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Muscle co-contraction of ankle joint in young adults in functional reach test at different distances

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Purpose: It has been reported that young people may be able to modulate simultaneous contraction depending on the task. The functional reach test (FRT) is widely used as a method to assess dynamic balance. Although there are several reports on the center of pressure (COP), there are few reports on muscle activity and no studies focus on muscle co-contraction during FRT at different distances. We aimed to clarify how the differences in reach distance affect the activity of the lower limb muscles by measuring COP and muscle activity during FRT at different distances. *Methods*: Eighteen healthy young adults performed FRT at different distances (maximum, 75%, and 50%) and measured COP and muscle activity of tibialis anterior (TA) and soleus (SOL). Postural control variables were calculated from the COP, and mean muscle activity and muscle co-contraction index (CI) were calculated from muscle activity. Each variable was compared between the reach distance conditions and the correlation between the variable was examined. *Results*: Most COP variables were significantly higher as the reach distance increased. A significant increase in muscle activity and CI was similarly observed with increasing distance. There was no consistent correlation between COP variables and CI, but there was a positive correlation between TA muscle activity and CI. *Conclusions*: The results of the present study showed that the young people used task-specific strategies by modulating lower limb muscle contraction and varying the degree of simultaneous muscle contraction during reaching movements at different distances.

Key words: *functional reach test, muscle co-contraction, center of pressure, postural sway*

1. Introduction

Muscle co-contraction is a simultaneous contraction of agonist and antagonist muscles around a joint. Previous studies reported increased muscle co-contraction of the ankle joint in elderly people during a postural control task [13], [14], [20], and increased muscle co-contraction of the knee joint in patients with knee osteoarthritis [1]. In the dynamic postural control task, Nagai et al. [20] showed a negative correlation between the amount of muscle co-contraction between tibialis anterior (TA) and soleus (SOL) and distance of the functional reach test (FRT), suggesting that muscle co-contraction became stronger in older adults who could not sufficiently move their center of pressure (COP) within their base of support.

On the other hand, young people may have a different strategy about muscle co-contraction. Hortobágyi et al. [12] showed that as gait velocity increased muscle co-contraction between TA and SOL consistently increased in young but remained unmodulated in old adults. Additionally, we found that the muscle co-contraction (TA-SOL) increased as the speed of movement increased during a postural control task and decreased as the stability increased due to upper limb support during a single-leg standing in young subjects [13], [14]. These studies suggested a possibility that young adults could modulate their muscle co-contraction according to the situation.

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Gebel et al. [7] found that the balance task difficulty modulated with a base of support could affect COP and muscle activation during postural control tasks in healthy adolescents. They also showed that postural sway and muscle co-contraction between TA and medial gastrocnemius (MG) increased as the balance task difficulty increased by using a multi-directional balance board. Whether the SOL and MG have the same attachment to the calcaneus, their pattern of activity during standing balance was different [3], [9], [10]. The SOL is almost continuously active in standing balance, but the MG is more intermittently active in standing balance [10]. Therefore, it is important to examine the relationship between the SOL muscle, which acts as the main movement muscle in antigravity posture, and the TA, which is the antagonist muscle.

The FRT devised by Duncan et al. [4] measures the maximal distance an individual is capable of reaching forward without taking a step or losing balance. The FRT was considered to be able to evaluate dynamic balance and for subjects across all ages and a high positive correlation was found between the excursion of the center of pressure and reach distance during FRT [4], [5], [15]. Regarding muscle activity during FRT, Jonsson et al. [15] showed TA was identified as the first muscle to contract. On the other hand, Maranesi et al. [17] reported TA EMG varied by kinematics strategies among elderly subjects. Also, Tyler et al. [26] reported that the timing of TA firing differed for different reaching tasks at different distances. These studies suggested the importance of TA activity in forward-reaching tasks like FRT and TA activity might be able to vary with reach distance. However, there was no study focusing on muscle co-contraction during FRT with different reach distances.

The purpose of this study was to evaluate postural sway, TA and SOL muscle activity, and muscle co-contraction between TA and SOL during FRT tasks at different reach distances, and to investigate how the differences in reach distance affect the activity of TA and SOL muscles. We hypothesized that young people could modulate muscle co-contraction between TA and SOL depend on reach distance.

2. Materials and methods

Subjects

Eighteen healthy young adults (12 males and 6 females) [mean ± standard deviation (SD) age: 22.2 ± 1.4 [years]; height: 1.68 ± 0.09 [m]; mass: 61.4 ± 9.6 [kg]; body mass index: 21.7 ± 2.4 [kg/m^2]] without any disease and/or current illness that would affect a task participated in this study. To determine which lower limb to measure, we identified their dominant leg as a leg they used to kick a ball [8].

Subjects provided written informed consent to participate in this study after receiving a detailed explanation regarding the purpose, potential benefits, and risks involved with participation. The experimental procedures of this study were conducted according to the Declaration of Helsinki and approved by the Ethical Committee for Epidemiology of Hiroshima University (E-467).

Task

Subjects performed anterior-reaching tasks like the FRT (Fig. 1) [5]. We made them did the task under the following three conditions: (1) maximum reach distance, MAX; (2) 75% of maximum reach distance, 75%; (3) 50% of maximum reach distance, 50%. First, subjects were asked to stand on two force plates (TF-400-A, Tec Gihan, Kyoto, Japan) in a natural position with their feet separated at acromion interval distance. They were asked to extend their arms horizontally (approximately 90°) and place their fingertips against a bar of a device (CK-101, SAKAI Medical, Tokyo, Japan). Then, subjects slid the bar as far forward as they could without taking a step, losing their standing balance, or raising their heels from the ground in the maximum reach distance condition. In the other two conditions, the participants were instructed to reach the target distance calculated from the reach distance in the maximum reach distance condition. They were asked to keep their posture for 3 s at the goal position in each condition to get the data of postural sway and muscle activity and perform the task three times. The mean value of three trials was used for statistical analysis.

Postural sway measurement

The ground reaction force with two force plates with the Nexus 2 software (Vicon Motion Systems, Oxford, UK) at a sampling frequency of 1,000 [Hz] was measured, and the collected data were then low-pass filtered with a fourth-order Butterworth filter at a cutoff frequency of 20 [Hz] [24]. Then, the coordination of COP was calculated from the ground reaction force at a sampling frequency of 100 [Hz] with Nexus 2 software.

From the coordination of COP during keeping their goal position, the following variables were calculated to evaluate the postural sway during the task:

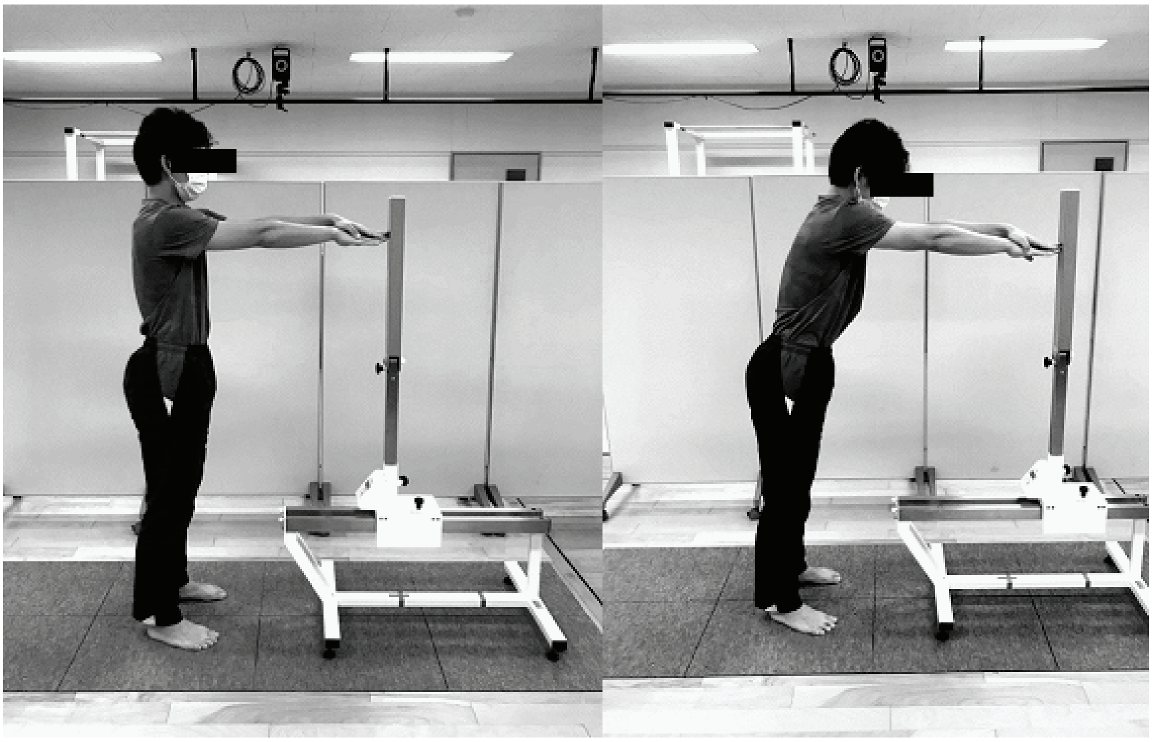

Fig. 1. The functional reach test (FRT) task Subjects were asked to extend their arms horizontally (approximately 90°) and place fingertips against a bar of device (CK-101, SAKAI Medical, Tokyo, Japan). Then, they slid the bar as far forward as they could without taking a step, losing their standing balance or raising their heels from the ground in the maximum reach distance condition

the total excursion of COP (TOTEX), the root-mean-square distance of COP (RDIST), the mean velocity of COP (MVELO), the standard deviation area of COP (AREA-SD) [18], [23].

Muscle activation measurement

EMG data were collected using the Multichannel Amplifier (MEG-6108, Nihon Kohden, Tokyo, Japan) at a sampling frequency of 1,000 [Hz]. As preparing for placing an electrode, we shaved subjects' skin of the fibular head, TA, and SOL and clean with an agent (Skin Pure, Nihon Kohden, Tokyo, Japan). We placed active electrodes (NM-512G, Nihon Kohden, Tokyo, Japan) in line with the muscle fibers [25] (TA: placed at 1/3 on the line between the tip of the fibula and the tip of the medial malleolus, SOL: placed at 2/3 of the line between the medial condyles of the femur to the medial melleous). The ground electrode was affixed to the skin over the fibular head.

Before the experiment, EMG activity from the TA and SOL was recorded while the subjects were performing maximal voluntary contraction (MVC). The MVC of the TA was recorded during maximal isometric dorsiflexion of the ankle at 90° (anatomically neutral position), and the MVC of the SOL was obtained during maximal isometric plantarflexion with standing calf raises (knee flexed). Strong verbal encouragement was given during every contraction to promote the maximal effort.

The original raw EMG signal was band-pass filtered at a range of 20–500 [Hz]. Then, the root-mean-square amplitude of the signal was computed using a 50 [ms] window [19]. EMG of each muscle was then normalized with the EMG value during MVC (%MVC).

We calculated the co-contraction index (CI) between TA and SOL to evaluate the relative level of co-contraction using the method described by Falconer and Winter [6] (Fig. 2). We used the following equation:

$$\mathrm{CI}\,[\%] = \frac{2I_{ant}}{I_{total}} \times 100\,,$$

where I_{ant} is the total antagonistic activity, calculated with the following equation:

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

where t_1 to t_2 denotes the period during which the TA EMG is less than the SOL EMG, t_2 to t_3 denotes the period during which the SOL EMG is less than the TA EMG, and I_{total} is the integral of the sum of the TA and SOL EMGs while subjects performed the task, calculated using the following equation:

$$I_{total} = \int_{t_1}^{t_3} [EMG_{TA} + EMG_{SOL}](t)dt\ .$$

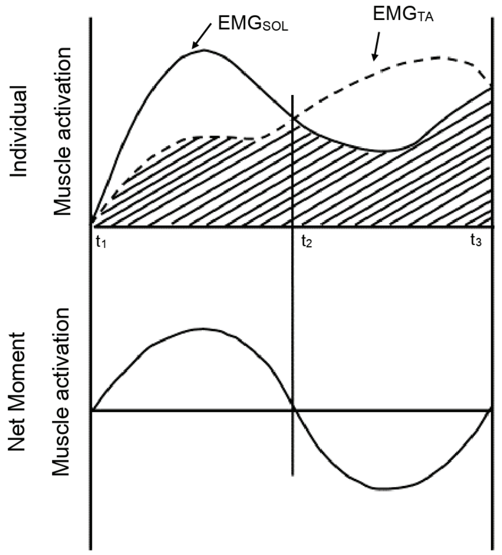

Fig. 2. Method of evaluation of the relative level of co-contraction described by Falconer and Winter [6]

Statistical analysis

SPSS Ver. 22.0 (IBM Japan, Tokyo, Japan) was used for statistical analysis. First, the Shapiro–Wilk test was used to assess normality. Then, if the variables were according to the normal distribution, Student's *t*-test was used. Otherwise, the sequential Bonferroni correction factor was used to adjust the alpha level for multiple comparisons [11]. Also, a correlation analysis for COP variables, muscle activity, and CI was conducted. The significance level for all tests was 5%.

3. Results

After normality testing, reach distance and SOL %MVC was defined as normally disturbed variables and are presented as mean ± standard deviation. The other variables were non-normally disturbed and are presented as medians (and interquartile range). The mean reach distance of FRT in each condition is demonstrated in Table 1. There were significant differences in distance between each condition.

Postural sway

All COP variables were the largest in maximum reach conditions among all conditions (Table 1). Variables other than RDIST were larger in the 75% reach condition than in the 50% reach condition (Table 1).

Muscle activity

The mean muscle activity during the task (TA %MVC, SOL %MVC) became higher as the reach distance increased (Table 1). Moreover, CI became higher as well (Table 1).

Correlation analysis

There was a negative correlation between CI and TOTEX, MVELO in the maximum reach condition, but not in the other two conditions (Table 2). In all conditions, there was a significant positive correlation between TA%MVC and CI (Table 2).

Table 1. Variables among three FRT conditions

	MAX	75%	50%
reach distance [cm]	37.94 ± 5.85 $^{a, b}$	28.47 ± 4.38 ^{c}	19.06 ± 3.00
TOTEX [mm]	82.52 (70.12–103.71) $^{a, b}$	69.69 (62.81–80.00) ^{c}	63.81 (55.68–66.72)
RDIST [mm]	3.93 (3.66) $^{a, b}$	2.94 (2.10–4.24)	2.55 (1.92–3.06)
MVELO [m/s]	27.51 (23.37–34.57) $^{a, b}$	23.23 (20.94–26.67) ^{c}	21.27 (18.56–22.24)
AREA-SD [mm^2]	14.04 (9.53–19.71) $^{a, b}$	8.19 (5.10–16.20) ^{c}	5.67 (3.85–7.71)
TA %MVC [%]	2.75 (1.41–3.78) $^{a, b}$	1.89 (1.11–2.33) ^{c}	1.49 (0.97–1.98)
SOL %MVC [%]	18.41 ± 5.94 $^{a, b}$	16.04 ± 5.57 ^{c}	15.07 ± 5.38
CI [%]	23.06 (17.32–26.97) $^{a, b}$	19.80 (15.34–25.45) ^{c}	18.46 (11.99–23.08)

Value: mean ± standard deviation, Value: median (interquartile range); TOTEX – the total excursion of center of pressure; RDIST – the root-mean-square distance of center of pressure; MVELO – the mean velocity of center of pressure; AREA-SD – standard deviation area of center of pressure; TA – tibialis anterior; SOL – soleus; MVC – maximum voluntary contraction; CI – co-contraction index.

Significant difference between MAX and 75% conditions are indicated by a ($p < 0.05$), significant difference between MAX and 50% conditions are indicated by b ($p < 0.05$), significant difference between 75% and 50% conditions are indicated by *c* ($p < 0.05$).

Table 2. Correlation coefficients between CI and COP variables, muscle activity

	CI [%]		
	MAX	75%	50%
TOTEX [mm]	$r = -0.546$ $p = 0.019$*	$r = -0.290$ $p = 0.243$	$r = -0.174$ $p = 0.489$
MVELO [m/s]	$r = -0.546$ $p = 0.019$*	$r = -0.022$ $p = 0.381$	$r = -0.100$ $p = 0.693$
TA %MVC [%]	$r = 0.789$ $p < 0.01$*	$r = 0.792$ $p < 0.01$*	$r = 0.740$ $p < 0.01$*
SOL %MVC [%]	$r = 0.051$ $p = 0.842$	$r = -0.335$ $p = 0.174$	$r = -0.501$ $p = 0.034$*

Value: mean ± standard deviation, Value: median (interquartile range); TOTEX – the total excursion of center of pressure; MVELO – the mean velocity of center of pressure; TA – tibialis anterior; SOL – soleus; MVC – maximum voluntary contraction; CI – co-contraction index; r = correlation coefficient, * – $p < 0.05$.

4. Discussion

In this study, we investigated postural sway and muscle activity during FRT at different reach distances in young people. The postural sway variables, muscle activity, and CI increased with reach distance. These findings support our hypothesis that young people correspond to changes in the distance by altering their postural adjustment strategy with muscle co-contraction. However, there was no consistent correlation between postural sway variables and CI among three different reach distance conditions. Therefore, the effect of muscle co-contraction on postural sway during the reaching motion remains unclear. On the other hand, there was a strong positive correlation between TA activity and CI, the changes in muscle co-contraction during FRT were shown to be related to the muscle activity of TA.

Since the FRT was known as a test to assess dynamic postural control ability [4], [5], [15], it has been studied in a wide range of subjects from young to old. It was well known that FRT distance was correlated with the amount of COP movement in the anteroposterior and mediolateral direction [5]. Also, previous studies have shown that as the reach distance increases, the amount of COP movement during motion increases [16], [26]. In this study, we calculated the TOTEX from the COP while holding the same posture after reaching the target distance. Although the analysis intervals differed from those in previous studies, we found that the amount of COP movement increased as the reach distance increased in FRT. The variables used in this study evaluated different characteristics of COP movement. TOTEX and MVELO were considered time-domain "distance" measures and evaluated the excursion of COP during tasks [23]. Besides, AREA-SD was considered a "sway" measure and evaluated the magnitude of sway amplitude in COP movement [18]. In this study, we showed that the magnitude of sway in the COP also increased as well as the movement length during keeping reached posture with the reach distance increased.

A few studies have focused on lower limb muscle activity during a postural control task in which the subject voluntarily leans from a standing posture [2], [22], but few studies have examined lower limb muscle activity during FRT. Maranesi et al. [17] measured several muscles during FRT with elderly subjects and showed there were two different TA activation patterns were associated with the two different kinematic strategies. Tyler et al. [26] showed that TA muscle activity occurred earlier with greater distance not to resist a postural perturbation but to launch the body and arm forward in reaching movements at different target distances during reaching movements. These studies suggest that TA muscle activity is important in forward-reaching movements, including FRT. In the present study, TA muscle activity increased with increasing reach distance, demonstrating the importance of TA muscle activity in FRT as in previous studies. On the other hand, SOL activity showed higher values in the maximum reach condition, but there was no significant difference between the 75% and 50% conditions. The SOL is a continuously active muscle in standing balance [10], and we evaluated the steady-state posture during FRT in this study. Therefore, in FRT, the SOL acted as the main operating muscle with eccentric contraction, therefore, it is necessary to focus on the relationship between the two muscles, not only on the individual muscle activity.

We demonstrated the differences in muscle co-contraction between TA and SOL muscles among the three reach distance conditions. In terms of increased muscle activity and joint stability, Nielsen et al. [21] showed that the stiffness of the joint increases when the simultaneous muscle contraction is strong, contributing to the stability of the joint. Our study also showed that muscle co-contraction of TA-SOL increased with increasing reach distance during FRT, and the subjects might have gained stability by increasing the stiffness of the ankle joint. While we found that young people modulated muscle co-contraction (TA-SOL) in response to changes in motion speed during voluntary postural sway (similar to the FRT) in previous study [13], we evaluated dynamic state muscle activation in that study. Besides, Gebel et al. [7] evaluated simultaneous contraction between TA and GM during a standing postural control task with a balance board and showed that the muscle co-contraction increased as the balance task difficulty increased. These studies have not considered whether task difficulty like reach distance during the FRT affected the amount of muscle co-contraction between TA and SOL. In this study, we showed increased muscle co-contraction (TA-SOL) in the steady-state during the long-distance reach task. The results of this study and previous reports indicate that young people may be able to successfully regulate simultaneous ankle contraction and perform the task according to the characteristics of the task.

We found a negative correlation between the CI and TOTEX, MVELO which were considered time domain "distance measure" [23], in FRT under the maximum reach distance condition. Nagai et al. [20] showed that there was a negative correlation between FRT distance and simultaneous ankle contraction in the elderly, but not in the young. Simultaneous contraction of the muscles might increase joint stability, but it might limit foot pressure-centered motion. However, there were no similar correlations under the 75% and 50% conditions, which did not provide a consistent view about the relationship between the muscle co-contraction and COP movements. On the other hand, there was a positive correlation between CI and TA muscle activity in all conditions. It has been reported that the muscle activity of the TA was important in the forward reaching motion, including FRT [17], [26], and it was suggested that the muscle activity of the TA may have been altered to modulate the simultaneous contraction of the muscle.

The present study did not examine differences in the timing of muscle activity or the strategy of FRT and there was no consistent correlation between the results related to postural sway and simultaneous muscle contraction under all conditions. Therefore, it is not possible to determine how the presence or absence of simultaneous muscle contraction affects the postural control strategy during reach tasks and we must investigate the relationship between them in the future study.

5. Conclusions

The results of our study showed that young people increased muscle co-contraction between TA and SOL by modulating TA muscle contraction during reaching movements at different distances. On the other hand, no consistent correlation was found between postural sway and muscle co-contraction. These results clarify that young people could modulate the muscle co-contraction depend on the task difficulty and contribute to the clarification of the relationship between posture.

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