabilization. Therefore, we discovered that the elderly had no consistency in their ability to recover dynamic balance and showed individually different characteristics.

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