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Original Article

Motion analysis of operating a balance exercise assist robot system during forward and backward movements

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Abstract. [Purpose] Stand-and-ride personal mobility devices controlled by movements of the user's center of gravity are used for balance training. We aimed to describe the physical activity required to operate this type of mobility device. [Participants and Methods] Eleven healthy males performed the following tasks: 1) moving their center of gravity forward or backward while standing on the floor (control task) and, 2) moving the mobility device forward or backward by moving their center of gravity (experimental task). [Results] We observed that the displacement of the center of gravity and the center of pressure, as well as angular displacements of the hips and knee joints, and maximum muscle activities of the biceps femoris, the medial head of the gastrocnemius and peroneus longus muscles were lesser during the experimental than during the control task. The distance moved by the device was significantly greater than the displacement of the user's center of gravity during the experimental task. [Conclusion] We observed that moving the device forward or backward required lesser physical activity than that required to shift the user's center of gravity forward or backward while standing on the floor. Additionally, we observed that even a small displacement of the user's center of gravity produced a large displacement of the device. We concluded that during balance training, the greater and more easily perceived movement of the mobility device would provide helpful feedback to the user.
Key words: Personal mobility device, Postural control, Motion analysis

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INTRODUCTION

Balance is the ability to maintain and restore a state of equilibrium during any situation and to adjust the relationship between the base of support and the center of gravity (COG) by referring to input from the motor and sensory systems[1, 2)]. Dysfunction of these systems causes falls[3)]. Exercise is an important treatment modality for preventing falls and keeping patients with balance disorders safe in their daily lives. Exercise involving multiple components (i.e. balance, muscle strengthening, and gait) is effective for improving balance ability[4)]; in particular, an exercise program including postural control exercises has been recommended[5)].

Stand-and-ride personal mobility devices, like the Segway Personal Transporter (Segway Inc., Bedford, NH, USA) and

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the Winglet (Toyota Motor Corporation, Toyota, Aichi, Japan), were introduced for use by healthy individuals. Recently, these devices have been applied as posture control exercise tools for patients with balance disorders[6–12]. The balance exercise assist robot (BEAR, Toyota Motor Corporation, Toyota, Aichi, Japan) system is a training device combining video games with a stand-and-ride personal mobility device (PMD) based on the Winglet. The PMD employs inverted pendulum control via two motors that are controlled by sensors that detect the user's posture. In the BEAR system, the PMD communicates with a computer via Bluetooth; this computer is connected to a large monitor that displays the movement of the PMD as a moving character. By visualizing the PMD's movement, which corresponds to the movement of the user's COG, the device gives the user useful feedback[8].

Previously, training using the BEAR system has been shown to improve dynamic balance ability and lower limb muscle strength in patients with chronic stroke[9] and frail elderly people[10]. Studies in healthy participants using the BEAR system have described the characteristics of leg muscle activities during three different tasks[11] and the changes in postural strategy during training against perturbation[12]. However, the mechanism involved in the training effects of the BEAR system has not been described. The first step in clarifying this mechanism is to investigate the nature of the physical activities required to operate the PMD, including stopping, forward/backward movements, and left/right turning movements, in healthy individuals. A previous study has described the characteristics of postural control during the action of stopping the PMD[13]. The purpose of this study was to describe the physical activities involved in operating the PMD in forward and backward motion.

PARTICIPANTS AND METHODS

Eleven healthy male participants without a history of neurologic or orthopedic disease (mean age 26 ± 5 years; height 171 ± 7 cm; weight 62 ± 7 kg) were enrolled in this study. The procedures were performed in accordance with our institutional ethics committee clearance (approval No. ERB-C-878). Written informed consent was received from all participants.

Participants stood with their heels 20 cm apart while looking ahead and performed two tasks: (1) control task (CT): move COG forward or backward to the maximum possible distance while standing on a force-plate (GP-5000, Anima Co., Ltd., Chofu, Tokyo, Japan); (2) experimental task (ET): move the PMD (R332 yellow model, Toyota Motor Corporation, Toyota, Aichi, Japan) forward or backward to the maximum distance required during forward or backward training with the BEAR system. The PMD employs inverted pendulum control via two motors that are controlled by sensors that detect the user's posture. By moving their COG forward or backward, the user causes the PMD (maximum cruising speed: 2 m/s) to travel forward or backward, respectively. By moving their COG to the left or right, the user can turn the PMD in the corresponding direction[8]. During the CT, participants crossed their arms against their chests; during the ET, participants placed their hands on the handlebars of the PMD. Each task was performed for 2 s, and repeated 10 times.

Sixteen markers (30 mm in diameter) were placed bilaterally on the following points: the acromia, lateral epicondyle of the humerus, ulnar styloid process, iliac crest (at the position of each iliac crest on a vertical line passing through the hips), hip joint (one-third distance from the great trochanter on a line joining the anterior superior iliac spine and great trochanter), knee joint (midpoint of the anteroposterior diameter of the lateral femoral epicondyle), ankle joint (lateral malleolus), and toes (5th metatarsal head). A six-camera 3D motion-capture system (KinemaTracer®, Kissei Comtec Co., Ltd., Matsumoto, Nagano, Japan) recorded marker positions at a sampling rate of 60 Hz. Force data were recorded at a sampling rate of 20 Hz by a force-plate during the CT, and at a sampling rate of 125 Hz by the PMD's foot sensors during the ET. Surface electromyography (EMG) data from the following six muscles in the right lower limb—the gluteus medius (GM), rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), medial head of the gastrocnemius (MG), and peroneus longus (PL)—were recorded at 1,000 Hz using a wireless EMG device (MQ16, Kissei Comtec Co., Ltd., Matsumoto, Nagano, Japan). Placement of the EMG electrodes was performed according to SENIAM recommendations[14].

The data capture was synchronized by a start signal from the 3D motion-capture system during the CT; during ET, the start signal was generated by a custom-made trigger box[13].

The COG, which was defined as the total values of the center of mass in each segment calculated by segment weight and segment length as proposed by Matsui[15], was calculated based on 14 markers, excluding the iliac crest. In addition, to evaluate the COG movement excluding the influence of the PMD's movement, the COG based on the position of the midpoint of both ankle joints was calculated. Each angle of the hip, knee, and ankle joints in the sagittal plane was calculated as the motion of the distal segment relative to the proximal segment in the right lower limb. Center of pressure (COP) was calculated from the force data obtained from the force plate (CT) and the PMD's foot sensors (ET). COG and COP were resampled at 125 Hz with the KineAnalyzer® (Kissei Comtec Co., Ltd., Matsumoto, Nagano, Japan).

The raw EMG signals underwent 20–500 Hz bandpass-filtering using KinemaTracer® (Kissei Comtec Co., Ltd., Matsumoto, Japan) to convert them into 100 msec root mean square waveforms. The EMG data were normalized to the maximum voluntary contraction for each participant. During the ET, the distance moved by the PMD was calculated from the coordinate information on the computer.

All offline data were normalized with 100 points per cycle for each task performed in 2 s. The mean values for displacement of COG and COP, joint (hip, knee, ankle) angle, and maximum muscle activity (GM, RF, BF, TA, MG, PL) during the CT and ET were calculated from the 10 task repeats performed by each of the 11 participants.

A repeated measures analysis using a mixed model was performed to evaluate differences in kinetic and kinematic values and lower limb muscle activities between CT and ET tasks. The fixed effects were the two tasks (CT, ET), and these models also estimated random effects due to differences between participants. In the analysis, p values <0.05 were considered statistically significant. JMP® Pro 12 (SAS Institute Inc., Cary, NC, USA) was used for statistical analyses.

RESULTS

During the ET, the distances moved by the PMD were 43.2 ± 6.3 cm in forward movement and 43.1 ± 7.9 cm in backward movement.

During the CT in the forward direction, COG and COP moved forward, whereas during the ET in the forward direction, COP moved forward, but COG moved backward (Fig.1). In addition, COG and COP displacements were smaller during the ET than during the CT. Hip flexion, knee extension, and ankle dorsiflexion occurred during the CT. During the ET, the changes in hip and knee motions were small, and ankle plantarflexion occurred (Fig. 2A). Compared with the CT, angular displacements of hip and knee joints were smaller, and ankle joint displacement was larger, during the ET. Muscle activity of the MG and PL increased in the second half of the CT, whereas the changes in muscle activity were small in each muscle during the ET (Fig. 2B). Maximum muscle activity during the ET was greater for the GM and RF, and smaller for the BF, MG, and PL, than during the CT. There was no difference in TA activity between two tasks (Table 1).

During the CT in the backward direction, COG and COP moved backward, whereas during the ET in the backward direction, COP moved backward and COG moved forward (Fig. 3). During the ET, displacements of COG and COP were smaller than during the CT. Hip extension and knee flexion occurred during the CT, while ankle plantarflexion occurred in the first half of the task and ankle dorsiflexion in the second half. During the ET in the backward direction, the changes in hip and knee motions were small, and ankle dorsiflexion occurred (Fig. 4A). The angular displacements of the hip and knee joints during the ET were smaller than during the CT. During the CT, muscle activity of the MG and PL increased in the first half, and TA and RF muscle activity increased later. During the ET, the changes in muscle activity were small in each muscle (Fig. 4B), and maximum muscle activity was smaller during the ET than the CT for all muscles except the GM (Table 1).

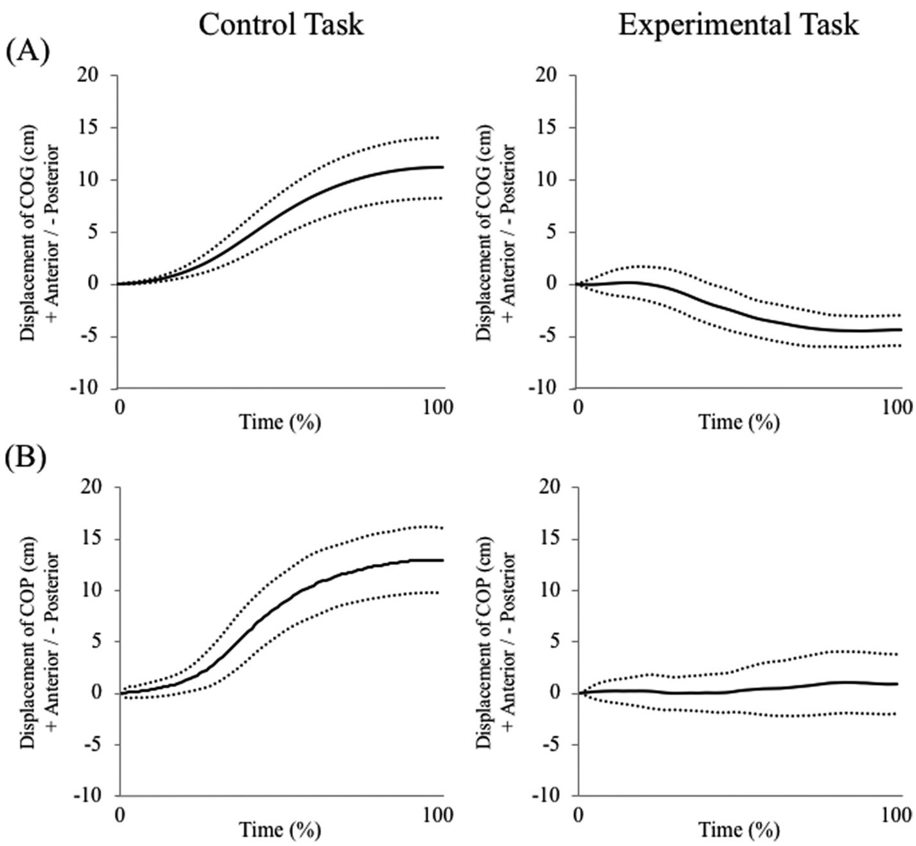

Fig. 1. COG and COP displacement during the control and experimental tasks in the forward direction.
Graphs of time course for (A) COG and (B) COP are shown. In all graphs, the solid line represents the mean value for 110 trials (10 trials by 11 participants), and the dotted line represents ± 1 SD.

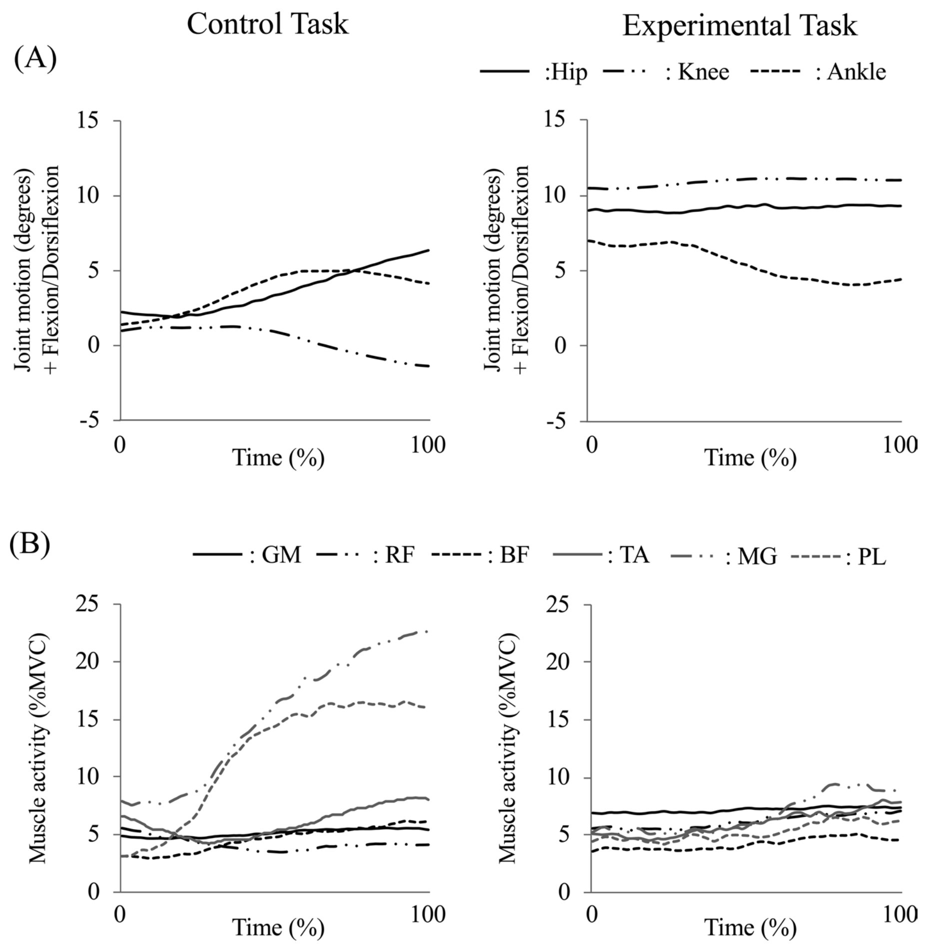

Fig. 2. Joint motion and muscle activity for each muscle during the control and experimental tasks in the forward direction.
Graphs of time course for (A) hip, knee, and ankle joints and (B) each muscle are shown. In all graphs, each line represents the mean value for 110 trials (10 trials by 11 participants).

DISCUSSION

This study showed that operating the PMD required smaller physical activities than when participants shifted their COG forward and backward maximally while standing on the floor. Although the displacements of the user's COG and COP during the ET were smaller than during the CT, in comparison the distance moved by the PMD was large. Thus, the PMD can be operated by small displacements of the user's COG and COP, which are converted into a large PMD movement. Balance is improved by external feedback such as visual feedback, biofeedback, and vibrotactile feedback[16–18]. Operating the PMD requires moving the COG and the passenger receives easily perceptible feedback on their COG movement via the PMD movement. While COP was displaced in the direction of travel, COG was displaced in the opposite direction after the PMD started moving. This is because, soon after the PMD started moving, the user's COG was returned to the starting position above the PMD's axle, and the PMD decelerated and stopped.

Hip flexion, knee extension, and ankle dorsiflexion occurred when the COG shifted forward, whereas hip extension, knee flexion, and ankle plantarflexion occurred when the COG shifted backward while standing on the floor[19]. This agrees with our results of lower limb joint motions during the CT. On the other hand, during the ET, hip and knee motions were small, ankle plantarflexion occurred when the PMD moved forward, and ankle dorsiflexion occurred when the PMD moved backward. It appears that ankle motion during the ET differed from that during the CT and shifted the COG in the opposite direction to travel. The postural strategy to maintain balance on an unstable seesaw, which is a useful device to improve balance ability, has been reported to be ankle plantarflexion when the seesaw leans forward and dorsiflexion when the seesaw leans backward[20, 21]. The postural strategy during the ET is similar to the relationship between COG and ankle motion observed with an unstable seesaw.

Several studies have reported that muscle activity of the dorsal lower limb muscles increases when the COG shifts forward, whereas activity of the ventral lower limb muscles increases when the COG shifts backward on the floor[19, 22–24]. In

Table 1. Comparison of measured parameters during the control task (CT) and experimental task (ET) in the forward and backward movements

Parameter	Forward movement			Backward movement		
	CT	ET	p value	CT	ET	p value
Amount of displacement (cm)						
COG	11.2 (2.9)	6.3 (1.5)	<0.01*	9.9 (2.2)	6.8 (1.5)	<0.01*
COP	13.4 (3.1)	3.9 (2.9)	<0.01*	12.4 (2.3)	3.9 (2.4)	<0.01*
Angular displacement (degrees)						
Hip	6.8 (5.1)	5.2 (3.6)	<0.01*	7.4 (5.2)	5.2 (2.7)	<0.01*
Knee	4.2 (2.6)	2.7 (2.5)	<0.01*	7.0 (6.5)	2.5 (2.1)	<0.01*
Ankle	4.9 (2.1)	5.9 (1.9)	<0.01*	5.9 (3.9)	6.4 (1.9)	0.17
Maximum muscle activity (%MVC)						
Gluteus medius	6.9 (2.4)	9.2 (8.2)	<0.01*	7.3 (3.8)	8.8 (8.2)	0.06
Rectus femoris	7.5 (5.7)	9.9 (7.7)	<0.01*	14.2 (8.6)	8.9 (5.9)	<0.01*
Biceps femoris	8.4 (4.6)	7.2 (6.6)	0.04*	7.8 (5.8)	6.3 (4.8)	<0.01*
Tibialis anterior	11.6 (6.8)	12.0 (9.2)	0.63	28.6 (18.6)	10.2 (5.2)	<0.01*
Medial head of gastrocnemius	22.7 (11.5)	12.3 (8.4)	<0.01*	17.7 (10.3)	10.9 (7.8)	<0.01*
Peroneus longus	26.8 (15.8)	13.7 (16.0)	<0.01*	15.3 (8.3)	10.6 (11.2)	<0.01*

Values are displayed as mean (SD). * indicates $p<0.05$.

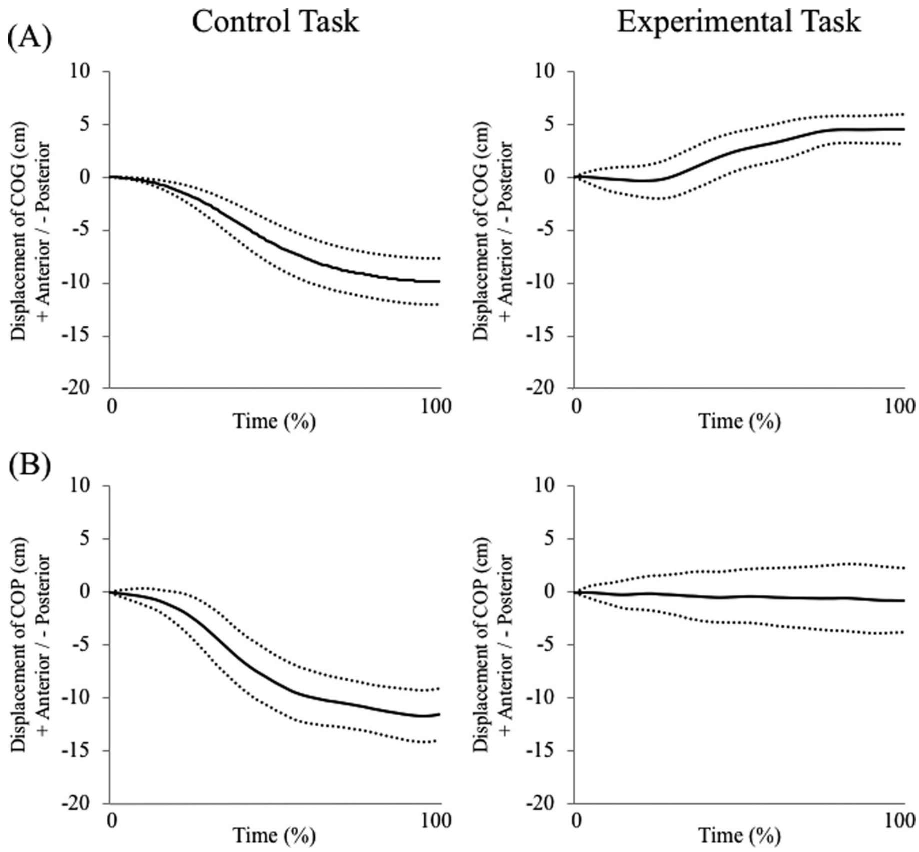

Fig. 3. COG and COP displacement during the control and experimental tasks in the backward direction.
Graphs of time course for (A) COG and (B) COP are shown. In all graphs, the solid line represents the mean value for 110 trials (10 trials by 11 participants), and the dotted line represents ± 1 SD.

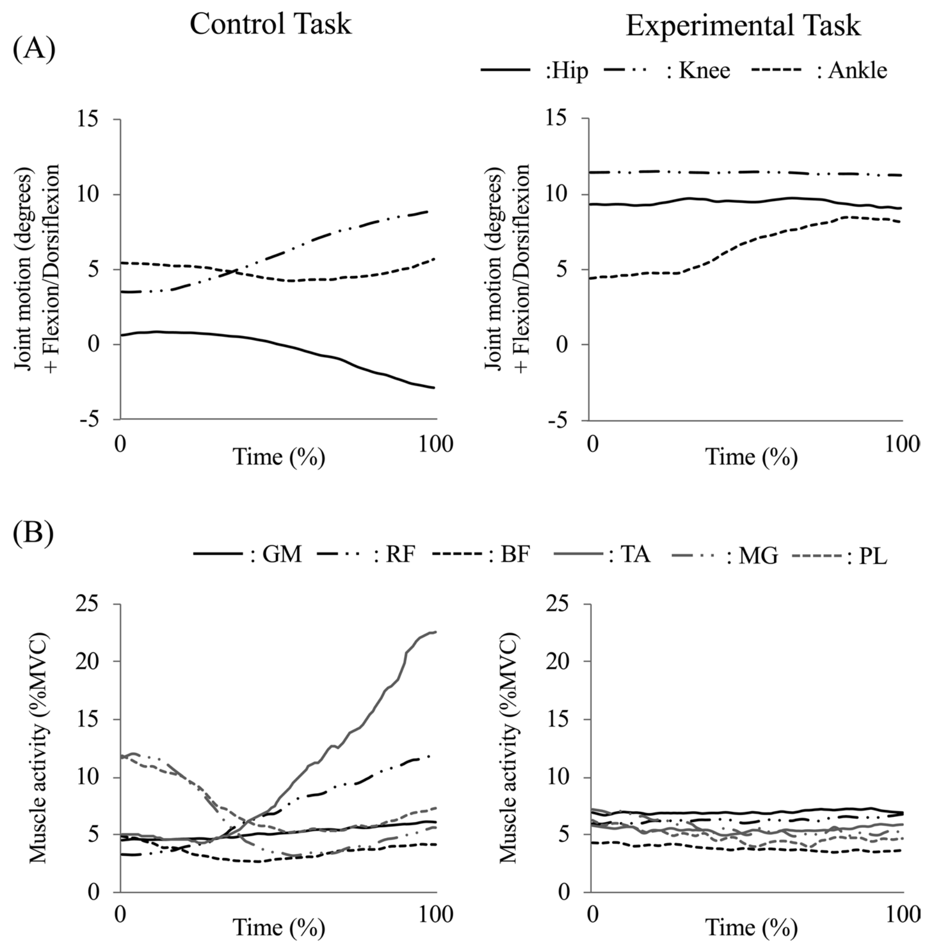

Fig. 4. Joint motion and muscle activity for each muscle during the control and experimental tasks in the backward direction.
Graphs of time course for (A) hip, knee, and ankle joints and (B) each muscle are shown. In all graphs, each line represents the mean value for 110 trials (10 trials by 11 participants).

addition, greater muscle activity increases are observed when subjects shift their COG to the edge of the base of support[25]. This agrees with the muscle activity results during the CT in this study. In comparison, during the ET, temporal changes in lower limb muscle activities for forward or backward movement of the PMD and the maximum muscle activity for the BF, MG, and PL were smaller than during the CT.

The present study has some limitations. The motions of the head, neck, and trunk were not analyzed. Hsu et al.[26] reported that displacement of six angles in the longitudinal direction—the ankle, knee, hip, lumbosacral, 7th cervical-1st thoracic, and atlanto-occipital joints—was coordinated to minimize the impact on the center. The amount of load on the handlebars and upper limb motion were also not measured. Furthermore, head, neck, trunk, and upper limb motions should be analyzed to clarify their influence on the PMD's operation. The present study described the physical activity required by healthy young males to operate the PMD; however, this does not necessarily reflect the physical activity required by the elderly people and patients with balance disorders targeted in previous studies using the BEAR system[8–10]. Postural strategy is known to depend on age and disability[27]. In the next study, it will be important to study elderly people and those with balance disorders to understand the mechanism of the training effect achieved with the BEAR system.

In conclusion, moving the PMD forward or backward required smaller physical activities than when shifting the COG forward or backward while standing on the floor. However, the small COG displacement was converted into a large PMD movement, which may provide users with a more easily perceived change for the small physical activity, and ankle motions were similar to maintaining a standing position on an unstable seesaw. Therefore, the PMD is a useful device for balance training.

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None.

Conflict of interest

The authors received support from Toyota Motor Corporation through the loan of the balance exercise assist robot.

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