Simple Device to Measure Physical Strength to Move Manual Wheelchair

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***Abstract*-It is important for manual wheelchair users to be able to move independently in order to maintain good quality of life. To be able to move independently, users should know the route on which they can move based on their physical strength in order to move a manual wheelchair. This paper proposes a system to estimate the wheelchair handrim force necessary to move on roads of many kinds. To support outdoor activities by wheelchair users, a measurement device is developed to measure a wheelchair user's physical strength to move a manual wheelchair. The measurement device, which measures the applied handrim force during movement, is composed primarily of strain gauges, amplifiers, and a microprocessor. Results indicate that the measured handrim force and the physical strength when moving a wheelchair are mutually related. Additionally, the device can evaluate the physical strength necessary for wheelchair movement based on measurements of the handrim force. Traditional measurement methods may be superior for detailed physical strength evaluation; however, the wheelchair user's handrim force can be measured in a few minutes with this simple measurement device using the methods implemented in this study. Moreover, the developed measurement device does not require a large treadmill or ergometer. This research will contribute to the measurement of the physical strength of manual wheelchair users.**

Keywords- Manual Wheelchair; Physical Strength Measurement; Physical Capacity; Handrim Force; Slope; Ergometer; Strain Gauge; Stroke Pattern

I. INTRODUCTION

Wheelchair users must be able to move independently in order to maintain good quality of life. A person's active life is reduced by the risk of lifestyle-related diseases [1-3]. Physical activity and the sphere of daily life of wheelchair users are related to their physical capacity and skill at operating a wheelchair [4-6]. However, the degree to which people hesitate to move independently remains unclear. To help wheelchair users move independently, it is important to ascertain whether a person's physical strength is sufficient to reach their destination. Slopes pose severe obstacles that hinder wheelchair movement [7-10]. Therefore, it is important to assess the strength of wheelchair users to climb a slope as a factor affecting their willingness to move independently. This paper proposes a system to estimate the wheelchair handrim force (i.e., applied force directed tangentially to the handrim) during movement on roads of many kinds in order to navigate a route that can reach a destination using a low amount of physical strength. Such a route must be determined according to the physical strength of respective wheelchair users, because the physical strength of wheelchair users varies greatly. Therefore, a device that can easily measure a manual wheelchair user's physical strength is necessary.

An accurate evaluation of physical strength can indicate the potential of a wheelchair user's ability to reach a destination. The indices reported to evaluate wheelchair user's physical strength are the following: heart rate, oxygen consumption, and data from upper limb electromyography and accelerometry [9-12]. Studies using an accelerometer have increased recently because accelerometry is convenient, but the method still requires a treadmill [11, 12] and an ergometer [13-16] to achieve physical strength measurements. In addition, a wheelchair that uses such an apparatus must measure physical strength when travelling outdoors.

A treadmill and an ergometer for wheelchairs can accept any load and can measure a wheelchair user's physical strength. The treadmill and the ergometer can perform operations that require rotating the wheelchair wheels many times without moving the wheelchair. However, the treadmill and ergometer must be large in order to accommodate rotation of the wheelchair wheels on the roller. Moreover, wheelchair users cannot measure physical strength by themselves because a wheelchair must be fixed to a treadmill and ergometer so that the wheelchair does not fall off the belt and roll off the treadmill. Wheelchair users must visit a specialized facility such as a rehabilitation centre or a medical institution where the measurement system is provided.

To solve this problem, a device is developed that can easily measure the physical strength of wheelchair users, and assess their physical strength when climbing a slope. As described in this paper, the design of a small and inexpensive device to measure physical strength indoors is presented. Furthermore, a method of assessing a wheelchair user's strength for ascending slopes independently is explored.

II. DESIGN AND IMPLEMENTATION OF PHYSICAL STRENGTH MEASUREMENT DEVICE

The power to propel a wheelchair differs according to a wheelchair user's muscular strength or ability, in addition to other factors [17-18]. It is effective to use the accelerometer to easily measure a wheelchair user's physical strength. Nightingale, et al., measured the acceleration of the wrist, which was effective to infer the energy expenditure of physical activity exerted by manual wheelchair users [19, 20]. However, a wide space or treadmill is necessary to measure the acceleration. Moreover the propulsion efficiency of the wheelchair is changed by the pattern of the wheelchair's stroke [21]. For these reasons, a physical strength measurement device that can measure the handrim force without rotating the wheel is developed. This measuring method can report only the force that the wheelchair user applies to the handrim. The measurement method is unsuitable for evaluating the skill necessary to operation of a wheelchair or muscular power of wheelchair users, but it can easily measure a wheelchair user's physical strength without the encumbrances of a large open space and a treadmill.

Fig. 1 presents measurement results of the handrim power of a manual wheelchair as it climbed a steep slope (10 degrees). The manual wheelchair operator was a healthy man (age = 22 years, weight = 635 N). Presumably, a strong handrim force is required when a wheelchair user climbs a steep slope. Devices used to measure the physical strength necessary to operate a wheelchair only measure the force exerted on the wheelchair handrim. It is necessary to continue applying the handrim force, as shown in Fig. 1. For the method examined in this study, the force applied to the wheelchair handrim was measured without rotation of the wheels.

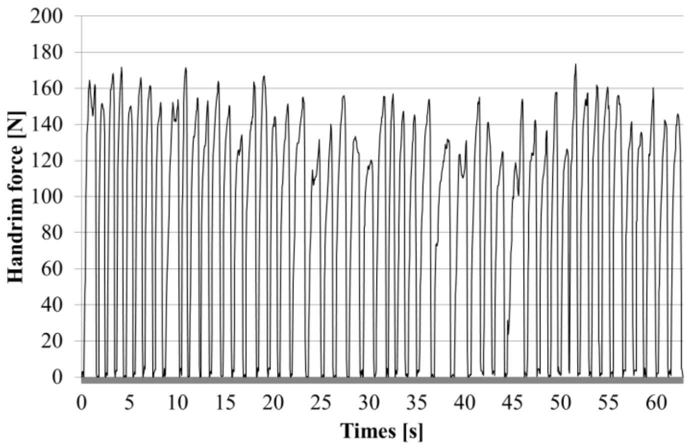

Fig. 1 Example of applied handrim force on a steep slope

A. Design and Implements of Measuring Device

Fig. 2 and 3 present illustrations of a device for measuring the handrim force. For this study, the junction of the handrim was perpendicularly connected with a wheel to a metal bar using a metal wire. The wire length was equal to the distance from the length between the axles to the armrest of the wheelchair. The junction side of the handrim was fixed by a quick-release metal clasp. A strain gauge was attached to the metal bar median. The strain quantity of the metal bar was measured using an analogue-to-digital convertor in the microcontroller, and was recorded on a personal computer (PC). A wheelchair user applied a force to the handrim (Step 1 in Fig. 3). Then, the wire was pulled downward (Step 2 in Fig. 3). The wire slightly strained the metal bar by pulling both ends of the metal bar. Then, the strain gauge resistance was changed by the strain of the metal bar (Step 1 in Fig. 3). The voltage difference between the distortion gauges can measure the distortion of the metal bar. It is possible to estimate the applied handrim force by the measured strain gauge resistance. Using this structure, the handrim force can be measured without rotating the wheel. The electronic portions of the mounting are shown in Table 1. The metal bar material used in this study was an aluminium square pipe (length = 1000 mm, width and height = 20 mm, thickness = 2 mm) that can withstand 2200 N maximum weight [22]. A diameter of stainless steel stranded wire was 2 mm, which can withstand a maximum 2843 N force. The quick-release metal clasp was a stainless-steel carabiner that can withstand 784 N. The overall maximum force of the measurement device was 784 N.

An illustration of the apparatus after mounting is presented in Fig. 4. Installation of the measuring device to a wheelchair was done according to the following steps: (1) place the metal bar on the armrest, (2) connect the metal bar to the handrim via a wire, (3) adjust the metal bar, forming a vertical angle with the wire, (4) connect the microcontroller and the PC. The microcontroller measured the strain gauge voltage at sampling intervals of 20 Hz. The measured voltage was calibrated to 0 V when the metal bar had no applied force. The measured voltage was transmitted to a PC by serial communications and recorded using the PC.

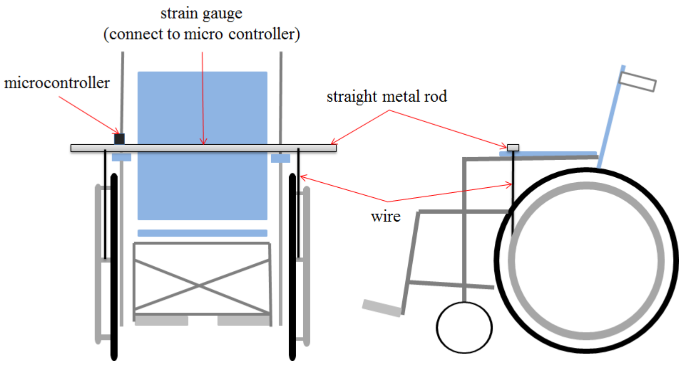

Fig. 2 Design of device used for handrim force measurements

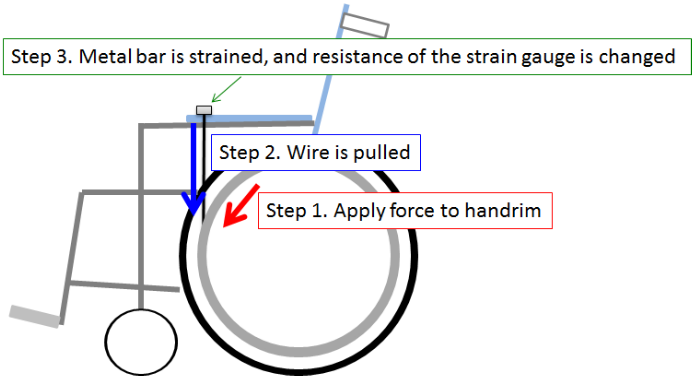

Fig. 3 Method of measurement of handrim force

TABLE 1 HANDRIM FORCE MEASUREMENT DEVICE COMPONENTS

Type name	Part name (product)	No.
strain gauge	N11-FA8-120-23 (Kyowa Electronic Instruments Co. Ltd.)	2
op amp	INA101HP (Texas Instruments Inc.)	1
voltage converter	LTC1144 (Linear Technology Corp.)	1
microcontroller	Arduino UNO (Arduino SRL)	1
straight metal rod	aluminium square pipe	1

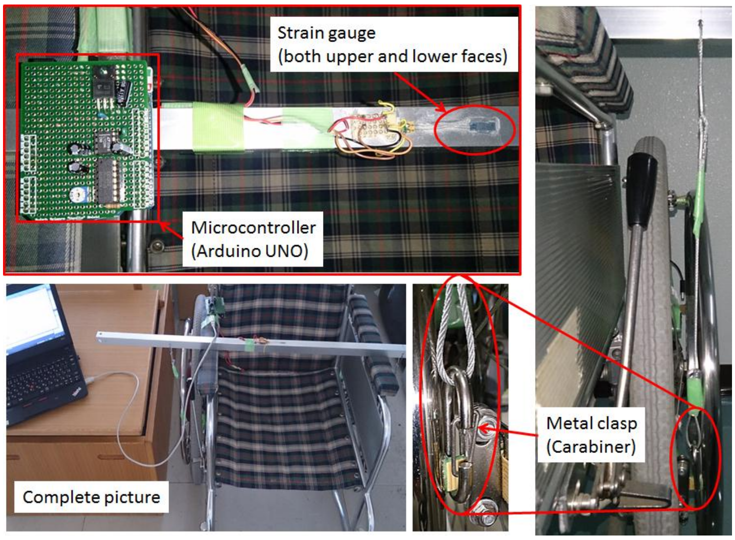

Fig. 4 Illustration of handrim force measuring device

III. CALIBRATION FROM THE AMOUNT OF METAL BAR DISTORTION CAUSED BY HANDRIM FORCE

The amount of metal bar strain was calibrated for the handrim force. The measuring device was attached to the wheelchair. Then force was then applied to the wheelchair handrim by a weight, using a pulley. Weights of 0 N, 49 N, 98 N, 147 N, and 196 N were hung on the pulley. The relationship to the amount of metal bar strain was then investigated. Fig. 5 presents the scatter diagram of the voltage of strain gauge and handrim force. The metal bar strain was calibrated to the force applied by the handrim using the approximate expression.

Fig. 6 presents the results of the handrim force measurement. The handrim force depicted in Fig. 6 shows measurement results of the same person as the results depicted in Fig. 1. Individual differences exist; although the peak value of the handrim force gradually decreases over time, constant force is exerted in the latter half, probably because the experimental participant cannot grasp the pace of the applied handrim force as the experiment progresses. Therefore, the peak of the handrim force was averaged, after excluding first and end quarters from the measurement data.

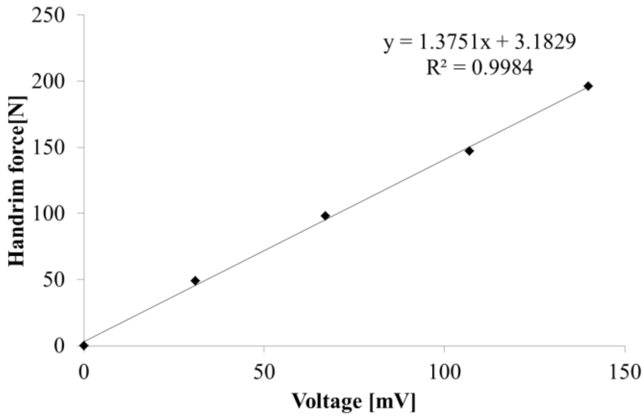

Fig. 5 Scatter diagram of the voltage of strain gauge and handrim force

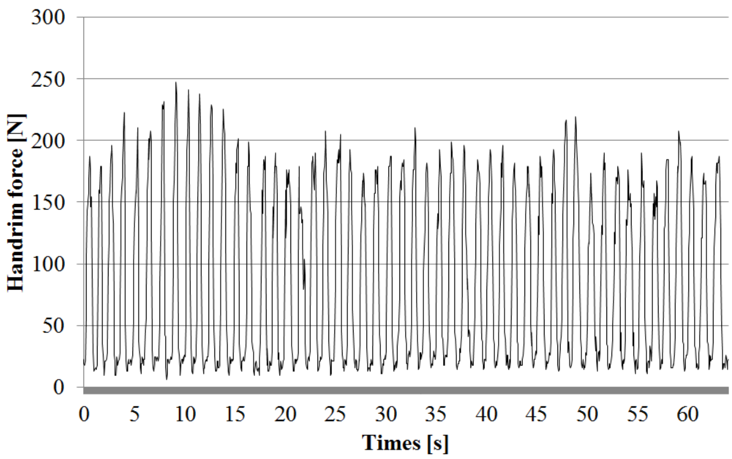

Fig. 6 Handrim force assessed using a device to measure physical strength

IV. EXPERIMENTAL VERIFICATION MEASUREMENT DEVICE OPERATION

An experiment was conducted to investigate the relationship between the handrim force of the measurement device and the handrim force of moving up a slope by a manual wheelchair.

A. Measurement of the Handrim Force

The work necessary for climbing the slope was measured by the following procedures:

(1) The measuring device was attached to a wheelchair. The front wheel of the wheelchair was fixed so that the wheelchair was unable to move. (2) The following instructions were provided: “After an indicator alarm sounds, please continue applying force to the handrim for about 1.5 seconds. Then please rest for approximately 1 s. Please repeat this operation 100 times.” (3) The steps described above were repeated 50 times. The reason for the difference in the number of motions is to prevent strong force by the experiment participants operating at the end of experiment.

B. Measurement of Force and Work on the Slope

The experimental participants ascended four slopes. The applied handrim force and wheel rotation angle were measured. The weight of the wheelchair used for measurement was 160 N, the wheel radius was 30.4 cm, the stainless steel handrim radius was 25.4 cm, and the rolling-resistance coefficient was 0.51. The experimental participant ascended four slopes while the handrim force and wheel rotation angle were measured. A manual wheelchair was used to measure the handrim force and the wheel rotation angle. The experimental participants were 10 healthy male subjects (age = 22 ± 2 years; weight = 593.0 ± 75.6 N). Table 2 presents the slopes used in the experiment. The road surface used for measurements was flat asphalt concrete. Each experimental participant ran each slope twice. The measurement values were averaged.

TABLE 2 VERTICAL SLOPES USED IN EXPERIMENT

Distance [m]	Slope angle [deg]
15	0
19	2.1
19	2.7
15	5.8

C. Experiment Results

We assumed that the handrim force per unit of weight would have strong effects when a wheelchair user ascends a slope. Therefore, the relationship between the experimental participant's force per unit of weight and the force or work on the slope was investigated. The number of strokes, the maximum handrim force, the handrim force per stroke, the work per stroke, the work per metre, and work rate were calculated. Fig. 7 depicts the relationship between the handrim force per unit of weight and the other parameters on a slope of 5.8 degrees. The number of strokes was negatively correlated to the handrim force per unit of weight. Positive correlations were found between the handrim force and weight for the remaining five items.

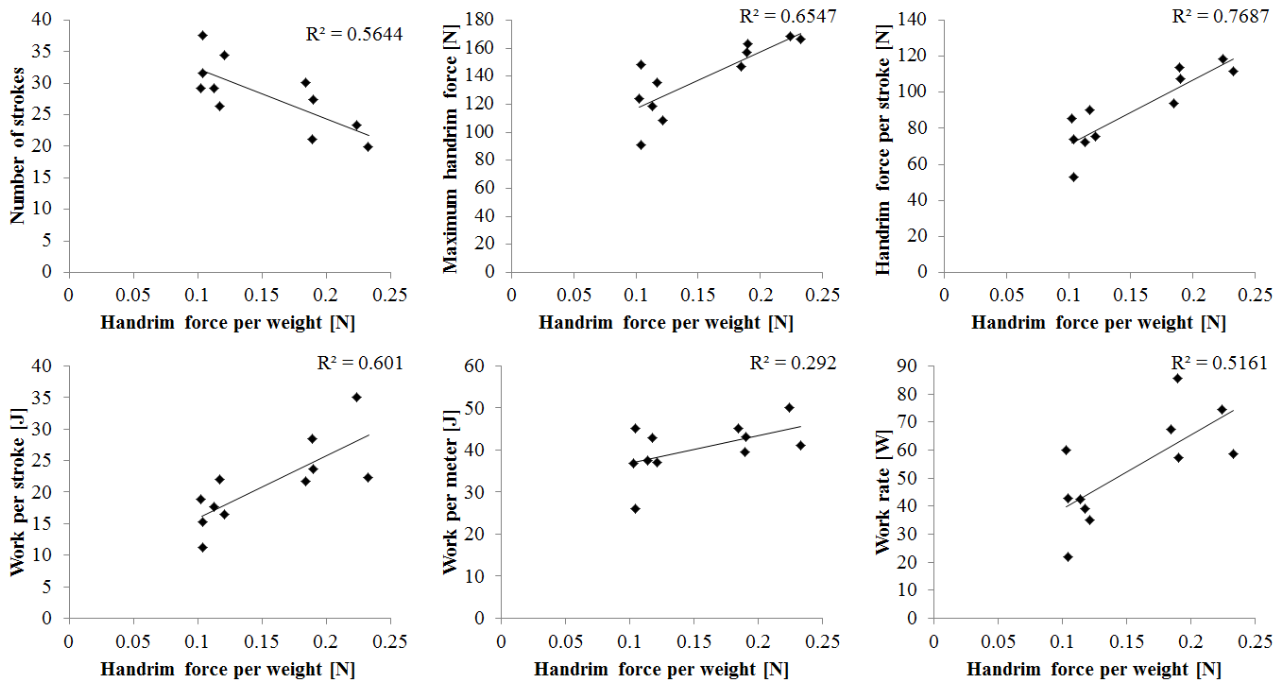

Fig. 7 Relationship between the experimental participant's force per unit of weight and the force or work on the slope

Next, multiple regression analysis was employed to examine the factors affecting the force and work of the handrim. Objective variables were used for the maximum handrim force, the handrim force per stroke, the work per stroke, the work per metre, and work rate. Explanatory variables were used for the slope angle and the handrim force per weight, and included the weight of the wheelchair and the weight of each experimental participant. The multiple linear regression analysis results are presented in Table 3. All adjusted R^2 values were high, indicating significance of the regression model. The standard partial regression coefficients were also significant. The partial regression coefficient of the slope angle was greater than the handrim force per weight, but the handrim force per unit of weight was a significant effect. However, the partial regression coefficient of the work per metre was smaller than the other objective variables. In addition, the value of the adjusted R^2 was smaller than the multiple regression analysis by slope angle and weight. Therefore, it is assumed that the effect of the handrim force per weight is small in terms of the work per metre.

Results suggest that a wheelchair user with the greatest handrim force per unit of weight tends to apply great power to a single stroke. In doing so, the number of strokes decreases along with running time. The handrim force per stroke and work per stroke also decrease according to the number of times a stroke becomes shorter. Moreover, as the running time decreases, the work rate also decreases. Presumably, the wheelchair user with the greatest handrim force per unit of weight uses force more effectively. These observations suggest similarity between handrim operation with the measuring equipment and the handrim operation at the time of the slope run.

TABLE 3 RESULT OF MULTIPLE REGRESSION ANALYSIS

Objective variable	Explanatory variable	Standard β	R^2_{Adj}
Maximum handrim force	slope angle	0.77^{**}	0.64^{**}
	force/weight	0.26^{**}	
Handrim force per stroke	slope angle	0.80^{**}	0.68^{**}
	force /weight	0.25^{**}	
Work per stroke	slope angle	0.77^{**}	0.70^{**}
	force /weight	0.35^{**}	
Work per metre	slope angle	0.95^{**}	0.93^{**}
	force /weight	0.20^{**}	
Work rate	slope angle	0.75^{**}	0.61^{**}
	force /weight	0.23^{**}	
Degrees of freedom	43		
β, Partial regression coefficient; R^2_{Adj}, Adjusted R-squared			
** $p < 0.01$, * $p < 0.05$			

V. PHYSICAL STRENGTH EVALUATION EXPERIMENT USING THE MEASUREMENT DEVICE

The designed measurement device was used to conduct an experiment to verify that a wheelchair user's physical strength can be estimated by measuring the handrim force. Experimental procedures were as follows: measure handrim force using the measurement device, drive a course of approximately 360 m, including a steep slope (at a maximum 6.2 degrees) in a manual wheelchair; measured the required time, and the distance from the starting point to the first resting point. The experimental participants were 21 healthy subjects (age = 22 ± 2 years; weight = 642.0 ± 106.4 N (mean ± SD); 20 male, 1 female).

The scatter plot in Fig. 8 shows the putative relationship between the handrim force and the required time. The experimental participants who demonstrated strong handrim force were able to move quickly; these were found to have some correlation (r = -0.6, $p < 0.05$). Fig. 9 shows a scatter plot of the handrim force and the distance from the starting point to the first resting point. The "Destination" line in Fig. 9 shows the final point of the experimental course. A point on this line shows the handrim force of the experimental participant who never rests. These were found to have some correlation (r = 0.57, $p < 0.05$). The experimental participants who demonstrated strong handrim force were able to arrive early at the destination and move longer without taking a rest. In addition, Fig. 10 presents the difference median between the group who took a rest and the group who did not take a rest. The handrim force of the group that did not take a rest is significantly high according to the Mann–Whitney U test.

Experimental results indicate that the measured handrim force and the physical strength when moving a wheelchair are mutually related. This simple measurement device for measuring handrim force can provide results approximating the handrim force measured during outdoor running.

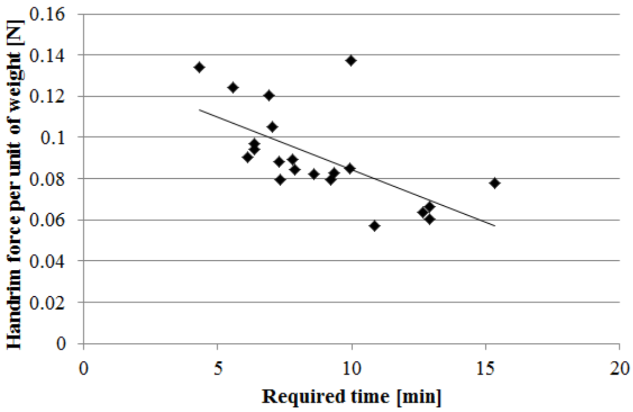

Fig. 8 Scatterplot of handrim force and required time

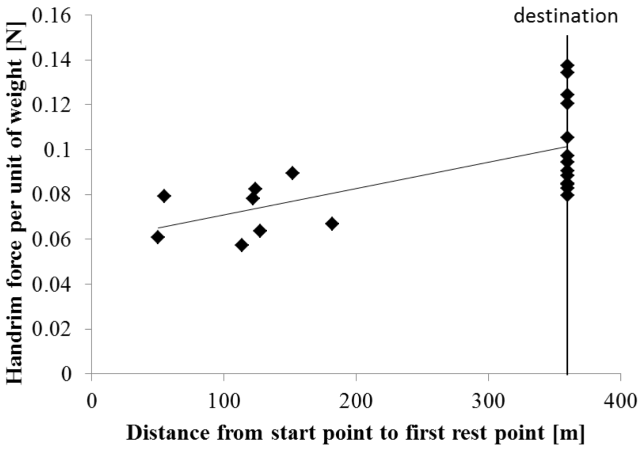

Fig. 9 Scatterplot of handrim force and first rest distance

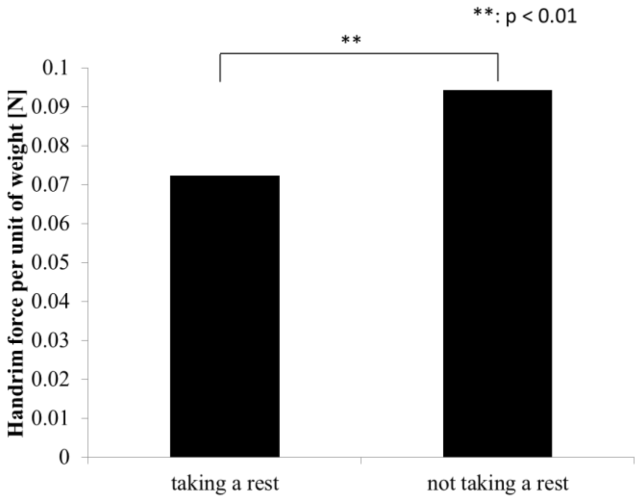

Fig. 10 Difference in handrim force between group who took a break, and group who did not

VI. CONCLUSIONS

For this study, a measurement device that can measure the applied handrim force of manual wheelchair was developed to support independent movement by wheelchair users. Results indicate that the measured handrim force and the physical strength when moving by a wheelchair are mutually related. Additionally, the device can evaluate the physical strength necessary for movement with the wheelchair based on measurements of the handrim force. Traditional measurement methods may be superior for detailed physical strength evaluation; however, the wheelchair user's handrim force can be measured in a few minutes with this simple measurement device using the methods implemented in this study. Moreover, the developed measurement device does not require a large treadmill or ergometer. This research will contribute to the measurement of the physical strength of wheelchair users.

Additionally, the possibility of evaluating a stroke pattern or work rate when a wheelchair user ascends a slope is presented, based on values obtained using the handrim force measurement device. However, the relationship between the handrim force per weight and the stroke pattern or work rate might differ among actual wheelchair users. In future studies, we intend to measure the handrim force of actual wheelchair users. If the correlation between the handrim force per weight and the stroke pattern or work rate can be confirmed, it could be also expected to help manual wheelchair users learn efficient handrim operation. We further plan the development of a navigation system that presents the route by which the wheelchair user can move using the measured handrim force. A route-finding system for wheelchair users that records correlative data between slope angles and necessary physical strength has been developed [23-26]. Thus, we are examining a method of presenting the best route for each manual wheelchair user based on simple handrim force measurements.

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