

Title	Effects of balance training on muscle coactivation during postural control in older adults: a randomized controlled trial.
Author(s)	Nagai, Koutatsu; Yamada, Minoru; Tanaka, Buichi; Uemura, Kazuki; Mori, Shuhei; Aoyama, Tomoki; Ichihashi, Noriaki; Tsuboyama, Tadao
Citation	The journals of gerontology. Series A, Biological sciences and medical sciences (2012), 67(8): 882-889
Issue Date	2012-03-01
URL	<a href="http://hdl.handle.net/2433/172454">http://hdl.handle.net/2433/172454</a>
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Type	Journal Article
Textversion	author

1 **Title:** Effects of balance training on muscle coactivation during postural control in older  
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3 **Authors:** Koutatsu Nagai, PT, MS<sup>1</sup>, Minoru Yamada, PT, PhD<sup>1</sup>, Buichi, Tanaka, PT,  
4 MS<sup>2</sup>, Kazuki Uemura, PT<sup>1</sup>, MS, Suhei, Mori, PT, Tomoki Aoyama, MD, PhD<sup>1</sup>, Noriaki  
5 Ichihashi, PT, PhD<sup>1</sup>, Tadao Tsuboyama, MD, PhD<sup>1</sup>

6 **Affiliations:** <sup>1</sup>Department of Physical Therapy, Human Health Sciences, Graduate  
7 School of Medicine, Kyoto University, Japan

8 <sup>2</sup> Tenri Yorozu Hospital, Japan

9 **Corresponding author:** Koutatsu Nagai, PT, MS

10 **Address:** <sup>1</sup>Kyoto University, 53, Kawahara-cho, Shogoin, Sakyo-ku, Kyoto, 606-8507,  
11 Japan

12 E-mail: [k.nagai@ky2.ecs.kyoto-u.ac.jp](mailto:k.nagai@ky2.ecs.kyoto-u.ac.jp)

13 Tel: +81-75-751-3935 Fax: +81-75-751-3948

14 **Running head:** EFFECTS OF BALANCE TRAINING ON MUSCLE  
15 COACTIVATION DURING POSTURAL CONTROL

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1 **Abstract**

2 **Background.** Recently, several studies have reported age-associated increases in  
3 muscle coactivation during postural control. A rigid posture induced by strong muscle  
4 coactivation reduces the degree of freedom to be organized by the postural control  
5 system. The purpose of this study was to clarify the effect of balance training on muscle  
6 coactivation during postural control in older adults.

7 **Methods.** Forty-eight subjects were randomized into an intervention (mean age: 81.0  
8  $\pm$  6.9 years) and a control group (mean age: 81.6  $\pm$  6.4 years). The control group did  
9 not receive any intervention. Postural control ability (postural sway during quiet  
10 standing, functional reach, and functional stability boundary) was assessed before and  
11 after the intervention. A co-contraction index (CI) was measured during the postural  
12 control tasks to assess muscle coactivation.

13 **Results.** CI values in the intervention group significantly decreased following the  
14 intervention phase for functional reach ( $p < 0.0125$ ). CI values had a tendency to  
15 decrease during functional stability boundary for forward and quiet standing tasks.  
16 Functional improvements were observed in some of the tasks after the intervention, *i.e.*  
17 functional reach, functional stability boundary for forward, one leg stance and timed up  
18 and go ( $p < 0.05$ ).

1 **Conclusions.** Our study raised the possibility that balance training for older adults was  
2 associated with decreases in muscle coactivation during postural control. Postural  
3 control exercise could potentially lead older adults to develop more efficient postural  
4 control strategies without increasing muscle coactivation. Further research is needed to  
5 clarify in greater detail the effects of changes in muscle coactivation.

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1 Both static and dynamic postural controls are fundamental components of human  
2 activity. Aging has been associated with deterioration in postural control manifesting  
3 itself by an increase in postural sway (1-2) and a decrease in the voluntary movement  
4 capacity of the body's center of gravity (3-4). Deterioration in these functions leads to a  
5 higher risk of falling, which in turn may increase the number of people with high levels  
6 of disability (4-5).

7 Recently, several studies have reported age-associated increases in muscle coactivation  
8 during dynamic movements (*i.e.* walking and stair climbing) (6-7) and postural control  
9 (8-9), although evidence on whether coactivation is elevated during maximal effort  
10 contraction is inconclusive(10). Increased muscle coactivation in older adults is most  
11 commonly described as a compensatory mechanism to increase joint stiffness which  
12 thereby enhances stability (6-9, 11).

13 However, some researchers have pointed out negative effects of coactivation on  
14 postural control and movement, observing that excessive muscular coactivation  
15 increases postural rigidity (12-13). A rigid posture induced by strong muscle  
16 coactivation reduces the degrees of freedom to be organized by the postural control  
17 system (14) and may actually compromise the execution of voluntary or compensatory  
18 responses (12, 15).

1 In an effort to prevent deterioration in postural control ability, patients undergo balance  
2 training in clinical settings. Multiple studies have reported on the effect of balance  
3 training on postural control ability. A systematic review of these studies has documented  
4 improvements in the ability to stand on one leg and to reach forward without losing  
5 balance in postural control tasks (16).

6 However, the effect of balance training on muscle coactivation during postural control  
7 in older adults remains unclear. Investigation of muscle coactivation changes after  
8 balance training thus could be an important step towards clarifying the mechanisms by  
9 which balance training might improve postural control. In addition, this information  
10 could serve as a useful reference for optimizing rehabilitation strategies in older people.

11 The purpose of this study was to clarify the effect of balance training on muscle  
12 coactivation during postural control in older adults. In our previous cross-sectional study,  
13 muscle coactivation was negatively correlated with postural control ability in older  
14 adults(9). This result raises the possibility that the improvement in postural control after  
15 balance training correlates with decreased muscle coactivation.

16 We hypothesized that muscle coactivation during postural control in older adults  
17 would decrease after balance training.

18

1   **METHODS**

2   **Participants**

3   Resident subjects were recruited using advertising literature from three nursing homes.

4   The inclusion criteria were set as follows: aged 65 or older, dwelling in a nursing home,

5   able to walk independently (or with a cane), willing to participate in group exercise

6   classes, and with minimal, if any, auditory or visual impairment. Oral and written

7   explanations of the study were offered to the participants. Subjects were excluded if

8   they had acute neurological impairment (stroke, Parkinson's disease, paresis of the

9   lower limbs), severe cardiovascular disease, severe cognitive impairment (Rapid

10   Dementia Screening Test score of four points or less (17)), persistent joint pain, or

11   severe musculoskeletal impairment (inability to participate in the training regimen). Any

12   subjects who were willing to participate and met the entry criteria were accepted into

13   the study. Written informed consent was obtained from each participant in the trial in

14   accordance with the Declaration of Human Rights, Helsinki, 1975. This research was

15   approved by the Ethical Review Board of Kyoto University Graduate School of

16   Medicine, Kyoto, Japan.

17

18   **Study design and randomization**

1 Randomization *via* computer-generated random numbers was performed in blocks of  
2 four subjects stratified according to 10 m walking time. The 48 subjects were randomly  
3 assigned to the intervention group (n = 24) or the control group (n = 24). The subject  
4 assignments were not blinded to the research staff members who performed  
5 measurements during the postural control tasks.

6

## 7 **Sample size**

8 Our pilot study investigated the immediate effect of repetitive balance training on  
9 muscle coactivation during wobble board standing in young adults and demonstrated  
10 that muscle coactivation during standing on the wobble board decreased 12%  
11 (co-contraction index), which is accompanied by significant improvement in balance  
12 ability (18). The longer intervention period would provoke greater reduction of muscle  
13 coactivation in older adults. Therefore, we aimed to detect a 15% (co-contraction index)  
14 reduction in muscle coactivation in the intervention group compared with the control  
15 group. Furthermore, based on the data from our pilot study, we estimated the SD  
16 (standard deviation) of this degree of change in coactivation to be 14% (co-contraction  
17 index)(18). Based on these assumptions, a total sample size of 34 participants would be  
18 required with alpha set at 0.05, beta at 0.2, and a given power of 0.8. We increased the



1 sample size to a minimum of 44 to account for an anticipated dropout rate of 20%.

2

### 3 **Intervention**

4 Subjects assigned to the intervention group received 40 minutes of group balance  
5 training sessions twice a week for eight weeks focused on improving postural control  
6 ability. There were three subgroups in the intervention group. Each subgroup consisted  
7 of 4 - 10 people. Exercise classes, which were supervised by a physical therapist,  
8 consisted of 10 minutes of warm up and stretching exercises followed by 30 minutes of  
9 balance training. Subjects with a risk of falling during the exercise session were  
10 permitted to hold the back of a chair to ensure their postural stability. The level of  
11 exercise difficulty was adjusted according to the ability of each subject by altering reach  
12 distance or base of support. Subjects who held a chair during exercise were  
13 instructed to decrease the assistive level when they were able to acquire  
14 postural ability without losing balance during the tasks.

15 The control group did not receive any intervention but were simply instructed to  
16 spend their time as usual during the intervention phase. In order to avoid contamination  
17 during the exercise period, the training location was set at a place where the subjects in  
18 the control group were not usually visiting when the training session was under way.

1 Subjects assigned to the control group were offered the same exercise program after the  
2 conclusion of the study period.

3

#### 4 **Warm up and stretching**

5 Before training, subjects participated in warm up and stretching exercises consisting  
6 of finger joint movement, bending fingers backward, shoulder rotation, waist rotation,  
7 upward stretching, lateral bending of the trunk, forward bending, and lower leg  
8 stretching. Lower leg stretching was targeted on the hamstrings (bending trunk forward  
9 with extended knee) and gluteus maximus (hip flexion using arms) in a sitting position.

10

#### 11 **Balance training**

12 Balance training consisted of standing on one leg, tandem standing, shifting weight  
13 laterally from one foot to another (19), anterior-posterior or lateral weight shifting, and  
14 reaching forward and laterally (20). Subjects were instructed to maintain their position  
15 for five or more seconds during each task and performed three sets of these exercises  
16 during each training session. The training sessions also included stepping forward and  
17 sideways in which the instructor called out each stepping direction. Subjects were  
18 provided a wall or chair for safe support as needed.

1

## 2 **Testing procedures and protocol**

3 The postural control tasks selected for testing consisted of postural sway during quiet  
4 standing, functional reach (4, 21), and functional stability boundary (forward and  
5 backward) (3) because similar movements are performed frequently during activities of  
6 daily living.

7

## 8 **Postural sway**

9 Postural sway during quiet standing was measured by a force plate (Kistler 9286  
10 force platform, Kistler Instruments Inc, Amherst, NY). Signals were sampled at 20 Hz  
11 and processed by a low-pass filter (6 Hz cut off frequency). The participants stood on  
12 the force plate with their feet together and then were asked to gaze at a mark at eye  
13 level while maintaining a stationary posture as symmetrically as possible. Quiet  
14 standing balance was registered for a period of 10 seconds, from which the root mean  
15 square (RMS) area was calculated. Electromyography (EMG) activity was also  
16 recorded for the first three seconds of quiet standing. The intraclass correlation  
17 coefficient ( $ICC_{S1.1}$ ) for the RMS area was 0.72 in this study, which indicates  
18 ‘substantial’ reliability (22).

1

## 2 **Functional reach**

3 Functional reach was defined as the difference between arm's length and maximal  
4 forward reach (4). The position of the fingertip was determined with the shoulder flexed  
5 at 90° along a wall. Subjects then were instructed to reach as far forward as possible  
6 without moving their feet, thus moving the center of gravity forward over a fixed base,  
7 and to maintain this maximal forward reach position for three seconds for EMG  
8 measurements.

9

## 10 **Functional stability boundary**

11 Functional stability boundary tasks were performed on the force plate (3). Standing  
12 with their heels on a line 10 cm anterior to the posterior edge of the plate, subjects  
13 were instructed to stand still for five seconds and then to shift their body weight first  
14 toward their toes and then towards their heels over the largest possible amplitude while  
15 maintaining full contact between their feet and the plate (avoiding toes off or heels off).  
16 For each direction (forward and backward), the subject maintained their posture for  
17 three seconds for EMG measurements, from which the averaged peak center of  
18 pressure (COP) displacement from the initial position was calculated. The COP

1 displacement for each subject was normalized by the length of that subject's foot.

2

### 3 **Additional physical function characteristics**

4 To calculate the 10 m walking time, which we utilized as the stratification variable,  
5 we had subjects perform walking trials at their preferred speed over a 12 m walkway,  
6 during which we measured the walking time for the middle 10 m(23). The timed up and  
7 go test (TUG)(24) and the timed one-leg standing test for the dominant leg with eyes  
8 open were performed without EMG monitoring. The maximum duration of the one-leg  
9 standing test was set at 30 seconds.

10

### 11 **EMG recording**

12 Electromyography (EMG) data were collected with the Telemetry 2400 (Noraxon USA  
13 Inc, Scottsdale, AZ). The skin of the dominant leg was shaved over the fibula head,  
14 tibialis anterior, and soleus (25) and then washed with alcohol. Bipolar surface  
15 electrodes (Ambu, Blue sensor M, Denmark) with a 2.0 cm inter-electrode distance  
16 were placed on the skin around the probable motor point of the muscles (26). The  
17 ground electrode was affixed to the skin over the fibula head of the dominant leg. The  
18 EMG data were sampled at 1500Hz.

1 EMG activity was recorded from the soleus and tibialis anterior while the subjects  
2 were performing maximal voluntary contractions (MVC)(27). The MVC of the soleus  
3 was obtained during maximal isometric plantar flexion, and maximal tibialis anterior  
4 activation was recorded during maximal isometric dorsiflexion of the ankle at 90°  
5 (anatomically neutral position). Strong verbal encouragement was given during every  
6 contraction to promote maximal effort. The EMG data from the MVCs were used to  
7 normalize the EMG amplitude (%MVC) during the postural tasks. The MVCs were  
8 re-calculated for the post-training measurement.

9

#### 10 **Muscle coactivation analysis**

11 The original raw EMG signal was band-pass filtered at 20-500Hz. We computed the  
12 root mean-square amplitude of the signal using a 50-ms window. The EMG of each  
13 muscle was then expressed as a percentage of the EMG value during the MVC.

14 To evaluate the relative level of co-contraction of the tibialis anterior and soleus  
15 muscles, the co-contraction index (CI) was calculated using the method of Falconer and  
16 Winter (28). Specifically, the following equation was used:

17

$$18 \text{ CI (\%)} = \frac{2I_{ant}}{I_{Total}} \times 100$$

1

2  $I_{ant}$  is the area of the total antagonistic activity, calculated in accord with the  
3 following equation:

4

$$I_{ant} = \int_{t_1}^{t_2} EMG_{TA}(t) dt + \int_{t_2}^{t_3} EMG_{SOL}(t) dt$$

5

6

7 where  $t_1$  to  $t_2$  denotes the period during which the tibialis anterior EMG is less than  
8 the soleus EMG, and  $t_2$  to  $t_3$  denotes the period during which the soleus EMG is less  
9 than the tibialis anterior EMG.

10  $I_{total}$  is the integral of the sum of tibialis anterior and soleus EMG during  
11 performance of the task, calculated in accord with the following equation:

12

$$I_{total} = \int_{t_1}^{t_3} [EMG_{agon} + EMG_{ant}](t) dt$$

13

14

15 The CI calculation was done by a staff member who was blinded to the subject  
16 assignments.

17

18 **Testing reliability**

1 The test-retest interday reliability of EMG measurements related to electrode  
2 positioning was estimated by calculating intraclass correlation coefficients ( $ICC_{1,1}$ ). The  
3  $ICCs_{1,1}$  for the co-contraction index were as follows: 0.68 (95%CI: 0.36 to 0.86) for  
4 quiet standing, 0.75 (95%CI: 0.47 to 0.89) for functional reach, 0.86 (95%CI: 0.66 to  
5 0.94) for functional stability boundary (forward), and 0.91 (95%CI: 0.78 to 0.96) for  
6 functional stability boundary (backward). These ICC values indicated ‘substantial’ to  
7 ‘almost perfect’ reliability for all measurements of CI (22). The  $ICC_{1,1}$  for  
8 co-contraction index without electrode repositioning during quiet standing was 0.93  
9 (95%CI: 0.72 to 0.98), which indicates ‘almost perfect’ reliability(22).

10

## 11 **Statistics**

12 The results were analyzed using an intention to treat analysis. Baseline characteristics  
13 of the intervention and control groups were compared to examine comparability of the  
14 two. The Kolmogorov-Smirnov test was used to test the normality of distributions.  
15 Differences between groups were analyzed using the chi-square test for categorical  
16 variables, Student’s t-test for continuous variables with normal distribution, and the  
17 Mann-Whitney U-test for non-normally distributed variables.

18 The effect of exercise on outcome measurements was analyzed using mixed design 2



1 × 2 (group (intervention and control groups) × time (pretraining, posttraining) analysis  
2 of covariance (ANCOVA). Baseline values were used as covariates in the ANCOVA.  
3 Statistical significances in co-contraction index and muscle activation (%MVC) were  
4 set at 0.0125 (0.05/4) because four tasks measured by electromyography were included  
5 to assess the muscle coactivation. *Post-hoc* Bonferroni tests were used to assess which  
6 group or time periods showed significant differences. Statistical significance in post-hoc  
7 Bonferroni tests was also set at 0.0125 (0.05/4).  $P < 0.05$  was considered statistically  
8 significant in ANCOVA for physical functions. Data were entered and analyzed using  
9 SPSS (Windows version 12.0, SPSS, Inc., Chicago, IL). For all outcome measures,  
10 missing data values were imputed using mean values for each corresponding group.

11

## 12 **RESULTS**

13

### 14 **Study population**

15 Our initial pool of study subjects comprised 108 residents from three nursing homes,  
16 out of whom 51 refused to participate in the study and 9 did not meet the inclusion  
17 criteria. The remaining 48 individuals (mean age  $83.0 \pm 6.8$  years) agreed to participate  
18 in the study and provided written consent. Of the 48 subjects who enrolled in the study,

1 40 (83%) completed the 8-week intervention phase and post-intervention assessment:  
2 20 in the intervention group (83%) and 20 in the control group (83%). The other 8  
3 subjects dropped out because of hospitalization due to chronic illness (2 subjects) or  
4 absence on the day of the assessment for personal reasons (6 subjects). After the  
5 imputation of missing data, we performed an intention to treat analysis on the 48  
6 subjects.

7

#### 8 **Adherence to the study protocol**

9 During the 8-week intervention phase, 16 exercise sessions were scheduled and all  
10 took place. Excluding the four who dropped out, the intervention group subjects  
11 attended an average of 14 sessions and had an overall attendance rate of 82% over the  
12 eight weeks. No health problems, including cardiovascular or musculoskeletal  
13 complications, occurred during training sessions or testing.

14

#### 15 **Baseline characteristics**

16 Table 1 summarizes baseline data for the 48 subjects who completed the study. No  
17 significant differences between the intervention and control groups were observed in  
18 any of the characteristics examined, including age, height and weight.

1 <Insertion position of Table 1>

2

3 **Effects of intervention on muscle coactivation and muscle activity**

4 After the 8-week intervention phase, CI values in the intervention group showed a  
5 significant decrease compared with pre-intervention values for functional reach (pre:  
6  $33.8 \pm 21.4\%$ , post:  $24.1 \pm 15.9\%$ , group  $\times$  time interaction:  $F_{1,46} = 10.311$ ,  $p = 0.002$ ,  
7  $\eta^2 = 0.186$ ). Although there was a significant group by time interaction in CI during  
8 functional stability boundary (forward) (pre:  $41.3 \pm 25.7\%$ , post:  $33.2 \pm 20.4\%$ , group  $\times$   
9 time interaction:  $F_{1,46} = 7.226$ ,  $p = 0.010$ ,  $\eta^2 = 0.138$ ), no significant decrease was  
10 found in CI during this task by post hoc test ( $p \geq 0.0125$ ) (Figure 1).

11 CI did not significantly change in standing (pre:  $51.3 \pm 24.4\%$ , post:  $40.1 \pm 19.9\%$ ,  
12 interaction:  $F_{1,46} = 4.975$ ,  $p = 0.031$ ,  $\eta^2 = 0.100$ ) or functional stability boundary  
13 (backward) in the intervention group (pre:  $60.8 \pm 19.7\%$ , post:  $60.9 \pm 14.1\%$ ,  
14 interaction:  $F_{1,46} = 0.099$ ,  $p = 0.754$ ,  $\eta^2 = 0.002$ ).

15

16 <Insertion position of Figure 1>

17

18 Significant group-by-time interactions in tibialis anterior activity were observed during

1 functional stability boundary (backward), but not during functional reach ( $p = 0.055$ )  
2 (Table 2). Although there was no significance across the board, tibialis anterior activity  
3 remained constant or decreased, and soleus activity increased during the tasks such as  
4 standing, functional reach and functional stability boundary for forward in the  
5 intervention group (Table 2). Tibialis anterior activity increased during functional  
6 stability boundary (backward) in the intervention group ( $p < 0.0125$ ).

7

8 **<Insertion position of Table 2>**

9

#### 10 **Effects of intervention on physical function**

11 Functional reach, functional stability boundary (forward and backward), timed up and  
12 go and one leg stance significantly improved after the eight-week intervention (group  $\times$   
13 time interaction:  $p < 0.05$ , Table 3). No significant improvements in other postural  
14 control abilities or physical functions were observed.

15 **<Insertion position of Table 3>**

16

#### 17 **DISCUSSION**

18 Our study results provided evidence partially supportive of our hypothesis that muscle

1 coactivation during postural control would decrease after balance training. Specifically,  
2 we found that balance training decreased muscle coactivation in dynamic postural  
3 control tasks (*i.e.* functional reach and functional stability boundary for forward),  
4 although no significance was seen in functional stability boundary for forward in post  
5 hoc test. These findings suggest that exercise may be able to modify redundant muscle  
6 coactivation during dynamic postural control in older adults.

7 Previous studies have reported that older adults showed greater muscle coactivation  
8 during postural control in static or dynamic conditions compared with young adults (9,  
9 25, 29). A previous study of ours showed that muscle coactivation was significantly  
10 higher in older adults with low postural control ability than in older adults with high  
11 postural control ability(9). All of these studies described coactivation with resultant  
12 ankle joint stiffness as a compensatory strategy to maintain postural stability. The result  
13 of our current study suggests that trained subjects could maintain dynamic postural  
14 stability without the stiffening of their ankle joint associated with higher muscle  
15 coactivation.

16 Functional reach, functional stability boundary (forward), timed up and go and one leg  
17 stance time significantly improved in the intervention group. The improvements we  
18 observed in functional reach and functional stability boundary were associated with

1 decreased muscle coactivation after the intervention. Our previous, cross-sectional study  
2 showed that balance ability is negatively related to muscle coactivation during postural  
3 control in older adults(9). The result of the present study suggested that changes in  
4 muscular coactivation are related with changes in postural control ability. However, the  
5 postural sway area and CI during standing did not improve in the intervention group.  
6 The lack of the effect on postural sway might be attributable to training frequency and  
7 duration. The training program in this study was 40-minute balance sessions conducted  
8 twice a week for eight weeks. A previous study proposed an effective balance training  
9 program conducted three times per week for one hour for 3 months(16). Longer  
10 programs may produce greater effects on physical function and muscle coactivation. If  
11 postural control ability in functional stability boundary for backward had improved in  
12 present study, coactivation during this task might also have changed after training.

13 Our study found that tibialis anterior activity during postural sway, functional reach  
14 and functional stability boundary for forward had a tendency to remain constant or  
15 decrease modestly in the intervention group. On the other hand, soleus activity was  
16 subject to increase especially in the intervention group. Functional reach and functional  
17 stability boundary (forward) involve a forward movement of the center of pressure,  
18 which requires increased plantar flexor torque at the ankle joint to control posture, while

1 the tibialis anterior plays a role of antagonist. The results of the study suggest that the  
2 balance training led to an increase in agonist (soleus) activity and a decrease or  
3 maintenance in antagonist (tibialis anterior) activity. Carolan and Cafarelli have  
4 measured muscle activation in the biceps femoris during knee extension and found that  
5 as knee extensor strength increased, biceps femoris activity also increased (30). This  
6 finding indicates that greater effort to recruit agonist induces increased muscle  
7 coactivation in the antagonist. In the present study, after balance training, subjects could  
8 recruit the agonist (soleus) without enhancement of the antagonist (tibialis anterior).  
9 This decrease or conservation in the antagonist activity, in turn, could help optimize the  
10 work of the agonist (soleus) during postural control. Postural control exercise therefore  
11 could potentially lead older adults to more efficient postural control strategies without  
12 increasing muscle coactivation.

13 Not much has been done to define the contribution of muscle coactivation during  
14 physical activity or in falls in older adults, although the change of muscle coactivation  
15 strategy has been reported during postural control or joint movements (6, 8, 31-32). The  
16 present study showed decreased muscle coactivation during postural control after  
17 training. However, it remains unclear from our study how neural adaptation (i.e.  
18 decrease of muscle coactivation) contributes to fall avoidance or changes with increased

1 physical activity. Further studies should investigate the effect of decreased muscle  
2 coactivation after training on functional outcomes other than balance ability.

3 This study has several limitations. First, our study examined only the ankle joint and  
4 thus provides no information on postural strategies for the knee or hip joint. Second, our  
5 data did not measure changes in kinematics, which therefore did not enable us to  
6 evaluate any possible relationship between muscle coactivation and kinematics during  
7 postural tasks in older adults. It is a matter of further study to clarify the effect of  
8 kinematic change on muscle coactivation with information from multiple joints. Third,  
9 the information on subject assignment was not blinded to the research staff members  
10 during the postural control tasks. Possible bias cannot be ruled out in this study design.

11 However, the effect of bias on coactivation, which is the main outcome in this study, is  
12 not considered significant because it would be difficult for the research staff members to  
13 manipulate the coactivation intentionally. Also, the CI calculation process was done in a  
14 blinded way. Finally, the ICC for postural control ability (sway area) during quiet  
15 standing was not very high (0.72) because of the short measurement time (10 seconds).

16 This might have had an effect on the results of the postural sway area. However, ICC for  
17 co-contraction index without electrode repositioning during quiet standing was very  
18 high (0.93). We conclude that the results for muscle coactivation were not influenced



1 very much by the measurement time in quiet standing.

2

### 3 **CONCLUSIONS**

4 Our study found that coactivation during postural control decreases after balance  
5 training in older adults, which can be associated with improvement of postural control  
6 ability. Postural control exercise could potentially lead older adults to develop more  
7 efficient postural control strategies without increasing muscle coactivation. Further  
8 research is needed to clarify the contribution decreased muscle coactivation makes to  
9 balance ability and to other functional outcomes such as fall prevention or increased  
10 physical activity.

11

### 12 **ACKNOWLEDGMENTS**

13 This project was supported by Japan Health Foundation for the prevention of chronic  
14 diseases and the improvement of QOL of patients.

15

### 16 **CORRESPONDANCE**

17 Address correspondence to Koutatsu Nagai, PT, MS, Kyoto University, 53,  
18 Kawahara-cho, Shogoin, Sakyo-ku, Kyoto, 606-8507, Japan. E-mail:

1 k.nagai@ky2.ecs.kyoto-u.ac.jp

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### 13 **Figure captions**

14

#### 15 **Figure 1**

16 Pre- and post-training comparisons of coactivation during postural control tasks.

17 Significance was tested using mixed design ANCOVA and *post-hoc* Bonferroni tests.

18 The black lines indicate the intervention group, and the gray lines indicate the control  
19 group.

20 Interaction by ANCOVA, †:  $p < 0.0125$

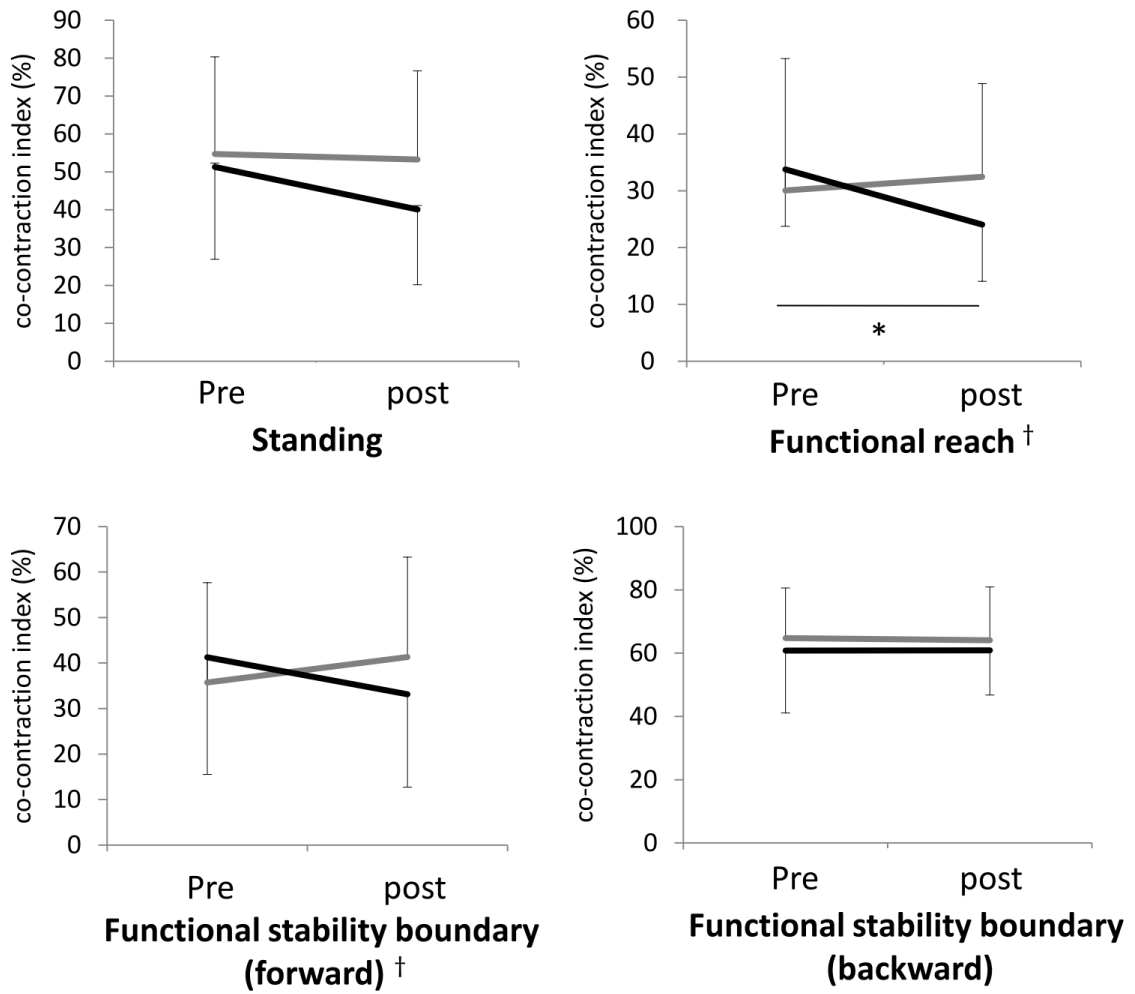
21 Post-hoc test, \*:  $p < 0.0125$

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1 **Figure 1**



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**Table 1. Baseline characteristics (mean  $\pm$  standard deviation) of subjects**

	Intervention group (n = 24)	Control group (n = 24)	p value
Age, y	81.0 $\pm$ 6.9	81.6 $\pm$ 6.4	0.762
Body weight, kg	51.3 $\pm$ 8.4	52.4 $\pm$ 7.6	0.680
Height, cm	150.7 $\pm$ 6.8	153.1 $\pm$ 6.5	0.247
Female, %	83.0	92.0	0.620
Medication, n (%)	20 (83)	20 (83)	1.000
Number of comorbidities, n (%)			0.604
$\leq 3$	20 (83)	18 (75)	
4 - 6	4 (17)	5 (21)	
$\geq 7$	0 (0)	1 (4)	
Falls in the last year, n (%)	4 (17)	6 (25)	0.613
Postural sway area, cm <sup>2</sup>	1.7 $\pm$ 0.9	1.8 $\pm$ 1.0	0.684
Functional reach, cm	21.3 $\pm$ 4.6	19.8 $\pm$ 6.3	0.365
Functional stability boundary for forward, %	19.5 $\pm$ 6.8	18.8 $\pm$ 7.1	0.877
Functional stability boundary for backward, %	13.1 $\pm$ 5.4	11.7 $\pm$ 5.8	0.161
10m walking time, s	11.3 $\pm$ 2.5	11.5 $\pm$ 2.9	0.843
TUG, s	8.3 $\pm$ 2.2	9.2 $\pm$ 2.2	0.150
One leg stance, s	14.4 $\pm$ 11.5	10.1 $\pm$ 9.9	0.168

1 Significance was tested using the  $\chi^2$ -test for categorical variables, Student's t-test for  
2 continuous variables, and the Mann-Whitney U-test for non-normally distributed  
3 variables. \*:  $p < 0.05$ .

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**Table 2. Mean normalized electromyographic activity (%MVC: mean  $\pm$  standard deviation) during tasks**

Tasks	Muscle		Pre (n = 24)	Post (n = 24)	Group $\times$ Time F-value	Effect size $\eta^2$
Standing	TA	Intervention group	12.4 $\pm$ 10.5	9.8 $\pm$ 8.7	1.806	0.039
		Control group	12.6 $\pm$ 11.3	12.3 $\pm$ 11.0		
	SOL	Intervention group	21.5 $\pm$ 9.2	24.9 $\pm$ 9.9	0.368	
		Control group	19.3 $\pm$ 15.3	21.9 $\pm$ 13.7		
Functional reach	TA	Intervention group	12.3 $\pm$ 14.6	11.7 $\pm$ 14.2	3.938	0.080
		Control group	8.2 $\pm$ 8.6	11.0 $\pm$ 8.7		
	SOL	Intervention group	46.3 $\pm$ 16.5	58.8 $\pm$ 17.6	1.982	
		Control group	42.3 $\pm$ 19.6	50.2 $\pm$ 19.3		
Functional stability boundary for forward, %	TA	Intervention group	16.0 $\pm$ 15.0	16.4 $\pm$ 14.5	0.513	0.011
		Control group	13.2 $\pm$ 12.0	17.3 $\pm$ 12.1		
	SOL	Intervention group	48.6 $\pm$ 19.2	61.1 $\pm$ 13.2	2.706	
		Control group	45.3 $\pm$ 19.0	52.9 $\pm$ 19.7		
Functional stability boundary for backward, %	TA	Intervention group	35.6 $\pm$ 18.0	64.7 $\pm$ 16.6	21.223*	0.320
		Control group	39.3 $\pm$ 16.9	46.1 $\pm$ 17.1		
	SOL	Intervention group	22.3 $\pm$ 11.2	30.6 $\pm$ 12.6	1.072	
		Control group	23.0 $\pm$ 12.6	27.6 $\pm$ 14.1		

Significance was tested using mixed design ANCOVA. \*:  $p < 0.0125$

F value; F value is a test statistic to decide whether the sample means are within sampling variability of each other. The null hypothesis is rejected when the F value is large.

$\eta^2$  ; Effect size ( $\eta^2$ ) is a measure of the strength of the relationship between two variables.

**Table 3. Pre- and post-training comparison of postural control abilities and physical function.**

		Pre-intervention (n = 24)	Post-intervention (n = 24)	Group × Time F value	Effect size $\eta^2$
Postural sway area, cm <sup>2</sup>	Intervention group	1.7 ± 0.9	1.3 ± 1.0	0.001	<0.001
	Control group	1.8 ± 1.0	1.43 ± 0.87		
Functional reach, cm	Intervention group	21.3 ± 4.6	25.2 ± 4.0	19.808*	0.306
	Control group	19.8 ± 6.3	19.6 ± 6.0		
Functional stability boundary for forward, %	Intervention group	19.5 ± 6.8	25.2 ± 6.8	28.777*	0.390
	Control group	18.8 ± 7.1	17.9 ± 7.4		
Functional stability boundary for backward, %	Intervention group	12.7 ± 5.2	15.7 ± 6.2	3.886	0.079
	Control group	11.7 ± 5.8	12.3 ± 4.6		
10m walking time, s	Intervention group	11.3 ± 2.5	10.5 ± 2.1	3.926	0.080
	Control group	11.5 ± 2.9	11.7 ± 3.4		
One leg stance, s	Intervention group	14.4 ± 11.5	16.1 ± 10.0	9.737*	0.178
	Control group	10.1 ± 9.9	8.3 ± 6.8		
TUG, s	Intervention group	8.3 ± 2.2	7.5 ± 1.7	7.420*	0.142
	Control group	9.2 ± 2.2	9.2 ± 2.3		

Significance was tested using mixed design ANCOVA. \*:  $p < 0.05$

F value; F value is a test statistic to decide whether the sample means are within sampling variability of each other. The null hypothesis is rejected when the F value is large.

$\eta^2$ ; Effect size ( $\eta^2$ ) is a measure of the strength of the relationship between two variables.