Analysis of Force Applied to Horizontal and Vertical Handrails with Impaired Motor Function

Ryoya Kihara[1], Qi An[2], Kensuke Takita[3], Shu Ishiguro[4], Kazuto Nakashima[1] and Ryo Kurazume[1]

***Abstract*— People depend on medical equipment to support their movements when their motor function declines. Our previous study developed a method to estimate motor function from the force applied to a vertical handrail while standing. However, the effect of the handrail direction on movement remains unclear. Additionally, the force applied to the handrail and floor reaction forces on the buttocks and feet may also change with a decline in motor function. Here, this study constructed a system with force plates and handles in both the horizontal and vertical directions to measure the forces applied to the handrails, buttocks, and feet. Furthermore, the change in accuracy of the estimation of motor function, depending on the direction of the handrails and input information, was investigated. In the experiment, healthy participants stood up using a handrail with unrestricted movement and while wearing elderly experience kits that artificially impaired their motor function. The results showed that people exert more downward force on horizontal handrails than on vertical handrails. However, people rely on the vertical handrail for a longer period of time to stabilize anterior-posterior movement. These results indicate that different directions of handrails cause different strategies of the standing-up motion. Additionally, the accuracy of the estimation of motor function improved when the horizontal handrail was used rather than the vertical handrail. This suggests that the classification accuracy could be improved by using different handrail directions, depending on the subject's condition and standing-up motion.**

I. INTRODUCTION

People perform various movements in daily life, such as walking and standing up. Since the difficulty of these movements increases as motor function decreases due to aging or illness; rehabilitation becomes important to restore physical function. During rehabilitation, reduced motivation hinders effective treatment [1], adversely affecting the prognosis of rehabilitation and prospects of independent daily living [2] [3]. Thus, improving patients' motivation in clinical situations is essential and one of the key factors influencing a patient's motivation is having a clear goal set [4]. Therefore, it is essential to clarify the patients' current motor function status relative to the desired goal, to indicate improvement and maintain motivation. In addition, a patient's current motor function must be measured to select the most appropriate intervention for the patient, from the vast variety of available therapies [5] [6] [7]. Therefore, a system that can easily display the motor function of patients to therapists, medical doctors, and the patients themselves is required.

Previously, we developed a vertical handrail and measured the force applied to it. Furthermore, the force data was used to classify the motor function of hemiplegic patients into two classes, severely and moderately impaired [8]. However, it is necessary to improve the classification accuracy and describe the differences in standing-up motion in more detail, for more effective rehabilitation. In addition, the previous system could not be easily operated by a single user making it inappropriate for typical rehabilitation facilities.

To improve the classification accuracy of the motor impairments, it was hypothesized that the strategy used during the standing-up motion changes according to the direction of the handrail. In a previous study [8], it was found that people had difficulty applying downward force when they used a vertical handrail, indicating that vertical handrails are not suitable for people who have difficulty lifting their body upward. Additionally, elderly people tend to apply a larger force to a curved handrail than to a vertical handrail [9] and the difference between horizontal and vertical handrails causes a change in the force applied to the feet [10]. Therefore, the direction of the handrail affects the method used to stand up when motor function decreases. In other words, the direction of handrails must vary depending on the type of motor disability. Thus, in this study, the change in standing-up motion, according to the direction of the handrails, was compared and verified whether the classification accuracy of motor function improved using different types of handrails.

Furthermore, additional information was considered that may improve the classification accuracy. A previous study showed that the body trajectory during the standing-up motion can be estimated by the force applied to the buttocks and feet [12]. Another study showed that foot strength correlates with the fall ratio during the standing-up motion [13]. This suggests that the reaction force on the buttocks and feet is correlated with motor function. Thus, in this study, the forces on the buttocks and feet in addition to the handrails were analyzed and verified whether the classification accuracy of motor function improved using these forces.

The study followed the following procedure; first, a system to measure the force applied to horizontal and vertical handrails, buttocks, and feet was developed. Second, the system was used to measure how the forces applied var-

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[1]Ryoya Kihara, Kazuto Nakashima, and Ryo Kurazume are with the Faculty of Information Science and Electrical Engineering, Kyushu University, Fukuoka, Japan kihara@irvs.ait.kyushu-u.ac.jp

[2]Qi An is with the Department of Human and Engineered Environmental Studies, Graduate School of Frontier Science, The University of Tokyo, Chiba, Japan anqi@robot.t.u-tokyo.ac.jp

[3]Kensuke Takita is with the Faculty of Advanced Engineering, Nippon Institute of Technology, Saitama, Japan

[4]Shu Ishiguro is with the Future Robotics Technology Center, Chiba Institute of Technology, Chiba, Japan

ied depending on standing-up motion and motor function. Finally, machine learning was used to classify whether the classification accuracy of the motor function improves by using the force on the buttocks and feet while using different types of handrails.

II. Development of handrail

A. Handrail hardware

A handrail system is required to measure the force applied to both horizontal and vertical handrails. Furthermore, the reaction force on the buttocks and feet must be measured simultaneously. Based on commercially available handrails (Yazaki Kako Corp., CKH-21), the handrail was at a height of 780 mm with a diameter of 34 mm. In addition, the handrail was designed to measure forces up to 1,470 N, which allows users up to 150 kg to be measured, even when applying their entire weight onto the handrail. Force sensors (Leptrino Inc., FFS-080YS102-A6) were selected to satisfy the maximum load required to measure the force applied to the handrail and were implemented on both sides of the handrail to measure the force applied to the horizontal and vertical handrails. Finally, force plates (TechGihan Co., Ltd., TF3040 and TFG4060) were placed under the buttocks and feet of the users and the developed handrail system is shown in Fig. 1.

B. Force measurement software

An IC card reader was used to identify the user who performed the standing-up motion and a monitor with a touch panel efficiently performed required operations. Furthermore, the analog data of the force applied to the handrail, buttocks, and feet obtained from the force sensors and force plates was recorded as digital data via an AD conversion board. The system operation screen is shown in the top right side of Fig. 1. The system can easily measure and display the force applied by simply operating the touch panel according to the instructions on the screen.

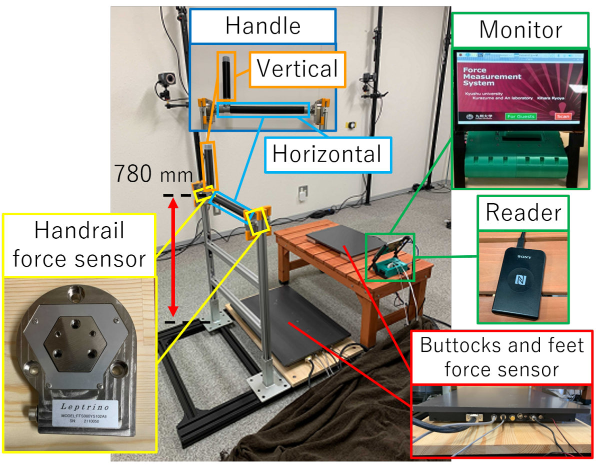


Fig. 1. The whole picture of the completed handrail

III. Force measurement experiment

A. Experiment procedures

A measurement experiment was performed to clarify whether people change their way of standing up with horizontal and vertical handrails when their motor function decreases. Furthermore, whether the classification performance of motor function changes between the horizontal and vertical handrails was analyzed. First, all participants stood up naturally, without any motor restriction. Second, they were asked to wear elderly experience kits to artificially impair their motor function. Specifically, the participants wore additional weight, to simulate decreased muscle strength, and had the range of motion of their knees and elbows restricted to simulate impaired motor function. The elderly experience kit has been used by other research groups [15] for healthy participants to simulate the decreased motor function. Specifically, as shown in Fig. 2, supporters, weighted bands, and weighted vests from SANWA were used.

B. Analysis of the force applied during standing-up motion

To examine the change in forces, the force applied to the handrails, buttocks, and feet in the anterior-posterior and upward-downward directions was the focus of this study, as shown in the left figure of Fig. 2. In addition, the same characteristics as in previous studies were analyzed [8]: maximum value F_{max}, average value F_{ave}, time to reach the maximum force T_{max}, time to start applying force T_{st}, time to finish applying force T_{ed}, and time duration applying force T_{dur}, as shown in Fig. 3. The maximum value F_{max} is the maximum force, and the average value F_{ave} is the average force of each applied to the handrails, buttocks, and feet during the standing-up motion. The maximum time T_{max} is defined as the time at which the force reaches its maximum value. The start time T_{st} is defined as the time when the force applied to the handrail reaches 50 % or more of the maximum value for the first time. The end time T_{ed} is defined as when the force applied to the handrail reaches 50 % or less of the maximum value for the first time after reaching the maximum value. Time T_{dur} is defined as the time between T_{st} and T_{ed}. Forces F_{max} and F_{ave}, which can be defined in the same manner as the handrail, were analyzed for the force applied to the buttocks and feet. In the following sections, the subscripts on the right shoulder of the variable represent the body part and the direction of the force,

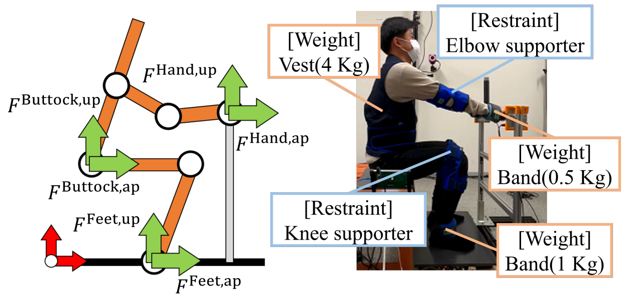


Fig. 2. Direction of the movement of each part while standing

for example, force $F_{\max}^{\text{Hand,ap}}$ represents the maximum force applied to the handrail in the anterior-posterior direction; and time $T_{\text{ed}}^{\text{Hand,ud}}$ represents the time to finish applying upward-downward directional force to the handrail.

C. Data collection and signal processing

The force values were measured at 250 Hz and filtered using a 20 Hz second-order Butterworth low-pass filter. Additionally, the force values were normalized to 100% by using the subject's weight (including the mass of the weight when wearing the elderly experience kit). To compare the data among the different conditions, the data was cut based on the time at which the participants rose their buttocks from the chair. When the upward reaction force to the buttocks during the standing-up movement was 25 N or less, equivalent to 5% of the average body weight of all subjects, it was regarded as the time at which the buttocks lost contact with the chair and the data from 1.0 s before to 2.0 s after this time were defined as one trial.

D. Experimental conditions

In this experiment, four conditions were examined, which were divided based on the difference between the usage of the horizontal or vertical handrail and the presence or absence of movement restrictions by the elderly experience kit. They were used to evaluate whether the evaluation of motor function changes between horizontal and vertical handrails and to analyze the changes in the force applied to the handrails, buttocks, and feet due to decreased motor function. In this experiment, ten males (height: 1.7 ± 0.08 m, weight: 57.1 ± 8.2 kg, age: 23.1 ± 0.83 years) participated and performed the standing-up motion 15 times under these four conditions, as shown on the right-hand side of Fig. 2. During the experiment, the participants were asked to hold the handrail with their right arm extended straight out. In addition, they were instructed to use a handrail to help themselves stand up comfortably. The experimental procedure was approved by the Ethics Committee of the Graduate School of Information Science and Electoral Engineering at Kyushu University.

E. Results of force change due to motion restriction

Figure 4 shows the forces applied to the handrail, buttocks, and feet during the standing-up motion. The black solid and red dashed lines indicate the forces applied to the horizontal and vertical handrails, respectively. The black solid lines and red dashed lines with circle markers show the force when the participants with restricted motions used horizontal and vertical handrails, respectively. First, 15 trials of force data were averaged for each condition of one subject, followed by an average of all the participants. The positive and negative values correspond to the directions shown in Fig. 2.

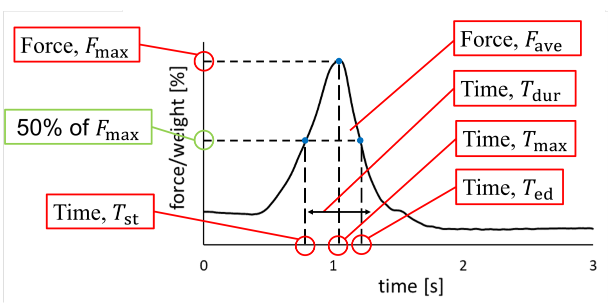


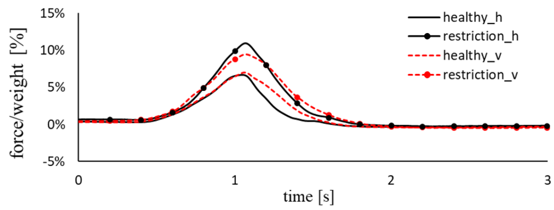
Fig. 3. Characteristic force feature

A two-way analysis of variance (ANOVA) was performed to assess the effect of handrail direction (horizontal or vertical) and whether the motion was restricted. Tables I and II show the mean and standard deviation of each pair of experimental conditions under which a statistically significant difference existed. From Table I, the results indicate that the participants applied a significantly larger force to the horizontal and vertical handrails and feet in the anterior-posterior and upward-downward directions when their motion was restricted. It was also found that the end time of applying force to the handrail increased owing to the motion restriction, regardless of the handrail direction.

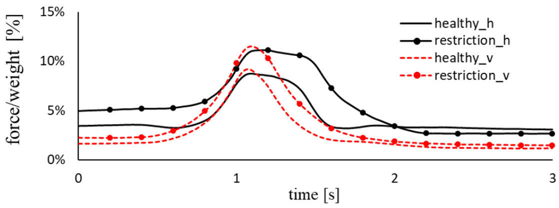
From Table II, it can be seen that the maximum force in the upward-downward direction became larger in the vertical handrail than in the horizontal handrail when motion was unrestricted. When the motion was restricted, the participants applied a larger force in the upward-downward direction to the horizontal handrail than to the vertical handrail. It was also found that the time taken to apply the maximum force to the handrail was delayed when the participants used the horizontal handrail. Furthermore, participants applied anterior-posterior directional force for a longer period with the vertical handrail, and in contrast, they applied a force for a longer period in the upward-downward direction to the horizontal handrail.

These results suggest that participants changed their strategy of using a handrail to complete the standing-up motion when their motion was restricted. As shown in Fig. 5, the standing-up motion is completed by generating the rotational moment as a yellow arrow by pulling the handrail to move the body forward and pushing the floor with the feet. In the restricted condition, participants wore a heavy vest to have difficulty extending their body using the original motion strategy, and in this case, they chose to generate a rotational moment rather than move their body forward to lift the trunk to compensate for this change.

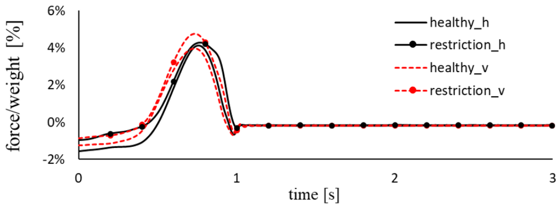
In addition, Table II shows that the participants applied an anterior-posterior force longer with the vertical handrail suggesting that they utilize the vertical handrail to stabilize their anterior-posterior posture. Moreover, the maximum upward-downward force applied was greater for the horizontal handrail than for the vertical handrails. This implies that the participants tended to use the horizontal handrail to generate an upward force to extend their bodies. From these results, it was found that the participants could easily apply the anterior-posterior force by pulling the vertical handrail and the upward-downward force by pushing down on the horizontal handrail. These results imply that the direction of the force that the user is likely to apply depends on the direction of the handrail.



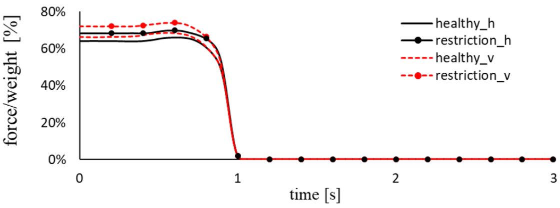
(a) Anterior-posterior directional force on the handrail



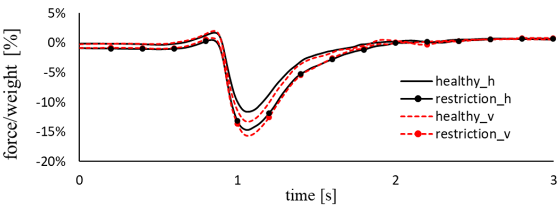
(b) Upward-downward directional force on the handrail



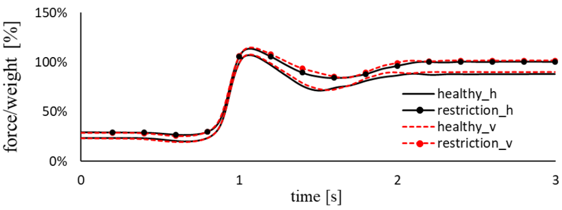
(c) Anterior-posterior directional force on the buttocks



(d) Upward-downward directional force on the buttocks



(e) Anterior-posterior directional force on the feet



(f) Upward-downward directional force on the feet

Fig. 4. The force applied during standing-up motion

Although restricted condition changes motion strategy of the participants, this phenomenon might be caused by compensation for restricted motion rather than replicating the condition of elderly. In the previous study [15], it is pointed out that people wearing the elderly experience kit tended to utilize balance function to compensate for the limited range of motion and lowered muscle strength. It is further needed to examine if people with decreased motor ability change their motion strategy.

TABLE I
RESULT OF THE TWO-WAY ANOVA IN MOTOR RESTRICTION CONDITION

Features	Handrail	Unrestricted	Restricted
$F_{\text{ave}}^{\text{Hand,ap}}$	Horizontal	1.4 ± 0.9 %	2.1 ± 1.1 %*
	Vertical	1.2 ± 1.0 %	2.1 ± 1.4 %
$F_{\text{ave}}^{\text{Hand,ud}}$	Horizontal	2,1 ± 1.0 %	3.7 ± 1.2 %***
	Vertical	1.9 ± 0.5 %	2.8 ± 0.7 %
$F_{\text{ave}}^{\text{Feet,ap}}$	Horizontal	-1.8 ± 0.9 %	-2.7 ± 1.2 %*
	Vertical	-2.0 ± 0.8 %	-2.7 ± 1.0 %
$F_{\text{ave}}^{\text{Feet,ud}}$	Horizontal	66.9 ± 10.4 %	76.3 ± 10.8 %**
	Vertical	67.9 ± 10.4 %	77.4 ± 10.3 %
$T_{\text{ed}}^{\text{Hand,ap}}$	Horizontal	1.19 ± 0.08 s	1.31 ± 0.07 s***
	Vertical	1.27 ± 0.05 s	1.36 ± 0.10 s

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

TABLE II
RESULT OF THE TWO-WAY ANOVA IN THE TYPE OF HANDRAIL

Features	Condition	Horizontal	Vertical
$F_{\text{max}}^{\text{Hand,ud}}$	Unrestricted	12.7 ± 5.0 %	15.0 ± 5.2 %*
	Restricted	9.7 ± 3.4 %	12.0 ± 5.2 %
$T_{\text{max}}^{\text{Hand,ud}}$	Unrestricted	1.36 ± 0.51 s	1.09 ± 0.07 s*
	Restricted	1.35 ± 0.39 s	1.11 ± 0.04 s
$T_{\text{ed}}^{\text{Hand,ap}}$	Unrestricted	1.19 ± 0.08 s	1.27 ± 0.05 s*
	Restricted	1.31 ± 0.07 s	1.36 ± 0.10 s
$T_{\text{ed}}^{\text{Hand,ud}}$	Unrestricted	1.77 ± 0.62 s	1.46 ± 0.33 s*
	Restricted	1.76 ± 0.48 s	1.43 ± 0.17 s

*: $p < 0.05$

IV. Classification of the Motor Function

The purpose of the system is to classify whether the motion is impaired by evaluating the force data during the standing-up motion. As discussed in the previous section, motor function was artificially impaired and restricted by an elderly experience kit. Previously, the force applied to the vertical handrail was used to classify whether the participant had severe or moderate motor impairments [8]. This study expanded upon this by investigating whether the classification performance is affected by the vertical and horizontal handrail orientations. Moreover, the contribution of the additional input, that is, the reaction force on the buttocks and feet was verified. The five proposed methods are presented in Table III.

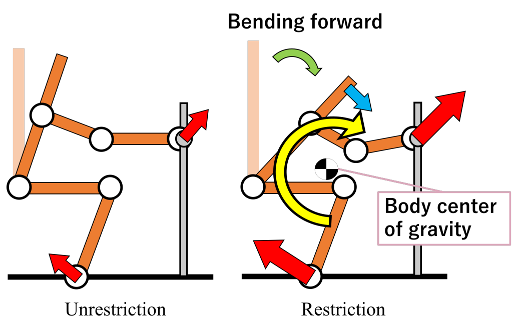


Fig. 5. Moment generated during the standing-up motion

TABLE III

TYPE OF DATA INPUT TO THE CLASSIFIER

Input data	Vertical handrail	Horizontal handrail
F^{Hand}	Baseline	Proposal 1
F^{Body}	Proposal 2	Proposal 3
$F^{\mathrm{Hand}} + F^{\mathrm{Body}}$	Proposal 4	Proposal 5

A. *Features that input to the classification model*

The force features extracted from the force applied to the handrails, buttocks, and feet were used to classify whether the data were obtained under motion restriction. Initially, six features were extracted from both the anterior-posterior and upward-downward forces applied to the handrail as follows: (1) maximum force F_{max}, (2) average force F_{ave}, (3) time to reach maximum force T_{max}, (4) time to start applying force T_{st}, (5) time to finish applying force T_{ed}, and (6) time duration applying force T_{dur}. Next, three features were extracted from three types of forces, such as anterior-posterior force to the buttocks and anterior-posterior and upward-downward force to feet: (1) maximum force F_{max}, (2) average force F_{ave}, and (3) time to reach maximum force T_{max}. The data of the standing-up motion using horizontal or vertical handrails were used separately for the training classification model. Three different combinations of the input data were investigated as follows:

1) F^{Hand} condition: features from handrail (12 inputs).
2) F^{Body} condition: features from buttocks and feet (9 inputs).
3) $F^{\mathrm{Hand}} + F^{\mathrm{Body}}$ condition: features from handrails, buttocks and feet (21 inputs).

B. *Classification model and evaluation method*

Following a previous study [8], we classified the data using a random forest [16], which is a method that randomly extracts data, repeats the steps of growing a decision tree, and finally determines the value predicted by the majority vote. In this study, the classification accuracy of the proposed model was evaluated using fivefold cross-validation. To compare the six conditions in Table III, we collected the labeled dataset of 300 trials in which 10 participants stood up 15 times with and without motion restriction. Each method was evaluated through fivefold cross-validation as split according to the subject; 2 out of the 10 subjects for the test set and the remaining 8 subjects for the training set.

C. *Tuning method of the classification model parameters*

To tune the classification model parameters, we used Optuna [17] as the optimization framework. Given a search space, objective function, and trial number, Optuna searches for the optimal parameters that maximize the objective function within the specified search space using the tree-structured Parzen estimator (TPE) algorithm [17] [18]. Figure 6 shows an overview of model tuning using Optuna. In this study, the search space of the parameters is given by the following five parameters: λ_1–λ_5. λ_1 adjusts the number of trees in each decision tree generated. λ_2 adjusts the maximum tree depth in each decision tree generated.

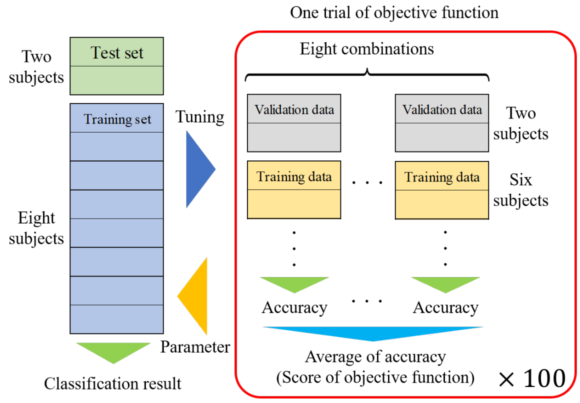


Fig. 6. Overview of model tuning

TABLE IV

SEARCH SPACE OF THE PARAMETERS OF A RANDOM FOREST

Features	lower limit	upper limit
λ_1	10	1000
λ_2	5	30
λ_3	2	10
λ_4	1	10
λ_5	2	9

λ_3 adjusts the minimum amount of data required to split an inner node. λ_4 adjusts the minimum amount of data that must remain in the left and right nodes at the branch point of an internal node. λ_5 adjusts the number of features to be selected when performing feature selection on the individual nodes [19]. Table IV lists the search range for each parameter. Regarding the objective function, the accuracy rate of the model trained using the training data when applied to the verification data, was used. The training data and validation data were generated by eight subjects' data described in Section IV-B and split according to the subject; two out of eight subjects for the validation data and the remaining six subjects for the training data. In one trial, training and classification were performed eight times by changing the combination of the training and verification data, and the average value of the accuracy rate for the verification data was the score in that trial. Optuna then searches for a combination of parameters that maximizes this score and the number of trials was set to 100.

D. *Classification result of the motor function*

Table V lists the mean and standard deviation of the classification accuracy for the six different conditions. As a result of the classification, all scores for classification accuracy, such as precision, recall, and accuracy, improved with proposal 1 compared to the baseline. As indicated in this result, the classification accuracy was improved by using the horizontal handrail rather than the vertical handrail for the dataset used in this study. The reason for this is thought to be that the weighted vest, used as a movement restriction device, hinders the upward movement of the subject, resulting in a difference in force on the horizontal handrail that facilitates upward movement. Therefore, it is thought that classification accuracy can be improved by using

TABLE V

RESULT OF THE CLASSIFICATION ACCURACY

Condition	Precision	Recall	Accuracy	Train accuracy
Baseline	60.7 ± 33	69.3 ± 16	61.7 ± 8	93.3 ± 2
Proposal 1	74.0 ± 12	82.7 ± 12	78.0 ± 11	96.4 ± 3
Proposal 2	63.3 ± 29	56.2 ± 23	55.7 ± 17	98.3 ± 1
Proposal 3	53.3 ± 7	53.6 ± 2	53.3 ± 2	98.3 ± 2
Proposal 4	61.3 ± 31	74.0 ± 18	65.7 ± 13	99.3 ± 1
Proposal 5	83.3 ± 9	79.1 ± 10	80.0 ± 10	99.3 ± 1

All units are [%].

handrails in different directions, depending on the subject's condition and standing-up motion.

In addition, the classification accuracy of proposals 2 and 3 is low, and there is not much improvement in the classification accuracy between the baseline and proposal 4 and between proposal 1 and proposal 5. From these results, it can be observed that the input data of F^{Body} cannot contribute to the classification of motor function. The reason for this is thought to be that the adaptation to the decline in motor function by the elderly experience kit differed from subject to subject, which caused variations in the force applied to the buttocks.

V. CONCLUSION

In this study, a system was developed that allows for easy and simple measurement of the force applied to horizontal and vertical handrails during standing-up motion to assess user's motor function. When an elderly experience kit restricted the motion of the participants, they change their standing-up motion strategy.

Regardless of handrail direction, it was found that it increased the rotational moment generated by pulling on the handrail and pushing off of the floor. However, the method of utilizing the handrail differed according to the direction of the handrail. It was found that people tended to support upward movement by the horizontal handrail and anterior-posterior movement by the vertical handrail, suggesting that the manner in which participants use handrails may reflect their motor functions.

When the classification model of motor function was developed, the classification accuracy improved when a horizontal handrail was used rather than a vertical handrail. It was found that classification accuracy can be improved by using handrails of different directions depending on the subject's condition and standing-up motion. In addition, the input data of F^{Body} cannot contribute to the classification of motor function because the adaptation to the decline in motor function by the elderly experience kit differed from subject to subject. Therefore, in the future, real patients with impaired motion, such as back or knee pain, will be asked to participate in the experiments. Then, we would like to increase the usefulness of the system by performing multiclass classification according to the level of nursing care required.

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