

# Development of Cybernic Mirror System for Improvement of Hand Motor Functions for Patients with Hemiplegia\*

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**Abstract**— In the case of cybernics treatment, the wearer performs voluntary movements, in which the neuromuscular and central nervous systems work to produce the intended movement of the integrated wearable cyborg and the wearer's body. In this way, the interactive Bio-Feedback (iBF) loop is established between the wearer and wearable cyborgs. Using wearable cyborg, motor function can be improvement. Cybernics treatment has been covered by medical insurance in Japan after a randomized controlled trial clinical evaluation. The cybernic mirror system is a wearable cyborg that performs intended bimanual symmetrical movements based on motor commands from the unaffected side. The cybernic mirror system has the potential to develop a new cybernics treatment specifically focused on improving finger functionality. The purpose of this study is to develop a cybernic mirror system for intention of bimanual symmetrical movements by transferring the hand motion of the unaffected hand to the affected hand and to confirm the feasibility of assisting finger motion by the developed system through basic experiments. The cybernic mirror system consisted of a hand motion assist unit and a hand motion control unit. The unaffected hand's skeletal information was obtained by the hand motion control unit using the camera. The hand motion assist unit, using a tendon-driven structure, achieved motion assist for flexion and extension of the affected hand. At the basic experiments with three participants, the developed system performs within the acceptable delay time between both finger sides. In addition, the developed system enabled the performance of bimanual symmetrical movements for each of the five fingers individually. In conclusion, we confirmed the feasibility of assisting the finger motion by the developed system through basic experiments.

## I. INTRODUCTION

Cerebrovascular disorders are conditions that affect brain function owing to nerve cell compression caused by blood vessel rupture in the brain or nerve cell necrosis caused by blood vessel occlusion. The global prevalence of cerebrovascular disorders is approximately 100 million [1]. Hemiplegia, which is characterized by motor paralysis, is a common sequela of cerebrovascular disorders. The study shows that regaining motor function in the upper limb after hemiplegia is more difficult than in the lower limb [2]. Particularly, the fingers exhibit residual paralysis, making it difficult for them to grasp objects and use tools in their daily

lives [3]. This limitation interferes with their daily activities and significantly reduces their quality of life (QOL).

In the case of cybernics treatment, the wearer performs voluntary movements, in which the neuromuscular and central nervous systems work to produce the intended movement of the integrated wearable cyborg and the wearer's body. The wearable cyborgs are synchronized with the intention to move in accordance with the motor unit potentials produced by a command from the central nervous systems. In this way, the interactive Bio-Feedback (iBF) loop is established between the wearer and wearable cyborgs. Using a wearable cyborg, this loop can be easily repeated without increasing the neuromuscular system's excessive load and fatigue. Consequently, motor function can be improvement [4]. Therefore, feedback of sensory information from proprioception related to hand motion and control without delay, such as proprioceptive sensation and vision resulting from voluntary movements realized with a wearable cyborg, is important for improving of hand motor functions. Cybernics treatment using wearable cyborg technology has been covered by medical insurance in Japan after RCT clinical evaluations for progressive neuromuscular intractable diseases as a treatment to improve brain/nervous system and muscle system functions. It is currently being implemented in 20 countries worldwide and is expected to be applied to various related diseases and disorders [5].

Balancing inter-hemispheric inhibition is crucial for functional improvement in patients with hemiplegia. Interhemispheric inhibition is essential for achieving smooth motor output and information processing. In patients with hemiplegia, the primary motor cortex becomes dysfunctional owing to brain damage. This causes increased activation of the primary motor cortex on the unaffected side, as well as increased inhibition from the unaffected side to the affected side. In addition, increased inhibition from the unaffected side to the affected side, resulted in a further functional decline of the primary motor cortex on the affected side. Furthermore, immobilizing one upper limb on the unaffected side for 10 h increased activity inhibition from usable the unused brain hemisphere [6]. Patients with hemiplegia rely on the unaffected side to perform movements, which can contribute to an imbalance in inhibition between the hemispheres. However, when both hemispheres were used, the inhibition decreased. Thus, using both hands can aid in maintaining the balance of interhemispheric inhibition.

We considered using both hands to improve the function [7]. In the dominant areas of the human brain and body, the left and right hemispheres of the brain cross each other. Bimanual asymmetrical movements may make it challenging to perform the intended movements stably, whereas bimanual symmetrical movements can perform the intended movements

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[8]. Thus, bimanual symmetrical movements have the potential to provide stable assistance according to the motor intention when assisting the motion of the affected side. For these reasons, a cybernic mirror system is proposed. The cybernic mirror system is a wearable cyborg that performs intended bimanual symmetrical movements based on motor commands from the unaffected side. Using a cybernic mirror system, an iBF loop has potential to establish between the wearer and wearable cyborgs.

In this study, to enable improvement of finger motion we developed a cybernic mirror system that realizes hand motion reflecting motor intention by transferring from the motion of the unaffected hand to the affected hand during bimanual symmetrical movements to improve of hand motor functions in patients with hemiplegia. Through basic experiments with 3 able-bodied participants, we confirm the feasibility of assisting finger motion synchronized with the wearer's movement intention, in terms of the delay time.

## II. CYBERNIC MIRROR SYSTEM

### A. Requirement

To achieve a bimanual symmetrical movement based on the wearer's intention, a sense of agency must be established, whereby the wearer feels that they are causing the motion. In addition, finger motion must be quickly recognized and assisted. In addition, a sense of agency is essential for improving functional movement [9]. Notably, this sensation is not felt if there is a delay of more than 0.490 s between the visual information and the sensation [10]. When the delay between the start of the hand motion on the unaffected side and the assist of the hand motion on the affected side was less than 0.490 s, the developed system can recognized the hand movement on the affected side as the wearer's intention of movement.

The mechanism for improving motor paralysis in patients with hemiplegia typically occurs in a specific order. First, there is a flaccid state where voluntary movement is not possible, then a joint motion where fingers move together, and finally an isolated movement where each finger can move individually [11]. Many individuals struggle with separate movements of each finger during the aftereffects. This could be because they are primarily trained to grasp objects rather than perform separate movements. A fundamental requirement is an assistive mechanism that focuses on assisting each finger individually. When training for functional improvement using a finger assisted mechanism, it is important to ensure that the assist mechanism weighs approximately 500 g. An overweight assist mechanism can be a burden on the wearer's system [12]. In addition, spasticity is an aftereffects of motor function in patients with hemiplegia. Spasticity is a symptom that causes difficulty in moving the fingers owing to muscle tension. Therefore, it is important to consider patients with spasticity. The torque required to flex and extend the finger joints in the patient with spasticity is 0.3 Nm [13].

### B. System configuration of cybernic mirror system

Fig. 1 shows an overview of the cybernic mirror system. Fig. 2 shows the configuration of system. The cybernic mirror system that assists hand motion from the unaffected side to the

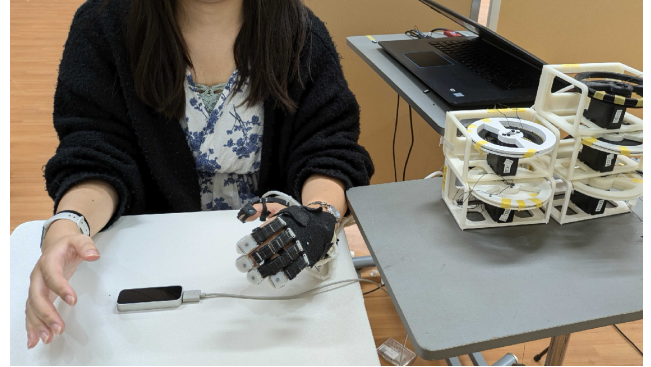


Figure 1. Overview of the cybernic mirror system

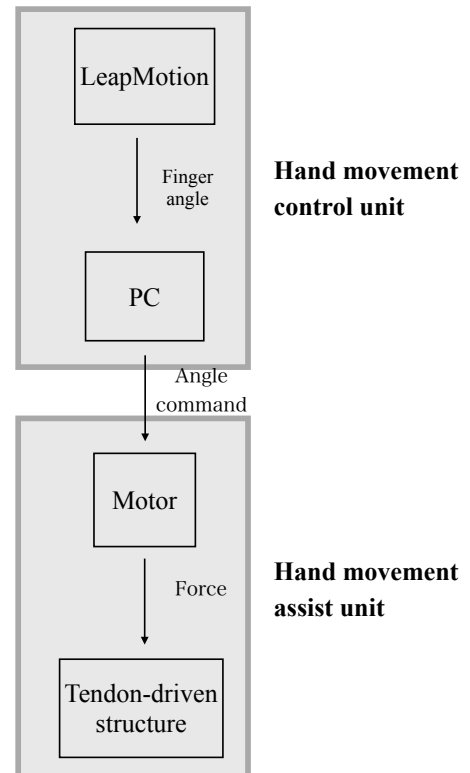


Figure 2. System configuration

affected side by considering the hand motion of the unaffected side as the motor intention of the affected side with the intention of bimanual symmetrical movements. The system consists of two units: a hand motion assist unit and a hand motion control unit. The hand motion assist unit uses an assist mechanism to apply external force to the affected hand. The hand motion control unit acquires information regarding the motion of a hemiplegic patient's unaffected hand and uses this information to operate the hand motion assist unit attached to the affected hand.

### C. Hand motion assist unit

The hand motion assist unit that applies an external force on the affected hand, to achieve bimanual symmetrical movements. As shown in Fig. 3, the hand motion assist unit

uses a Tendon-driven structure. The flexion and extension wires assisted in the flexion and extension motion of the fingers, respectively, when pulled by the motor. This enabled the hand motion assist unit to assist each finger while not interfering with the motion of the other fingers. In addition, the actuator could be installed outside the finger, reducing the weight of the hand-mounted component of the hand motion assist unit to 95 g. To assist the finger joints, we selected a motor with 0.3 Nm or more torque (Kondo Kagaku Co., Ltd., B3M-SC-1170-A). The length of the fingers can be changed in 3 mm increments by changing the dorsal part of the fingers.

#### D. Hand motion control unit

The hand motion control unit that acquires the motion of the fingers of the wearer's hand and uses this information to operate the hand motion assist unit. In Japan, the standard hospital stay for patients with hemiplegia is insufficient. Patients with incomplete improvement in hand motor function should be able to use the developed system independently to continue functional improvement training after hospital discharge. Until recently, patients had to wear sensors on their fingers, such as sensor gloves [14]. Attaching the sensor to the unaffected finger while using the affected finger is difficult. The sensor used in this study is a noncontact sensor that estimates the skeletal structure of the fingers and calculates finger angles to obtain information on finger motion. The hand motion control units controlled the hand motion assist unit by sending commands to the motor to ensure that the finger angle on the affected side is the same.

This hand motion control unit uses Leap Motion [15] to infer the hand's skeleton by extracting the feature points of the fingertip and joint positions of the fingers from images captured by sensors. Fig. 4 shows the definition of the finger posture for the developed system based on a previous study [16]. We calculated the finger angle by drawing a straight line connecting the wrist and metacarpophalangeal joint (MCP), followed by another line connecting the MCP. From the three-dimensional coordinates in Equation (1), the angle  $\theta$  of the finger can be expressed as in Equation (2). The current finger posture for obtaining hand and finger motion information acquired the finger angle  $\theta$ . Based on the motion information obtained from the unaffected hand, the hand motion assist unit attached to the affected hand was controlled to perform bimanual symmetrical movements.

$$\begin{aligned} P_w &= (x_{wrist}, y_{wrist}, z_{wrist}) \\ P_n &= (x_{mcp}, y_{mcp}, z_{mcp}) \end{aligned} \quad (1)$$

$$\begin{aligned} P_t &= (x_{tip}, y_{tip}, z_{tip}) \\ \mathbf{a} &= (x_{tip} - x_{mcp}, y_{tip} - y_{mcp}, z_{tip} - z_{mcp}) \\ \mathbf{b} &= (x_{wrist} - x_{mcp}, y_{wrist} - y_{mcp}, z_{wrist} - z_{mcp}) \end{aligned} \quad (2)$$

$$\cos(\pi - \theta) = \frac{\mathbf{a} \cdot \mathbf{b}}{|\mathbf{a}| |\mathbf{b}|}$$

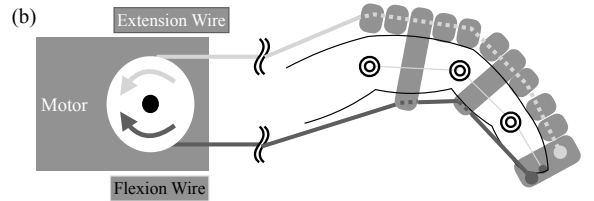


Figure 3. Hand motion assist unit: (a) attached to a finger; (b) tendon-driven structure

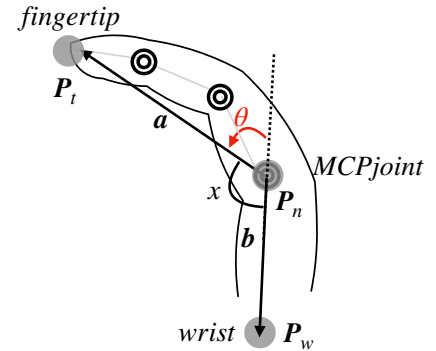


Figure 4. Definition of acquired finger angle

### III. BASIC EXPERIMENTS

First, basic experiments were conducted to assess the proposed cybernic mirror system. We validated the feasibility of response performance for bimanual symmetrical movements by transferring the motion of the unaffected side to the affected side. The participants were 3 able-bodied individuals. This study was approved by the Research Ethics Committee of the Institute of Systems and Information Engineering, at the University of Tsukuba. (Approval number: 2023R808) The study was explained to the participants in advance, and informed consent was obtained from all participants before the experiments.

#### A. Experimental setup

Fig. 5. shows the environment used for basic experiments. In this experiments, the participants' left hand in a seated position was simulated as the affected side and the right hand was simulated as the unaffected sides. To facilitate the explanation of the experimental results, we defined unit-attached and unit-unattached sides. The finger of the left

hand attached to the hand motion assist unit was defined as the unit-attached side. The right-hand side, simulating the unaffected side, was defined as the unit-unattached side. Participants placed their hands at a specified position on a desk. The participants did not have finger paralysis; therefore, their fingers remained in a state of no power.

### B. Bimanual symmetrical movements

Participants bent from a naturally extended state and then returned to the extended state as a flexion–extension motion. We performed the flexion–extension motion with a metronome set at 60 bpm for 2 s [17]. In the experiments, we conducted three trials for each finger, each consisting of one flexion–extension motion. The measurements included finger motion on both the unit-attached and unit-unattached sides. We assessed the finger motion by analyzing each video frame using motion capture software (Acuity Inc., OptiTrack Flex 13). The unit-attached side’s time delay for the motion of the unit-unattached and unit-attached sides was calculated using a frame shifted with the smallest mean absolute error, as shown in Equation (3) ( $n$  is the total number of frames per trial,  $\theta_h(i)$  is the angle of the finger on the unaffected side,  $\theta_a(i)$  is the angle of the finger on the affected side). As the camera used in this study captured images at 120 fps, the delay time  $t_d$  was used in the evaluation, as shown in Equation (4) (number of frames  $f$ ).

$$M = \frac{1}{n} \sum_{i=1}^n |\theta_h(i) - \theta_a(i)| \quad (3)$$

$$t_d = \frac{f}{120} \quad (4)$$

### IV. RESULTS

Table I lists shows the number of max seconds required to move the graph of finger angles on the side where the unit-attached side to minimized the mean absolute error between the participants tests. Fig. 6 shows representative results of sequential photographs of independent finger bimanual symmetrical movements from the palm side. The

maximum time required from the start of motion on the unit-unattached side to the start of assistance on the unit-attached side was 0.358 s.

### V. CONCLUSION

Using the developed system, the flexion-extension motion can be assisted within a delay of 0.358 s for all executions. The maximum delay time between the start of the motion on the unit-unattached side and the start of the assist on the unit-attached side was within 0.490 s. This is the delay time when a person feels the initiation of motor action. In addition, the developed system was capable of performing independent finger bimanual symmetrical flexion–extension motion We considered the developed system to be capable of recognizing hand motion on the affected side as motion executed by the wearer of the developed system. Therefore, the developed system has the potential to enable motion based on the wearer’s intentions. In addition, when asked about their impressions after using the developed system. The wearers felt moving with their own motor intention and bimanually symmetrically. . Therefore, the developed system has the

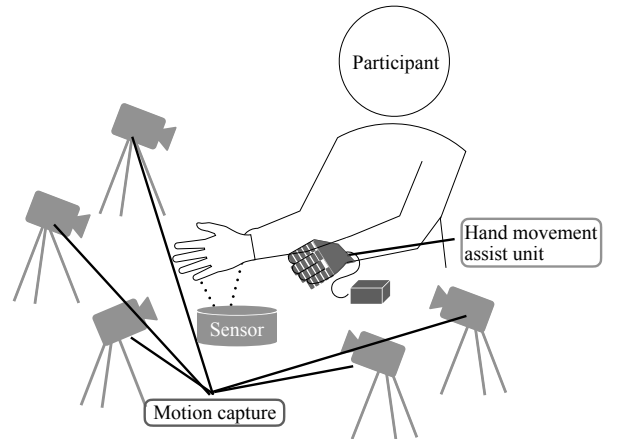







Figure 5. Environment for basic experiments

TABLE I. RESULT OF BASIC EXPERIMENTS

		Max delay time between finger without system and finger with system[s]		
		Participant1	Participant2	Participant3
Thumb		0.217	0.291	0.275
Index finger		0.192	0.233	0.275
Middle finger		0.192	0.242	<b>0.358</b>
Ring finger		0.300	0.291	0.300
Little finger		0.233	0.283	0.275

potential to realize bimanual symmetrical movements.

Pain can pose a risk for patients with spasticity and other complications. The system uses the motion of the unaffected side, allowing the patient to stop it immediately if they experience pain. Additionally, the range of motion can be limited, making the system usable even for patients with spasticity or other complications.

In addition, patients with hemiplegia have different muscle strength, joint range of motion, and reflexes compared to able-bodied participants, and the efficacy of the system in actual patients with hemiplegia will be tested in further experiments.

As a future challenge, to confirm the feasibility of improving hand motor function in patients with hemiplegia using the developed system, we plan to conduct experiments in real-world situations with the cooperation of patients with hemiplegia with hand paralysis.

## VI. CONCLUSION

In this study, we proposed and developed a cybernic mirror system to provide a cybernic mirror system that realizes hand motion reflecting motor intention by transferring the motion of the unaffected hand to the affected hand during bimanual symmetrical movements patients with hand paralysis. Through basic experiments, we confirmed the feasibility of

assisting finger motion synchronized with the wearer's movement intention, based on the delay time.

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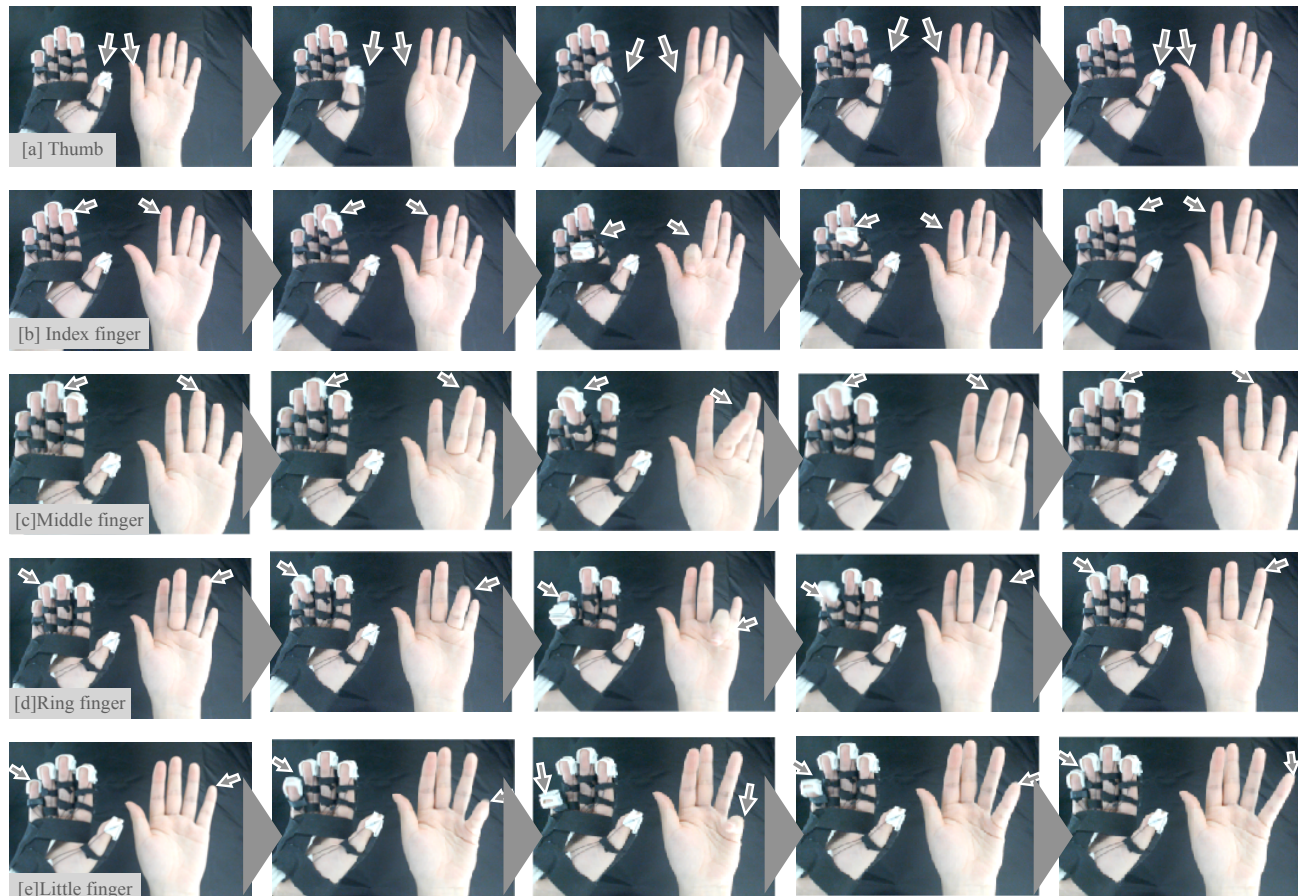


Figure 6. Representative results of sequential photographs for independent finger bimanual symmetrical movements from palm sides

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