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Original Article

Characteristics of leg muscle activity in three different tasks using the balance exercise assist robot

Ken Ishihara, MD,[1, 2] Satoshi Hirano, MD,[2] DMSc, Eiichi Saitoh, MD, DMSc,[2] Shigeo Tanabe, RPT, PhD,[3] Norihide Itoh, RPT, DMSc,[4] Ryuzo Yanohara, RPT,[5] Tsubasa Katoh, RPT,[5] Yuya Sawada, RPT,[5] Tetsuya Tsunoda, MD,[6] Hitoshi Kagaya, MD, DMSc[2]

[1]Gakusai Hospital, Kyoto Interdisciplinary Institute of Community Medicine, Kyoto, Japan
[2]Department of Rehabilitation Medicine I, School of Medicine, Fujita Health University, Toyoake, Aichi, Japan
[3]Faculty of Rehabilitation, School of Health Sciences, Fujita Health University, Toyoake, Aichi, Japan
[4]Department of Advanced Rehabilitation Medicine, Graduate School of Medical Science, Kyoto Prefectural University of Medicine, Kyoto, Japan
[5]Department of Rehabilitation, Fujita Health University Hospital, Toyoake, Aichi, Japan
[6]Department of Rehabilitation Medicine II, School of Medicine, Fujita Health University, Tsu, Mie, Japan

ABSTRACT
Ishihara K, Hirano S, Saitoh E, Tanabe S, Itoh N, Yanohara R, Katoh T, Sawada Y, Tsunoda T, Kagaya H. Characteristics of leg muscle activity in three different tasks using the balance exercise assist robot. Jpn J Compr Rehabil Sci 2015; 6: 105−112.
Objective: The balance exercise assist robot (BEAR) is a balance training device that uses robotic technology. The aim of this study was to clarify the characteristics of leg muscle activity while using the BEAR.
Methods: Subjects, comprising seven healthy adults, played three types of games composed of center of gravity movement tasks (tennis and skiing) and a coping with disturbance task (rodeo). The games had four levels of difficulty and each game was played for 90 seconds. Surface electromyography was used to measure the gluteus maximal muscle, gluteus medius muscle, rectus femoris muscle, vastus medialis muscle, biceps femoris muscle, tibialis anterior muscle, gastrocnemius and peroneus longus muscle on both sides. Mean muscle activity was calculated from muscle integrated electromyography.
Results: Muscle activity in each game increased with the degree of difficulty. Comparison of muscle activity between games indicated greater muscle activity in the tibialis anterior muscle during rodeo than tennis ($p = .009$) and skiing ($p = .017$). In the gastrocnemius, muscle activity was greater during rodeo than during skiing ($p = .045$) and in the peroneus longus muscle, muscle activity was greater during skiing than tennis ($p = .041$).
Conclusions: With the BEAR, the degree of difficulty can be altered to adjust the load placed on the legs. The three types of games each were able to promote different types of leg activity.
Key words: robot, rehabilitation, balance exercise, degree of difficulty, electromyography

Correspondence: Ken Ishihara, MD
Gakusai Hospital, Kyoto Interdisciplinary Institute of Community Medicine, 1−9 Higashitakada-cho, Mibu, Nakagyo-ku, Kyoto 604−8845, Japan.
E-mail: ishiken1978@gmail.com
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Introduction

As Japanese society ages at an unprecedented pace, the number of people requiring long-term care is rapidly increasing. Causes of long-term care include strokes, dementia, frailty due to old age, joint diseases, fractures and falls, and thus multilateral approaches are required to maintain a healthy life expectancy. Reports have indicated that 30−50% of elderly individuals aged 65 or older suffer falls each year [1, 2], with approximately 10−20% experiencing serious events such as fall-related fractures [3, 4]. The annual fall rate of stroke patients living at home is particularly high, at 40−50% [5−7]. Therefore, a safe and effective method of preventing falls needs to be established urgently in order to maintain the activities of daily living (ADL) in elderly individuals.

On the other hand, decreased balance function has been shown to be a risk factor for falls in the elderly [8, 9]. Balance function is defined as the function that controls a person's physical mass in relation to their base of support. It involves interactions among many elements including the musculoskeletal system, sensory functions (sight, somatic sensation, and vestibular sensation), sensory integration and cognitive function. Traditionally in the field of rehabilitation medicine, many methods of intervention have been utilized such as flexibility exercises, strength training, sensory training, postural control training, task-oriented training, and patient-related instruction on safety and injury prevention [10]. Of these, postural control training has been shown to be effective for improving center of gravity instability [11]. However, conventional methods of training suffer from various issues, such as the complexity of adjusting the degree of difficulty to the individual and boring training content due to the limited movements and little feedback. Therefore, postural control training with gradual adjustment of the degree of difficulty, varied movements and an element of fun need to be developed so that patients will want to continue training.

In recent years, there has been marked progress in the field of robotics, and robotic technology is now being introduced into rehabilitation medicine. With the idea that balance training using robotic technology could be useful as a type of postural control training, we developed the Balance Exercise Assist Robot (BEAR) based on the Winglet, a personal mobility device ridden in the standing position. The Winglet moves when the person on it moves their center of gravity forward or backward and left or right. Because the BEAR allows games and robot parameters to be adjusted, the degree of difficulty of each task can be easily adjusted and game elements can be incorporated. Ozaki et al. [12] performed three types of balance training using the BEAR in eight patients with central nervous system abnormalities as a therapy and found that dynamic balance and leg strength improved after the tasks as compared with before the tasks. However, the physical effects of the type of BEAR games and the adjustment of the degree of difficulty have not been clarified. Therefore, this study was designed to clarify the characteristics of leg muscle activity during BEAR use by evaluating leg muscle activity and coordinated movement during training using surface electromyography in healthy individuals performing three different games at four different degrees of difficulty.

Methods

1. Subjects

The subjects comprised seven healthy adults (men: 7, mean age: 25 ± 4 years, height: 173 ± 5 cm, weight: 63 ± 11 kg). Informed consent was obtained from all subjects.

2. BEAR

The BEAR is a robot based on the Winglet, which is a personal mobility device ridden in the standing position developed by Toyota Motor Corporation.

Figure 1. EMG measurement using BEAR.
Four degrees of difficulty (level) were set in each of 3 types of game. EMG was measured in a total of 16 muscles in both the left and right legs. These muscles were the gluteus maximus, gluteus medius, rectus femoris, vastus medialis, biceps femoris, tibialis anterior, gastrocnemius and peroneus longus.

This device employs inverted pendulum control by means of an in-wheel motor with two bases: one on the left and one on the right. The motor is controlled so that the rider remains in an upright position by means of sensors that sense the posture of the rider (Figure 1). Accordingly, when the rider moves their center of gravity forward or backward, the robot also moves forward or backward. In addition, when the rider moves their center of gravity to the left or right, the robot rotates. Because center of gravity is reflected in the robot's movement, the center of gravity can be visualized, so the device provides useful feedback to the user. Moreover, as the game and robot parameters can be adjusted, balance training can be offered with the optimal degree of difficulty. For safety, there is a bar fixed to the front of the robot to assist the rider in mounting and dismounting. In addition, the height and angle of the handle can be altered to keep the handle at the optimal position for the user, and a specialized frame and harness with a suspension system have been manufactured to prevent falls.

3. Training tasks

Three specialized games were developed to allow the subjects to enjoyably concentrate on balance training (Figure 2). These tasks were center of gravity movement tasks (tennis involving forward-backward motion and skiing involving left-right motion) and a coping with disturbance task (rodeo). The games had four levels of difficulty and each game was played for 90 seconds. To promote more effective exercise learning during balance training, the degree of difficulty of a task was automatically increased the next time if the subject achieved a task success rate of 80% or higher. By contrast, if the subject achieved a task success rate of 60% or lower, the degree of difficulty was decreased.

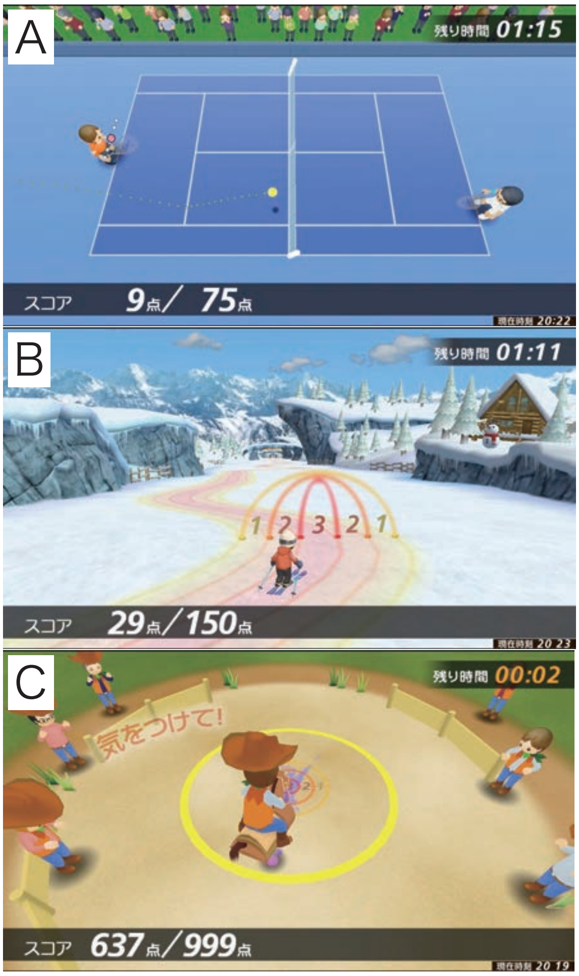

Figure 2. Game screens.
A) Tennis game. The character had to be actively moved forward or backward to return the tennis ball that came flying at them. The objective was to reach the ball in good time. B) Skiing game. The character was moved to the left or right of the screen that was scrolling forward. The objective was to pass through the center of the gates on the course. C) Rodeo game. The character had to remain in the starting position irrespective of the disturbances occurring at irregular intervals.

In this study, each game was divided into four levels of difficulty so that each subject conducted balance training a total of 12 times.

For tennis, the character had to be actively moved forward or backward to return the tennis ball that came flying at them. The objective was to reach the ball in good time, and the degree of difficulty was adjusted by altering the number of balls and the racket width. For skiing, the character was moved to the left or right of the screen that was scrolling forward. The objective was to pass through the center of the gates on the course, and the degree of difficulty was adjusted by altering the number of gates. For rodeo, disturbances occurred at irregular intervals 16 times during the 90 seconds. The objective was for subjects to remain in the starting position, and the degree of difficulty was adjusted by altering the angle of inclination of the footplate and duration of inclination during the disturbances.

Four degrees of difficulty (level) were set for measurement. From level 1 through 4, the number of balls in tennis was increased gradually from 9 to 24, whereas the racket width (m) was decreased from 0.16 to 0.08. In skiing, the number of gates was increased from 22 to 58. In rodeo, the anteroposterior angle of inclination was increased from 1° to 3° and the duration of inclination was increased from 2 to 4 seconds. In levels 3 and 4 respectively, left-right inclination angles of 1.5° and 2° and inclination durations of 2.3 and 3 seconds were added as disturbances. All subjects performed sufficient practice before measurements. The order of games and degrees of difficulty during measurement were randomized for each subject using a random number table.

4. Surface electromyography

EMG was measured in a total of 16 muscles in both the left and right legs. These muscles were the gluteus maximus muscle, gluteus medius muscle, rectus femoris muscle, vastus medialis muscle, biceps femoris muscle, tibialis anterior muscle, gastrocnemius and peroneus longus muscle. The skin surface was wiped with cotton moistened with alcohol, and disposable electrodes (LecTrode; Sekisui Plastics Co., Ltd., Osaka, Japan) 10 mm in diameter were affixed 2 cm distally from the center of each muscle with a distance of 10 mm between electrodes. EMG was performed using a wireless EMG device (MQ16; Kissei Comtec Co., Ltd., Matsumoto, Japan). EMGs were A/D converted at a sampling frequency of 1,000 Hz, after which each waveform underwent 10−500 Hz band pulse filtering using KinemaTracer® (Kissei Comtec Co., Ltd., Matsumoto, Japan) to convert them into 20 Hz root mean square waveforms. Maximal voluntary isometric contraction (MVIC) was used for waveform normalization. The start and end signals for each game were given by trigger output from the BEAR. The 90-second integrated EMG values for each game were found and the MVIC per unit of time (%MVIC) was calculated.

5. Analysis methods

To examine changes in muscle activity in accordance with the degree of difficulty, the mean %MVIC of each muscle was calculated for all 14 limbs of the seven subjects. IBM SPSS Statistics 23 was used for statistical testing. Data for each game were tested using a repeated measures analysis of variance (ANOVA) and data were compared between games using a one-way ANOVA in addition to a Bonferroni post-hoc test. The level of statistical significance was set at 5%.

Results

Muscle activity increased in each game as the level of difficulty increased (Table 1). In tennis, muscle activity increased significantly in the gluteus medius muscle (p = .018), rectus femoris muscle (p = .025), vastus medialis muscle (p = .013), tibialis anterior muscle (p = .004) and gastrocnemius (p < .001). In skiing, muscle activity increased significantly in the gluteus medius muscle (p = .033), rectus femoris muscle (p = .004), vastus medialis muscle (p = .008), tibialis anterior muscle (p = .005), gastrocnemius (p = .019) and peroneus longus muscle (p = .043). In rodeo, muscle activity increased significantly in the gluteus medius muscle (p < .001), rectus femoris muscle (p < .001), vastus medialis muscle (p = .026), tibialis anterior muscle (p = .001), gastrocnemius (p = .001) and peroneus longus muscle (p = .002).

Muscle activity in each game was characterized by a marked increase as the degree of difficulty rose. In level 4 tennis, the greatest muscle activity was observed in the gastrocnemius (7.7 ± 3.9), followed by the peroneus longus muscle (4.4 ± 2.9). Muscle activity then decreased in order from the vastus medialis muscle (4.3 ± 2.9), biceps femoris muscle (4.1 ± 3.4), rectus femoris muscle (3.4 ± 1.8), gluteus medius muscle (3.3 ± 3.3) and tibialis anterior muscle (2.3 ± 1.5), with the lowest muscle activity observed in the gluteus maximus muscle (0.9 ± 0.6) (Figure 3). In level 4 skiing, the greatest muscle activity was observed in the peroneus longus muscle (9.8 ± 7.8), followed by the gastrocnemius (6.6 ± 5.3). Muscle activity then decreased in order from the vastus medialis muscle (4.5 ± 3.4), biceps femoris muscle (3.9 ± 1.8), gluteus medius muscle (3.3 ± 2.9), rectus femoris muscle (3.3 ± 1.8) and tibialis anterior muscle (2.5 ± 2.1), with the lowest muscle activity observed in the gluteus maximus muscle (1.3 ± 0.8) (Figure 4). In

Table 1. Average muscle activity in each game and the degrees of difficulty (%MVIC).

Tennis	Lv1	Lv2	Lv3	Lv4	*p*
Gluteus maximus	0.8 (0.5)	0.8 (0.5)	0.8 (0.5)	0.9 (0.6)	.23
Gluteus medius	2.6 (2.8)	2.4 (2.0)	2.6 (2.1)	3.3 (3.3)	.018
Rectus femoris	2.7 (1.8)	2.8 (1.9)	3.4 (2.3)	3.4 (1.8)	.025
Vastus medialis	2.8 (2.2)	3.1 (2.7)	3.5 (2.7)	4.3 (2.9)	.013
Biceps femoris	3.2 (3.6)	3.4 (3.1)	3.5 (3.5)	4.1 (3.4)	.056
Tibialis anterior	1.3 (0.8)	1.6 (1.0)	2.1 (2.0)	2.3 (1.5)	.004
Gastrocnemius	4.1 (2.2)	5.2 (3.0)	6.3 (2.9)	7.7 (3.9)	<.001
Peroneus longus	3.3 (2.3)	3.6 (3.1)	4.1 (3.2)	4.4 (2.9)	.191

Skiing	Lv1	Lv2	Lv3	Lv4	*p*
Gluteus maximus	1.0 (0.7)	1.0 (0.7)	1.1 (0.8)	1.3 (0.8)	.063
Gluteus medius	2.7 (2.4)	2.5 (1.9)	3.3 (2.9)	3.3 (2.9)	.033
Rectus femoris	2.3 (1.4)	2.6 (1.5)	2.9 (1.7)	3.3 (1.8)	.004
Vastus medialis	2.8 (2.3)	3.1 (1.9)	2.4 (1.3)	4.5 (3.4)	.008
Biceps femoris	3.8 (3.4)	3.6 (2.3)	3.2 (2.1)	3.9 (1.8)	.707
Tibialis anterior	1.3 (0.9)	1.5 (1.1)	2.2 (1.4)	2.5 (2.1)	.005
Gastrocnemius	4.4 (3.9)	5.5 (4.3)	5.7 (5.2)	6.6 (5.3)	.019
Peroneus longus	7,5 (5.9)	7.3 (6.5)	8.5 (6.3)	9.8 (7.8)	.043

Rodeo	Lv1	Lv2	Lv3	Lv4	*p*
Gluteus maximus	0.9 (0.6)	1.2 (0.8)	1.0 (0.8)	1.1 (0.7)	.198
Gluteus medius	2.5 (2.3)	3.2 (2.4)	4.6 (3.1)	5.1 (3.6)	<.001
Rectus femoris	2.6 (1.7)	3.7 (2.3)	4.1 (2.5)	4.4 (1.9)	.008
Vastus medialis	2.7 (2.4)	4.3 (2.0)	4.1 (3.7)	4.5 (2.9)	.026
Biceps femoris	3.1 (3.0)	4.2 (4.3)	3.6 (2.8)	4.2 (3.2)	.401
Tibialis anterior	1.4 (0.9)	2.8 (2.9)	4.0 (3.1)	4.8 (2.7)	.001
Gastrocnemius	5.7 (6.4)	8.7 (7.1)	10.4 (6.0)	11.5 (5.8)	.001
Peroneus longus	5.1 (5.2)	5.6 (5.5)	7.2 (4.5)	8.0 (4.7)	.002

Average muscle activity (standard deviation)
repeated measures ANOVA

level 4 rodeo, the greatest muscle activity was observed in the gastrocnemius (11.5 ± 5.8), just like in tennis, and this was followed by muscle activity in the peroneus longus muscle (8.0 ± 4.7). In contrast to tennis and skiing, muscle activity was also high in the gluteus medius muscle (5.1 ± 3.6) and tibialis anterior muscle (4.8 ± 2.7). Muscle activity then decreased in order from the vastus medialis muscle (4.5 ± 2.9), rectus femoris muscle (4.4 ± 1.9) and biceps femoris muscle (4.2 ± 3.2), with the lowest muscle activity observed in the gluteus maximus muscle (1.3 ± 0.8) (Figure 5). A comparison of games at level 4 indicated that tibialis anterior muscle activity was significantly greater during rodeo than during tennis ($p = .009$) and skiing ($p = .017$). Gastrocnemius muscle activity was also significantly greater during rodeo than during skiing ($p = .045$) and peroneus longus muscle activity was significantly greater during skiing than during tennis ($p = .041$) (Figure 6).

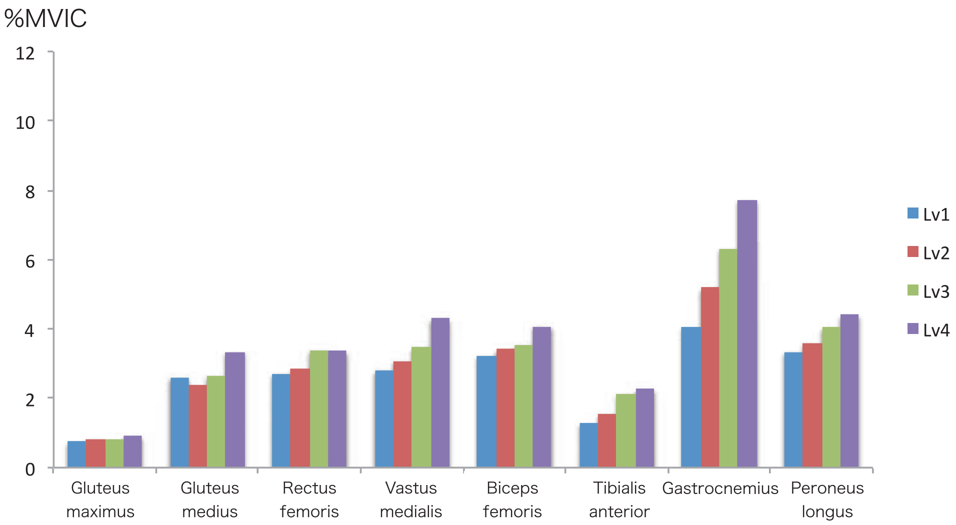

Figure 3. Changes in average muscle activity during tennis.
In tennis, the greatest muscle activity was observed in the gastrocnemius, followed by the peroneus longus. Muscle activity then decreased in order from the vastus medialis, biceps femoris, rectus femoris, gluteus medius and tibialis anterior, with the lowest muscle activity observed in the gluteus maximus.

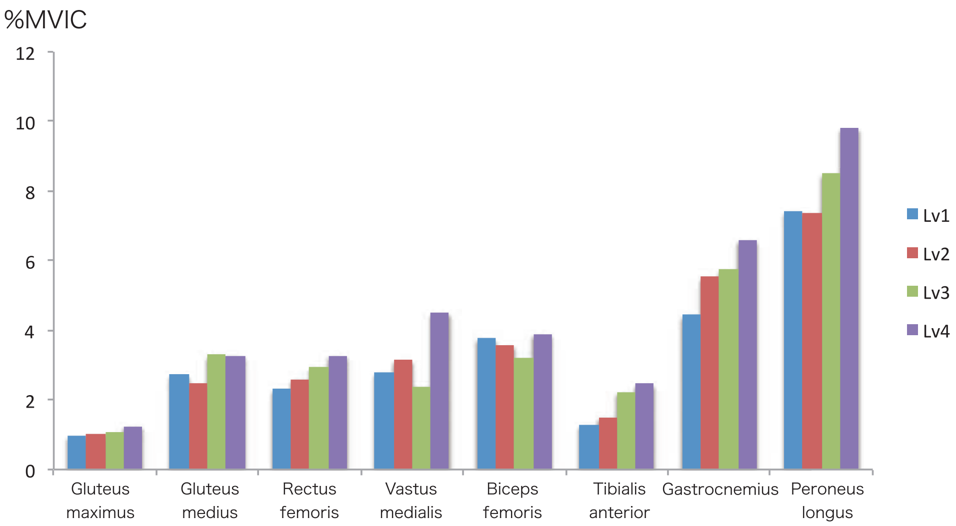

Figure 4. Changes in average muscle activity during skiing.
In skiing, the greatest muscle activity was observed in the peroneus longus, followed by the gastrocnemius. Muscle activity then decreased in order from the vastus medialis, biceps femoris, gluteus medius, rectus femoris and tibialis anterior, with the lowest muscle activity observed in the gluteus maximus.

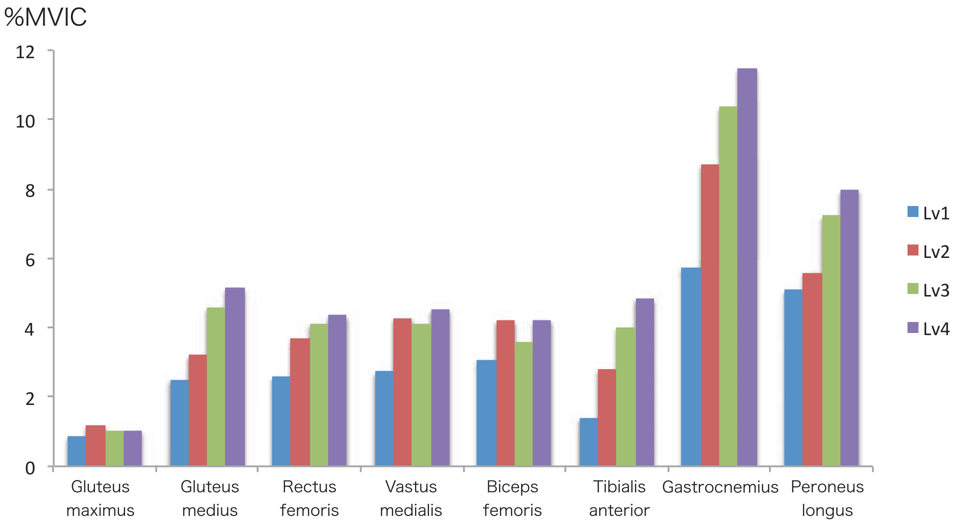

Figure 5. Changes in average muscle activity during rodeo.
In rodeo, the greatest muscle activity was observed in the gastrocnemius, like in tennis, and this was followed by muscle activity in the peroneus longus. In contrast to tennis and skiing, muscle activity was also high in the gluteus medius and tibialis anterior. Muscle activity then decreased in order from the vastus medialis, rectus femoris and biceps femoris, with the lowest muscle activity observed in the gluteus maximus.

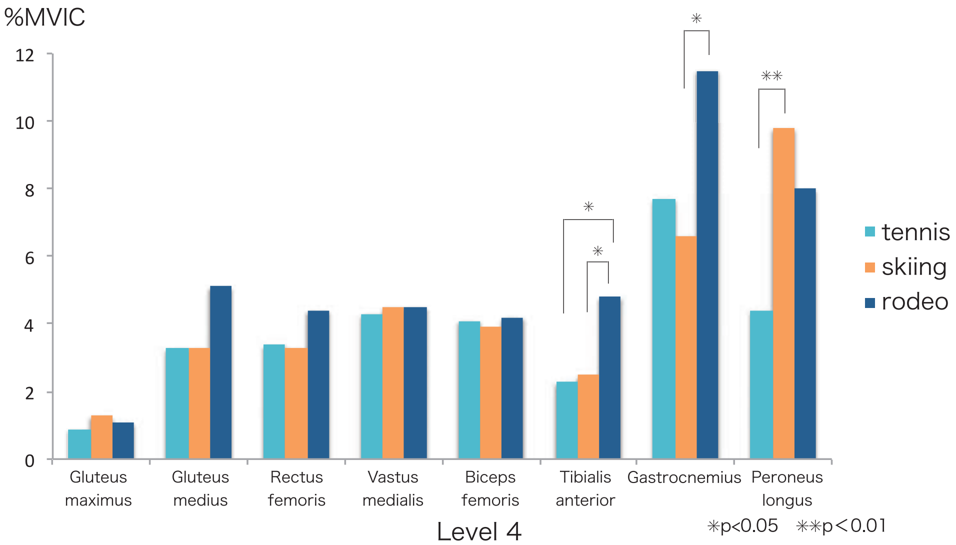

Figure 6. Comparison of the mean muscle activity between games.
Muscle activity in each game was characterized at level 4. Tibialis anterior muscle activity in rodeo was significantly greater than that in tennis and skiing. Gastrocnemius muscle activity in rodeo was also significantly greater than that in skiing, while peroneus longus muscle activity in skiing was significantly greater than that in tennis.

Discussion

In humans, the center of mass is maintained within the base of support in order to maintain balance while standing. By returning the center of mass to its original position during postural sway, the spatial location of the body can be continuously adjusted. Ankle and hip movements are considered to play an important role in adjusting standing balance. These methods of control are called the ankle strategy and hip strategy, respectively [13]. With the ankle strategy, the ankle creates torque, which moves the entire body as a single inverted pendulum to return the center of gravity to the base of support. This strategy is thought to function when there is little postural sway during quiet standing. Meanwhile, with the hip strategy, the body is moved like a double inverted pendulum with the ankle and hip joints moving in opposite directions in order to return the center of gravity to the base of support. This strategy functions during fast or intense postural sway. Van Ooteghem et al. [14] reports that when disturbance occurs, the ankle strategy is employed first. In addition, Runge et al. [15] conducted research using a disturbance device and reported that the hip strategy is employed in accordance with the necessary ankle torque concomitant with the ankle strategy. Creath et al. [16] reports that the ankle strategy is dominant when standing on a flat surface such as the floor, but this shifts to the hip strategy when standing on an unstable surface. Thus, the two strategies are not independent of each other, but rather function by adjusting in relation to one another in accordance with the extent of postural sway. Improvement of these two strategies is an important part of balance training. In the present study, the BEAR was used to conduct three types of balance training.

In all the games, activity of the gluteus medius muscle, rectus femoris muscle, vastus medialis muscle, tibialis anterior muscle and gastrocnemius increased significantly as the degree of difficulty rose. Hip abduction, knee extension and ankle dorsiflexion were found to work to maintain standing balance. These results suggested that the three games using the BEAR could be used for regular balance training through hip, knee and ankle exercises while adjusting the level of muscle activity in accordance with the degree of difficulty. It has been reported that elderly individuals feel anxiety and fear from past experiences of falls, making them prone to increased postural sway [17, 18]. Therefore, such individuals should start training with a smaller load. With the BEAR, it is easy to introduce balance training with lower loads, and the amount of load can also be adjusted in accordance with the individual's improvement in each game.

Tennis was a task in which center of gravity movement was adjusted forward and backward. Around the ankle, the greatest muscle activity was observed in the gastrocnemius, which revealed that the gastrocnemius plays an important role during active anteroposterior center of gravity movement. In skiing, the subjects adjusted center of gravity movement to the left and right. Unlike tennis, there was greater muscle activity in the peroneus longus muscle than in the gastrocnemius, which suggested that the increased amount of load placed on one leg as a result of moving the center of gravity to the left or right may have required control of ankle inversion and eversion. In rodeo, the subjects had to maintain the position of their center of gravity in relation to forward-backward and left-right disturbances. High levels of muscle activity in the gastrocnemius and peroneus longus muscle around the ankle were also observed during rodeo. Unlike tennis and skiing, there was also a considerable amount of tibialis anterior muscle activity.

These results suggested that rodeo required subjects to use an ankle strategy integrating ankle dorsiflexion and inversion/eversion to control the position of their center of gravity. Thus, our results revealed that the three games each promoted muscle activity in different leg muscles.

The purpose of postural control training is not just to master specific strategies in tasks to prevent or improve decreased balance ability, but also to enable the individual to implement these strategies in changing environmental conditions. This requires repeated practice of coordinated muscle movements of various patterns. The results of the present study revealed that the BEAR allows different leg muscles to be exercised through regular tasks, and that it has a particular effect on the activity of leg muscles used in the ankle strategy. However, changes in muscle activity of the gluteus maximus, which is a hip extensor used in the hip strategy, were not clarified.

This study had a number of limitations. These included the fact that because the subjects were healthy, they mainly used the ankle strategy. Moreover, the depth of the gluteus maximus muscle meant that surface EMG measurements were insufficient. Going forward, analyses of elderly individuals and patients with balance disorders will need to be conducted. Furthermore, in addition to muscle activity measurements, postural control patterns in each game could be compared by three-dimensional motion analysis of range of movement and changes in joint angles among other factors.

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