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Development of wearable rehabilitation device using parallel link mechanism: rehabilitation of compound motion combining palmar/dorsi flexion and radial/ulnar deviation

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Abstract

In recent years, the total number of physical therapists is increasing in Japan. However, it is not sufficient to nurse of patients requiring long-term care. In order to cope with the shortage of manpower, it is desirable to develop the rehabilitation equipment. This paper describes the development of a wearable wrist rehabilitation training device using the parallel link mechanism. It is possible to train the translational and rotational motion of the wrist joint by the adoption of parallel links. Training of the translational motion of the wrist joint has not been discussed in existing methods. Therefore, compared to existing methods, this method can be expected to reduce the burden on the wrist joint. And it is possible to move about 60% of the wrist joint movable range of motion. This device performs repetitive training to prevent contracture of the wearer's joints. In experiments, assumed wrist circumduction motion was trained to the six subjects. The correlation coefficient between the target trajectory and the training result was obtained and evaluated whether correct operation was trained. The validity of the proposed method was demonstrated.

Keywords: 23rd robotics symposia, Wearable, Parallel link, Muscle and skeleton, Joint

Background

A questionnaire survey performed in 2014 by Japan's Care Work Foundation concluded that not enough people are working in the field of physical therapy and similar occupations [1, 2]. To address this issue, efforts are underway to develop training equipment to support and assist therapists. The existing rehabilitation equipment [3] is often operated using a serial link mechanism. It tends to accumulate errors as the number of joints increases; hence, the serial link makes it difficult to provide multiple degrees of freedom (DOF) of movement to a joint, which limits its use in joints, such as wrist joints that require a high DOF of movement. To address these issues, efforts are underway to develop rehabilitation training devices that use parallel link mechanisms. The existing training devices that use parallel links [4, 5] utilize a pneumatic cylinder as an actuator, which can be difficult to position and is noisy because of the use of a pump. This study hopes to improve the ease of operation of the device by adopting a linear servomotor. Accordingly, we develop a wearable rehabilitation device using parallel link mechanism that uses a servomotor [6]. We target the wrist joint because it is a major focus of rehabilitation, and the complexity of its range of motion is clear. In previous studies [6], the mounting position tended to be slightly misaligned because the measuring and training devices were separate, it causes a decrease in training effect. In this study, we improve the equipment by integrating the measuring and training devices, reducing the weight of the mounting part, and expanding the range of motion. We first describe a motion experiment targeted at assumed rehabilitation training for wrist joint circumduction movements using the developed device, and then address the effectiveness of the device based on a discussion of the experiment.

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Methods

Required specifications of the wrist training device

As part of this study, we develop a device that supports rehabilitation training for human wrist joints. Especially, it is assumed to be used for repetitive training to prevent contracture of the joint. Figure 1 shows the wrist joint comprising the radius, ulna, carpal, and metacarpal bones [7–9]. The palmar/dorsi flexion and radial/ulnar deviation actions at the wrist joint are accompanied by deformation and translation to the palm because the carpal bones form a structure in which a bundle of small bones is held in place at the wrist joint. The pronation and supination movements of the radioulnar joint also cause the radius to tilt toward the elbow and the palm to translate. Hence, a support that includes 3 DOF of translation is required in addition to the 3 DOF of rotation at the wrist joint.

The circumduction motion of the wrist joint targeted for rehabilitation training herein is the action of moving the palm in a circular motion starting from the distal end of the ulna, as shown in Fig. 1 [7]. This "circumduction motion", which is a combination of the palmar/dorsi flexion action and the radial/ulnar deviation action at the wrist joint, is a complex operation that simultaneously performs all the movements of the wrist joint, and has been adopted as a functional evaluation exercise for rehabilitation training. The device must satisfy all DOF of motion of the wrist joint to train the circumduction motion in the wrist joint. Furthermore, passive rehabilitation training requires the ability to move the palm, which typically weighs approximately 500 g (the body weight-corrected value for the palm assuming a body weight of 60 kg). The training device used in our proposed method satisfies the abovementioned conditions.

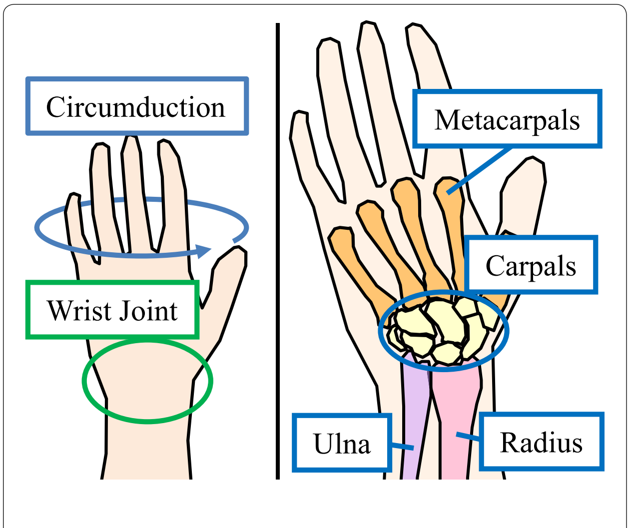

Fig. 1 Structure of the wrist joint

Table 1 shows the maximum range of motion of the device and the human wrist joint. The device can train approximately 60% of the movement of the wrist joint. However, the operation width of the device in Table 1 is the maximum value when operating with only a single rotation motion. And, when performing a compound rotation motion, the range of motion decreases. Also, the maximum range of motion decrease depending on the mounting position. Therefore, in this experiment, training is carried out within the movable range of the present apparatus.

Proposed method

This section provides an overview of the wearable parallel link-type rehabilitation device that developed.

Overview of the parallel link-type training device

The rehabilitation device developed in this study consisted of a measuring device part, which measured the movement of the wearer's palm, and a training device part, which supplied translational and rotational motion to the wearer's palm. Figure 2 shows the relation of the training device part and measuring device part. First, the wearer's motion is measured using measuring device part, and the obtained motion is set as the target motion. Next, by training along the target movement using a

Table 1 Maximum range of motion of the device and the human wrist joint

	Human body	Developed device
Palmar/dorsi flexion (°)	− 70 to 90	− 50 to 60
Radial/ulnar deviation action (°)	− 50 to 25	− 45 to 45
Pronation and supination movements (°)	− 90 to 90	− 45 to 45

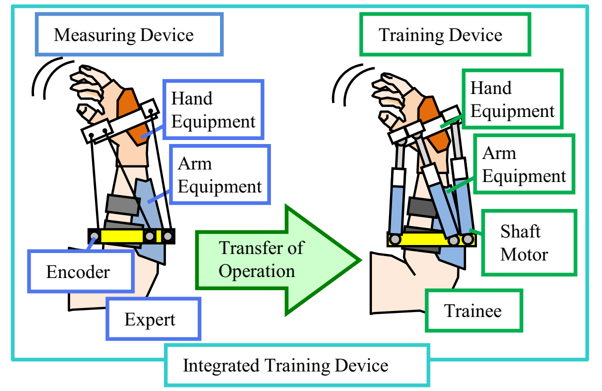

Fig. 2 Relation of the training device

training device, contraction of the wrist joint can be prevented. Since this device can support the above translational motion, it can be expected to reduce the burden on training. In normal rehabilitation exercises, the trainee is asked to repeat the necessary actions while the therapist provides assistance. In the training proposed herein, the trainee first performed the actions under the instruction and assistance of the therapist. The motion was measured by the measuring device. The trainee then repeatedly performed the training based on the measurement results using the training device without therapist intervention. Note that in the experiment described in later "Rehabilitation scenario experiment" section, the movements were performed unassisted during the motion measurement because the "trainees" were healthy subjects.

Structure of the developed integrated training system

Figure 3 shows the developed system diagram of the training device. For the training part, the system used the linear DC servomotor LM1247-120-11-C manufactured by Shinko Electronic Co., Ltd. as the actuator and the MCLM-300G-S RS as the motion controller. The linear DC servomotor was equipped with a Hall element and allowed length control based on PID control in combination with the controller. An MLS-12-1500-E-250 manufactured by Microtek Laboratory Co., Ltd. was used for the linear encoder, and an EN02 encoder receiver module manufactured by Arc Device Co. was used for the counter. The sampling time of the encoder was set to 10 ms. A 24VC150T2 lithium-ion battery made by Nissen Chemitec Co., Ltd. was used as the power source. Table 2 lists the training device specifications.

Calculation of the position and posture of the wrist

This section explains the technique for measuring wrist joint motion with the device developed in this study [10]. Figures 4 and 5 shows a model diagram of the parallel links used in this study. The length of each slider is measured by a linear encoder. The points in the parallel links are named as shown in Fig. 4, and the constants and variables are shown in Fig. 5. The lengths of the slider are

Table 2 Specification of the training device

Installation weight	1.5 kg
Maximum stroke speed	100 mm/s
Minimum resolution	0.01 mm
Actuator maximum acceleration	82.9 m/s^2
Rated thrust (total value)	21.6 N
Standard deviation at training (angle)	0.41°
Standard deviation at training (position)	0.22 mm

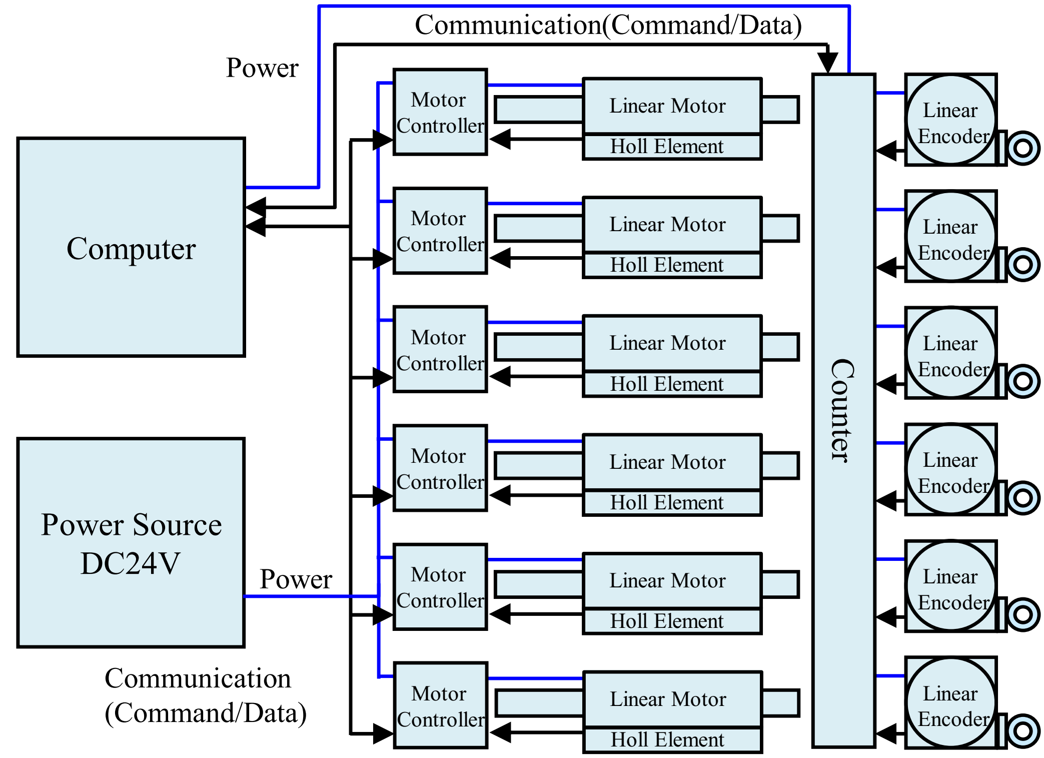

Fig. 3 System chart of a developed device

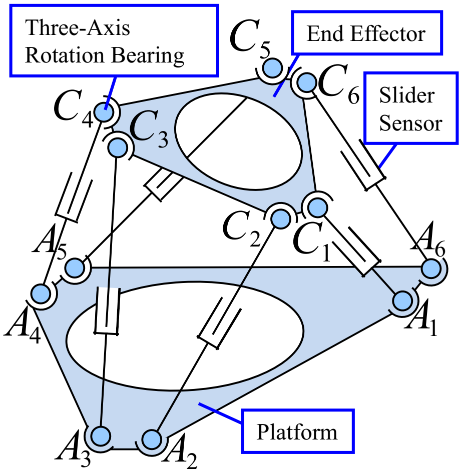

Fig. 4 Parallel-link model

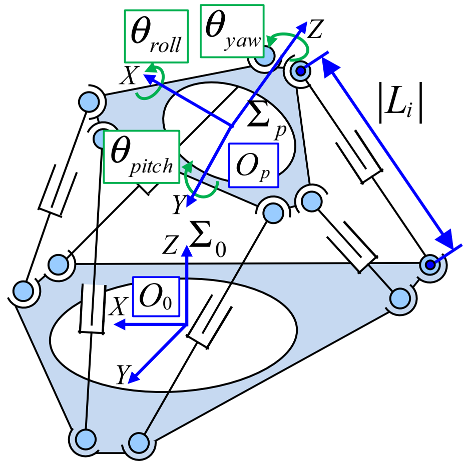

Fig. 5 Variables of the parallel-link model

denoted by $|L_1|$, $|L_2|$, $|L_3|$, $|L_4|$, $|L_5|$, and $|L_6|$, as shown in Fig. 5. The points O_0 and O_p are at the centers of the forearm equipment and the palm equipment, respectively, and are the origins of the coordinate system Σ_0 and Σ_p for each device. O_0 is assumed to match the center of the palm of the subject, and O_p is assumed to match the center of the forearm of the subject. The z-axis of each coordinate system is defined as the long axis of the palm and the forearm.

The x-axis rotation angle of the coordinate system Σ_0 is θ_{roll}, the y-axis rotation angle is θ_{pitch}, and the z-axis rotation angle is θ_{yaw}. The position and posture of the palm equipment are denoted by $Q=[{}^0O_{px}\ {}^0O_{py}\ {}^0O_{pz}\ \theta_{roll}\ \theta_{pitch}\ \theta_{yaw}]^T$, using ${}^0O_p=[{}^0O_{px}\ {}^0O_{py}\ {}^0O_{pz}]^T$, θ_{roll}, θ_{pitch}, and θ_{yaw}, where ${}^0O_p$ is the coordinate of O_p in the coordinate system Σ_0, and the order of rotation is with respect to the z-axis(θ_{yaw}), the y-axis(θ_{pitch}), and the x-axis(θ_{roll}). The points C_1–C_6 of the palm equipment are defined as ${}^PC_1=[{}^PC_{xi}\ {}^PC_{yi}\ {}^PC_{zi}]^T$ in Σ_p. The points C_1–C_6 of the palm equipment are defined as ${}^0C_1=[{}^0C_{xi}\ {}^0C_{yi}\ {}^0C_{zi}]^T$ in Σ_0. The points A_1–A_6 of the forearm equipment are defined as ${}^0A_1=[{}^0A_{xi}\ {}^0A_{yi}\ {}^0A_{zi}]^T$ in Σ_0. ${}^0A_1$ and ${}^PC_1$ are constants determined during the design process. The slider lengths $|L_1|$–$|L_6|$ are variables that depend on Q.

The palm equipment position and posture relative to the forearm equipment are calculated by iterative calculation from the slider lengths (L_1–L_6). The iterative calculation is performed according to the procedure shown in Fig. 6 to maximize the accuracy of the results. In the calculation, s is the differential operator, K is a proportional gain, Q_d is the current value of Q, and $I(Q_d)$ is the calculation of the inverse kinematics of the parallel links.

Rehabilitation scenario experiment

This section describes the rehabilitation exercise experiment performed to evaluate the effectiveness of the developed device.

Purpose of the experiment

We conducted an experiment based on the rehabilitation training of the circumduction motion of the wrist joint using the developed parallel link-type training device to demonstrate the effectiveness of our method.

Subjects

The experiment was conducted on the left hands of six male subjects aged 21–31 with no history of injury to the wrist joint (mean ± standard deviation: age 25.7 ± 4.7 years old, height 168.2 ± 10.2 cm). The purpose and content of the research were fully explained in accordance with the Declaration of Helsinki. Moreover, the subjects' informed consent was obtained prior to the experiment.

Experimental procedure

Figure 7 shows a photograph of the training device, while Fig. 8 presents the coordinate system of the training device when it is worn. Using a numerical analysis,

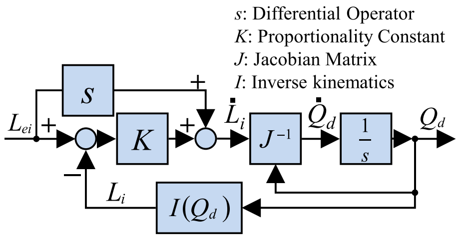

Fig. 6 Iterative calculation of the developed device

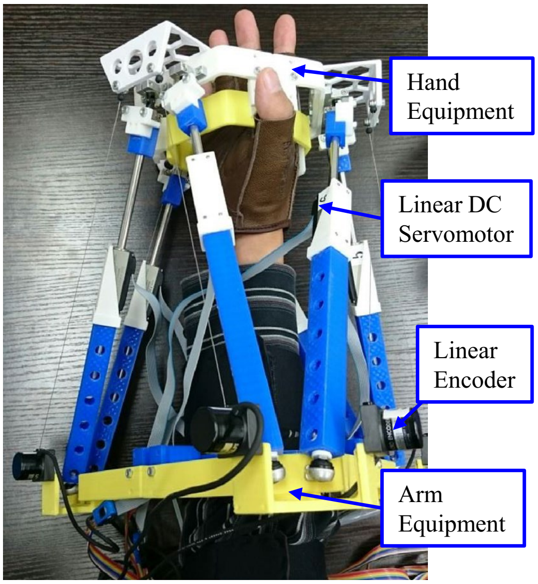

Fig. 7 Overview of training device

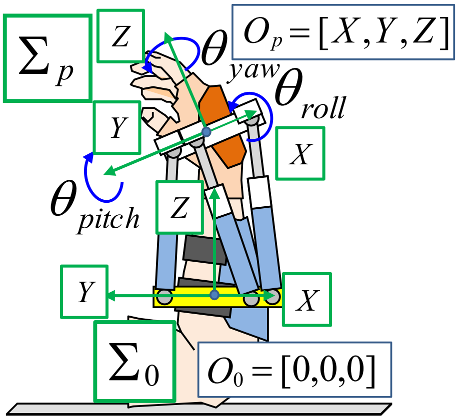

Fig. 8 Relationship between model and device

the device was able to find the palm's position (X, Y, Z) and posture (θ_{roll}, θ_{pitch}, θ_{yaw}) based on the length changes in the measurements of the six linear encoders [6]. The mounting position of the training device varied depending on the length of the subject's forearm. The device can measure where it is mounted, and it can be adapted to different mounted positions. As the starting position of the circumduction motion, the palm, radius, and ulna were lined up side-by-side, with the palm positioned perpendicular to the body. The subject was fitted with the training device at the beginning of the experiment, and his wrist joint was oriented in the starting position. The radial flexion was then applied in the direction of the thumb; after which, the subject was instructed to rotate his own wrist joint in a clockwise direction as seen from his vantage point. The changes in the length of the linear encoder during the motion were measured using the measuring part of the device. Three complete, consecutive circumduction motions were performed and measured. Motion patterns were created and passed to the training part of the device based on the acquired changes in length, which executed the rehabilitation training for the wearer. The palm motion during the training was measured from the measurement part of the device to perform a motion analysis. The subjects were instructed to begin the training exercises in a tension-free state. In order to prevent accumulation of error by iterative calculation, it is performed the absolute position control for the actuator control. Absolute position control is performed based on the initial position when device mounted.

Results and discussion

Results of the experiment

Figure 9 shows the palm movements during each subject's rehabilitation training. The graphs show the changes in the translational and rotational motion during the training of the six subjects. For the rotational motion, the vertical axis represents posture. For the translational motion, the vertical axis represents the position. The horizontal axis represents time in both cases. The graph on the left represents the palm movements of each subject during the motion measurement (measured motions). The graph on the right represents the movement during training (training results). The green line in Fig. 9 shows the temporal change in measurement of θ_{roll}, θ_{pitch} θ_{yaw} in order from the thinner one. Similarly, the blue line shows the temporal change during training. The orange line shows the temporal change in measurement of X, Y, Z in order from the darker one. Similarly, the red line shows the temporal change during training.

Discussion of the experiment

The measurement of the circumduction motion can be modeled as the combined motions of palmar/dorsi flexion (θ_{roll}) and radial/ulnar deviation (θ_{pitch}) based on the device structure. Focusing on temporal changes of θ_{roll} and θ_{pitch} of all subjects in Fig. 9, it is possible to confirm periodic increase and decrease. And it can be confirmed that the peaks of the two increase/decrease cycles are deviated. Circumduction is an operation to move the palm in a circular motion. By simultaneously and periodically carrying out the dorsiflexion flexion motion and the radicular flexion motion, the motion is realized. The measured motion is a reasonable motion. A similar change can be confirmed in the measurement result and the training result. For about 1–2 s from the start

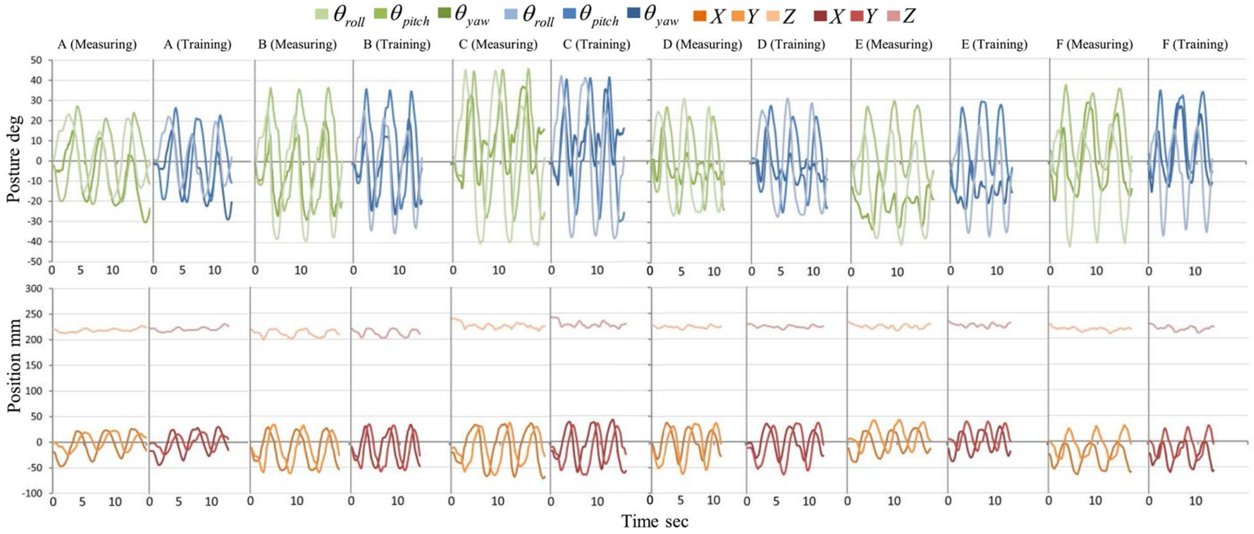

Fig. 9 Position and posture in training (all subjects)

of motion, each subject exercises a movement different from the periodic motion. This is expected to be the radial flexion in the thumb direction which is done at the start of the experiment, it is considered to be a reasonable operation.

From the experimental results, it can be confirmed that the trend of the measurement operation and the training operation is consistent. In this research, in order to quantitatively evaluate consistency of trends, correlation coefficients between the motions of training and measuring were obtained. The obtained correlation coefficient is shown in Table 3. Since this method is aimed at preventing contractures, speed control is not performed only by setting the upper limit of the speed. For that reason, as can be seen from experimental results, there is a time lag between the measurement result and the training result. From past research, due to the resistance of the human body, a delay occurs during training, it was known that would be difficult to realize the target motion [6]. Therefore, position control has priority in this study. Calculation of the correlation coefficients was made after picking up the first cycle of the circumduction movements both measuring and training, and then matching the time of one cycle. Generally, since the correlation coefficient is considered to have a high correlation if it is 0.7 or more, from Table 3, it can be confirmed that each movement has high correlation between measuring and training. From results of the correlation, it was demonstrated that this device can be used to train the wearer to perform the combined radial/ulnar deviation and palmar/dorsi flexion actions corresponding to a circumduction motion. The rest of this section offers further discussion of the effectiveness and challenges of this method.

Examining Fig. 9, θ_{yaw} changed over time in a different manner for each subject. The circumduction motion, which rotates the palm, was achieved by a combination of actions of the forearm muscle group, including the palmaris longus in the forearm. These muscles also contribute to the realization of the pronation and supination movements; hence, it is natural to unconsciously perform both movements at the same time. The measurement results from the experiment also indicated that

Table 3 Correlation coefficient between measuring and training

	θ_{roll}	θ_{pitch}	θ_{yaw}	X	Y	Z
A	0.96	0.99	0.99	0.99	0.99	0.96
B	0.94	1.00	0.97	0.98	0.99	0.94
C	0.96	0.99	0.99	0.99	0.99	0.82
D	0.93	0.94	0.96	0.96	0.94	0.94
E	0.98	0.98	0.99	0.98	0.99	0.94
F	0.91	0.94	0.96	0.96	0.96	0.74

Table 4 The operation width difference between measuring and training

	θ_{roll} (°)	θ_{pitch} (°)	θ_{yaw} (°)	X (mm)	Y (mm)	Z (mm)
A	− 0.1	− 0.1	− 0.8	6.0	− 1.3	− 0.4
B	1.8	3.2	4.9	− 1.0	3.2	3.1
C	2.9	3.6	6.5	4.5	1.0	1.4
D	1.4	1.8	1.8	− 1.5	3.0	− 2.3
E	4.6	0.9	2.2	− 2.2	8.2	2.1
F	4.8	1.4	6.5	− 0.7	− 1.6	− 0.5

θ_{yaw} varied across all subjects. A typical training device, with its low DOF of movement, does not support this motion, therefore, become a burden to the wearer. Hence, our method would seem to be more effective for training exercises, such as the circumduction motion that requires a high DOF of movement.

The experiment found some degree of correlation between θ_{roll} and θ_{pitch} across the subjects, but almost no correlation among θ_{yaw}, θ_{roll}, and θ_{pitch} because of the variations in how the subjects used their muscles when performing the circumduction motion. Therefore, predicting θ_{yaw} from the θ_{roll} and θ_{pitch} values to create the motion patterns in advance was difficult. This result suggests that methods, such as this device, which take measurements that include θ_{yaw} (pronation and supination movements), are effective for conducting training exercises with a high DOF of movement of the wrist joint.

Table 4 shows the differences in the operation width between the motion measurements and the training results for each subject. The differences in the operation width were obtained by finding the maximum and minimum widths of each movement, then calculating the differences between the measured motion widths and the training result widths. Examining the differences among the subjects, the minimum value for posture was − 0.8°, whereas the maximum value was 6.5°. Meanwhile, for the position, the minimum value was − 2.2 mm, and the maximum value was 8.2 mm. The minimum values were negative because the movements were greater during training than during the measurement. This phenomenon can be explained by the compensatory movements the subjects made to perform the training action. Examining the operation widths of subject A, for whom all movements, except in the x-axis direction, were negative, greater movements during training and a relatively large difference in movement in the x-axis direction were found. In other words, the subject can be seen trying to execute the training action by causing the other values to move in a manner that matched the difference in the x-axis direction movement. These compensatory movements caused by the fact that the motion measurements required active participation by the subjects, while the training was a passive exercise. As noted earlier, the circumduction motion was realized by the movement of the forearm muscle group, and at that time, the wrist joint was experiencing tension in the direction of the elbow. However, no such tension was generated in a device such as this one that performs passive training. We suspect that the compensatory movement caused by this difference in tension, but this issue will be left to future work. In addition to the method to control only the trajectory as in this method, implementation of speed control and force control will be a future subject.

Conclusion

This study described a developed parallel link-type wrist joint rehabilitation device. The developed device can train not only three degrees of freedom of rotation but also three degrees of freedom of translation in the wrist joint. Using the developed device, we carried out training assuming the circumduction motion to six subjects, and measured the movement of the palm when training. We calculate the correlation coefficient between the training target and the training result, and confirmed that this method is effective because high correlation is obtained. And, the performance of this method was evaluated by calculated the difference of the range of motion between training target and training result. Since the evaluation results, the necessity of force control is indicated, and the implementation of force control on this method becomes a future task. The necessity of temporal agreement between the training target and the training result has been indicated, implementation of speed control is also a future subject.

Authors' contributions

YK carried out the design of the wearable rehabilitation device, the systems integrating, testing. TT carried out the design of device control circuit and testing. KY provided advice on future works and proof-reading of the paper. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

Ethics approval and consent to participate
The experiment was approved by the Ethics Committee of Utsunomiya University, and the committee's directives, including the completion of consent forms, were complied with. Written informed consent was obtained from the patient for the publication of this report and any accompanying images.

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