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System for Operating Electric Wheelchairs Using Only the Remaining Functions of the Thumbs of Muscular Dystrophy Patients

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***Abstract*— For patients with muscular dystrophy, a motor dysfunction, who have difficulty operating an electric wheelchair with joysticks, a simplified one-input device is used. However, avoiding obstacles can be time-consuming. In this study, we analyzed the motor functions of the thumb of a patient with severe muscular dystrophy and identified the operations that did not cause physical fatigue. Then, we developed an operation support system to continuously operate. Finally, we conducted experiments comparing the proposed system with the conventional system and verified the effectiveness of the proposed system based on the steering accuracy of the electric wheelchair and the task completion time.**

I. INTRODUCTION

Muscular dystrophy is an intractable disease. There are currently about 25,400 patients with muscular dystrophy in Japan [1]. Patients with muscular dystrophy exhibit progressive motor dysfunction with a weakening of muscle strength throughout the body. Eventually, the dysfunction progresses until they can only flex their thumbs [2]. In this condition, they cannot operate joysticks, and it becomes very difficult for them to use an electric wheelchair [3].

On the other hand, a variety of interfaces have been developed for physically challenged people who are no longer able to exert sufficient force to operate a joystick. One such interface, a simplified one-input device, which is operated on a switch-input electric wheelchair by flexing only the thumb, is shown in Fig. 1.

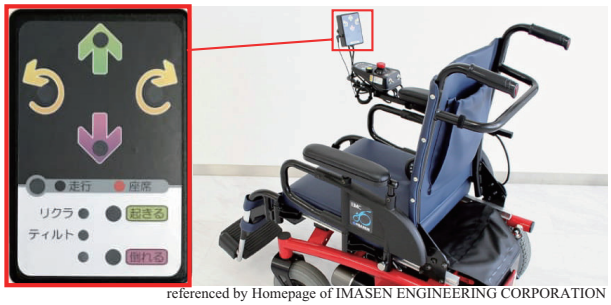

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Fig. 1. Simplified one-input device

A simplified one-input device is an operation support system that controls the moving of an electric wheelchair. To operate the system, the user selects one of four directions (forward, backward, right turn, left turn) by pressing a switch toward one of four lights that blink in sequence. However, due to such non-continuous operation with the switch, the user must stop the wheelchair before each change in direction and select the new direction.

Recently, a variety of interfaces that improve the operability of electric wheelchairs have been developed. An operation support system managed by tapping and sliding on a pressure-sensitive touch pad was developed [4]. This system functions effectively for patients who do not have severe symptoms and can perform thumb adduction and flexion. However, patients with muscular dystrophy in stage eight who can only perform flexion of the thumb, have difficulty performing tapping movements. Thus, it is difficult for them to use this system. In addition, operation systems have also been developed such as eye movements [5], intentional eye blink patterns [6], and biometric signals of the jaw, shoulders and cheeks [7]. However, the eye movements and intentional eye blinking cause mental fatigue, and the continuous exertion of muscle causes muscle fatigue. Therefore, continuous operation using such interfaces in daily life may be impractical.

In this study, we first analyzed the characteristics of the residual functions in patients with muscular dystrophy in the worst stage of the disease, and identified operations that do not cause mental and physical fatigue. Then, we developed an operation support system that enables them to continuously operate an electric wheelchair without stopping. Therefore, we extended the functions of the simplified one-input device, which have been used for many patients and have been confirmed to be safe. Finally, for health people and a patient with muscular dystrophy, we conducted experiments that compared the performance of avoiding obstacle between the proposed system and the conventional operating system, a simplified one-input device. This study was conducted with the approval of the Experimental Ethics Committee of the Faculty of Engineering, Mie University (Approval Number: No. 44).

II. ANALYSIS OF RESIDUAL FUNCTION IN A PATIENT WITH MUSCULAR DYSTROPHY

Muscular dystrophy is categorized into many types, including the X-chromosome recessive, congenital, limb-girdle, facial-scapulohumeral, and Duchenne-types, in which the proximal muscles deteriorate, and the myotonic-type, in which the distal muscles deteriorate [8]. The severity of symptoms is divided into eight stages according to the progression of symptoms, and the range of movements

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decreases as the stage progresses [9]. In stages one to four, patients exhibit symptoms of lower-extremity muscle weakness. In stages five to seven, patients lose the ability to stand due to spinal deformity and use joystick-type electric wheelchairs for mobility. In stage eight, patients require systemic management for respiratory failure or heart failure and have difficulty moving their hands forward horizontally on a desk and difficulty using joysticks.

This study focused on patients with Duchenne-type muscular dystrophy in stage eight. These patients begin to suffer from weakening muscle around the waist and shoulder blades, which are close to the trunk. Moreover, the intrinsic hand muscles perform complex and elaborate functions of the hand, are more likely to remain functional.

Specifically, the functioning of the thumb adductor muscle tends to decline in the early stages of muscular dystrophy; however, the functioning the short thumb abductor muscle, short thumb flexor muscle, and thumb opposers remain [10]. Therefore, we developed an operation support system for electric wheelchairs that requires the user to perform only thumb flexion using the short thumb flexor muscle.

We analyzed the residual function of a patient with muscular dystrophy. The subject is a male patient with Duchenne-type muscular dystrophy in his 50s with functional disability category eight. Since the subject is in the worst stage of the disease, the results of the analysis may also apply to patients in other stages. He uses an electric wheelchair while wearing a ventilator, as shown on the left side of Fig. 2.

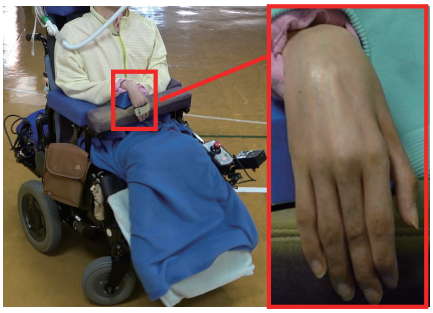

Fig. 2. Operation of electric wheelchair by a patient with Duchenne-type muscular dystrophy

We found that the proximal interphalangeal joint from the second to fifth fingers and the fingertips were in a state of extension contracture, and the joints were fixed in the extended position, which made flexion difficult. Therefore, in order to facilitate thumb movement, a drooping hand, as shown on the right side of Fig. 2, is the basic posture. The range of flexion of the thumb was 2[mm], but the range of adduction could not be verified. From these results, it was verified that the short thumb flexor muscle used for flexion of the metacarpal phalangeal joint of the thumb remained functional. Then, we measured the flexion of the thumb with the drooping hand. We attached a neodymium magnet to the fingertip of his thumb and used a hall sensor to measure the movement while varying the time allotted for flexion and repeated flexion. The results are shown in Fig. 3.

Based on the subject's opinion and the experimental results, it was verified that periodic movement and changing

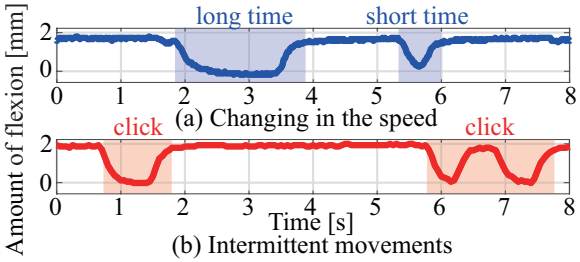

Fig. 3. Results for characteristics of flexion of the thumb

in the speed of the thumb movement were possible in the blue area (a). However, since movements like slow pressing a switch lead to physical fatigue, it is difficult for the subject to perform them continuously. On the other hand, click operations, which are intermittent movements such as those in the red area in (b), can be easily performed with the remaining functions, greatly reducing the physical fatigue.

We then tried to extending the operating dimension by using click operation. To differentiate between a click operation, we measured the time it took for the subject to press the switch and release the switch during repeated flexion of the thumb. When the subject repeated the click operation, the maximum time between the two times clicks T_f was 0.82[s]. Therefore, we set the standard click time $F_e = 0.82$[s]. We defined the thumb release operation as $F_e < T_f$ and the click operation as $T_f < F_e$. Here, F_e can be set to adjust for differences in the physical condition of each patient. Based on the above results, by adding a click function to the conventional a simplified one-input device, we developed a new operation support system.

III. PROPOSED OPERATION SUPPORT SYSTEM

In the living environments of patients with muscular dystrophy, there are obstacles that must be avoided. However, a simplified one-input device is necessary to stop and select a new direction repeatedly. Due to poor operability of the interface, it takes a long time to avoid obstacle. In this study, by improving the operability of a simplified one-input device, we developed an operation support system that enables users to continuously operate an electric wheelchair using only their remaining thumb functions.

The operation of the conventional simplified one-input device is as follows. For the switch input S_{in}, when the user presses the switch, the input becomes 1. When the user removes his thumb from the switch, the input becomes 0. In the case when the scan that determines the direction of the electric wheelchair according to the flashing lights is not started (reset state), if $S_{in} = 1$, the input will be set to 1, and the scan will start immediately. An example of this input is shown in Fig. 4.

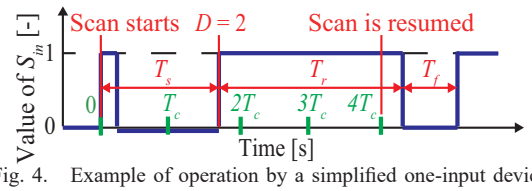

Fig. 4. Example of operation by a simplified one-input device

The time from the start of the scan until the switch is

pressed is defined as the scan time T_s, and the time from the light turning off to the next light turning on is defined as the scan count T_c. When $T_s = 4T_c$ or the switch is released, $T_s = 0$ and the scan is resumed.

We defined the variable D to determine the direction of the electric wheelchair. It is determined based on the timing of T_s, if the switch is not pressed during the scan ($S_{in} = 0$), $D = 0$ and the scan continues. However, when the switch is pressed, movement commands ($D = 1$ ($T_s < T_c$): Forward; $D = 2$ ($T_c < T_s < 2T_c$): Right; $D = 3$ ($T_c < T_s < 2T_c$): Left; $D = 4$ ($3T_c < T_s < 4T_c$): Backward) are sent to the electric wheelchair, and the wheelchair moves accordingly.

On the other hand, in the proposed system, in order to improve the operability of proposed system, we added a moving mode to avoid obstacle through a click function. The algorithm is shown in Fig. 5.

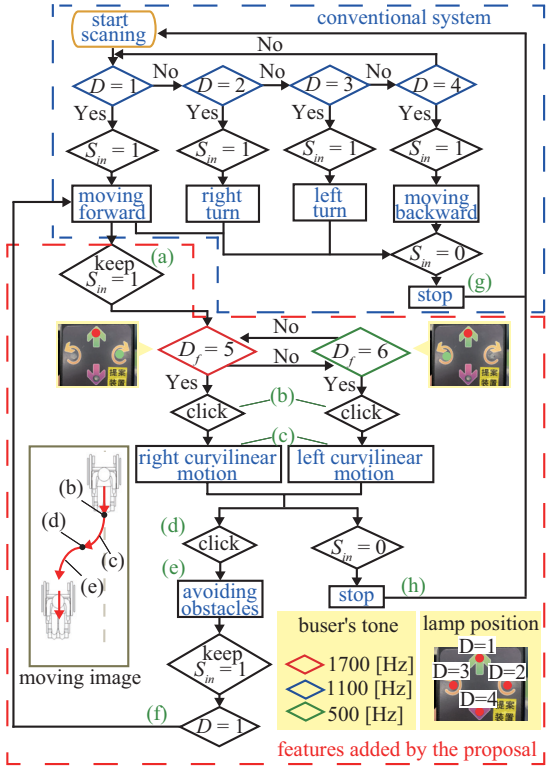

Fig. 5. Algorithm of the proposed system

The proposed system shown in Fig. 5, with different steps in the process marked with the letters (a) through (h). During forward motion, the red light that indicates the forward direction is always on (a), while the left and right lights flash green alternately. Then, the scan for inputting left and right curvilinear motion begins. Here, the parameter D_f determines the direction of the curvilinear motion, and the amount of time that the switch needs to pressed to move the wheelchair forward is T_r, while D_f becomes 5 ($0 < T_r < T_c$) or 6 ($T_c < T_r < 2T_c$). When $T_r = 2T_c$, T_r becomes 0 and the scan to determine the curve direction is repeated. In order to induce curvilinear motion, it is necessary to perform the click operation (b). If a click operation is detected, the command to turn the wheelchair to move right or left is sent to the operating voltage conversion model when $D_f = 5$ and $D_f = 6$. In order to communicate the direction to the user, while the light for the forward direction remains on, a high-tone buzzer (1700[Hz]) sounds when $D_f = 5$, and a low-tone buzzer (500[Hz]) sounds when $D_f = 6$.

A click operation is detected when $T_f < F_e$, where T_f represents the time from when the switch is released to when it is pressed again. When performing the click operation to avoid obstacle (d), the electric wheelchair moves toward the opposite direction compared to the previous direction in curvilinear motion (e) for the same amount of time it had engaged in curvilinear motion (c). The command $D = 1$ is sent to move the wheelchair into forward motion (f). With the above operation, the click operation reproduce the process of avoiding obstacle but without the unnecessary stopping and selecting a new direction. Here, for an emergency stop function as well, in any moving mode, when $F_e < T_f$ and $S_{in} = 0$ is satisfied, the stop command is sent to the electric wheelchair, and the system will restart a new scan at step (g) or (h).

Finally, we introduced the output of the voltage instruction value to the electric wheelchair. The microcomputer used in the control system is a RaspberryPi 3 model B. The voltage instruction values sent to the electric wheelchair are determined by D and D_f, which set the forward and curve speeds to 0.5 and 0.3[m/s], respectively.

IV. VERIFICATION OF EFFECTIVENESS THROUGH MOVING TESTS

We conducted experiments to compare the performance of the conventional a simplified one-input device with the proposed system. The experimental subjects were three healthy males in their 20s and a male patient with Duchenne-type muscular dystrophy in stage eight. We required the healthy subjects to avoid pressing the switch immediately after a rescan in order to simulate a patient with Duchenne-type muscular dystrophy. In the experiment, the healthy subjects used EMC-270 electric wheelchair, while the patient with muscular dystrophy used EMC-250 electric wheelchair, both of which were made by IMASEN ENGINEERING CORPORATION. We designed a course that required subjects to avoid obstacle shown in Fig. 6.

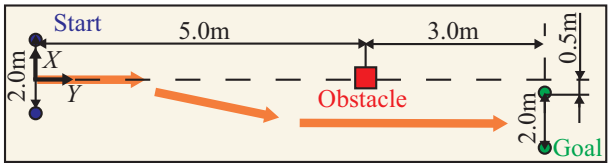

Fig. 6. Running course used in experiments

The experiments were conducted after the subjects had become sufficiently familiar with the operation through practice. We measured the task completion time, the number of stops, and the path over which the electric wheelchair moved. Here, the path was calculated from the acceleration and angular velocity measured by a 9-axis sensor module installed on the electric wheelchair.

Fig. 7 shows a comparison of the paths in which the points indicates the stopping position of the electric wheelchair and Fig. 8 shows the input data for the switch and the task

completion time. For the task completion time, we give the average data for the healthy subjects. The letter C in the figure represents the conventional system, P represents the proposed system, H represents the healthy subjects, and M represents the patient with muscular dystrophy. In addition, in order to match the timing of switch input and the path of electric wheelchair, the letters such as A_1 to A_3 are used in both Fig. 7 and Fig. 8.

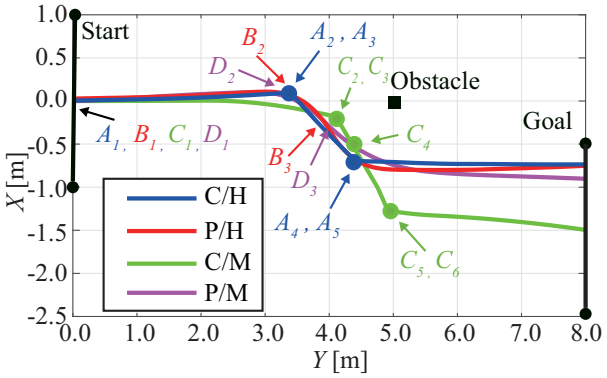

Fig. 7. Comparison of path in the experiment

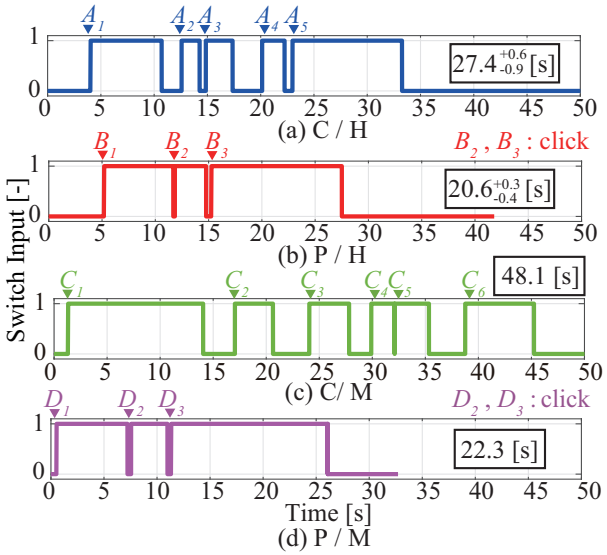

Fig. 8. Switch input data in the experiment

We compared the two control systems by matching the paths and switch operations in each experiment. In this experiment, we set $T_c = 0.7$[s], and it took 0.8 [s] to restart the scan after stopping. With the proposed system, the number of stops and the task completion time decreased compared to the conventional system for both healthy subjects and the muscular dystrophy patient. Therefore, we analyzed the reasons for this. In the proposed system, the wheelchair begins its curvilinear motion with the click operation B_2 and corrects its direction with the click operation B_3. Thus, the proposed system is able to reduce the pressing operations A_2 to make a right turn, A_4 to make a left turn, and A_3 and A_5 to move forward again, which were necessary in the conventional system. For this reason, the proposed system reduces the task completion time for the scan and decreases the task completion time by 3.2[s] compared with the conventional system. Based on the above results, the proposed system did not require the wheelchair to stop moving during the operation. Therefore, we succeeded in decreasing the task completion time and showed the effectiveness of the proposed method.

V. CONCLUSIONS

For patients with muscular dystrophy, a motor dysfunction, who have difficulty operating an electric wheelchair with joysticks, a simplified one-input device is used. However, since a simplified one-input device is a system that requires the user to select one of four directions discontinuously by pressing a switch, as a result, avoiding obstacle is time-consuming. In this study, we analyzed the flexion of the thumb, which is the only remaining function of patients with severe muscular dystrophy, and identified the operations that do not cause mental and physical fatigue. We then developed an operation support system that enables patients with muscular dystrophy in stage eight, who have the minimal freedom of movement, to continuously operate an electric wheelchair using only their remaining thumb function. Finally, we conducted comparison experiments and verified the effectiveness of the proposed system. From these results, it is expected that patients with muscular dystrophy will be able to move more comfortably in their daily living environment using the proposed operating system and will experience improvements in their quality of life.

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