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Development of a Virtual Reality System to Evaluate Skills Needed to Drive a Cycling Wheel-Chair

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Abstract— **A cycling wheel chair (CWC) is a useful tool to provide physical exercise for patients who face difficulty walking, caused by stroke or other brain disorders. A system has been developed for rehabilitation, which allows patients to practice driving a CWC in a virtual environment. In this study, hardware improvements were developed and methods for evaluating driving skills were investigated to improve the practical application of this system. The hardware was changed to enable users to drive the CWC they were using in their daily lives. In addition, four types of test scenarios that focused on basic and important actions necessary to drive a CWC, such as pedaling and steering, were developed. An experiment with healthy young and elderly persons was conducted to evaluate the validity of the system. Results showed that pedaling and steering skills were improved in both the young and elderly subjects but the improvement patterns differed between them. These results indicate that repeated practice with the proposed system enhances the safety of driving a CWC, particularly for elderly users.**

I. Introduction

Motor function can be impaired by brain disorders (stroke, brain damage, and degenerative disease), neurologic diseases, or spinal cord injury. Stroke is a common disorder of the elderly, and it can be expected that the number of stroke patients in Japan will increase in the future because the population is aging.

In general, patients with motor dysfunction use wheelchairs. They never use their feet while moving with wheelchairs because most wheelchairs are made to be operated either by the user's hands or an electric motor. However, human legs act as a pump for carrying blood back to the heart. For this reason, if the patients do not move their feet and legs for a long period of time, blood circulation in their lower limbs is reduced, and risks of disuse syndromes such as muscle weakness and joint contractures are increased.

Pedal-driven wheelchairs or cycling wheel chairs (CWCs–Fig.1) are attracting attention as a tool to solve this problem [1]-[7]. These chairs are useful in that they provide physical exercise for patients with severe impairment in their lower extremities. These individuals can move around more quickly and travel longer distances without fatigue using a CWC instead of a traditional wheelchair [1]. In addition, they can also use their hands while driving a CWC. This encourages the patients to be independent and improves their quality of life.

However, the CWC does require the patients to pedal and steer simultaneously. This simultaneous motion can be so complicated that in some situations, it is dangerous for beginners to move around in a CWC without practice. For this reason, patients should be tested to see if they can safely use a CWC. Also, they should practice maneuvering the chair before using it to move around in their daily lives. However, practice maneuvering requires not only large, safe practice areas but also a lot of assistance by attendants when the patients or elderly people use a CWC for the first time.

To tackle these problems, a virtual reality (VR) system for CWC driving was developed in previous studies [5]-[6]. However, the hardware used in those studies was relatively large and heavy, and it was impossible to modify the CWC for each individual user because the sensors measuring the user's pedaling and steering actions were embedded in the CWC. The users could not use the same CWC they were using in their daily lives. Also, the previous study [6] reported results reflecting CWC driving skills based on the results of experiments in which only six patients and three young normal subjects practiced. Additionally, the times that each subject spent training on the system were not the same. Thus, the effect of practice by the patients was not clear, and the effect of changing and modifying the system could not be quantified.

Figure 1. Cycling wheel chair (CWC)

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This study attempts to improve the usability of the VR system for driving a CWC and establish an improved method for evaluating user's driving skills with more data. In particular, the system was changed to enable users to practice with the CWC they were using in their daily lives. Furthermore, we proposed new evaluation scores for CWC driving skills. We also compared changes in these scores between the young and elderly subjects and monitored how these scores changed in each group over the course of 4 weeks.

II. VIRTUAL CYCLING WHEEL CHAIR

Figure 2 shows the VR system developed for this study. A user sits on a CWC fixed to the base unit of the system, rotates pedals, and manipulates a handle on the CWC while viewing a VR image on a 65-inch wide-screen display. The speed of rotation of the pedals and steering angle of the handle are measured by rotary encoders (E6A2-CWZ3E; Omron Corp.) and data are transmitted to a PC through a microcomputer (SH7144F; Renesas Technology Corp.). Based on this information, the image on the display is updated in real time. The CWC used in this system is easily exchangeable because no sensor is embedded in the CWC. This enables the users to use the CWC they are using in their daily lives. To measure the user's pedaling balance between the right and left feet, removable wireless acceleration sensors (WAA-006, Wireless Technologies, Inc.) are attached on both their feet as shown in Fig.3.

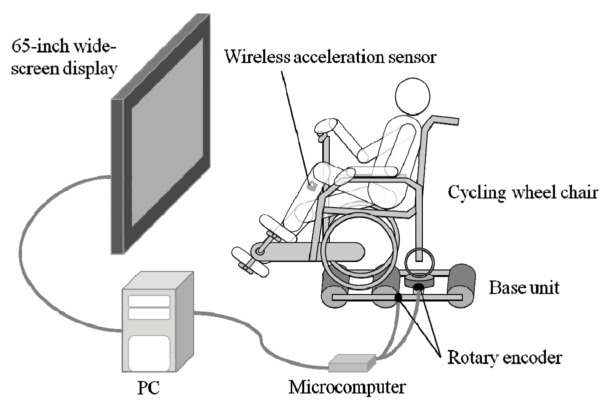

Figure 2. Virtual reality system for driving a CWC developed for this study

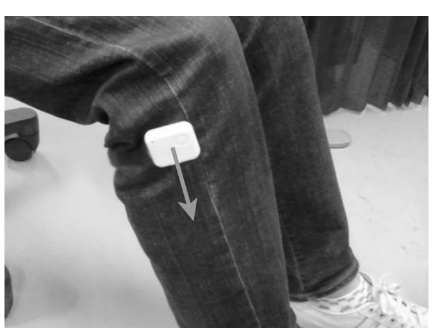

Figure 3. Wireless acceleration sensor used for the evaluation of pedaling balance between the right and left feet

III. TESTS TO EVALUATE DRIVING SKILLS

As shown in Table I, four types of tests were developed to evaluate the users' CWC driving skills. The previous study [8] was a good reference to develop some of these tests. The tests evaluated the basic and important motions required to drive a CWC.

TABLE I. TESTS FOR DRIVING SKILLS EVALUATION

Test	Course	Evaluation Objective
Pedaling balance	Straight line	Pedaling balance between the right and left feet
Pedaling speed control	Straight line with a target car running	Ability to control pedaling speed
Handle steering	S-shaped curve	Skill in using a steering handle on a CWC
Obstacle avoidance	Straight line with obstacles	Overall driving skills

A. Pedaling balance test

This test evaluates pedaling balance between the feet. In the test, users are instructed to drive a CWC forward in a straight line at a constant speed. In the real world, the test course would be approximately 10 m long.

Based on acceleration signals obtained from the wireless acceleration sensors attached on both the user's feet, it is possible to evaluate the pedaling balance between the right and left feet as shown in Fig.4.

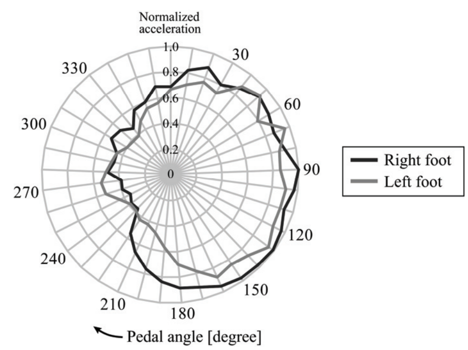

Figure 4. Example of acceleration signals measured from sensors attached to the feet of a user pedaling the CWC

B. Pedaling speed control test

This test evaluates how well the user controls pedaling speed. In the test, users drive a CWC while attempting to maintain a constant distance from a leading virtual car. The test course would have a real world length of approximately 22 m. The virtual speed of the virtual car increased from 1.8 to 3.7 km/h after it reaches the halfway point of the course.

The skill of controlling the pedaling speed is evaluated by measuring the *RMSEv* defined as:

$$RMSEv = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\{V_{\mathrm{VIR}}(i) - V_{\mathrm{CWC}}(i)\}^2} , (1)$$

where $V_{VIR}(i)$ and $V_{CWC}(i)$ are the velocities of the virtual car and the CWC at the *i*-th sample point of time, respectively, and N is the number of sample points.

C. Handle steering test

This test is used to evaluate how well the user steers the CWC. In the test, users drive a CWC in an attempt to follow a virtual S-shaped white line as accurately as they can.

Some reference or "judge" points are included along the white line on the course. The steering skill is evaluated by measuring the *RMSEp* defined as:

$$RMSEp = \sqrt{\frac{1}{M}\sum_{j=1}^{M}\{Er(j)\}^2}\ , (2)$$

where $Er(j)$ is the error between the position of the CWC and the *j*-th judge point, and M is the number of the judge points, 21 points in this study. The judging is done every time the CWC passes the virtual lines drawn across the white line at the judge points.

D. Obstacle avoidance test

Overall driving skills were evaluated by having the user drive a CWC along a straight virtual road with obstacles (traffic cones) placed in it, which had to be avoided. The length of the course is the same as that of the pedaling speed control test. A screenshot of this test course is shown in Fig.5. The time to complete the test T_c was measured and used as the index to evaluate the user's overall driving skill.

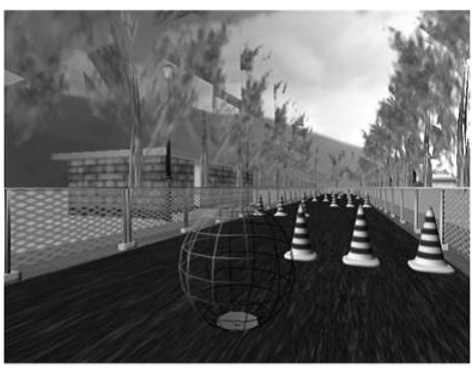

Figure 5. Screenshot of the obstacle avoidance test

IV. Experiment

An experiment was carried out to evaluate the effectiveness of the proposed tests.

Eight young subjects (6 males and 2 females) and 15 elderly ones (13 males and 2 females) participated in the experiment. The ages of the young subjects were between 21 and 29 and those of the elderly subjects were between 66 and 74. None of them had driven a CWC before this experiment. They participated in the experiment once a week, for 4 weeks. They tried an experimental task that consisted of the aforementioned tests once both in the morning and in the afternoon of the day. Consequently, they tried the same task eight times. The experimental protocol was approved by the Internal Review Board of the Tohoku University and informed consent was obtained from all the subjects before the experiment.

V. Results and Discussion

A. Pedaling balance test

No subjects participated in the pedaling balance test experiment because the test is only designed to evaluate paralysis. Therefore, no results are reported here.

B. Pedaling speed control test

Figure 6 shows the change, from the 1st to the 8th trial, in the mean value of *RMSv* of the young and elderly subject groups for the speed control tests. The results are shown separately for the two different speeds of the virtual car, 1.8 km/h and 3.7 km/h. These results show that the *RMSv* decreased significantly, which means the subject's skill at controlling the pedaling speed improved with practice in both groups under either speed condition. Note that *RMSv* tends to be lower at low speed than at high speed. This is natural because the more slowly a target car runs, the more easily a CWC driver can follow it. Furthermore, at the 1st trial, there was a significant difference in the *RMSv* between the two groups under either speed condition. However, this difference disappeared at the 8th trial under the high-speed condition but not under the low-speed condition. This result indicates that the skill to pedal at high speed was acquired more easily by the elderly subjects. One possible reason for this might be that the subjects learned to pedal more easily by timing the push on each pedal to coincide with the inertial force of the pedals as they rotate at relatively high speed. On the other hand, if the rotation speed is low, they must rotate the pedals more by muscular force than by inertial force.

C. Handle steering test

Figure 7 shows the change, from the 1st to the 8th trials, in the mean value of the *RMSp*, which reflects the skill in steering a CWC. As shown in the figure, the *RMSp* of the elderly subjects decreased significantly (that is, their skill increased) and reached the same level of the young subjects. In contrast, the *RMSp* of the young subjects did not change significantly even after eight trials. These results indicate that a) the young subjects had a high level of the skill necessary to steer the handle even before the tests had begun, and b) the elderly subjects were able to improve their steering skills to a level similar to that of the younger subjects through practice.

D. Obstacle avoidance test

Figure 8 shows the change, from the 1st to the 8th trial, in the mean value of T_c, which is the amount of time required to complete one trial of the obstacle avoidance test, for each subject group. As this figure shows, T_c decreased for both groups but there was a significant difference ($p < 0.01$) between them before and after practice. This difference is probably caused by age-related decline in performance such as the quickness of handle manipulation and pedaling speed.

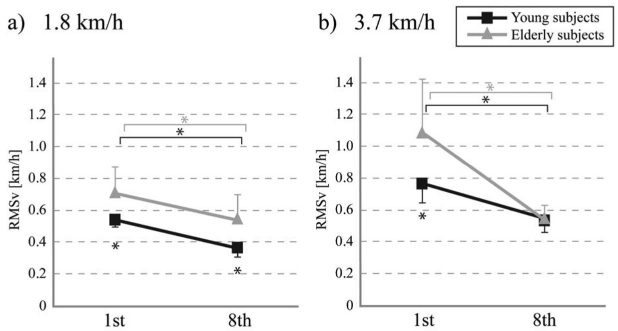

Figure 6. Change, from the 1st to the 8th trials, in the mean value of *RMSv* of the young and the elderly subjects. During each the trial, speed of the virtual car is changed from a) 1.8 to b) 3.7km/h. * $p < 0.01$

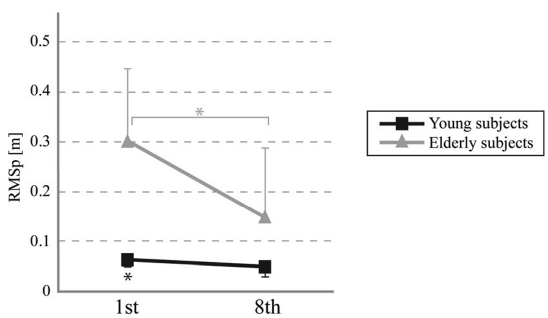

Figure 7. Change, from the 1st to the 8th trials, in the mean value of *RMSp* of the young and the elderly subjects. * $p < 0.01$

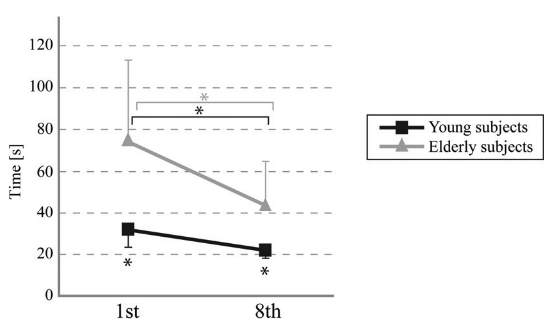

Figure 8. Change, from the 1st to the 8th trials, in the average amount of time required for the young and the elderly subjects to complete a trial of the obstacle avoidance test. * $p < 0.01$

The traveling direction of the current CWC is changed by moving the handle forward and back. However, there is a conceptual problem for the user with this interface because the users must translate the axis from forward and back to left and right in their mind. For this reason, the current steering interface should be changed. We believe the developed VR system is useful for designing a new user-friendly CWC interface because the CWC used in the system is exchangeable.

VI. CONCLUSION

In this study, we improved the usability of the VR system, a system in which patients with motor dysfunction can safely drive a CWC without requiring a large open space in which they can practice. Most importantly, the system was improved to enable users to use the CWC they were already using in their daily lives.

We also proposed some new indices to evaluate the user's CWC driving skills and applied them to data obtained from a group of subjects who had practiced driving a CWC for 4 weeks. The experimental result showed that the indices worked well for reflecting the users' improved performance after practice. In addition, these indices showed a difference in the characteristics of driving a CWC and effects of practice between ages. These results indicate that repeated practice with the proposed system enhances the safety of driving a CWC for practical purposes, particularly for elderly users.

In the future, we plan to collect data using patients who practice using a CWC for specific, measured time periods to test the efficiency of the proposed VR system. Virtual Reality training programs to motivate patients should also be developed. A training scenario whose difficulty level changes based on the user's skill may be effective. Also, a load feedback function should be added in the system to make the sensation of driving the CWC more realistic. The load feedback function would enable a user to practice driving a CWC in near-real conditions.

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