KJSB

Korean Journal of Sport Biomechanics 2018; 28(4): 213-218
http://dx.doi.org/10.5103/KJSB.2018.28.4.213
http://e-kjsb.org eISSN 2093-9752

ORIGINAL

Uncontrolled Manifold Analysis of Whole Body CoM of the Elderly: The Effect of Training using the Core Exercise Equipment

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Received : 10 November 2018
Revised : 03 January 2019
Accepted : 04 January 2019

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Objective: The purpose of this study was to examine the effect of the core muscle strength enhancement of the elderly on 8 weeks training using the core exercise equipment for the elderly on the ability to control the whole-body center of mass in posture stabilization.

Method: 16 females (10 exercise group, 6 control group) participated in this study. Exercise group took part in the core strength training program for 8 weeks with total of 16 repetitions (2 repetitions per week) using a training device. External perturbation during standing as pulling force applied at the pelvic level in the anterior direction was provided to the subject. In a UCM model, the controller selects within the space of elemental variables a subspace (a manifold, UCM) corresponding to a value of a performance variable that needs to be stabilized. In the present study, we were interested in how movements of the individual segment center of mass (elemental variables) affect the whole-body center of mass (the performance variable) during balance control.

Results: At the variance of task-irrelevant space, there was significant test * group interactions ($F_{1,16}$=7.482, p<.05). However, there were no significant main effect of the test ($F_{1,16}$=.899, p>.05) and group ($F_{1,16}$=1.039, p>.05). At the variance of task-relevant space, there was significant test * group interactions ($F_{1,16}$=7.382, p<.05). However, there were no significant main effect of the test ($F_{1,16}$=.754, p>.05) and group ($F_{1,16}$=1.106, p>.05).

Conclusion: The results of this study showed that the 8 weeks training through the core training equipment for the elderly showed a significant decrease in the Vcm_{TIR} and Vcm_{TR}. This result indicates that the core strength training affects the trunk stiffness control strategy to maintain balance in the standing position by minimizing total variability of individual segment CMs.

Keywords: Uncontrolled manifold analysis, Elderly, Core training, Whole body CoM, Segment CoMs

INTRODUCTION

The core strength of the elderly has a close relationship with the balance ability in daily life (Akuthota & Nadler, 2004; Granacher, Gollhofer, Hortobágyi, Kressig, & Muehlbauer, 2013; Koh, Park, Park, Hong, & Shim, 2016). Most falls occur as a result of loss of stability during daily life activities, such as sit-to-stand movement (Pavol, Runtz, Edwards, & Pai, 2002), simply turning around movement (Nevitt, Cummings, & Hudes, 1991). Core muscle plays an important role on to perform movements that requires dynamic balance capabilities such as walking, running, and stair climbing (Willardson, 2007; Willardson, Fontana, & Bressel, 2009). Core muscles are a kinetic link that facilitates the transfer of torque and momentum between the upper and lower extremities during activities of daily living (Behm, Drinkwater, Willardson, & Cowley, 2010). Previous studies have suggested that the core strengthening of the elderly through trainings improves a "Short Physical Performance Battery (SPPB)" score for activities in daily function (Johnson, Larsen, Ozawa, Wilson, & Kennedy, 2007; Suri, Kiely, Leveille, Frontera, & Bean, 2009), spinal mobility, and balance and functional mobility (Granacher et al., 2013).

Stability can be predicted based on physical constraints such as muscle strength, size of base of support, and floor surface contact forces within an environment (Pai & Patton, 1997). In particular, during balance performance, the primary goal is to control the whole-body center of mass (WCM) in relation to base of support (Lugade, Lin, & Chou, 2011; Shumway-Cook, Brauer, & Woollacott, 2000). Even though core strength may be highly associated to ability to control WCM for the stabilization

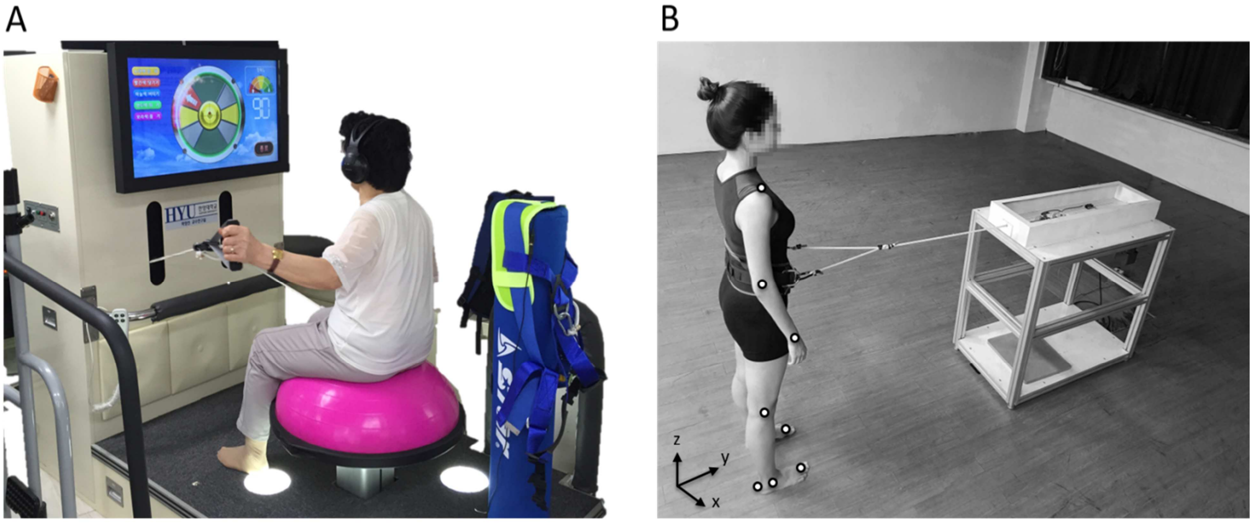

Figure 1. (A) shows a core exercise training equipment for elderly. (B) shows an experiment setup using a perturbation device.

of balance, much attention has been paid to strengths and functional performance in the elderly. However, it is little known whether the core strength training of the elderly improves the control ability of stability.

The central nervous system (CNS) controls balance of human body to coordinate multiple segments for the stabilization of the WCM. The location of the WCM is determined by the position and orientation of these segments. This multi-segment system yields significantly higher degrees of freedom than the dimension of the WCM coordinates and therefore causes the difficulty in regulating and coordinating these segments (Hsu, Chou, & Woollacott, 2013). Previous studies investigated that age-related differences in multi joint coordination to control the WCM during balance recovery (Wu, McKay, & Angulo-Barroso, 2009), and also investigated how children utilize the variability of multiple body segment movement to facilitate the control during quiet stance (Hsu et al., 2013). However, to our knowledge, no study has been conducted to examine how elderly core strength training utilize the variability of multiple body segments to facilitate the control of the WCM during quiet standing.

The uncontrolled manifold (UCM) approach has been employed in studying multi joint coordination in recent postural control research (Hsu, Scholz, Schoner, Jeka, & Kiemel, 2007; Latash, Krishnamoorthy, Scholz, & Zatsiorsky, 2005; Scholz & Schöner, 1999). The UCM analysis provides decomposition of movement variability of multi joints into task-irrelevant (variance in Uncontrolled manifold space, VUCM) and task-relevant (variance in orthogonal space to the uncontrolled manifold space, VORT) variabilities to explain the stabilization of WCM in terms of multi-segment system (Schoner, 1995; Scholz & Schöner, 1999; Krishnamoorthy, Yang, & Scholz, 2005; Hsu et al., 2007). The purpose of this study was to examine the effect of the core muscle strength enhancement of the elderly on 8 weeks training using the core exercise equipment for the elderly on the ability to control the WCM in posture stabilization.

METHODS

16 female (10 exercise group: mean age: 75±5 yrs; mean mass: 62±8 kg; mean height: 151±7 cm, 6 control group: mean age: 77±5 yrs; mean mass: 61±8 kg; mean height: 150±8 cm) with no history of muscular skeletal disease or injuries were recruited for this study. Exercise group took part in the core strength training program for 8 weeks with total of 16 repetitions (2 repetitions per week) using a training device (Figure 1-A). The training device we developed was useful for strengthening the core trunk muscles by inducing instability on the surface of the subject's seat (gym ball shaped) while performing upper limb exercise only (pulling on the arms). All participants performed full body stretching for five minutes before and after the training to prevent injury. Major training was conducted separately by low, middle and high level. The level of training was divided into the number of movements per song in which the arms were pulled and held. The low level was set to 44 times per song, the middle level was 74 times, and the high level was set to 128 times on average. The detail of the training program is shown in (Table 1). The equipment was easy to maneuver by the elderly and could provide information of the center of gravity as exercise feedback during core muscle exercise (Koh et al., 2016). This study was approved by the institutional review board (IRB) at Hanyang University.

In this study, six infrared high-speed cameras were used to capture movements during stimulation (100 field/sec, Shutter speed 1/500, 6Hz low pass filter), 19 reflection markers were attached to each subject's body and the position of the WCM was obtained. The focus of this study was on control of the anterioi-posterior (AP) position of the WCM because the perturbation direction was anterior. The tester instructed the subjects not to lean against the spring connected to a belt at the waist. The examiner instructed the subject to gaze forward while maintaining a standing posture with both arms naturally lowered within the basal plane. To unify the subjects' position, the location of the feet were presented shoulder width and then stood naturally. Perturbation stimulation was given in the form of a waist-pull in which the line connected

Table 1. The 8-week core training program

Training weeks	Composition
1	Stretching (5 min) / Low level of the core program (10 min) / Stretching (5 min)
2	Stretching (5 min) / Low level of the core program (10 min) / Stretching (5 min)
3	Stretching (5 min) / Low (5 min) and middle levels of the core program (10 min) / Stretching (5 min)
4	Stretching (5 min) / Low (5 min) and middle levels of the core program (10 min) / Stretching (5 min)
5	Stretching (5 min) / Middle level of the core program (15 min) / Stretching (5 min)
6	Stretching (5 min) / Middle level of the core program (15 min) / Stretching (5 min)
7	Stretching (5 min) / Middle (5 min) and high levels of the core program (10 min) / Stretching (5 min)
8	Stretching (5 min) / Middle (5 min) and high levels of the core program (10 min) / Stretching (5 min)

to the belt worn on the waist was pulled as far as possible in the front and back direction of the subject due to the force of the spring connected to the motor. Subjects were instructed to try to maintain their balance from moving as much as possible when external perturbation stimuli came. Motor-driven anterior waist-pull perturbations were given twice at a random time interval. The time profile of the perturbation force was 400 ms ramp up to target force of 30 N (Figure 1-B). All measurements were performed before and after training.

The obtained position data were analyzed by using Kwon 3d XP software (VISOL, Inc., Seoul, Korea) for WCM and center of mass of 14 individual segments (head, trunk, upper arm, fore arm, thigh, shank and foot)(CM). In a UCM model, the controller selected within the space of elemental variables a subspace corresponding to a value of a performance variable that needs to be stabilized. In the present study, we were interested in how movements of the individual segment CM (elemental variables) affect the WCM position (the performance variable) during balance recovery. Analysis phase was defined as period from onset perturbation to after 2 sec. MatLAB programs (MatLAB 7, MathWorks, Inc., Natick, MA, USA) were written for data processing and analysis.

Whole-body center of mass (wcm) was computed by weighted summation of segment's center of mass (cm)

$$wcm = A \cdot cm$$

where A is a 1 by n matrix with the i[th] element, $\frac{m_i}{\sum_{i=1}^{n} m_i}$ and cm is an n by 1 matrix for cm positions.

UCM analysis is a linear transformation that transform the element variables (i.e. segment's cm) into task-relevant and task-irrelevant spaces where the performance variable (i.e. wcm) is affected or unaffected, respectively.

The task-irrelevant space was determined by the null space spanned by the basis vector e

$$0 = A \cdot e$$

Segment's cm in task-irrelevant space (cm_{TIR}) was obtained through projection of segment's cm onto the null space

$$cm_{TIR} = \sum_{i=1}^{n-k} (e_i^T \cdot cm)\, e_i$$

and the component perpendicular to the null space, segment's cm in task-relevant space (cm_{TR}) was obtained as follows:

$$cm_{TR} = cm - cm_{TIR}$$

where n and k are the DOFs of the element variable and the performance variable, respectively.

The amount of variability of cm in each space was estimated as variance normalized by its DOF as:

$$Vcm_{TIR} = \frac{var(cm_{TIR})}{n}$$

$$Vcm_{TR} = \frac{var(cm_{TR})}{k}$$

Data were processed by using IBM SPSS Statistics 21.0, two way repeated measures ANOVA was used to verify the difference between the test (pre and post) and groups (exercise and control). For the post hoc test, a paired *t*-test used to compare the test (pre and post), and an independent t-test was performed to compare between the groups (exercise and control). The significance level of all statistics was set at $p<.05$.

RESULTS

Figure 2 shows the results of Vcm_{TIR} and Vcm_{TR} of two groups over 8 weeks of core training in the elderly. At the variance of task-irrelevant space, there was significant difference in test * group interactions ($F_{1,16}=7.482$, $p<.05$). However, there were no significant main effect of the test ($F_{1,16}=.899$, $p>.05$), group ($F_{1,16}=1.039$, $p>.05$) (Figure 2-A) and post-hoc test. At the variance of task-relevant space, there were signifi-

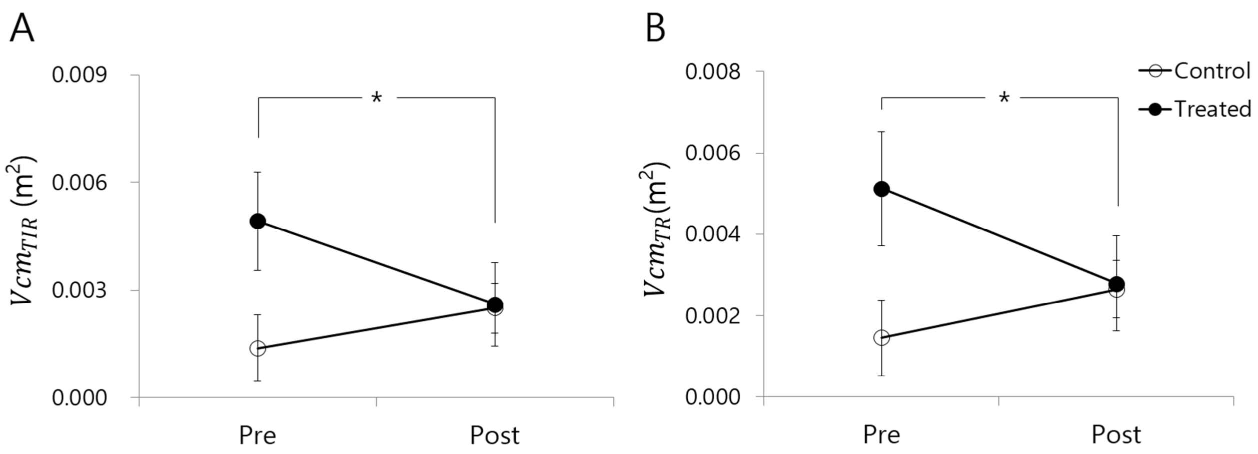

Figure 2. The results of Vcm_{TIR} (A) and Vcm_{TR} (B). (*, $p<.05$; interaction between test and group).

cant test * group interactions ($F_{1,16}$=7.382, $p<.05$). However, there were no significant main effect of the test ($F_{1,16}$=.754, $p>.05$), group ($F_{1,16}$= 1.106, $p>.05$) (Figure 2-B), and post-hoc test.

DISCUSSION

The purpose of this study was to examine the effect of the core muscle strength enhancement of the elderly on 8 weeks training using the core exercise equipment for the elderly on the ability to control the WCM in posture stabilization during external perturbation. The results of this study showed that the 8 weeks training through the core training equipment for the elderly showed a significant decrease in the Vcm_{TIR} and Vcm_{TR}.

One of the characteristics of the elderly is that as the aging process progresses, the task-irrelevant variability (i.e. V_{UCM}) decreases and the task-relevant variability (i.e. V_{ORT}) increases (Park, Sun, Zatsiorsky, & Latash, 2011; Verrel, Lövdén, & Lindenberger, 2012; Hsu et al., 2013). Previous study has found that during a constant force production task with four fingers, the task-relevant variability of the finger forces increased when the finger force and moment are controlled by the elderly (Park et al., 2011). Also, it was reported that the elderly deteriorated the ability to coordinate multi joint for stabilization of the WCM by decreasing the task-irrelevant variability and increasing the task-relevant variability (Hsu et al., 2013). Verrel et al. (2012) also found that the elderly decreased the task-irrelevant variability during one arm pointing task. This study shows that the task-relevant variability (i.e. V_{ORT}) decreases. We suggested that the exercise effect through the movement of the core reduced the error value while the elderly maintained the center.

Previous study demonstrated the training effects of core exercise equipment for elderly (Koh et al., 2016). This study reported that improving the ability to maintain the center of pressure in the center after the core strength training. The results of daily function test showed a significant improvement in SPPB score (going up and down 4 stairs and the gait speed), rising from a chair 5 times and one-leg static balance test with open eyes. In the current study, we found that both Vcm_{TIR} and Vcm_{TR} decreased after core strength training. Vcm_{TIR} and Vcm_{TR} refers to the variability of individual segment CMs which does not affect and does affect changes in the WCM, respectively. Based on the results from the previous study and the decreased variability in present study, these results indicates that the core strength training affects the trunk stiffness control strategy to maintain balance in the standing position by minimizing total variability of individual segment CMs.

Previous studies found that the effect of core muscle training increase the stiffness of trunk muscles (Bergmark, 1989; Panjabi, 1991). It was also reported that increasing the stiffness of the joint or muscle is highly related to the stability of the posture. Several studies have suggested that an increase in joint stiffness due to muscle co-contraction might improve lower limb stability and motion (Gribble & Ostry, 1999; Koshland, Galloway, & Nevoret-Bell, 2000; Lacquaniti & Maioli, 1989; Osu et al., 2002; Thoroughman & Shadmehr, 1999). In addition, other stiffness studies have also been reported that the stiffness of the calf muscles has highly influenced on the stability of dynamic movements (Nashner, 1976; Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998; Winter, Patla, Rietdyk, & Ishac, 2001). Thus, in the current study, the core exercise effect may affect the stiffness of joints (especially hip joints) related to trunk muscle, mullus muscle, and gluteus maximus, leading to the reduction of total variability of individual segment CMs.

According to Haiil et al. (1999), excessive variability could reflect injuries or disease and altering motor control patterns. In Hsu et al. (2007) study, movement variability reflects flexible control of exercise performance. In order to adapt to the pattern of movement, the elderly may need to have appropriate amount of movement variability (Harbourne & Stergiou, 2009). In the consistent with findings in the previous studies, our findings in the current study suggested that the effect of core strength training improves balance ability in the elderly by minimizing total variability of individual segment CMs. In conclusion, the core exercise training effect may contribute to the stiffness of the muscle and joint of the elderly, leading to the reduction of the movement variability at an optimal level to maintain the posture.

The limitation of this study is that the analysis of the UCM of the WCM analysis in each segment CMs has not been analyzed as a relational relationship. These restrictions are thought to have to be done in future research.

CONCLUSION

The present study investigated the effect of 8-week core strength training on the WCM control ability for the elderly. The WCM control ability after external perturbation stimuli was examined using UCM analysis. The results of this study showed that the 8 weeks training through the core training equipment for the elderly showed a significant decrease in the task-irrelevant and task-relevant variability. This result indicates that the core strength training affects the trunk stiffness control strategy to maintain balance in the standing position by minimizing total variability of individual segment CMs.

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