Balance Control Learning Method for Improving Pulling Chair Movement: A Case Study of a Quadriplegic Wheelchair User

Ryoichiro SHIRAISHI,*, **, # Yoshiyuki SANKAI ***

Abstract This paper proposes a specific method of balance control learning at a half-rising posture using an assistive system for improving the pulling chair movement, and reports a case study of a quadriplegic wheelchair user. The system provides informatics-based biofeedback and user weight support. It does not require attaching any equipment or sensor to the user’s body. Although our participant was able to transfer from a wheelchair to a chair, she was not able to pull a chair until the desired position. We analyzed the physical kinematics and kinetics during pulling chair movement and developed a balance control learning method that enables the user to move the center of gravity (COG) backward when assuming a deep half-rising posture. We conducted an experiment on a quadriplegic participant once a week for four weeks. Before learning, the participant was not able to realize the pulling chair movement even though a lot of time was provided. However, after learning, the participant could move the COG backward when attempting to realize the half-rising posture, and pull a chair completely. This case proved our hypothesis that a half-rising posture with backward shifting of the center of pressure is effective in improving the pulling chair movement. Through the experiment, we achieved proof of concept of the proposed learning method and the first case study of successful application of the method.

Keywords: balance control learning, half-rising posture, pulling chair, support system, wheelchair user.


1. Introduction

Balance control of the body is an important ability in maintaining a standing posture and in performing sit-to-stand transfer and gait. The decline of the balance control ability and an unstable center of gravity (COG) often induce falls and fear of standing. As such, they are considered as important falling risk factors [1]. Thus, some wheelchair users who are paralyzed are forced to use their wheelchair when they are at home or outdoors, to prevent falls and injury. The lack of balance control ability eliminates the possibility of living without having to use a wheelchair. Although balance training at an upright standing posture is often performed at rehabilitation sites, balance control at the half-rising posture is also needed for independent living. In addition to the sit-to-stand movement, we focus on balance control for wheelchair users. In order to pull a chair, they must be able to realize a half-rising posture by exerting strong muscle force and by performing postural control simultaneously. If wheelchair users cannot achieve the pulling chair movement, they cannot approach or work at a desk even though they can transfer themselves from their wheelchair to a chair. Being unable to perform the pulling chair movement is a limiting factor to the possibility of living without the use of a wheelchair. Therefore, a specific balance control training method at a half-rising posture would be useful in realizing the pulling chair movement.

Several studies have proposed balance control learning using an assistive system for physically challenged persons such as the elderly [2] and stroke patients [3–7]. Mostly, balance training is performed to improve an upright standing posture or a sit-to-stand transfer. Very few case studies that apply balance training to improve movement at a half-rising posture have been reported. Thus, there is a need to analyze the movement of the pulling chair task for designing a balance training method based on the characteristics of the movements involved. In addition, some balance training methods use a simple force platform [4, 5]. Although such training can be conducted easily, these methods target people who can stand stably and they lack any safety function to prevent falling or knee buckling. In order to prevent falls, some systems require the patient to either use a harness [2, 3] or wear/attach a system on their body [6, 7]. However, these balance training methods require physical therapists to attach the equipment. Training methods that require the assistance of therapy specialists often limit the amount of training time of the patients. A safety function without attachment would be effective in promoting active balance training and also advantageous for both patients and therapists.

We propose a support system for sit-to-stand and balance control learning aiming to improve the movements of hemiplegic or paraplegic patients [8–10]. This support system does not require attachment of any equipment and can be used without assistance from therapists. The preliminary study showed that the user was able to move the COG wider during the test with this system compared to the test without the system. However, we did not confirm the improvement of the pulling chair movement by con-
ducting continuous intervention. We propose a specific balance control learning method to execute the pulling chair movement and report the experimental result before and after the intervention.

2. Physical Analysis

When a person pulls a chair forward to approach a desk and sit on the chair, he/she has to exert strong muscle force for performing a half-rising posture and controlling the postural balance simultaneously. It would be difficult for patients with lower limb paralysis to learn how to execute this movement, because the pulling chair movement is a multi-task that controls muscle exertion and body balance. To enable such patients to acquire the movement effectively, we divided the pulling chair movement into simple tasks so that they could perform them easily from the viewpoint of task-specific training [11]. Then, we analyzed the kinematics and kinetics of the pulling chair movement to propose a new balance learning method for the participant.

In the pulling chair movement, it is important to control the posture to make space between the person, the chair, and the desk. With little space between the person and the chair, the person cannot pull the chair because the chair touches his/her body. Furthermore, with little space between the person and the desk, the person is unable to pull the chair because the upper body touches the desk. According to human postural research, human beings control their posture by adjusting hip and ankle joint angles [12]. Figure 1 shows two different types of half-rising postures (Models A and B). In this study, we used the deep half-rising posture because the posture is similar to that during the pulling chair movement [13]. Using half-rising posture, we designed a human model of pulling a chair until the chair touches the back of the thigh and moving forward until the body touches the desk. Figure 2 shows the relative positions between the person, a desk, and a chair at the above-mentioned two postures, and indicates the condition at which the body touches the chair and the desk. As shown in this figure, the distance between the front of the chair and the leg of the desk is two times longer in Model A than in Model B. This indicates that the posture of Model B is more appropriate compared to Model A with regard to the pulling chair movement. In order for Model A to move nearer the desk, the person needs to place the feet forward and raise the upper body. The two postures differ not only in the joint angle but also the COG. The COG position of Model A is at the front of the feet, while that of Model B is at the rear of the feet, as shown in Fig. 3. For these reasons, we hypothesize that the person can accomplish the pulling chair movement efficiently if he/she moves the COG position backward at the half-rising posture.

3. Methods

3.1 Support System

As shown in Fig. 4, the proposed system integrates a commercially available wheelchair with a support unit and comprises a ground reaction force (GRF) sensor, battery, seat reaction force (SRF) sensor, and monitor. A wheelchair support system is used to allow wheelchair users to do daily active exercise. The system has the same components and functions as the model described previously [8–10]. It is a support system for sit-to-stand movement that can also be applied to improve balance control. The characteristics of the system are as follows: the user’s weight is supported by the seat without attaching a harness and arbitrary half-rising posture is supported by adjusting the seat height based on the user’s balance control ability. Users can perform balance control at shallow or deep half-rising posture just by sitting in the system. Even if knee bulking occurs, users do not fall from the system because the seat of the system is located just under their buttocks. The GRF sensor measures the center of pressure (COP) using four load cells, including strain gauges, to estimate the COG of the user. In addition, the system provides quantitative COP values visually as biofeedback.

3.2 Balance control Learning

The biofeedback on the monitor includes the present COP position, target COP position, present total GRF value, and target total GRF value, as shown in Fig. 5(a). Biofeedback is often utilized to promote motor learning in the central nerve system (CNS). The target COP positions are divided into nine areas by the four target values. The monitor draws a rectangle based on the present COP position.
position and total GRF values. When the present total GRF value exceeds the target value, the color of the rectangle turns green from red. The proper condition of balance control is to draw the green rectangle to a rear position, as shown in Fig. 5(b). In addition, the difficulty level of the method is adjustable by setting the target COP position. In the case where the value of the target COP position of the rear area increases, the line of the target COP moves downward, as shown in Fig. 5(c).

In testing the method, the degree of difficulty can be controlled by adjusting the target COP values or the target total GRF value. We propose a balance control learning method based on task-specific training because the difficulty level of the test affects user motivation [14]. Initially, a task that users can achieve easily is set, and the target value is gradually increased thereafter. In addition, users can focus on moving the COP because the system supports the user’s weight by the seat. In this manner, we divided the task of balance control at half-rising posture to increase the possibility of success of the experiment and to maintain the user’s motivation.

4. Experiments

To evaluate the performance of the pulling chair movement before and after the intervention test of the system, we conducted a four-week experiment on a wheelchair user with paralysis in both lower limbs. The experiments were performed in accordance to the procedures approved by the Research Ethical Committee of the Graduate School of System and Information Engineering, University of Tsukuba (#2016R125), and the participant gave informed consent before participating in this experiment.

4.1 Participant

The participant was a 54-year-old female with cervical spine injury at C3 and C4 (ASIA classification; grade D) positions. Manual muscle test (MMT) scores are shown in Table 1. Barthel Index (BI) and Functional Ambulation Categories (FAC) were 65 and 4, respectively. She used a wheelchair at home to perform her daily activities. She was able to stand up and sit down without using her upper arms and perform the movements on a daily basis. Thus, improvement in the pulling chair test, if observed, would not be due to familiarity with the half-rising posture.

4.2 Procedures

The participant underwent balance control learning in a half-rising posture using the proposed learning support system once a week for four consecutive weeks. Each learning session lasted approximately 30 min or less. The participant’s comments were recorded during and after each learning session. To evaluate the effectiveness of the learning method, we performed the pulling chair test before initiation of the above-mentioned learning pro-

![Fig. 4](image-url) Configuration of the proposed wheelchair-type learning support system.

![Fig. 5](image-url) (a) Biofeedback on monitor (improper condition)  
(b) Proper condition  
(c) Moving rear target COP  
Visual biofeedback at balance learning.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>MMT score.</th>
</tr>
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<tbody>
<tr>
<td>Body part</td>
<td>R</td>
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<tr>
<td>U/E Shoulder joint</td>
<td>Fl</td>
</tr>
<tr>
<td></td>
<td>Ex</td>
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<td></td>
<td>Abd</td>
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<tr>
<td>Elbow joint</td>
<td>Fl</td>
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<td></td>
<td>Ex</td>
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<tr>
<td>Grip</td>
<td>0 kg¹</td>
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<tr>
<td>L/E Hip joint</td>
<td>Fl</td>
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<tr>
<td></td>
<td>Ex²</td>
</tr>
<tr>
<td>Knee joint</td>
<td>Fl</td>
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<tr>
<td></td>
<td>Ex²</td>
</tr>
</tbody>
</table>

Fl; Flexion, Ex; Extension, Abd; Abduction.
¹Her grip was too weak to measure that by a digital grip force meter (Takei Scientific Instruments, TKK5401).
²These parts were not measured because the participant has a catheter in the stomach and could not lie herself face down.
gram (pre-test), after the learning program (post-test), and one week after the post-test (final test).

4.2.1 Pulling chair test
The chair actually used in the participant’s home was used as the evaluation equipment, because the aim of the test was to enhance the participant’s independent living. The height, width, depth, and weight of the seat were 420 mm, 400 mm, 400 mm, and 450 g, respectively. Lubrication materials were pasted on the bottom of the chair’s leg to prevent scratches on the floor. In the experimental setup, the chair was placed such that the distance between the chair and the desk was 300 mm, as shown in Fig. 6. The movement was achieved when the distance between the chair and the desk became zero or less. We first asked the participant to pull the chair at will until the distance needed for the participant to work at the desk. We set two time limits (30 s and 3 min) and measured the distance between the chair and the desk after each time limit. If the participant was unable to pull the chair for 30 seconds, an experimenter and physical therapists advised her on how to complete the task, in order to evaluate the participant’s current maximal performance. The content of the advice was, “Place your feet forward some more and refrain from leaning your upper body as much as possible. Then, use this posture to pull the chair”. As the performance index of the test, we measured either the time required to pull the chair completely or the distance between the chair and the desk after 30 s and 2 min.

The pre-test was a baseline test to measure the performance before conducting the intervention using the system. The post-test was performed on the third day after the balance control learning. The participant took a sufficiently long break before the post-test. The final test was performed 1 week after the post-test.

4.2.2 Half-rising posture balance control test
The balance control test was conducted in a deep half-rising posture based on the physical analysis in Section 2. In the first test, we compared balance performance using the COG position by conducting the test with and without the proposed system. In the test without the proposed system, the system was used to measure GRF and the SRF, but the participant had no access to biofeedback. The test was also a baseline test to determine the target value of total GRF and the COP position. The participant was also asked to lift her buttocks from the seat completely, maintain that position, and move her COG following the therapist’s order as much as possible. We set the seat height to 450 mm from the floor to conduct the test at a deep half-rising posture. In the test with the proposed system, we asked the participant to attempt to move the COP position backward as much as possible by looking at the visual biofeedback. Backward COP position corresponds to point number 3 on the biofeedback [Fig. 5(a)]. Using the result of the baseline test, we adjusted the target total GRF and the initial target COP position. In the balance control learning, we need to set the target values that improve the participant’s ability but do not impose excessive load on the participant. Thus, we determined the target total GRF and the initial target COP position based on the results of the baseline test and advice from the cooperating physical therapists. We finally set the target total GRF at 200 N, which was approximately half the participant’s weight. We verified that the participant was able to maintain the half-rising posture several times when we set the target total GRF at 200 N. In all the tests, we set the target total GRF at 200 N. When the participant was able to maintain the COP position at point number 3 for 3 s, the target COP position value was increased. We measured the mean COP position and the maximum target COP position when there was a green rectangle at position number 3. To evaluate the COP position, we calculated the COP position ratio as a percentage of the length of the foot, as shown in Fig. 7.

5. Results
In the pre-test, the participant was unable to pull the chair until the desired position, as shown in Fig. 8(a). The participant was also not able to pull the chair completely even though she received advice from the experimenters. When she placed her feet forward, she was unable to raise her buttocks from the chair because she could not lean the upper body forward because of the distance between her body and the desk. Likewise, when she was asked to raise her upper body, she was unable to perform the half-rising posture. For the latter half of the test, the chair was moved back because the chair touched the back of both thighs after she pulled the chair. The distances between the chair and the desk in the 30-s and 2-min tests were 190 mm and 110 mm, respectively.

Figure 9 shows the GRF and SRF while the participant maintained the half-rising posture with and without the proposed system. In the test without the system, the participant attempted to lift her buttocks from the seat but did not achieve a complete lift [Fig. 9(a)]. These results showed that achieving a half-rising position was extremely difficult for the participant. Nevertheless, with the system supporting her weight, the participant was able to maintain a half-rising posture after the total GRF exceeded the target GRF [Fig. 9(b)]. Thus, the participant needed a small load.
relief to perform the balance test at the half-rising posture. Figure 10 shows the mean and standard deviation of the COP position ratio and total GRF in the 3-s test. The COP position ratio increased gradually and was approximately 10% higher on day 3 compared to day 1. However, we verified that the total GRF was the greatest in the day-2 test. In this test, the participant probably performed weight transfer from the buttocks to the feet excessively because she might not be able maintain the posture without doing that. The aim of the balance control learning is to move the COP backward while maintaining the half-rising posture. Thus, we considered that the result in the day-3 test was better than that in the day-2 test.

In the post-test, the participant was able to pull the chair by approximately 300 mm in 30 s, as shown in Fig. 8(b). When the participant performed the test to the best of her ability, she pulled the chair an additional 10 mm in 1 min 22 s. However, she stated that she could work on the desk when the distance between the chair and the desk was 0 mm because she could rest her upper arm on the desk.

In the final test, the participant achieved the task within 30 s, as shown in Fig. 8(c). The time required to complete the task in this test was 4 s less than the time in the post-test. The participant expressed pleasure because she could perform a task that she could not previously do by herself. The participant commented that she had become conscious of the COP position when she attempted realizing a half-rising posture or sit-to-stand transfer on a daily basis since the learning started.

6. Discussion

At baseline, the participant was able to maintain a half-rising posture for a long time and perform the posture on a daily basis. However, as shown in the result of the pre-test, the participant could not execute the pulling chair movement completely because she could only realize the half-rising posture as in Model A without the proposed system. In addition, the result showed that the participant was unable to move the COP unless the system supported the user’s weight by the seat. Thus, we considered that the participant could not realize the half-rising posture while simultaneously moving the COP backward. In other words, the participant could not utilize her CNS resources to move the COP backward while attempting to maintain the half-rising posture. Unless users acquire the experience of success, they find it difficult to learn the proper movements. Therefore, we divided the pulling chair movement into relatively simple tasks and proposed the balance control method using a system based on the principal task of specific training to focus the participant on moving the COP backward and to promote motor learning in the CNS [15].

The results of the experiments show that the user could move the COP backward by utilizing informatics-based biofeedback and physical support. When the COP moves backward, the COG
also moves backward based on the human body structure. For this reason, the participant could perform the pulling chair movement completely not only in the post-test but also in the final test. The participant was successful in the post-test, implying that she remembered the movement. We also confirmed that she raised her buttocks by using her body dynamics when she pulled the chair. Even though a static test was performed using the proposed learning method, since inertia and velocity of the movements were not considered, the user’s pulling chair movement improved dynamically. Therefore, we deduced that users could acquire dynamic movements even by conducting static tests. From the basic principle of task-specific training, if the divided task is adjusted properly, the final task or movement will be achieved. Therefore, we confirmed the proof of concept of the balance control learning method based on the COG position during a half-rising posture for executing the pulling chair movement.

In daily life, human beings hardly move their COG backward during a half-rising posture. However, from the physical analysis in Section 2, the user needs to not only maintain the half-rising posture but also move it backward in order to efficiently achieve the pulling chair movement. The participant had undergone gait and sit-to-stand training regularly in a special facility for a year or more but was unable to learn the movement she learnt through this learning. By conducting the balance control learning using the system 3 times, the participant was able to perform the pulling chair movement. Thus, the experimental result is the first case report of successful application of the learning method. This learning method also has the advantage of helping the participant realize the pulling chair movement, which is a barrier to living without having to use a wheelchair like the participant. At present, the participant does not need to use her wheelchair when she works at a desk at home. Being able to perform the pulling chair movement could decrease the need for a wheelchair.

In this paper, we confirmed that the participant’s performance improved remarkably through the continuous balance control learning experiment. In the future, we will work with patients with similar difficulties as the participant in this study. Then, a test employing the proposed method will be conducted on a larger number of wheelchair users to evaluate the effectiveness of the system.

7. Conclusion

We propose a new method of balance control learning at a half-rising posture using an assistive system for executing the pulling chair movement, which creates a barrier to living without a wheelchair. We also report a specific case of applying the learning method to a quadriplegic patient who could transfer from a wheelchair to a chair by herself, but could not perform a pulling chair movement.

The characteristic of the support system is that it does not require any attachment to the user’s body. It also provides informatics-based biofeedback on a monitor, and the user’s weight is supported by a seat. The proposed learning method enables users to move their COG backward. This approach is based on the physical analysis of the kinematics and kinetics during the pulling chair movement. A participant who has cervical spine injury was trained using the system once a week for four weeks. Although the participant was unable to perform the pulling chair movement completely in the pre-test, she improved her balance control ability and accomplished the movement in several seconds in the post-test. Furthermore, the participant was able to execute the movement even one week after the post-test. Therefore, we confirmed the proof of concept of the proposed balance control learning method based on physical analysis that improves the participant’s balance control ability and the pulling chair movement. For wheelchair users who can stand up and transfer to a chair by themselves, but cannot perform a pulling-chair movement, our learning method will help them realize an independent life.

Conflict of Interest

We have no conflict of interest and relationships with any companies and commercial organizations based on the definition of the Japanese Society for Medical and Biological Engineering.

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