

# Effects of Repetitive Reaching Movements on Performance and Postural Control

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**Abstract.** [Purpose] The purpose of this study was to examine whether muscle activity and joint movement in the lower limbs related to postural control are affected by repetitive reaching movements. [Methods] Fourteen healthy subjects attempted to reach a small target as fast as possible while standing. The target was placed at approximately the maximum reach distance. The reaching movement was repeated 50 times. Positions of each body segment were measured by three-dimensional motion analysis. Surface electromyograms (EMG) of tibialis anterior (TA) and gastrocnemius (GAS) were recorded. Parameters related to reaching performance and postural control were analyzed. [Results] With repetition of reaching movements, movement time and peak reaching velocity related to performance significantly increased. In addition, the onset of the EMG activity of TA appeared earlier, the integrated EMG activity of TA and GAS increased, and the maximum ankle dorsiflexion angle increased significantly. Changes in postural response were correlated with those of reaching performance. Moreover, postural response changed earlier than reaching performance. [Conclusion] Changes in postural control were induced by repeated reaching movements. These results suggest that changes in postural control associated with the central nervous system occur in advance in order to improve reaching performance.

**Key words:** Reaching movement, Performance, Postural control

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## INTRODUCTION

The reaching movement, performed to touch an interesting object, is the most common and important action in daily life. Repetitive reaching practice while sitting or standing leads to improvement in reaching performance, which is defined in terms of accuracy, movement time, and peak velocity<sup>1,2)</sup>. One of the main reasons for the improvement in reaching performance may involve motor learning of the arm movement<sup>3,4)</sup>. In addition, previous studies of the investigation of postural control during the reaching movement suggest that postural muscle activity and joint movement in the lower limb are changed by repetitive practice, and these changes affect improvements in performance.

Effects of different posture on reaching performance and postural control have been reported. During whole body reaching while standing, which requires greater postural stability than while sitting or side-lying, activities of erector spinae and the tibialis anterior increases, and the peak reaching velocity decreases<sup>5,6)</sup>. Thus, the central nervous system (CNS) may adequately influence postural muscle activity under environmental conditions and during tasks.

This suggests that postural stability is closely related to postural muscle activity during reaching and that it affects performance.

Whole body movements are evoked when reaching is directed to a target placed at a distance considerably greater than arm length while standing. Thus, a driving force to initiate forward body movement and braking force to compensate the postural stability are required. These forces are created by postural muscle activity and joint movement in the lower limbs<sup>7-9)</sup>. Anticipatory postural adjustments (APAs) observed in postural muscles prior to the onset of movements affect the performance of fast voluntary movements, including the reaching movement<sup>9-11)</sup>. These facts suggest that it is possible to perform rapid, stable reaching with appropriate postural control delivered by the lower limbs. Moreover, postural responses of the lower limbs rapidly adapt to the motion of the support surface, and postural disturbance decreases when subjects are asked to maintain an upright stance during repeated translation or rotation of the support surface in the anteroposterior direction<sup>12,13)</sup>.

On the basis of previous results, we hypothesized that muscle activity and joint movement in the lower limbs,

which occur in order to control the reaching movement, change during repetitive reaching movements, and this change plays an important role in reaching performance. However, postural adaptation and motor learning by the lower limbs is not well understood. Therefore, we examined whether muscle activities and joint movements of the lower limbs, which are related to postural control, are affected by repetitive whole body reaching while standing. In addition, we examined the relationship between improvements in reaching performance and changes in postural control.

## SUBJECTS AND METHODS

Fourteen healthy subjects (8 males and 6 females; mean age,  $22.7 \pm 2.6$  years; height,  $163.3 \pm 9.6$  cm; weight,  $56.1 \pm 7.2$  kg; foot length,  $24.0 \pm 1.3$  cm) without a history of orthopedic, neurological, or musculoskeletal diseases participated in this study. Prior to participation, all subjects gave their written informed consent according to procedures approved by the ethics committee of Hokkaido University School of Medicine.

The subjects stood barefoot on a force platform (Kistler Type 9286A, Winterthur, Switzerland) with their feet shoulder width apart and their arms hanging naturally on the sides of the body. Feet positions were marked by vinyl tape attached to the force platform surface to enable standardization of the subsequent trial. Subjects were asked to reach to a small target with the right arm as fast as possible after a brief beep sound. The beep signal was provided at a random interval of 2–5 s after subjects had attained an upright posture<sup>14)</sup>. The target (diameter, 2 cm) was positioned at shoulder height to the front and center of the subjects' bodies. The distance to the target was decided as approximately the maximum reach distance of each subject according to the functional reach test described by Duncan et al<sup>15)</sup>. A small force sensor (FlexiForce, Nitta Corporation, Osaka, Japan) was attached to the target, which permitted the measurement of termination time and pushing force of the reaching movement. A failed trial was defined as a trial in which the sensor was pushed with a force greater than 3 N, the subjects were unable to touch the target, or their heel moved more than 2 cm during the reaching movement. Before the experiment, the subjects were told about the conditions of a failed trial and were asked to perform the reaching movement as accurately and fast as possible. The reaching movement was repeated 50 times<sup>16)</sup>. The intertrial interval was adequate to prevent any effects of fatigue<sup>17)</sup>. When subjects failed a trial, they received immediate feedback from experimenters. To ensure that the reaching movement started from the identical standing posture in each trial, the experimenter confirmed that both toes were located on the vinyl tape, and the initial position of the center of pressure (COP) during static standing was located at approximately 45% of foot length from the heel<sup>18)</sup>.

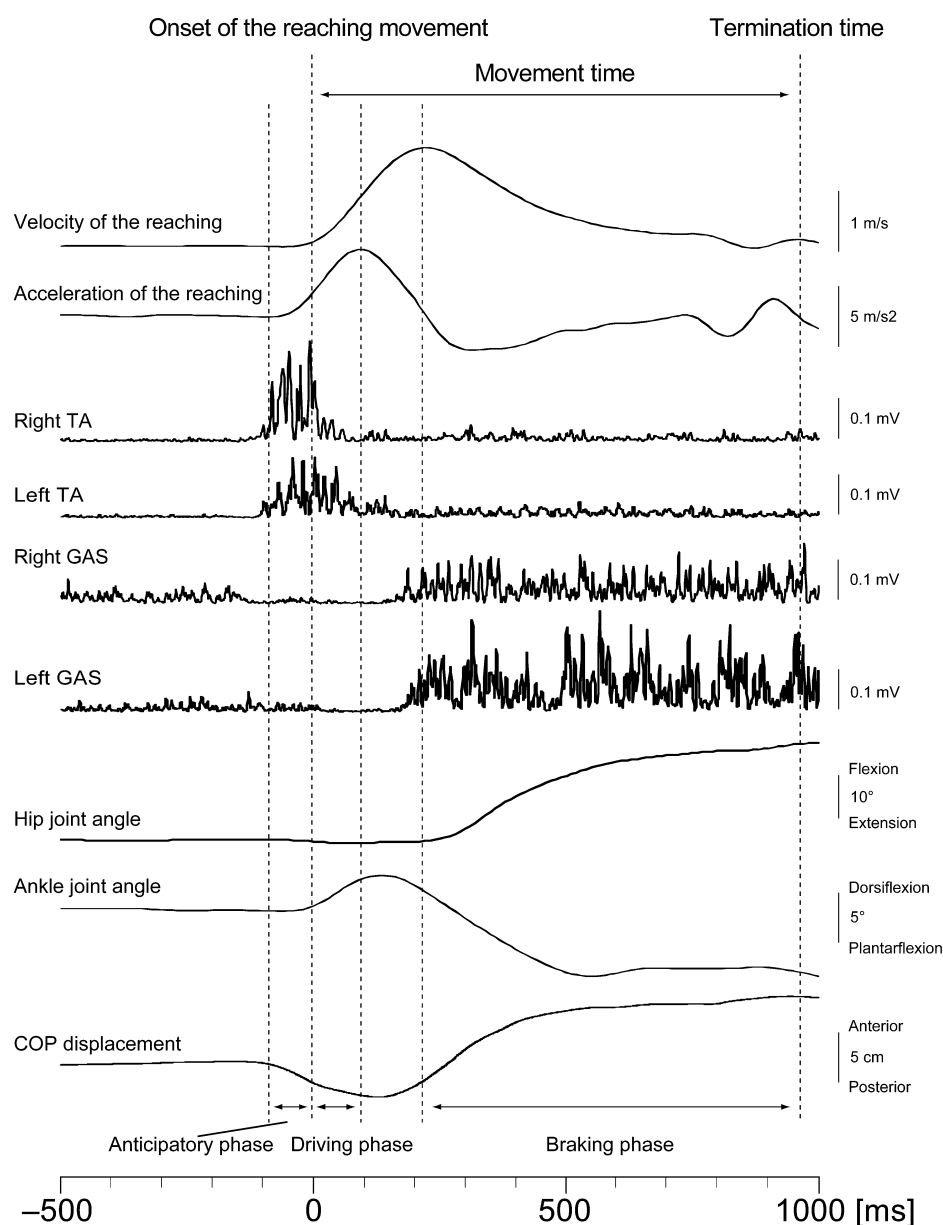
Kinematic data were collected using a three-dimensional motion analysis system (Motion Analysis Corporation, Santa Rosa, CA, USA). To derive the trajectory of the center of mass (COM) and the magnitude of joint angles, 27

reflective markers (diameter, 20 mm) were placed at the following anatomical landmarks<sup>19,20)</sup>: top of the head, auricle of the ear, acromion process, lateral humeral epicondyle, radial styloid process, head of the third metacarpal bone, iliac crest, anterior superior iliac spine, xiphoid process, angulus inferior scapulae, inferior angle of the ribs, greater trochanter, knee, ankle, and head of the fifth metatarsal. All marker locations were bilateral, except for the top of the head, xiphoid process, and angulus inferior scapulae. Six cameras were used to record the positions of these markers; the collection frequency was 100 Hz. Surface electromyographic (EMG) data were collected bilaterally using disposable self-adhesive electrodes (Ambu Corporation, Copenhagen, Denmark) from the following muscles: tibialis anterior (TA), gastrocnemius (GAS), rectus femoris, and biceps femoris. The electrodes were placed over the muscle bellies with their centers 3 cm apart. In addition, a reference electrode was attached to the lateral aspect of the fibula. To check the initial position of COP, the ground reaction force was recorded from the force platform. All analog signals were digitized at a sampling frequency of 1000 Hz with 16-bit resolution.

In this study, data from failed trials were excluded from the analysis. Failed trials were 33.9% of all trials. In addition, trials in which the onset of TA started less than 50 ms after the beep signal were eliminated from the analysis, since we observed that subjects anticipated when the beep signal would occur rather than reaching in reaction to the actual auditory stimulus. Trials estimated as anticipatory responses were 5.1% of all trials. The remaining trials (61.1%) were defined as successful trials. The success rate was calculated for each of the 10 trials. All signals were processed off-line using the MATLAB 7.7 software (Mathworks, Natick, MA, USA).

All data collected using the three-dimensional motion analysis system were digitally low-pass filtered using a dual-pass Butterworth filter with a cut-off frequency of 8 Hz. To determine the onset of the reaching movement, the velocity of the right hand movement was obtained by differentiating the position of the marker attached to the third metacarpal bone. The onset of the reaching movement (time zero,  $t_0$ ) was determined as the time when the velocity of the right hand movement exceeded 5 cm/s. The termination time of the reaching movement was determined as the time when the subjects touched the force sensor attached to the target. The time of the reaching movement was the time from  $t_0$  to the termination time. Acceleration of the right hand movement was obtained by differentiating its velocity. Hip, knee, and ankle joint angles were calculated in the sagittal plane. The hip joint angle was defined by the position of the acromion process, greater trochanter, and knee, while the knee joint angle was defined by the position of the greater trochanter, knee, and ankle. The ankle joint angle was defined by the position of the knee, ankle, and head of the fifth metatarsal. The position of the whole body COM was calculated using the 14-segment COM model described by Winter<sup>19)</sup>. The velocity of the COM was obtained by differentiating its position.

Integrals of the EMG activities during the reaching



**Fig. 1.** Typical example of a reaching movement. Excitation of anticipatory activity in TA and inhibition in GAS were observed prior to the change in velocity of the right hand. Ankle dorsiflexion occurred simultaneously with the onset of the reaching movement and plantarflexion occurred immediately before the braking phase. Excitation of activity in GAS and hip flexion increased in the braking phase. TA, tibialis anterior; GAS, gastrocnemius; COP, center of pressure.

movement were calculated for 3 different phases (Fig. 1). The time windows for these phases were from  $-100$  ms to  $t_0$  (anticipatory phase), from  $t_0$  to the time when the acceleration of the right hand movement was maximal (driving phase), and from the time when the velocity of the right hand movement was maximal to termination time (braking phase)<sup>21,22</sup>. Because high activities in TA and GAS were rarely observed in the period from the peak acceleration to the peak velocity of the right hand movement of all subjects, this period was excluded from the analysis. All EMG signals were rectified and band-pass filtered from 20 to 500 Hz using a fourth-order Butterworth

filter. EMG onset times were calculated in relation to the right hand movement ( $t_0$ ). The mean and standard deviation (SD) of muscle activity at the baseline level were calculated from  $-500$  to  $-300$  ms prior to  $t_0$  in individual trials. EMG onset was defined as an event lasting for at least 50 ms when the EMG amplitude was more than 3 SD from the mean baseline level<sup>21</sup>. The integrated EMG (IEMG) was calculated by subtracting the baseline activity from the integrated muscle activity in each phase<sup>21</sup>. To compare muscle activities among repetitions of the reaching movements and across subjects, individual IEMG was normalized to the maximum IEMG across all trials for each

subject and each muscle. In particular, the onset and IEMG of TA and GAS, which contribute to the maintenance of postural stability, were examined as indicators of changes in postural control<sup>21)</sup>.

Only data from successful trials were analyzed in this study. The means of each parameter in consecutive sets of 10 trials were used for statistical analysis. One-way repeated measures ANOVA was used to examine the effect of the repetitive reaching movement. Moreover, the Bonferroni post hoc test was conducted to compare the means of each set of 10 trials. To examine the relationship between improvements in reaching performance and changes in postural control, Pearson correlation coefficients were calculated, and the two-tailed paired Student's *t*-test was used. All statistical analyses were performed using the statistical program SPSS 18.0J for Windows (SPSS Japan Inc., Tokyo, Japan). The significance level was set at  $p < 0.05$ .

## RESULTS

Improvements in performance during performance of the repetitive reaching movement are presented in Table 1. One-way repeated measures ANOVA of the success rate showed a significant main effect of repetition of the reaching movement [ $F(4, 65) = 13.5$ ;  $p < 0.01$ ]. The Bonferroni post hoc test revealed that the success rate was significantly higher in the 21st–30th, 31st–40th, and 41st–50th trials than in the first 10 (1st–10th) trials. In addition, ANOVA showed a significant main effect of repetition on movement time [ $F(4, 65) = 9.4$ ;  $p < 0.01$ ], peak velocity of the right hand [ $F(4, 65) = 9.2$ ;  $p < 0.01$ ], and peak velocity of the COM [ $F(4, 65) = 7.7$ ;  $p < 0.01$ ]. Post hoc tests also revealed that these parameters improved significantly in the 31st–40th and 41st–50th trials compared with the first 10 (1st–10th) trials.

Changes in muscle activities and joint angles related to postural control delivered by the lower limbs are presented in Table 2. One-way repeated measures ANOVA showed a significant main effect of repetition on the activity of the right TA [onset,  $F(4, 65) = 10.6$ ;  $p < 0.01$ ], IEMG in the anticipatory phase [ $F(4, 65) = 8.8$ ;  $p < 0.01$ ], IEMG in the driving phase [ $F(4, 65) = 3.0$ ;  $p < 0.05$ ], and of the left GAS [IEMG in the braking phase,  $F(4, 65) = 5.5$ ;  $p < 0.01$ ]. The Bonferroni post hoc tests revealed that the means of these parameters were significantly different from the first 10 (1st–10th) trials in the 21st–30th, 31st–40th, and 41st–50th

trials. Next, we examined changes in hip and ankle joint movements, which play important roles in maintaining standing posture. ANOVA showed a significant main effect of repetition on the peak hip flexion angles [ $F(4, 65) = 6.2$ ;  $p < 0.01$ ] and the peak ankle dorsiflexion angles [ $F(4, 65) = 9.1$ ;  $p < 0.01$ ] of the right limb. Similar to the results of muscle activities, post hoc tests revealed that the means of these parameters were significantly different from the first 10 (1st–10th) in the 11th–20th, 21st–30th, 31st–40th, and 41st–50th trials.

To investigate the effects of changes in postural control on improvement in performance, we examined the relationship between performance and postural control during repetitive reaching movements. First, we focused on the parameters of the right leg shown in Table 2 and calculated correlation coefficients between reaching performance and postural control. Postural control was significantly correlated with reaching performance (Table 3). In particular, the onset of TA advanced as movement time reduced ( $r = 0.62$ ;  $p < 0.01$ ), and the IEMG of TA in the anticipatory phase increased with increasing peak velocity of the COM ( $r = 0.61$ ;  $p < 0.01$ ). Next, we examined which parameters of performance or postural control changed at an early stage across trials. The number of the first trial with a value more than 2 SD above or below the mean for trials 1–10 was determined for parameters showing high correlations in Table 3. For the onset of TA and movement time, the number of the first trial was  $19.2 \pm 5.9$  and  $36.7 \pm 12.6$ , respectively. The number of the first trial for the onset of TA was significantly lower than that for movement time ( $p < 0.01$ ). Similarly, the number of the first trial for the IEMG of TA and peak velocity of the COM was  $20.7 \pm 6.6$  and  $29.9 \pm 11.6$ , respectively. The number of the first trial for the IEMG of TA was significantly lower than that for the peak velocity of the COM ( $p < 0.05$ ). Thus, postural control appears to change before an improvement in reaching performance is seen.

## DISCUSSION

Reaching performances (e.g., movement time and peak velocity of the COM) improved significantly during repetitive reaching movement while standing (Table 1). This improvement must involve effects of motor learning for the upper limbs and trunk movement<sup>2,23)</sup>. In addition, changes in postural control may affect this improvement ensuring postural stability for the performance of a

**Table 1.** Improvements in performance during repetitive reaching movement

| Parameters                             | Number of trials |                  |                   |                    |                      |
|--|------------------|------------------|-------------------|--------------------|----------------------|
|  | 1st–10th         | 11th–20th        | 21st–30th         | 31st–40th          | 41st–50th            |
| Success rate (%)                       | 40.0 $\pm$ 17.5  | 52.1 $\pm$ 24.2  | 63.6 $\pm$ 18.6 * | 67.9 $\pm$ 20.4 *  | 75.0 $\pm$ 11.6 *, † |
| Movement time (ms)                     | 983 $\pm$ 120    | 945 $\pm$ 104    | 927 $\pm$ 120     | 905 $\pm$ 100 *    | 879 $\pm$ 96 *       |
| Peak velocity of the right hand (cm/s) | 149.9 $\pm$ 37.9 | 157.5 $\pm$ 41.3 | 160.5 $\pm$ 44.2  | 165.5 $\pm$ 44.4 * | 169.1 $\pm$ 50.6 *   |
| Peak velocity of the COM (cm/s)        | 19.5 $\pm$ 2.7   | 20.2 $\pm$ 2.7   | 20.6 $\pm$ 3.0    | 21.2 $\pm$ 2.7 *   | 21.5 $\pm$ 2.8 *, †  |

Values are mean  $\pm$  standard deviation. COM, center of mass. \*Significantly different from mean of the first ten trials (1st–10th),  $p < 0.01$ . † Significantly different from mean of the second ten trials (11th–20th),  $p < 0.01$ .

**Table 2.** Changes in postural control during repetitive reaching movement

| Parameters                                | Number of trials |              |              |              |               |
|---|------------------|--------------|--------------|--------------|---------------|
|   | 1st–10th         | 11th–20th    | 21st–30th    | 31st–40th    | 41st–50th     |
| Right TA                                  |                  |              |              |              |               |
| Onset (ms)                                | −151 ± 49        | −199 ± 37*   | −214 ± 69*   | −213 ± 37*   | −216 ± 39*    |
| IEMG in anticipatory phase                | 0.40 ± 0.12      | 0.58 ± 0.13* | 0.57 ± 0.16* | 0.55 ± 0.10* | 0.58 ± 0.09*  |
| IEMG in driving phase                     | 0.23 ± 0.11      | 0.31 ± 0.21  | 0.38 ± 0.23* | 0.31 ± 0.14  | 0.37 ± 0.12*  |
| Left TA                                   |                  |              |              |              |               |
| Onset (ms)                                | −152 ± 63        | −170 ± 71    | −172 ± 70    | −184 ± 73    | −206 ± 70*, † |
| IEMG in anticipatory phase                | 0.48 ± 0.21      | 0.55 ± 0.17  | 0.55 ± 0.16  | 0.55 ± 0.16  | 0.54 ± 0.14   |
| IEMG in driving phase                     | 0.31 ± 0.17      | 0.40 ± 0.24  | 0.44 ± 0.22  | 0.32 ± 0.16  | 0.43 ± 0.13   |
| Right GAS                                 |                  |              |              |              |               |
| IEMG in braking phase                     | 0.63 ± 0.14      | 0.56 ± 0.16  | 0.64 ± 0.15  | 0.62 ± 0.11  | 0.59 ± 0.09   |
| Left GAS                                  |                  |              |              |              |               |
| IEMG in braking phase                     | 0.48 ± 0.13      | 0.59 ± 0.17  | 0.60 ± 0.15* | 0.60 ± 0.13* | 0.63 ± 0.12*  |
| Right peak hip flexion angle (deg)        | 14.6 ± 6.4       | 16.9 ± 7.0*  | 17.4 ± 6.8*  | 16.8 ± 6.4*  | 17.1 ± 6.4*   |
| Left peak hip flexion angle (deg)         | 10.0 ± 7.3       | 12.4 ± 8.3*  | 12.0 ± 8.4   | 12.1 ± 8.0   | 11.8 ± 7.2    |
| Right peak ankle dorsiflexion angle (deg) | 2.9 ± 1.5        | 4.0 ± 1.5*   | 3.9 ± 1.9*   | 3.9 ± 1.5*   | 4.1 ± 1.7*    |
| Left peak ankle dorsiflexion angle (deg)  | 2.9 ± 1.0        | 3.4 ± 1.3    | 3.2 ± 1.5    | 3.5 ± 1.4    | 3.2 ± 1.4     |

Values are mean ± standard deviation. TA, tibialis anterior; GAS, gastrocnemius; IEMG, integrated electromyography. \*Significantly different from mean of the first ten trials (1st–10th),  $p < 0.01$ . †Significantly different from mean of the second ten trials (11th–20th),  $p < 0.01$ .

**Table 3.** Correlation with reaching performance and postural control

|                          | Postural control |                                  |                         |
|--------------------------|------------------|----------------------------------|-------------------------|
|                          | Onset of TA      | IEMG of TA in anticipatory phase | Peak ankle dorsiflexion |
| Reaching performance     |                  |                                  |                         |
| Movement time            | 0.62 *           | −0.52 *                          | −0.46 *                 |
| Right hand peak velocity | −0.45 *          | 0.50 *                           | 0.47 *                  |
| COM peak velocity        | −0.50 *          | 0.61 *                           | 0.38 *                  |

COM, center of mass; TA, tibialis anterior; IEMG, integrated electromyography. \* significant difference ( $p < 0.01$ ).

voluntary movement with the arm while standing<sup>5,24</sup>). It has been reported that APAs observed in postural muscles prior to the onset of voluntary movement counteract the perturbation caused by the voluntary movement and contribute to the stability of posture<sup>25,26</sup>) and driving force required to initiate forward body movement<sup>9</sup>). In this study, anticipatory muscle activity in the right TA was observed prior to the reaching movement in all subjects, and the effects of repetition emerged as significant changes in muscle onset and IEMG (Table 2). We presume that an increase in postural stability and the driving force initiated by changes in variables such as muscle activity and joint movements of the lower limbs contributed to the improvement in reaching performance.

Previous studies investigating postural responses to translation or rotation of the support surface found that muscle activity in the lower limbs and postural sway decreased clearly after a few cycles when the amplitude of the perturbation was constant<sup>12,13</sup>). A study of postural control during voluntary movement reported that sufficient learning of a focal movement led to a decrease in the activity of the focal muscle<sup>3</sup>). However, the results of this study show that postural muscle activity in the lower limbs increased during repetitive reaching movements (Table 2).

The difference between the results of this study and those of previous studies can be explained by the instructions given to the subjects. Our subjects were asked to perform the reaching movement as fast as possible. Consequently, the movement time decreased and the peak velocity of the COM increased during the repetitive reaching movements, i.e., postural muscles may have been activated strongly to provide more powerful driving and braking forces for improvement in reaching performance.

Since the report by Magnus<sup>27</sup>), research on postural control has focused on the brainstem, which is involved in the control of postural reflexes. However, for the last few decades, it has been found that the brainstem reticular formation<sup>28</sup>), cerebellum<sup>29,30</sup>), basal ganglia<sup>31</sup>), and cerebral cortex<sup>32</sup>) play important roles in the control of dynamic postural balance. Recently, the role of the motor cortex in controlling forearm posture has been investigated. Kazennikov et al.<sup>16</sup>) examined the change in activity of the left forearm flexor muscle when participants held a load in the left hand and then lifted the load with the right hand. The amount of inhibition of the anticipatory activity of the left forearm flexor muscle increased during repetition of unloading, the onset of inhibition advanced, and left forearm displacement decreased. Moreover, use of transcranial

magnetic stimulation showed that the motor cortex contributed to the control of forearm posture. Thus, the responses of the postural muscles changed through the repetition of anticipatory perturbation caused by self-initiated movement. In this study, repetitive experience of perturbation caused by arm and trunk movement during the reaching movement may have led to changes in the postural control of the lower limbs. However, it is unclear whether the changes were temporary adaptations, because of enhanced excitability of muscles and motor neurons in the spinal cord, or retained learning effects associated with CNS. To resolve this question, future research must address the effects of the number of trials, the duration of reaching training, and generalization to the arm opposite to the arm that has been trained. Such studies may confirm the contribution of CNS to changes in postural control during repetitive reaching movements.

During rehabilitation of patients with impaired movement ability, physical therapists often instruct them to repeat the same movement and aim to improve their performance. However, it may be difficult to acquire functional arm movements if postural stability is not assured. From this point of view, a better understanding of the postural control mechanism during repetitive movement training is useful for physical therapy practices and presents an important challenge. The amount of training necessary for motor and postural learning and the duration of retention of the acquired ability after learning remain to be investigated. Further research on the effects of repetitive movement training not only in healthy young subjects but also the elderly and patients with CNS damage may enable resolution of brain function and the development of applications for physical therapy practice.

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