Integrated Sit-to-Stand and Stand-to-Sit Training System Providing Biofeedback Information and Physical Assistance to Hemiplegic Patients

Ryoichiro Shiraishi *, Hiroaki Kawamoto **, and Yoshiyuki Sankai **

Abstract: This paper proposes a novel sit-to-stand and stand-to-sit (STS) training system for hemiplegic patients with clonus. Most hemiplegic patients depend on the unaffected leg and perform plantar flexion involuntarily during STS movements. The developed system integrates a visual biofeedback method with a movement assistance mechanism. The system provides users' ground reaction force (GRF) through a monitor and supports STS movements by moving the seat. We also proposed STS training with physical inhibition by using the developed orthosis to manage clonus. We performed an experiment on a hemiplegic patient who experienced clonus in the affected leg to verify that the user was able to increase the GRF of the heel part (GRFh) of the affected leg while performing STS movements using the system and that the system employing the orthosis reduced clonus. The results showed that GRFh in the intervention test that employed the proposed system was greater than that in the baseline test without the system. We also verified that a significant difference existed between the baseline and intervention test results (p < 0.05). In addition, when the orthosis was used, the participant was able to prevent muscle cramps resulting from the clonus by avoiding the contraction of the affected leg muscles. The results indicated that STS training using the system helped the user to increase GRFh and reduce the clonus. In addition, from the viewpoint of motor learning, we deduced that an integrated assistive system with informatics-based biofeedback and physical human-machine interaction would be effective in reconstructing the feedback loop in users' central nervous system.

Key Words: hemiplegic patients, sit-to-stand and stand-to-sit movements, motor learning, human-machine interaction, biomedical engineering.

1. Introduction

Hemiplegia, which results from stroke or head injury, is the paralysis of one side of the body. One characteristic of most hemiplegic patients is that they are dependent on the unaffected leg to stand up and sit down. Though it would be desirable for both the legs to be used equally and for the center of pressure of the body to be in the center between the two feet, these patients find it difficult to increase the usage of the affected leg. They cannot recognize the motor information generated by sensory organs in relation to the affected leg because of sensory disturbance in this leg. In particular, in cases where hemiplegic wheelchair users depend on the unaffected leg to stand up and sit down, not only does the motor and physiological functions of the affected leg gradually decline but the physical burden on the unaffected leg also increases [1],[2]. To reduce such risks, it is important to ensure that patients recognize motor information and learn how to increase the usage of the affected leg.

We previously developed a new sit-to-stand and stand-to-sit (STS) training system for hemiplegic patients to improve their STS movements [3]. The system, which integrated a visual biofeedback method with a physical movement assistance mechanism, could provide users with motor information and supplement their STS movements. In the previous study, we defined the ground reaction force (GRF) to indicate the usage of the affected and unaffected legs and the GRFs were calculated by summing the strain values of load cells at the toe and heel parts. The results showed that by using the system, hemiplegic participants were able to increase the GRF of the affected leg and equalize the GRFs of the affected and unaffected legs. However, in an analysis after the test, when we divided the GRFs into those of the toe and heel parts of the affected patients, we found that the GRF of the toe part was greater than that of the heel part [3]. The users tried to perform plantar flexion to increase the GRF of the affected leg. Most hemiplegic patients often perform plantar flexion involuntarily because of Wernicke-Mann’s posture [4]. STS movements with excessive ankle stretch are different from the STS movements of an able-bodied person, who generally places his or her weight on the heel first while performing STS movements [5]. This phenomenon was confirmed from the GRF trajectory results for the unaffected leg in previous STS training studies [3]. We considered that STS movements made without touching the heel to the ground would be unstable and would make it difficult to increase the usage of the affected leg. The GRF of the heel part (GRFh) would need to be increased before the patient can increase the usage of the affected leg. Then, the patients can perform training aimed at equalizing the usage of the affected and unaffected legs. In addition, a participant experienced clonus during STS movements while using the system. Once clonus occurred, we had to intervene and stop the clonus because the participant was not able to stop it unaided. Clonus
and the GRF sensor is fixed to it by using bolts. The orthosis is made from polycarbonate by using a 3D printer, to users’ heels along with the GRF sensors as shown in Fig. 1. The orthosis assists the users’ feet in maintaining the condition because the phases are designed such that it provides GRFh instead of the total GRF. Thus, the proposed system provides an actual GRFh value and a specific target GRFh to focus on promoting the usage of the GRFh. The target value is calculated from the previous performance score, and specific goals are set to enhance patients’ motivation [14]. The system also has four control phases (phases 1–4), and the difficulty of the training can be changed by adjusting the target value. In addition, the movement speed of the seat can be adjusted by PID position control. When the speed is high and the difference between the actual and target seat positions is large, users can receive substantial assistance from the system. Therefore, the amount of movement assistance depends on the speed of the seat per unit time.

Figure 1 shows the variations in GRFh and the condition of the seat in each control phase in the STS training. When GRFh is less than the target value, the system is said to be in phase 1. In this phase, users understand that the GRFh value is not sufficient and they aim to increase GRFh by modifying their posture and movement. When GRFh becomes greater than the target value, the system is said to be in phase 2 or 3. The seat moves up in phase 2 to assist sit-to-stand movement and moves down in phase 3 to assist stand-to-sit movement. In these phases, the users try to maintain the condition because the phases are designated as proper conditions in the training. If the users abort the posture or stop maintaining the condition, the phase changes to

2. Methods

2.1 STS Support System

We have developed an STS support system that integrates GRF sensors and a graphical monitor with a movement assistance mechanism. The system measures users’ GRFs during STS movements and provides the users with quantitative motor information through a PC monitor. The GRF sensor consists of two load cells, which are placed in the front and rear parts of the sensor. The GRFs of both the legs are divided into those of the toe and heel parts, so that users can know the GRFs of the affected leg by looking at the monitor. In addition to GRFh, we defined the GRF of the toe part as GRFt. The previous works used commercial equipment to measure the GRFs [8],[10], but we developed a new measurement method, wherein the user’s foot was fixed to the floor, thereby ensuring that the heel touched the floor. Providing motor information from outside the body is called biofeedback, and this method is employed in training and rehabilitation fields [11]–[13]. The proposed system also assists users’ STS movements by moving the seat. Users can see their motor information and receive assistance simultaneously. The system can promote users’ motor learning by providing informatics-based biofeedback and physical assistance.

Moreover, the system consists of an orthosis that is attached to users’ heels along with the GRF sensors as shown in Fig. 1. The orthosis is made from polycarbonate by using a 3D printer, and the GRF sensor is fixed to it by using bolts. The orthosis controls the users’ foot freedom by fixing their ankle and prevents them from standing on their toes, which causes clonus to occur easily. In cases where users experience clonus in their affected leg, we recommend the use of the orthosis because such users will have difficulty in placing their heels on the ground.

2.2 Control Methods for STS Training

The aim of the training using the developed system is to perform STS movements such that GRFh increases with the stretching and bending of the lower limbs. The system provides users with information about proper and improper conditions so that they can understand how to perform proper movements. In a previous study [3], the system provided the total GRF of the toe and heel parts. However, to learn how to increase GRFh, the biofeedback information should be improved such that it provides GRFh instead of the total GRF. Thus, the proposed system provides an actual GRFh value and a specific target GRFh to focus on promoting the usage of the GRFh. The target value is calculated from the previous performance score, and specific goals are set to enhance patients’ motivation [14]. The system also has four control phases (phases 1–4), and the graphical motor information changes in each phase. The difficulty of the training can be changed by adjusting the target value. In addition, the movement speed of the seat can be adjusted by PID position control. When the speed is high and the difference between the actual and target seat positions is large, users can receive substantial assistance from the system. Therefore, the amount of movement assistance depends on the speed of the seat per unit time.

Figure 2 shows the variations in GRFh and the condition of the seat in each control phase in the STS training. When GRFh is less than the target value, the system is said to be in phase 1. In this phase, users understand that the GRFh value is not sufficient and they aim to increase GRFh by modifying their posture and movement. When GRFh becomes greater than the target value, the system is said to be in phase 2 or 3. The seat moves up in phase 2 to assist sit-to-stand movement and moves down in phase 3 to assist stand-to-sit movement. In these phases, the users try to maintain the condition because the phases are designated as proper conditions in the training. If the users abort the posture or stop maintaining the condition, the phase changes to
Fig. 2 Relationship between GRFh and each control phase. In phase 1, the seat does not move because the system judges that users are not going to stand up or sit down. In phases 2 and 3, the system provides physical assistance to supplement the users’ STS movement abilities. In phase 4, the system warns the users about an improper condition (GRFh indicated in red color) and does not provide any physical assistance.

<table>
<thead>
<tr>
<th>Phase</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<tbody>
<tr>
<td>GRFh</td>
<td>&lt; Target value</td>
<td>≥ Target value</td>
<td>&lt; 0</td>
<td></td>
</tr>
<tr>
<td>Seat</td>
<td>(Stop)</td>
<td>Move up</td>
<td>Move down</td>
<td>Stop</td>
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1 or 4 from 2 or 3. When the GRFh value becomes negative, the system is said to be in phase 4. Because the users’ affected foot is fixed using the orthosis, GRFh becomes negative when the users perform plantar flexion. In phase 4, the users try to stop flexing their foot because the movement is not proper. The color of the GRFh bar changes from blue (phase 1) to green (phases 2 and 3) and red (phase 4). Trial-and-error procedures carried out during the intervention test for various patients indicate that they can understand the conditions easily by looking at the color changes rather than by changing waveforms or numeric values. Most hemiplegic patients are elderly and they can understand intuitive information easily.

3. Experiment

3.1 Participant

We administered the training to the same patient considered in the preliminary test. The participant is a 61-year-old female patient with hemiplegia on the left side resulting from stroke (Height: 162 cm, Weight: 62 kg, Brunstrom stage: upper limb II, lower limb IV, Modified Ashworth Scale: upper limb 0, lower limb 1, foot ankle in muscle contraction 3, Barthel Index: 80/100). To perform her daily activities, she uses a wheelchair and is able to barely walk 10 m. She has been undergoing walking training once a week at a special facility for more than a year and home rehabilitation three times a week for seven years. She can stand up and sit down by using a handrail, but she often experiences involuntary clonus during STS movements. Once clonus occurs, she cannot control the affected leg. She signed informed consent before participating in the experiment.

3.2 Procedure

We performed a baseline test before the STS training to measure motor ability. Thereafter, on the same day, we performed the baseline and intervention tests and the STS training using the system for approximately 30 min. In the test, the participant rose from a chair repeatedly (10 times) without using the system and the GRFs were measured during the movements. The chair height was 450 mm from the ground, and a handrail or desk was used to prevent falling. The participant was asked to increase GRFh as much as possible.

A new type of STS training was carried out with visual biofeedback and movement assistance. The participant performed STS movements using the system 10 times and participated in the training once a week for three weeks. She was asked to increase GRFh and maintain phases 2 and 3. In cases where clonus occurred, she was asked to stop the movement. User comments were collected during and after testing.

3.3 Analysis

The calculation process for the mean GRFh during the STS movements in the baseline test is the same as that in the previous study [3]. The mean GRFh in the intervention test is calculated by using the GRFh values obtained in phase 2 or 3. Both the GRF values are recorded at a sampling frequency of 100 Hz and saved as text data. We calculate the means by using a spreadsheet application. To eliminate the effect of the tightening force of the orthosis, the GRF is calibrated for the situation in which the foot is on the GRF sensor and is fixed using the orthosis. Similarly, in the baseline test, the GRF is calibrated for the situation in which the foot is on the GRF sensor. We compare the GRFh value obtained in the baseline test with that obtained in the intervention test to evaluate the improvement effect produced by the system. We also compare both GRFh and GRFt obtained in the proposed test with those obtained in the previous test to evaluate the changes in the GRF.

4. Results

Figure 3 shows the GRFh values for the sit-to-stand and stand-to-sit movements. We verified that GRFh in the intervention test using the system was greater than that in the baseline test without using the system for not only the sit-to-stand movement but also the stand-to-sit movement. We also verified that a significant difference existed between the baseline and intervention test results (p < 0.05). According to the comments of the participant, she was able to understand how to increase GRFh and was somehow able to feel the load on her heel. Sometimes, she performed the training without looking at the monitor to feel the sensation of the heel part of the affected leg.

Figures 4 and 5 show the GRFh and GRFt values obtained during the training with and with the orthosis. When the ortho-
Fig. 3 GRFh values obtained in baseline test and new intervention test.

Fig. 4 Occurrence of clonus when using orthosis. In cases where clonus occurs, it is relieved after a few seconds.

Fig. 5 Occurrence of clonus without using orthosis. In cases where clonus occurs, it continues for 10 s or more because the participant cannot relieve it.

Fig. 6 Comparison of GRFh and GRFt values between proposed and previous tests [3].

5. Discussion

5.1 STS Training with Increasing GRFh

At the SICE Annual Conference 2016, we conducted GRFh training in four static postures because the participants could not increase GRFh while they were stretching and bending their lower limbs [9]. STS movements involve multiple tasks, and patients find it difficult to perform them. Therefore, we divided the STS movements into simple tasks to decrease the difficulty of the movements. Even when we asked the participant to perform these simple tasks, she could not complete them because biofeedback was not provided. However, when biofeedback was provided, she was able to place the weight on her heel. To get her accustomed to placing the weight on her heel, we asked her to perform the training in the walking posture wherein GRFh increased easily because of the natural body structure. After the training was performed several times, she gradually understood how to control the affected leg and maintain proper body posture. Under the guidance of physical therapists, the system moved the seat gradually when GRFh became greater than the target value. The results of this experiment (Fig. 3) showed that the participant was able to increase GRFh even though her limbs were stretching and bending. In addition, the participant was able to stop the muscle cramps resulting from the clonus by avoiding the contraction of the affected leg muscles when the foot of her affected leg was fixed using the orthosis. The system with the orthosis helped to reduce the clonus and decrease the period for which clonus continuously occurred. In an additional test performed in previous studies, we verified that when clonus occurred while the participant was wearing a common orthosis, she could not stop the clonus on her own and another person, usually a physical therapist, had to relieve it by providing leg massages. However, the proposed STS training does not require another person because she can stop the clonus by using the orthosis. Thus, the training is expected to be advantageous for patients with clonus and for physical therapists.

We started this research with the aim to develop a system for hemiplegic patients suffering from stroke and for physical therapists who help patients to increase the usage of the affected leg during STS movements. In our previous study, we proposed STS training to increase the usage of the affected leg and equalize the usage of the affected and unaffected legs [3].
In this training, the system provided users with the total GRF consisting of GRFt and GRFh. The results of the previous research (Fig. 6) indicated that GRFt was considerably larger than GRFh. The users tried to increase GRFt to increase the total GRF. We considered that increasing the usage of the affected leg would be difficult during the STS movements unless the heel of the affected leg touched the ground. Thus, we proposed a new type of STS training to increase GRFh. The results shown in Fig. 6 indicate that by conducting the proposed STS training, the participant was able to increase the GRFh to a level higher than that achieved in the previous study. At present, the total GRF values obtained in this study were less than those obtained in the previous study, but by conducting the training continuously, the total GRF values obtained in this study would be larger than those obtained in the previous study, and the participant would be able to perform the STS movements such that the heel of the affected leg touched the ground.

Hemiplegic wheelchair users hardly move their lower limb every day. While standing up or sitting down, most of them use their unaffected leg quite often. They can live without difficulty by extensively using the unaffected side rather than by equally using the affected side. This behavior is called learned non-use [15]. If they continue such movements, the motor and physiological functions of the affected leg will gradually decline and the joints of the affected leg will begin to hurt. Therefore, it is important to remove their learned non-use and to decrease the difference in the usage between the affected and unaffected legs. One of the problems of such patients is that the heel of their affected leg does not touch the ground at all during STS movements because they often perform plantar flexion involuntarily because of Wernicke-Mann’s posture [4]. In this condition, the risk of falling increases and clonus occurs easily. In normal STS movements, the center of body mass is transferred to the heel and GRFh increases before the increase in GRFt [5]. Moreover, because the heel of the unaffected leg is on the ground, the body weight is easily placed on the unaffected side when the upper body leans forward. As long as the heel of the affected leg stays off the ground, learned non-use would be encouraged. From the viewpoint of biomechanics, we consider that it is necessary to place the heel of the affected leg on the ground to increase the usage of the affected leg. Therefore, we proposed a new type of training (basic training of STS movements) that allowed users to learn to place the weight on the heel of the affected leg.

5.2 Man-Machine Interaction and Motor Learning

A training system would be required to control not only the movements of hemiplegic patients but also the learning process in their central nervous system (CNS). Although the participant has undergone walking and standing training for a few years, she is still a wheelchair user and cannot walk a long distance. However, we verified that after she used the system only for a few times, she understood how to place the weight on her heel. In a previous study [3], we also verified that two participants improved their STS movements by attending only three training sessions. We consider that there are differences in motor learning when training with and without the proposed system. From the results of the previous and present studies, we discuss the mechanisms of motor learning and motor improvement by considering informatics-based biofeedback and physical human-machine interaction.

Figure 7 shows the block diagram of human hemiplegic patients with clonus. The diagram shows sensory and motor functions by distinguishing between informatics signals and physical effects. The solid lines represent the physical effects, and the dashed lines represent the informatics signals. As in the case of a machine, the human body consists of a processing system (the CNS), effectors (limbs), and receptors (sensory organs). Generally, human beings can learn and modify movements by constructing a feedback loop [16]–[18]. However, hemiplegic patients have difficulty in constructing the feedback loop for motor learning because they experience motor and sensory disturbance. To achieve optimum control, proper movements should be performed so that the error between the target and actual values is reduced to zero. The aim of the training using the proposed system is to increase GRFh, and the error denotes the difference between the actual and target GRFh values. In Fig. 7, $\Delta e_i$ represents an error determined internally within the body between the target and actual GRFh values from the sensory system. The “Target” in this figure represents the desired usage of the affected and unaffected legs and denotes the GRF values required for the users to maintain the proper condition. Patients have to understand the error to perform proper STS movements, but they cannot recognize the actual GRFh. Actually, they hardly feel the load on their heel. We consider that they cannot control the feedback gain because of sensory disturbance (Fig. 7(a1)). Feedback gain is an important function to recognize the conditions of the entire system and make adjustments according to changes in the conditions. However, the patients do not know how to increase the feedback gain for STS movements. Some of them may understand the concept of $\Delta e_i$, but $\Delta e_i$ is a qualitative value and is dependent on the patients. By conducting training based on a qualitative target, it would be difficult to adjust the difficulty of the training and keep the patients motivated to continue the training. In addition, patients try to move the affected leg to increase GRFh, but they cannot move the affected leg at will because they also experience motor disturbance in the affected leg (Fig. 7(b1)). We also consider that they cannot adjust the feedback controller to output proper command signals. The feedback controller is also an important function that controls the system and decreases the error. In the case of the control system, unless the feedback gain functions properly, the condition of the system becomes unobservable. Similarly, unless the feedback controller functions properly, the system becomes uncontrollable. Stroke patients suffer from brain damage, and their feedback controller and feedback gain in the CNS are likely to be defective. Hence, the feedback loop is not constructed properly and motor learning is not encouraged. For these reasons, they have difficulty in controlling their movements.

Furthermore, patients having clonus find it more difficult to control their affected leg. It is believed that clonus occurs because of hyperactive stretch reflexes in the affected muscle [19] (Fig. 7(c1)). When clonus occurs, the command signals of the affected leg might be inputted repeatedly (Fig. 7(d1)). Therefore, the patients might not be able to control their affected leg because the involuntary signals occur outside the limit of the feedback controller. We consider that it is necessary to add an external inhibitory system to the motor system of such patients to manage clonus.
Fig. 7 Block diagram for hemiplegic patients. Hemiplegic patients cannot recognize their motor information from the sensory system because they experience sensory disturbance in the affected leg (a1). Though they also intend to increase the amount of muscle exertion, they cannot control their motor system at will and cannot perform complex STS movements (b1). We consider that the patients cannot control the feedback gain and cannot adjust the feedback controller to output proper command signals. Therefore, the feedback loop is not constructed properly and motor learning is not encouraged. Moreover, some of them experience clonus, which occurs because of hyperactive stretch reflexes in the affected muscle (c1). When experiencing clonus, they cannot control the affected leg by themselves (d1).

Fig. 8 Block diagram showing interaction between hemiplegic patients and STS training system. By visual biofeedback, the users understand the motor information pertaining to the affected leg, and the feedback loop in the CNS is reconstructed (a2). It is difficult for them to increase GRFh while performing STS movements, but the system assists their movements by moving the seat (b2). The users adjust the feedback controller when they recognize $\Delta e$. We consider that if they are able to reduce $\Delta e$ to zero, they can learn how to adjust the feedback controller. Moreover, physical inhibition using the orthosis relieves clonus during the training (c2).

Figure 8 shows an enhanced diagram that consists of human-machine interaction loops. The machine measures the foot load using GRF sensors and converts the physical quantities to digital quantities. The error $\Delta e$, between the target and actual GRFh values is presented to the human body via external means. By looking at the PC monitor, users can know the error value quantitatively. The feedback loop through the CNS in the human body is reconstructed by visual biofeedback (Fig. 8 (a2)). One of the reasons that biofeedback methods are employed in the training and rehabilitation fields is to realize task-specific training [20]. In training, it is highly recommended that quantitative and specific goals be set up [21]. Moreover, the proposed system can adjust the difficulty of the training by controlling the target GRFh value and the amount of movement assistance. In STS movements, human beings are required to control their body balance while stretching and bending lower limbs. Patients find it difficult to perform this complex task. However, users of the proposed system can undergo the STS training at a decreased difficulty level because the machine provides physical motor assistance and supplements a part of the energy spent in muscle exertion (Fig. 8 (b2)). If the system does not assist the patients, they cannot place the weight on their heel while performing the STS movements and they perform these movements by depending on the unaffected leg as usual. The system
makes them aware of their GRFh and supplements their motor abilities to stretch and bend their lower limb.

Finally, it is important to manage clonus or spasticity during training [22]. In cases where clonus occurs, users tend to relax the affected leg. During this time, we consider that the magnitude of the command signal is decreased to reduce the oscillation phenomenon. The users can recognize the relaxed condition of the affected leg by looking at the decrease in GRFh and GRFt and can learn how to relax the affected leg. The users can also receive external physical inhibition from the orthosis (Fig. 8 (c2)). Owing to these two strategies, the users can relieve clonus by themselves and concentrate on the training.

Machine-based training provides informatics-based biofeedback and physical human-machine interaction. We consider that the functional training has the following advantages: it provides users with a specific goal, and it controls the difficulty of training. Machine-based training controls and promotes motor learning in users while simultaneously controlling their motor and sensory functions. According to the participant’s comment, she was able to understand how to increase GRFh and was able to somehow feel the load on her heel by undergoing the training. Users adjust the feedback controller when they recognize $\Delta e_r$. We consider that if they are able to reduce $\Delta e_r$ to zero, they can learn how to adjust the feedback controller. The users adjust the feedback gain at the same time that they recognize $\Delta e_d$, that is, the distance between $\Delta e_t$ and $\Delta e_r$, as shown in Fig. 9 (a). We also consider that if they are able to reduce $\Delta e_d$ to zero, they can learn how to adjust the feedback gain.

In our consideration, motor learning for hemiplegic patients is defined as the process of reducing each error to zero while controlling the feedback gain and feedback controller. The users can construct a feedforward model in their CNS by adjusting the feedback controller repeatedly (Fig. 9 (b)). The improvement of the motor functions involves the reacquisition of the feedforward model that they had previously acquired before they suffered a stroke. Owing to the feedforward model, the users can move properly before they recognize each error. By using the feedforward model and proper feedback controller, they can make their command signal to converge at the optimum value (Fig. 9 (c)). It would be important to relearn the relationship of neurotransmissions between the brain-nervous system and the body to acquire a capacity for adaptation. Based on the results of previous and present studies, we verified that users improved their STS movements by using the proposed system. Therefore, we deduced that an integrated assistive system with informatics-based biofeedback and physical human-machine interaction would be effective in reconstructing the feedback loop in users’ CNS. This aspect would be discussed further when studying informatics-based biofeedback and physical human-machine interactions for motor learning and control in people with disabilities and in neuroscience fields.

5.3 Unilateral and Bilateral Training

We have proposed a new type of STS training using the assistive system for hemiplegic patients to increase the usage of the affected leg and equalize the usage of the affected and unaffected legs. Training that focuses on promoting the usage of the affected leg, such as the training method presented in this paper, is called unilateral training or constraint-induced movement therapy [23],[24]. On the other hand, training that realizes coordinated movements between both the legs, such as the one developed in our previous study, is called bilateral training [25]. STS movements are difficult exercises for hemiplegic patients because they are required to perform the following four tasks at the same time:

1. Increase GRFh such that it is greater than GRFt.
2. Increase the sum GRF of the affected leg.
3. Equalize the GRFs of the unaffected and affected legs.
4. Stretch and bend lower limbs.

The static training developed in the previous study concerns only task (1) [9]. In this study, we conducted training that enables users to perform tasks (1) and (4) while performing STS movements. To realize tasks (2) and (3), the patients should control both their legs. Thus, the proposed training is considered to be basic training of STS movements for hemiplegic patients. In bilateral training, coordinated movements that decrease the excessive usage of the unaffected leg and increase the usage of the affected leg are required. Human-machine interaction in bilateral training is more complex than that in unilateral training. In the future, we will continue the training to improve the STS movements of hemiplegic patients and compare the results of an intervention group with those of a control group to evaluate the improvement effectiveness of the system. We also plan to conduct bilateral training to improve the users’ motor ability.

6. Conclusion

We proposed a novel STS training system that aims to help hemiplegic patients with clonus by increasing the GRF of the heel in the affected leg. We considered that it is important for such patients to learn how to place the weight on their heel from the viewpoint of biomechanics. To focus on promoting the usage of the GRF of the heel part (GRFh), the system provided GRFh instead of the total GRF of the toe and heel parts. We performed an experiment on the same hemiplegic patient considered in the previous study to verify that the user was able to increase the GRFh of the affected leg while stretching and bending the lower limbs and that the system using the orthosis reduced the clonus; this verification is considered to be an initial step toward the development of an assistive system. The results indicated that GRFh in the intervention test that employed the proposed system was greater than that in the baseline test without the proposed system. We also verified that a significant difference existed between the baseline and intervention.
test results (p < 0.05). In addition, by using the orthosis, the user was able to stop the clonus without assistance from another person. Moreover, we deduced that an integrated training system with biofeedback information and physical assistance would be effective in performing functional training. These results and considerations suggest that it is necessary to reconstruct the feedback loop in the central nervous system to improve the motor functions.

In the future, we intend to continue the training for various hemiplegic patients to verify the effectiveness of the STS training using the assistive system.

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