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Original Article

Effect on the Center of Pressure of Vision, Floor Condition, and the Height of Center of Mass During Quiet Standing

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Background: Theoretically, balance is affected by the height of center of mass (COM) during quiet standing. However, no one examined this in humans with variables derived from the center of pressure (COP).

Objects: We have conducted balance experiment to measure COP data during quiet standing, in order to examine how the COP measures were affected by the height of COM, vision, floor conditions, and gender.

Methods: Twenty individuals stood still with feet together and arms at sides for 30 seconds on a force plate. Trials were acquired with three COM heights: 1% increased or decreased, and not changed, with two vision conditions: eyes closed (EC) and eyes open (EO), and with two floor conditions: unstable (foam pad) and stable (force plate) floor. Outcome variables included the mean distance, root mean square distance, total excursion, mean velocity, and 95% confidence circle area.

Results: All outcome variables were associated with the COM height ($p < 0.0005$), vision ($p < 0.0005$), and floor condition ($p < 0.003$). The mean velocity and 95% confidence circle area were 5.7% and 21.8% greater, respectively, in raised COM than in lowered COM (24.6 versus 23.2 mm/s; 1,013.4 versus 832.3 mm^2). However, there were no interactions between the COM height and vision condition ($p > 0.096$), and between the COM height and floor condition ($p > 0.183$) for all outcome variables. Furthermore, there was no gender difference in all outcome variables ($p > 0.186$).

Conclusion: Balance was affected by the change of COM height induced by a weight belt in human. However, the effect was not affected by vision or floor condition. Our results should inform the design of balance exercise program to improve the outcome of the balance training.

INTRODUCTION

Consequences of falls in older adults are often debilitating, and prevention is important. One method to prevent a fall is an exercise to improve balance, which may help to decrease a risk of fall. Some clinical studies suggest that exercises (i.e., group-based resistance and balance training, aquatic exercise, Tai Chi) help to decrease the fall risk (thereby reduce the fall incidence) [1-4], but others provide evidence that exercises (i.e., treadmill training with projected visual context, RESTORE intervention, water based exercise) do not help to improve one's balance [5-7]. While difficult to discuss what causes the discrepancy, the effectiveness of exercise may be improved by modifying environmental conditions surrounding individuals during tasks (i.e., eyes open or closed, stable or unstable floor, lowered or raised center of mass [COM]).

Balance is an ability to place the center of pressure (COP) within a base of support during movements, and the balance performance can be improved by exercise or balance training under various environmental conditions. Research has shown that the training effect becomes superior when exercised on the unstable floor (i.e., foam pad, BOSU) [8-10], and gait and balance performance improved 15% and 11%, respectively, in older adults with exercises administered on the BOSU and Swiss ball [9]. Kang and Kim (2019) [11] has shown that task oriented balance training with unstable surface has greater effects in improving Berg Balance Scale and 10 meter walking test when compared to training with stable surface in patients with stroke. Furthermore, the effect of balance training can be improved with visual deprivation during tasks, and the time to complete the Star Excursion Balance Test, a clinical measurement tool for balance performance, was reduced 16% with the eyes-closed exercise training, but only 4% with the eyes-open training [12].

Mechanically, balance is affected by changes of the height of COM (i.e., the higher COM, the more unstable), and this notion is supported, in part, by some clinical measures. Almeida et al. (2011) [13] have measured the height of COM between fallers and non-fallers in older adults to conduct regression analyses. They have found that fall risk increases 37% for every 1% increase in the height of COM. Furthermore, Dounskaia et al. (2018) [14] and Richardson et al. (2000) [15] have shown that the elevated height of COM due to a halo vest or weight adjustable jacket decreases single limb stance time and performance of quiet standing and functional reaching task. In these three studies, however, the changed height of COM was not measured in every individual, leaving the exact biomechanical effect of the change of COM height on balance unclear. One study tried to answer this question and placed a weight belt 10 cm below the individual's original COM to lower the COM height systematically across all participants. However, they did not measure the lowered COM height in every individual either, and their results should be interpreted in light of this limitation [16].

COP measures are widely used for the evaluation of standing balance and greater displacement and velocity of COP has often been interpreted as poor balance. Among variables extracted from the COP measure, mean distance (MDIST), root mean square distance (RDIST), total excursion (TOTEX), mean velocity (MVELO), and 95% confidence circle area (95% Conf Circle Area) are known to be sensitive in assessing standing balance under various environmental conditions [17-19]. Formulas to derive these variables are provided in data analysis section below. Clinically, the TOTEX and 95% Conf Circle Area concern the amount of body sway during standing, and the MDIST and RDIST refer to "average" of the body sway. Furthermore, the MVELO represents how fast the body sways given time.

Against the background, we have conducted balance experiment to measure COP data during quiet standing, in order to examine how the COP measures (i.e., velocity, distance, area) were affected by the height of COM, vision, floor conditions, and gender.

MATERIALS AND METHODS

1. Subjects

Twenty young healthy adults (10 men and 10 women) aged between 19 and 29 participated in the balance experiment. On average, participants' age, weight, height, body mass index, and height of COM were 23.85 (SD = 1.9), 69.7 (SD = 10.1), 168.4 (SD = 7.1), 24.5 (SD = 3.1), and 93.8 (SD = 4.7), respectively. Exclusion criteria included recent musculoskeletal injuries, including but not limited to, fractures, sprain and strain. The study protocol was approved by the Institutional Review Board at Yonsei University Mirae campus, and all subjects agreed to participate by providing a written informed consent form.

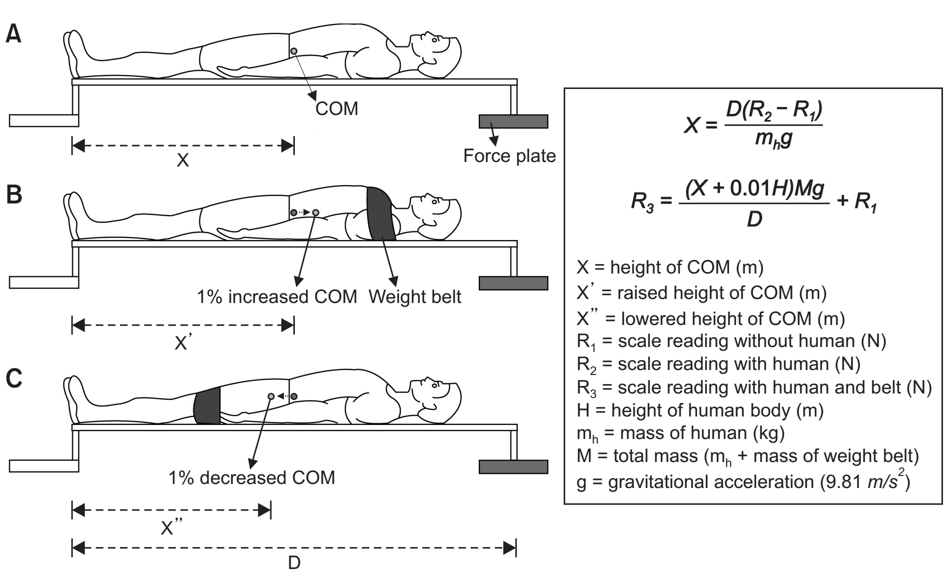

Figure 1. Participants lay on a reaction board to determine (A) the height of COM, and positions of a weight belt (5% of body weight) so the height of COM (B) increased or (C) decreased 1% with respect to the original height of COM.

2. Experimental Protocol

In the first session, participants lay on a reaction board to determine the location of COM and the position of a weight belt (5% of body weight; Weight Adjustable Aquatic Exercise Belt; ALLPRO®, Tampa, FL, USA), which changes the height of COM 1% higher or lower with respect to the original height of COM (i.e., raised or lowered 1.6 cm for an individual who is 160 cm tall) (Figure 1). We decided to apply the 1% change of COM height as it was the maximal capacity that the current experimental design provides. Associated steps and equations to compute the height of COM are provided in the inset of Figure 1.

In the second session, participants stood still with feet together and arms at sides for 30 seconds on a force plate (OR6-7-2000; AMTI, Waltham, MA, USA) to measure the trajectory of COP (Figure 2). Trials were acquired with three COM heights: increased, decreased, and not changed, with two vision conditions: eyes closed and eyes open, and with two floor conditions: unstable (foam pad) and stable (force plate) floor. Two trials were acquired for each combination of the conditions and averaged for data analyses. Participants took an one-minute rest between trials. To minimize learning effects, the order of testing conditions was randomized.

3. Data Analysis

COP data were sampled at a rate of 1,000 Hz and was filtered through a fourth-order zero phase Butterworth low-pass digital filter with a 5-Hz cut-off frequency [19]. The last 20 seconds COP data were used for data analyses. Outcome variables included the MDIST, RDIST, TOTEX, MVELO, and % Conf. Circle Area [19,20], and each variable was defined as follows:

$$\text{MDIST} = \frac{1}{N}\sum\sqrt{COPx(i)^2 + COPy(i)^2}, where\ i = the\ number\ of\ data\ point$$

$$\text{RDIST} = \sqrt{\frac{1}{N}\sum(COPx(i)^2 + COPy(i)^2)}$$

$$\text{TOTEX} = \sum\sqrt{(COPx(i+1) - COPx(i))^2 + (COPy(i+1) - COPy(i))^2}$$

$$\text{MVELO} = \frac{TOTEX}{t}, where\ t = 20\ seconds$$

$$\text{95\% Conf. Circle Area} = \pi * \left(MDIST + 1.645 * std\left(\sqrt{COPx(i)^2 + COPy(i)^2}\right)\right)^2$$

$$, where\ 1.645 = the\ z\ statistics\ at\ the\ 95\%\ confidence\ level$$

$$std = standard\ deviation$$

All outcome variables were computed using a customized Matlab routine (Matlab R2019a; MathWorks, Natick, MA, USA).

For statistical analyses, a three-way repeated measures ANOVA with gender as a grouping factor was used to test if these variables were associated with the COM height (3 levels), vision (2 levels), and floor condition (2 levels). When a main effect was significant, pairwise comparisons were conducted using Bonferroni correction with an alpha level at 0.05.

RESULTS

All outcome variables were associated with the COM height

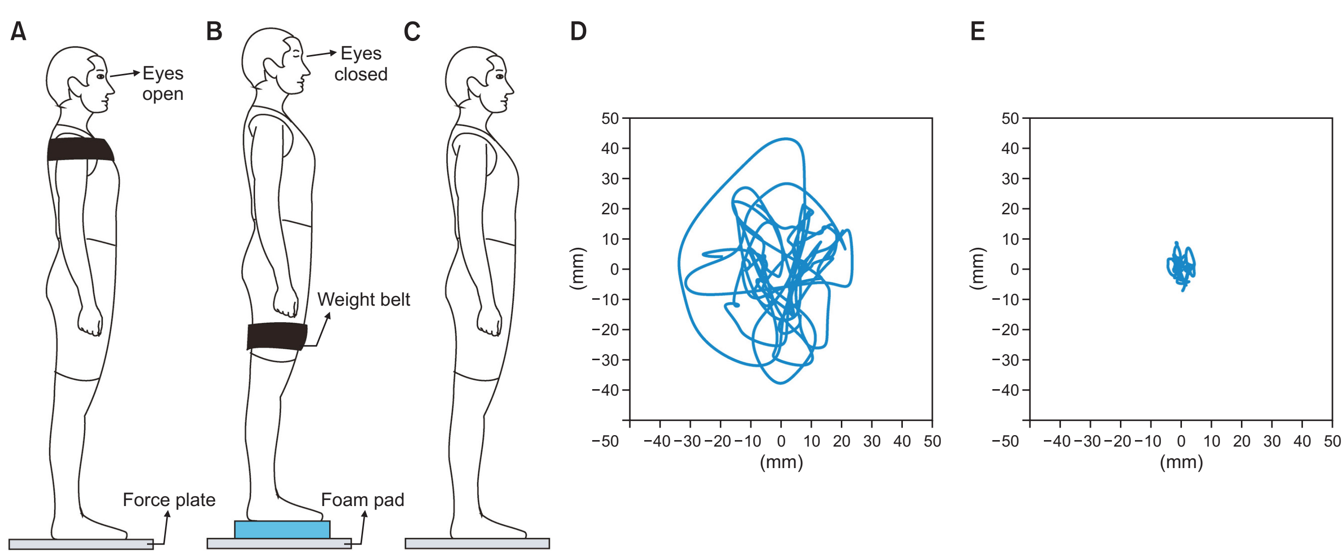

Figure 2. Sample schematics of quiet standing tasks with (A) eyes open, COM raised, and stable floor condition, (B) eyes closed, COM lowered, and unstable floor condition, and (C) eyes open, COM not changed, and stable floor condition, along with a sample COP trace under (D) eyes closed, COM raised, and unstable floor, and (E) eyes open, COM lowered, and stable floor condition.

($p < 0.0005$), vision ($p < 0.0005$), and floor condition ($p < 0.003$). The MVELO and 95% Conf Circle Area were 5.7% and 21.8% greater, respectively, in raised COM than in lowered COM (24.6 versus 23.2 mm/s; 1,013.4 versus 832.3 mm^2), 85.5% and 101.2% greater, respectively, in eyes closed than in eyes open (31.5 versus 17.0 mm/s; 1,241.9 versus 617.1 mm^2), and 129.6% and 216.5% greater, respectively, in unstable than in stable floor condition (33.7 versus 14.7 mm/s; 1,412.6 versus 446.3 mm^2) (Figure 3, Table 1). However, there were no interactions between the COM height and vision condition ($p > 0.096$), and between the COM height and floor condition ($p > 0.183$) for all outcome variables. Furthermore, there was no difference between male and female participants for all outcome variables ($p > 0.186$).

DISCUSSION

The goal of this study was to examine how balance was affected by the weight belt induced change in the height of COM during quiet standing. We found that individuals swayed more over greater area with greater velocity when the height of COM increased. This agrees well with a model prediction. In theory of one link inverted pendulum model (often used to describe standing balance in humans), the greater the COM height, the smaller leaning angle is needed to initiate instability (easier to loose balance) and the greater recovery ankle torque is required when lost balance, resulting in more sway and muscle

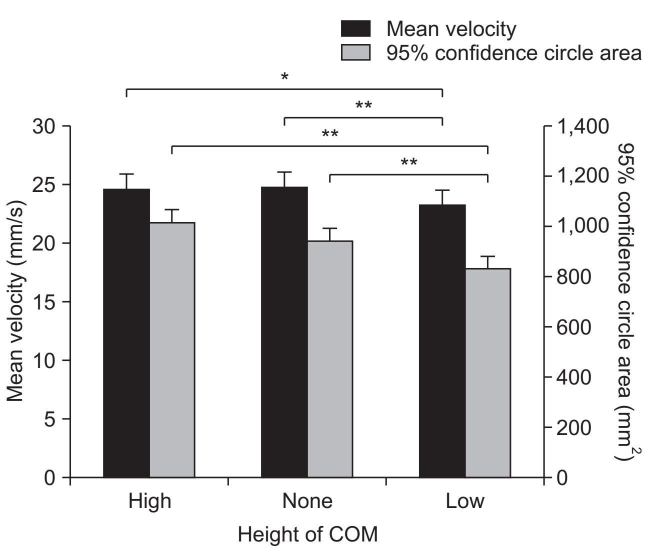

Figure 3. Effects of the height of COM on COP measures during quiet standing. Individuals swayed more over greater area with greater velocity. *p = 0.053; **p < 0.05.

Table 1. Average values of outcome variables in each testing condition (standard deviation shown in parentheses)

Measures	Eyes closed						Eyes open						Main effect (p-value)		
	Unstable floor			Stable floor			Unstable floor			Stable floor					
	High	None	Low	High	None	Low	High	None	Low	High	None	Low	Eye condition	Floor condition	Height of COM
MDIST (mm)	13.3 (3.4)	13.0 (2.3)	12.6 (2.7)	6.8 (1.4)	6.7 (1.9)	6.5 (1.6)	9.0 (1.7)	9.1 (1.4)	7.8 (2.1)	6.1 (1.4)	5.7 (1.3)	5.1 (1.5)	0.0005	0.0005	0.0005
RDIST (mm)	15.1 (4.0)	14.7 (2.6)	14.3 (3.1)	7.7 (1.6)	7.6 (2.2)	7.3 (1.8)	10.1 (1.9)	10.3 (1.5)	8.8 (2.4)	6.8 (1.5)	6.5 (1.5)	5.8 (1.7)	0.0005	0.0005	0.0005
TOTEX (mm)	916.0 (266.2)	931.1 (261.4)	905.0 (289.3)	342.3 (92.0)	341.4 (82.4)	339.1 (97.1)	443.3 (103.0)	455.7 (115.0)	395.9 (129.2)	264.9 (70.0)	255.2 (66.8)	219.6 (54.9)	0.0005	0.0005	0.004
MVELO (mm/s)	45.8 (13.3)	46.6 (13.1)	45.2 (14.5)	17.1 (4.6)	17.1 (4.1)	17.0 (4.9)	22.2 (5.2)	22.8 (5.8)	19.8 (6.5)	13.2 (3.5)	12.8 (3.3)	11.0 (2.7)	0.0005	0.0005	0.004
95% Conf. Circle Area (mm^2)	2,162.0 (1,473.0)	1,905.8 (695.7)	1,812.3 (850.2)	549.0 (242.7)	536.0 (289.4)	486.1 (245.7)	934.9 (325.7)	941.6 (291.3)	719.0 (405.1)	407.6 (154.3)	387.6 (175.2)	311.8 (185.7)	0.0005	0.0005	0.006

MDIST, mean distance; RDIST, root mean square distance; TOTEX, total excursion; MVELO, mean velocity; 95% Conf. Circle Area, 95% confidence circle area; COM, center of mass.

contraction (energy consumption) during quiet standing [21,22]. Collectively, the change of COM height with a weight belt successfully created a challenging environment, under which the outcome of balance training can be better.

We also found that balance performance was largely affected by vision and floor condition, and individuals swayed more with eyes closed, and on the unstable floor. These findings also agree well with previous findings, where impaired visual input decreases postural stability and unstable floor affects somatosensory inputs, resulting in poor balance [10,12,23-29].

Another goal of this study was to examine how the effect of COM change was affected by vision and floor condition during quiet standing. We found that the balance performance was largely affected by the COM height, vision, and floor condition (main effect). Interestingly, however, our data suggest that the three environmental conditions affect balance independently and not influence each other, indicating no combined effects among conditions. In balance training, one may want to change the level of difficulty depending on individuals' status (i.e., patients in early rehab stage or elite athletes) by combining several environmental conditions, and balance training with visual deprivation and/or on unstable floor condition have often been used [8-12]. However, our results suggest that such strategy provides no additional benefits in the outcome of training (i.e., balancing on the unstable floor while wearing a weight belt above waist, or training with eyes closed while wearing a weight belt above waist).

Recently, Phan et al. (2020) [16] have conducted the limit of stability (LOS) test (i.e., moving COP onto targets placed near the boundary of the base of support) while changing individuals' COM height using a weight belt, and found that the balance was not affected by the COM change. However, they did not control hip joint movements during the LOS task (therefore, participants were free to use hip strategy to reach targets). Furthermore, they mathematically calculated the changes of COM height, which never been confirmed experimentally. Whereas, our task limited hip strategy during experiments, and we directly determined positions of a weight belt when participants lay on a reaction board to confirm the 1% increase or decrease of COM height across participants. Therefore, our results should be interpreted in light of these differences.

CONCLUSIONS

Balance was affected by the change of COM height induced by a weight belt in human. However, the effect was not affected by vision or floor condition. Our results should inform the design of balance exercise program to improve the outcome of the balance training.

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CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

AUTHOR CONTRIBUTIONS

Conceptualization: WJC. Formal analysis: SK, KL. Investigation: SK, KL. Supervision: WJC. Visualization: SK, WJC. Writing - original draft: SK. Writing - review & editing: WJC.

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