Original article

Reproducibility between robot and human movements: preliminary development of a robotic device reconstructing therapeutic motion

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Abstract

Purpose: Robot-mediated therapy is a promising approach for restoration of upper limb motor function after stroke, but it has not demonstrated the expected effects because of the inability to reproduce the flexibility and complexity, which are associated with assistance skills of therapists. The purpose of this study was to develop a preliminary dicephalus (DiC) system and provide preliminary data on the reproducibility between motions of a robot and therapist.

Subjects and Method: The assessment for each human and robotic assistance comprised 10 movement cycles, including elbow flexion and extension. Seven volunteers were seated with the right forearm and upper arm fixed to the DiC system. One therapist was ins structed to make 10 similar elbow flexion and extension movements to assist in patient elbow movements. After therapist assistance, the DiC system reproduced the 10 repetitive elbow flexions and extensions made by the therapist. The highest and lowest elbow angles in each flexion and extension cycle and the time at which those angles were obtained were measured.

Results: The intraclass correlation coefficients of the highest and lowest elbow angles was 0.96 ($p < 0.0001$) and of the time for obtaining those angles was 0.96 ($p < 0.0001$) between human and robot assistances. Bland-Altman plots showed interchangeable differences in the time between human and robot assistances (96.4% within 2 standard deviations).

Conclusions: The DiC system shows excellent reproducibility between human and robot assistances and may be effective for upper limb training in stroke patients. This system was preliminarily developed for the rehabilitation of upper limb motor dysfunction after stroke.

Keywords: robot assistances; occupational therapy; rehabilitation; stroke; upper limb

Introduction

Robot-mediated therapy is one of the most promising approaches for the restoration of upper limb motor function after stroke (Simonetti, 2016; Germanotta,

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2018). Traditional training methods, such as constraint-induced movement therapy (Dromerick, 2000; Winstein, 2004) and neuro-developmental training (van der Lee, 1999), are employed with the goal of improving upper limb motor function. However, because these interventions involve voluntary movements of the affected upper limbs, they cannot be applied to patients with severe upper limb motor dysfunction. Therefore, especially for patients with severe upper limb dysfunction, rehabilitation training is a widespread method and is highly effective when it is delivered using repetitive movements with a device (Zondervan, 2013). In contrast, previous studies noted that the average time spent on upper limb training ranges from 0.9 to 7.9 min per therapy session, 2012) and suggested that this is a short amount of time to recover from upper limb motor dysfunction. In addition, patients with upper limb dys-function could partially improve upper limb motor function with repetitive motor training (Han, 2008; Kawahira, 2010).

Although robots will likely never replace therapists, robot-mediated therapy has the potential to deliver highly intense, reproducible, and repetitive training (Lo, 2010). Therefore, many research groups are developing robotic training devices for the upper limbs (Liao, 2012; Zondervan, 2013; Liu, 2017; Bertomeu-Motos, 2018). Many robotic devices for severe upper limb motor dysfunction have been designed as passive training systems. Researchers are focusing on adapting the robotic movements in order to synchronise them with the assistive movements provided by the therapists based on individual patient responses (Hu, 2009). Computational motor learning principles provide a framework for the design of optimal rehabilitation protocols (Huang, 2009), which may be similar to the ability to reconstruct the flexibility and complexity of the therapist's assistance skills. Considering that repetitive exercise is effective for the recovery of motor paralysis (Hatem, 2016), it is necessary to reproduce the precise movements made under the guidance of a therapist, and practice the changed movement strategies in different ways.

Therefore, we developed a play-back robot called the dicephalus robotic system (DiC system, Patent No. JP6307210B) and verified its performance compared with healthy subjects. This pilot study aimed to report the preliminary development of a robotic device for patients with upper limb motor dysfunction and assess the data regarding the reproducibility of robotic movements to mimic a therapist's assistance. The present research was approved by the ethics committee of Sendai Seiyo Collage with permission number No. 2910. It also conformed with the guidelines of the Declaration of Helsinki.

The authors declare that there is no conflict of interest (COI) regarding the publication of this paper.

Subjects and Methods

1. DiC System

The DiC system drives two variable rings grasping the human upper arm and forearm, which evaluate two different postures for a certain end-effector position (Figure 1). The forearm, consisting of the ulna and the radius, is connected to the humerus in the upper arm, forming the elbow joint. The humeral olecranon fossa and the olecranon process of the ulna are connected to each other, which limits the range of elbow extension. The DiC system is controlled by the LabVIEW 2014 Robotics Module (National Instruments Inc, Tokyo, Japan). The center of the DiC's ring was detected by LabVIEW with respect to the x-, y-, and z-coordinates. Accordingly, the tilt and

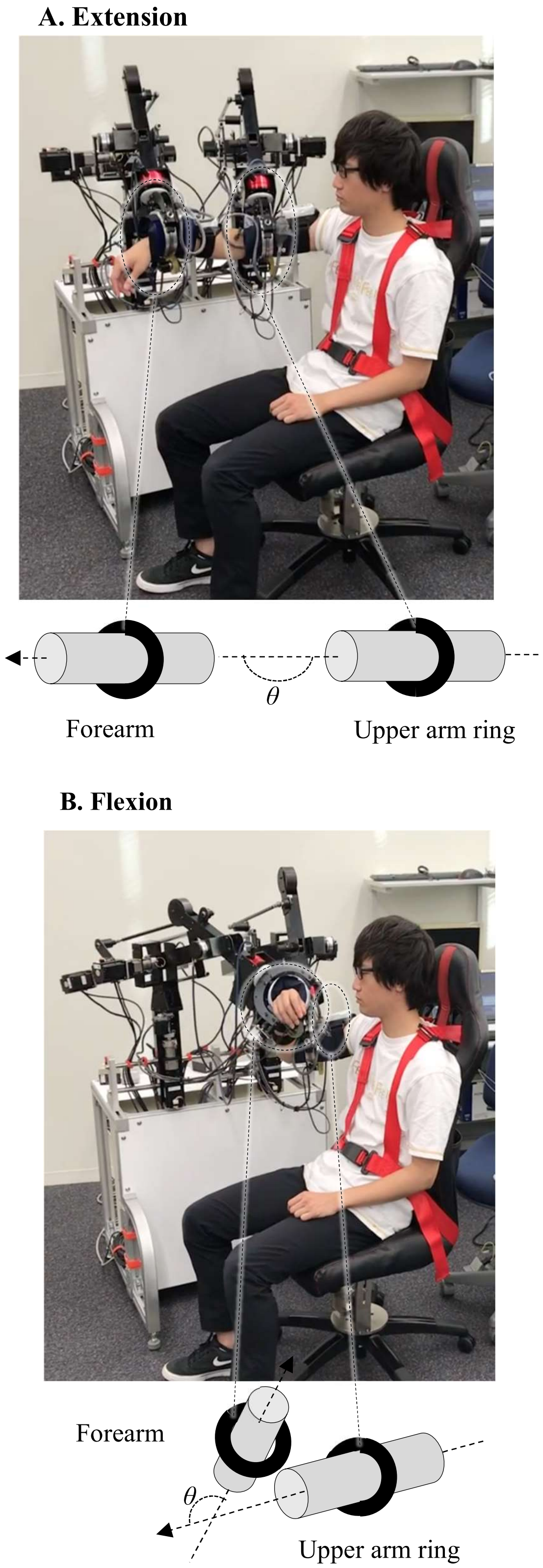


Figure 1: The DiC system. The DiC system has two variable rings that grasp the forearm and upper arm, which calculate the angles (θ) of elbow extension (A) and flexion (B), memorize the arm motions with human assistance, and consecutively reconstruct the same arm motions by using a teaching playback algorithm. DiC: Dicephalus

position of the two rings of the DiC system for the upper arm and forearm can reasonably estimate the upper arm and forearm positions during assisting movements. Therefore, we can determine the inverse kinematic solution by an algorithm related to the Euler formula and calculate the elbow angle (Wittenburg, 2016). In addition, the DiC system memorizes the tilt and position of the two rings and reconstructs the same motions of the upper arm and forearm based on the therapist's assisting motions (Figure 2).

2. Participants

Although we expect that the DiC system is clinically applicable, it is necessary to confirm the reproducibility between the motions of the DiC system and that of therapists, prior to clinical applications. For this study, we recruited 10 healthy volunteers with intact neurological status. All subjects were male occupational therapy students (aged 21 ± 1 years, height 167–179 cm, weight 55–73 kg). Prior to testing, the goals and procedures of the study were explained to all the participants, and they all provided written informed consent for participation in the study.

3. Procedures

The test subjects were seated in a hard chair and the trunk was fastened with seat belts with their right forearm and upper arm held by the two variable rings of the DiC system. The arm was maintained in a relaxed state throughout the

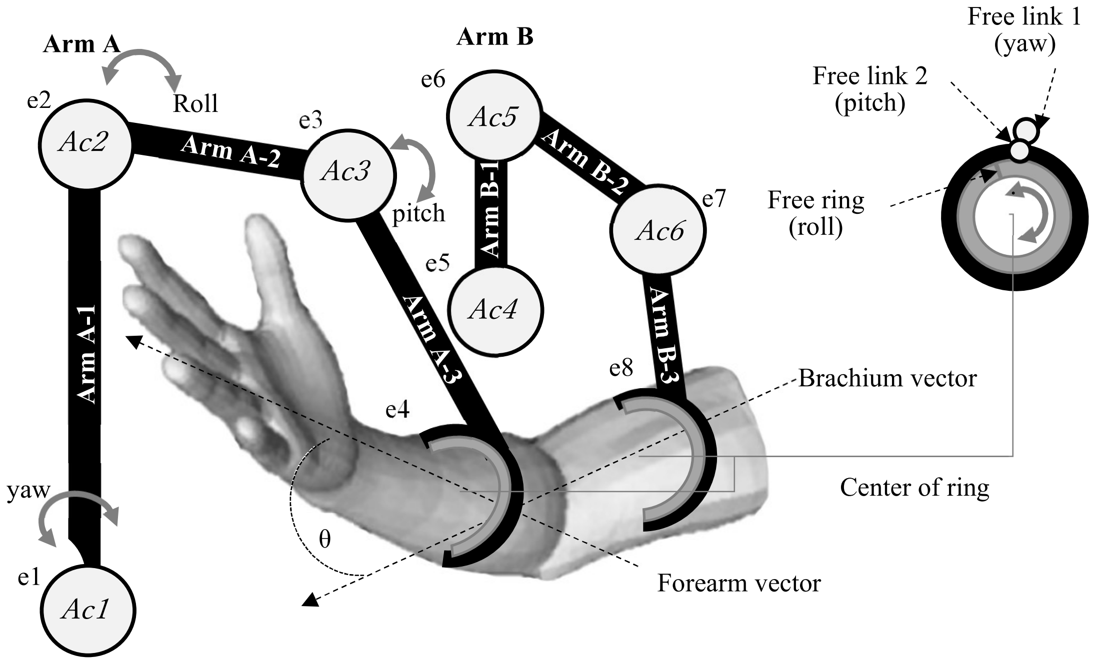


Figure 2: A kinematic model that estimates the human elbow joint in the DiC system. The DiC system has two independent robotic arms (arms A and B), three controlled actuators (Ac 1 to 6) for the three axes of motion, two free links, and a free ring for human arm mobility. Arms A-1 to 3 of the DiC are 28 cm in length, and arm B has the same material and shape. The range of motions of the arms are 120° for the yaw of A-1, 30° to 150° for the roll of A-2, and 40° to 120° for the pitch of A-3. All actuators are TUBAKI products PAT-B120S010KP2, with a maximum allowable output torque of 20.4 Nm (at the center of the output shaft length, with an output rotation speed of 100 rpm) and a reducer ratio of 1:10. According to these specifications, the DiC can be moved at a maximum angular velocity of 120°/s when the weight of a human arm is approximately 5 kg. In addition, depending on the seat positions, the subjects' shoulder joint can support movement from approximately 40° to 120° of flexion, and the elbow joint can support movement from 0° to 130°. The inner diameter of the ring is 13 mm, and a human arm with a circumference up to this size may be placed in it. Because the center of the ring at the distal end of the robot arm is fixed, information regarding the position of the ring's center can be recorded in the DiC with encoders (e1 to 3) attached to the three actuators. A ring holding the human arm is allowed free movement around three axes, and movements are recorded by an encoder (e4). The subject's wrist is not fixed, and the supination of the forearm is not fixed by the free ring inside the ring. The vectors of the brachium and forearm are estimated by the DiC control system. The elbow joint angle (θ) is calculated using the vector cosine theorem. Typical movements of the DiC are shown at https://youtube/BbO8c4oDWog

experiment. The trial involved 10 movement cycles, including elbow flexion and extension. An occupational therapist with 18 years of experience (male, age 40 years, height 170 cm, weight 67 kg) performed 10 repetitive elbow flexion and extension movements similar to the therapeutic assistance provided to the patients after hearing the "go" beep. Accordingly, the occupational therapist freely moved each subject's forearm from a position of complete elbow extension to the mouth of the subject. Subjects wore short-sleeved shirts, and the rings on the robot arms and the hands of the occupational therapist were in direct contact with the subject's skin. However, there was a manchette filled with air (40 mmHg) between the robotic rings and the skin of the subjects. The DiC system memorizes the therapist's assisting motions in reference to the tilt and position of the two rings. Therefore, immediately after each trial of the therapist's assistance, including the therapist's 10 repetitive elbow flexion and extension movements, the DiC system reproduced the same movements.

4. Data analyses

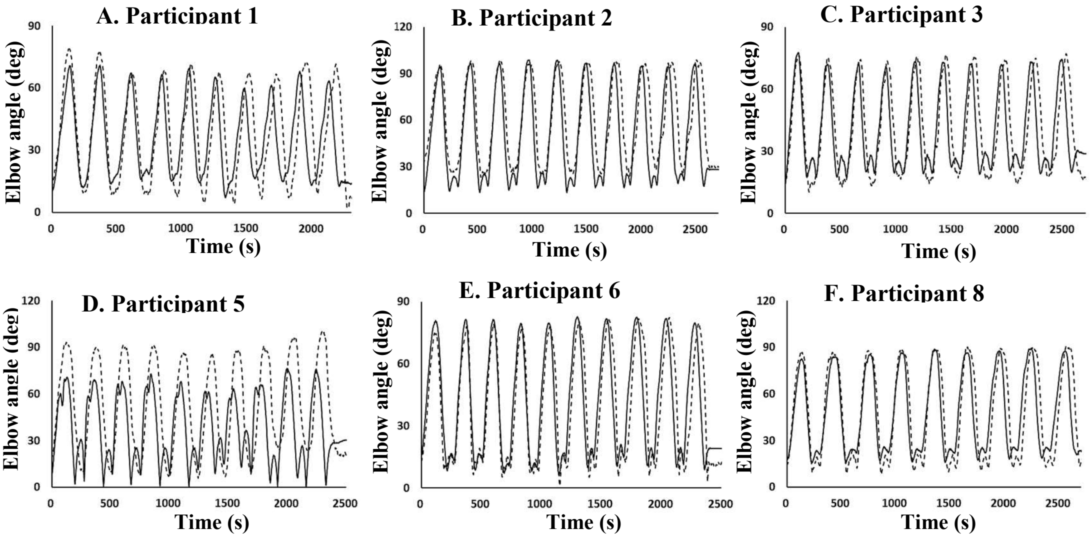
The elbow angle was calculated based on the tilt and position of the two rings of the DiC system. The peak velocity was quantified by the maximum inclination of the slope of the recorded elbow angle curve for movement duration, and movement onset was defined as the time point at which the elbow velocity exceeded 5% of the peak velocity. The highest and lowest elbow angles for each elbow flexion and extension cycle and the time points at which those angles were achieved were measured based on the time-series plots of each elbow flexion and extension movement assisted by the therapist and robot.

Statistical analyses were performed to assess the relationships and bias between elbow movements assisted by therapists and the robot. Two different mathematical approaches were used for intra-subject analysis. The intraclass correlation coefficient (ICC (2, 2)) was used for variance estimation. Generally, ICC values ranging from 0.80 to 1.00 were considered "excellent interchangeable"; those ranging from 0.60 to 0.80 were said to be "good interchangeable"; and values below 0.60 were considered "poor interchangeable." The Bland-Altman plots provided distributions of the means and standard deviations (SD) of the differences between human and robotic movements. The plot of differences against the mean allowed for investigation of any possible relationship between the measurement error and true value. If the mean difference was zero and 95% of the values lied within 2 SDs of the mean difference, the data were used to assess interchangeability. We defined statistical significance as $p<0.05$. All statistical tests were performed with R 3.4.0 software (R Foundation for Statistical Computing, Vienna, Austria).

Results

After visual inspection of all subjects, data from three subjects were excluded from the prospective data analysis because of excessive outliers associated with the malalignment between the rings and the subject's arms. Additionally, for each participant, the time required for achieving the highest and lowest elbow angles with robotic assistance from the DiC system gradually increased compared to that required for achieving the highest and lowest elbow angles with human assistance. The time-series plots of the movements achieved with assistance from the therapist and the robot for the seven test subjects are shown in Figure 3. The plot of the elbow angles showed that the time and angle at the highest and lowest elbow angles during each elbow flexion and extension cycle were almost consistent between human and robotic assistance (participants 1, 2, 3, 5, 6, 8, and 10). However, the highest elbow flexion angles achieved with robotic assistance were lower than those achieved with human assistance for participant 4 (30.6±2.0), participant 7 (29.3±1.7), and participant 10 (28.8±2.8). These data were excluded from the analysis performed using the Smirnov–Grubbs test to detect outliers.

Group analysis showed that the ICC between the time at the highest and lowest elbow



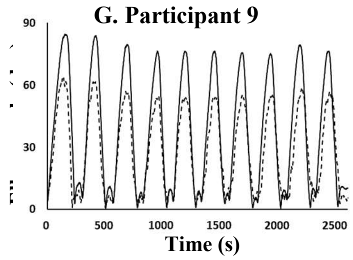


Figure 3: Time-series plots of the elbow angles noted with human assistance (solid line) and robotic assistance (dotted line) for each participant. The time 0 seconds represents the onset of movement. The time and angle at the highest and lowest elbow angles for each elbow flexion and extension cycle appear to be almost consistent between human and robotic assistance.

angles with robotic and human assistance was excellent (ICC = 0.999, 95% confidence interval [CI] = 0.990–0.999, $p < 0.0001$; Figure 4A). Similarly, The ICC between the angles at the highest and lowest elbow angles with robotic and human assistance was also excellent (ICC = 0.960, 95% CI = 0.945–0.971, $p < 0.0001$; Figure 4B). However, the results were basically unchanged even if the data from three excluded participants were included in the data analysis (the ICC (2,2) for the comparison of peak time and peak angle between humans and robots were as follows: time, ICC = 0.99, $p < 0.0001$; angle, ICC = 0.87, $p < 0.0001$). The Bland-Altman plot graphically depicts the difference in the mean values between human and robotic assistance (Figure 5). The mean ± 2 SD difference in the time between the human and robotic assistance was –26.43 ± 56.08 ms (Figure 5A, dotted line).

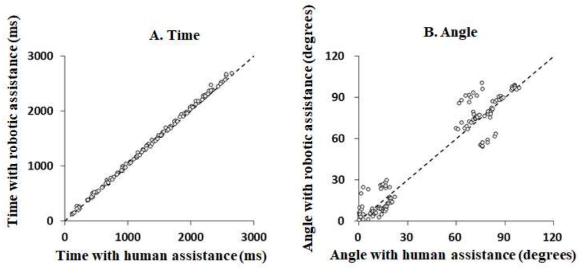


Figure 4: Scatterplots showing the relationship between human and robotic assistance. The time (A) and angle (B) at the highest and lowest elbow angles for each elbow movement cycle are plotted. The ICC (2, 2) values between human and robotic assistance were excellent (time: ICC = 0.999, p < 0.0001; angle, ICC = 0.960, p < 0.0001). ICC: intraclass correlation coefficient

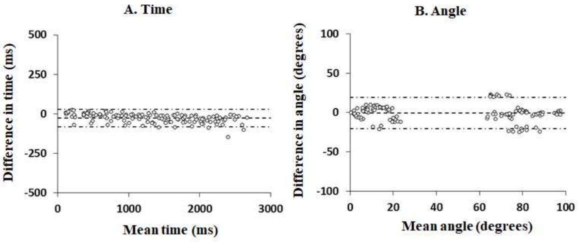


Figure 5: Bland-Altman plots for the time (A) and angle (B) at the highest and lowest elbow angles for each elbow flexion and extension cycle. The mean difference in time (dotted line in A) between human and the robotic assistance was –26.43 ms, and 96% of the difference values were within 2 SD of the mean. The mean difference in angle (dotted line in B) was 0.70°, and 87% of the difference values were within 2 SD of the mean. SD: standard deviation

Approximately 96% of the difference values were within 2 SD of the mean. However, the 2 SD difference in the mean value for the angle between human and robotic assistance was 0.70 ± 19.99° (Figure 5B, dotted line), and 87% of the difference values were within 2 SD of the mean. The distribution of the differences in the elbow angle with respect to human and robotic assistance was greater than that for time.

Discussion

We developed a preliminary robotic device, the DiC system, for patients with severe upper limb motor dysfunction. The DiC system, which reconstructs therapist's assisting motion, showed excellent reproducibility. Therefore, the results of the present study demonstrate a promising first step toward a therapeutic training system for severe upper limb motor dysfunction after stroke. In general, rehabilitation training for patients with severe upper limb dysfunction is performed using repetitive movement with a device (Zondervan, 2013). However, rehabilitation training can also be a burden for therapists, and the training time is shorter than the recovery time for upper limb motor dysfunction (Kaur, 2012; Zondervan, 2013). Therefore, developers of rehabilitation technology have noted the worldwide need for effective robotic devices for upper limb training. The passive training system can be applied to patients with severe upper limb motor dysfunction and can enhance sensory input that drives motor plasticity (Takahashi, 2008). Despite the development of a robotic device and the promise to restore upper limb motor function, the device was unable to reproduce the flexibility and complexity of the therapist's assistance skills (Lo, 2010).

The results of this study indicated that the DiC system can reconstruct the therapist's assisting motions. Robotic devices in previous studies (Lo, 2010; Liao, 2012; Zondervan, 2013; Liu, 2017; Bertomeu-Motos, 2018) have assisted the patient in aspects other than the therapist's assisting motion; however, they did not investigate the reproducibility between human and robotic performance. However, the DiC system could memorize the therapist's assisting motions for repetitive elbow flexion and extension and reconstruct the motions with high reproducibility. Therefore, the DiC system may serve as a robot-mediated therapy for severe upper limb motor dysfunction and may be an effective approach for upper limb training.

However, the DiC system may have under- and overestimated human movements because the rings grasping the subject's upper arm and forearm were out of alignment (see Figure 3, participants 5 and 9). This could have occurred because the soft tissue, including human skin, and the metal ring grasping the arm/forearm slipped during motion. A tight manchette can be used to prevent slippage between the rings and subjects' skin; however, this was not possible because the blood vessels in the subjects' arms were compressed and the blood flow was blocked when a manchette was used. In addition, there was a gradual delay in the movements of the DiC system in comparison with human movements. In the current method, when pressurization was set at 40 mmHg to fix the subject's arms, a problem occurred, in that the pressure of the manchettes increased and the subject's arm was compressed when the elbow joint was flexed. To solve this problem, the pressure of the manchette wrapped around the subject's arms can be kept constant by sandwiching a reservoir (like an air tank) in series without directly connecting a pump and a manchette. Alternatively, two manchettes can be used, connecting them in series and inflating them like a balloon. Therefore, the type of ring used for the arm/forearm and the algorithms used for determining the timing of the DiC system must be revised for clinical use.

In addition, the main impairment after stroke is reduced muscle strength on the side contralateral to the brain lesion (Sunderland, 1989; Harris, 2007). Moreover, previous studies noted that about 50% of stroke patients experience upper limb hemiparesis and are unable to perform daily living activities (Heller, 1987; Veerbeek, 2011). Kwakkel et al. suggested that the lack of appropriate scales to measure activities of daily living is a plausible explanation as to why the effects of robot-mediated therapy on daily function are small and non-significant (Kwakkel, 2008). Upper limb dysfunction in patients after stroke is complex due to the multidimensionality of the dysfunctions, including hemiplegia, muscle weakness, spasticity, and difficulty performing activities of daily living. Although the reproducibility of the DiC system, which reconstructs therapeutic motions, was ensured in this study, further research is needed to develop a training protocol that yields improvements in hemiplegia, muscle strength, and spasticity among patients after stroke. Additionally, the relationship between the improvement of upper limb motor dysfunction and independence in performing activities of daily living should be investigated in the future.

A potential limitation of our study is the small sample size; it does not reflect the complexity of the motor dysfunctions, which are multifactorial in nature and include factors such as hemiplegia, muscle weakness, and spasticity after a stroke. In fact, although we focused on elbow flexion and extension movements, patients have to control their upper limb with multiple degrees of freedom, including the shoulder, elbow, forearm, and hand, along with their multifactorial motor dysfunctions. Additionally, data acquisition failed in 3 of 10 subjects. This failure suggests that the DiC system did not obtained sufficient measurement settings in this experiment. Therefore, further studies with a larger number of participants, including those with spasticity, and detailed examination, including the assistive motions of the DiC system with multiple degrees of freedom and the robotic system, are warranted to improve the generalizability of our findings.

In conclusion, the difficulty of robot-mediated therapy for severe upper limb motor dysfunction has been recognized in the present study. The DiC system may serve as a feasible approach for upper limb training and may reconstruct the therapist's assisting skills. Further research is needed to investigate the effects of robot-mediated therapy using the DiC system.

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