Brain-controlled assistive wrist rehabilitation using a low-cost EEG Sensor

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***Abstract*—Robotically assisted rehabilitation therapy is effective in recovering motor function following impairment. It is essential to make sure patients be actively involved in the motor training process using robot-assisted rehabilitation to achieve better rehabilitation outcomes. This paper introduces a brain-controlled wrist rehabilitation method using a low-cost EEG sensor. Active rehabilitation training is realized using a threshold of the attention level measured by the low-cost EEG sensor as a brain-controlled switch for a flexible wrist exoskeleton assisting wrist flexion/extension and radial/ulnar deviation. We present a prototype implementation of this active training method and provide a preliminary evaluation. The feasibility of the attention-based control is proven with the overall actuation success rate of 95% and the subjective score of 7.5 out of 10 given by the participants to assess whether the attention-based control for the wrist exoskeleton feels natural. Although the general threshold performed slightly better in the system evaluation experiment regarding the success rates, the time used before the robot actuation and the subjective scores showed no significant difference on the performance using a general threshold and using customized threshold.**

***Index Terms*—Rehabilitation robots, wrist rehabilitation, exoskeleton, brain-controlled robots, brain-computer interface**

I. INTRODUCTION

OUR wrists enable us to adapt hand orientation to perform required tasks in activities of daily living (ADLs) [1]. Thanks to the complex structure of our wrist, our hand can be firmly locked while interacting with the external environment and can transfer forces generated by the forearm muscles to our hand to grasp objects [1]. Conditions such as stroke, loss of proprioception, post tendon surgery, spinal cord injury, cerebral palsy, and multiple sclerosis may cause inability to control the wrist in ADLs [1]–[5]. The aim of disabled patients' rehabilitation is to empower them for independent living and to assist them to be as productive as possible [2]. Repetitive movement exercise, which normally involves one-on-one interaction with a professional who assists and encourages the patient to perform the exercise, is considered an effective rehabilitation approach for patients with post-stroke motor impairments [6]. However, physical therapy involving professionals may be labor-intensive, time-consuming, and costly.

Wearing splints is another commonly used conventional technique for wrist therapy [1]. Wearing splints can prevent contracture and reduce spasticity [7]. However, prolonged splinting tends to reduce wrist mobility inducing disuse and consequent muscular atrophy [7]. Moreover, neuroplasticity induced by rehabilitation training exercises cannot be achieved by using splints [8].

Robotic rehabilitation devices are introduced to solve the aforementioned problems. A robotic rehabilitation device can act as an effective "therapist" that delivers reproducible motor learning experiences, quantitatively monitors patient performance, adjusts rehabilitation training according to patients' progress, and ensures consistency in planning a therapy program [9].

It is commonly understood by rehabilitation professionals that make sure the patient actively involved during the motor training process is very important to induce activity-dependent neuroplasticity and thus to promote motor recovery [10]. Brain-computer interface (BCI) technology enables people to control devices directly via decoding of neural activities of the brain [11]. Electroencephalogram (EEG)-based BCIs have been used to improve wrist rehabilitation training performance [12], [13]. Users could control the robot by performing motor imagery following the prompts on the screen to assist wrist extension and flexion. Motor intent could be detected by analyzing their EEG signals. The effects of promoting neuroplasticity during motor rehabilitation using BCIs have been proved [14], [15]. However, traditional EEG acquisition methods require patients to wear EEG caps and apply conductive gel, which is quite inconvenient. Moreover, current BCI approaches and devices are financially expensive. For example, a g.tec instrument (g.tec medical engineering GmbH, Schiedlberg, Austria), a commonly used EEG signal acquisition device, costs more than US$10,000. Therefore, it is very meaningful to find a cheap, convenient BCI solution to achieve active rehabilitation training. A preliminary study using an affordable EMOTIV device with 14 channel EEG data (about 800USD) combined with a robotic arm orthosis to assist

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drinking was reported [16]. In the experiment, volunteers completed the drinking maneuver with an average time of 127 seconds. The proposed system has potential to assist individuals with neurological disorders and hemiparetic stroke to independently drink from a glass. However, conductive gel was still required using this EMOTIV device.

In this paper, we propose a brain-controlled wrist rehabilitation method which is convenient to use either for a rehabilitation hospital environment or at-home rehabilitation training. A threshold of the attention level measured by a commercialized, cheap EEG sensor with dry electrodes is used in the proposed brain-controlled switch for the wrist exoskeleton. The attention level threshold for the proposed attention-based wrist rehabilitation robot control is investigated in experiments involving human subjects.

II. Methodology

A. *Overall design of brain-controlled wrist rehabilitation*

Fig. 1 shows the diagrammatic sketch of the proposed brain-controlled wrist rehabilitation based on attention level with visual guidance. Four motions including wrist extension, flexion, radial deviation, and ulnar deviation are supported in the proposed brain-controlled wrist rehabilitation. Motor imagery can be enhanced based on visual guidance and thus promote motor recovery [17]–[19]. A motion demonstration shows on the screen. The user should look at the motion demonstration on the screen and imagine the motion. The intensity of mental "focus" or "attention" of the user could be a substitution of motor imagery showing the motion intent of the user. A threshold of attention level was defined to turn on motion assistance from the wrist exoskeleton. Once the user reaches the threshold of the attention level, the wrist exoskeleton will be activated to conduct the same motion as shown in the motion demonstration on the screen. Visual guidance provides active stimulation to motor center by mirror neuron, while the wrist exoskeleton provides passive stimulation to the motion perception and proprioception. Hence, motor recovery of the patient could be promoted through the active and passive co-stimulation. The details of the exoskeleton design and attention-based brain-controlled switch are shown in the following sections.

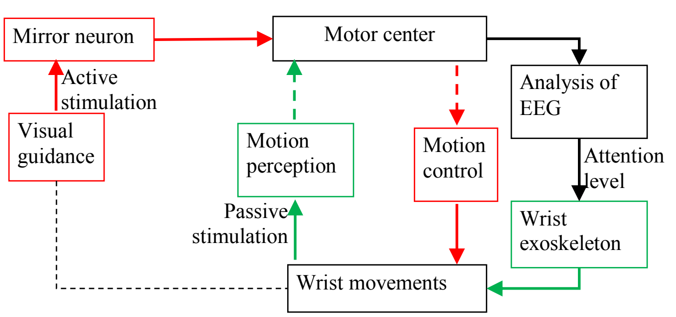


Fig. 1. The diagrammatic sketch of brain-controlled wrist rehabilitation based on attention level with visual guidance.

B. *Brain-controlled switch for wrist exoskeleton*

Human brain generates bioelectrical signals (brain waves) all the time. Different frequencies of EEG signals could be associated with actions and different stages of consciousness [20]. The most used frequency bands and their relations to the human brain wave activity as shown in TABLE I.

As shown in Fig. 2, an easy-to-wear, head-mounted device Brainlink Lite (Macrotellect Ltd., Shenzhen, China) was used here to acquire brain signals. This device is light-weight (39g) and cheap (less than 120 USD). Because of the 0.3mm dry electrode design of the EEG sensor, it does not need to apply conductive gel, which makes users more convenient to use this device. This device used a ThinkGear AM (TGAM) module (NeuroSky, Inc., Silicon Valley, United States) to process the brain signals. The feedback of this module was the attention and relaxation of the brain via its eSense biometric algorithms to detect whether the brain was focused or relaxed [21]. Different types of eSense meters (i.e. Attention, Meditation) were displayed on a relative eSense scale of 1 to 100. The current attention level of the subject was recorded through BrainLink, which was possible to analyze whether the subject was focused on the rehabilitation process at that time. A threshold of the degree of attention was defined to turn on the hand rehabilitation assistance. Hence, the patient can be more actively engaged in rehabilitation training.

Fig. 2 Head-mounted BrainLink Lite.

A motion demonstration was displayed on the screen. The user looked at the motion demonstration on the screen and to imagine the motion. A graphical user interface (GUI) was designed to display the visual guidance (see Fig. 3), which allowed the patient to understand the current rehabilitation training motion. The wrist rehabilitation training system was mainly composed of three parts, a rehabilitation action selection area, a motion demonstration area, and an attention level display area. The motion demonstration videos including wrist extension, flexion, radial deviation, and ulnar deviation were recorded in advance. When a rehabilitation action was selected, the corresponding video of motion demonstration would be displayed. The attention display area showed the current attention level of the user.

TABLE I
Relation Between Brain Signal Frequencies and Stages of Consciousness [20], [22], [23]

Type	Frequency	Stages of Consciousness
Delta	0.5 to 3.5 Hz	Sleeping
Theta	3.5 to 7.5 Hz	Inefficiency, Daydreaming
Alpha	7.5 to 12 Hz	Relaxation, Peace
Beta	12 to 30 Hz	Connection
Gamma	31Hz and Up	Mechanism of consciousness, Attention

C. Wrist exoskeleton using a soft-rigid combined mechanism

1) Trends towards soft-rigid combined mechanism

Mechanical design of rehabilitation robots for a wrist joint are usually complex since the wrist has two degrees of freedom, namely flexion/extension and adduction/abduction, and the axis of rotation moves according to motion owing to the complex anatomical structure [24]. Researchers have developed various robotic devices for wrist rehabilitation. For the mechanical structure, many adopted the form of holding a handle similar to MIT-Manus [25] to drive the wrist to rotate [9]. Different from the mechanical structures of those MIT-Manus like wrist rehabilitation robots, Xiao *et al*. designed a gear-driven wrist exoskeleton whose power was supplied by geared motors, force and torque were driven by gears with 2 degrees of freedom (DOFs) [26]. However, since the axes of wrist flexion/extension and radial/ulnar deviation are slightly pivoted in relation to each other and are on average 5 mm off each other, a fully rigid wrist exoskeleton with fixed rotation axes may result in an excess load being applied to the wearer's wrist joint because of the discordance of rotation axes [4].

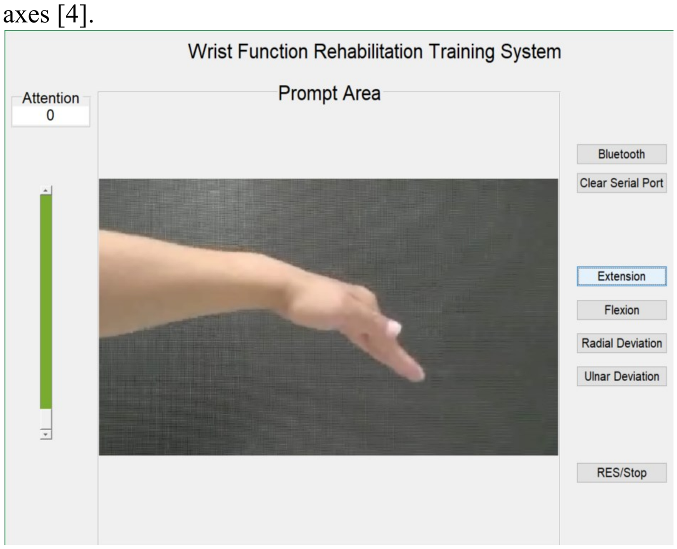


Fig. 3. User interface of wrist rehabilitation training system.

In recent years, flexible mechanical structures have been developed and widely used in wrist rehabilitation. Al-Fahaam *et al*. proposed a soft, wearable wrist joint rehabilitation exoskeleton using pneumatic actuators [27]. The movement of the wrist was controlled by three pneumatic contraction muscle actuators and to extensor bending muscles. Andrikopoulos *et al*. designed a similar wrist rehabilitation device [28]. Different from Al-Fahaam's design, four pneumatic muscle actuators were arranged around the wrist. Two actuators were placed on the back of the wrist while the other two were placed on the wrist pulse point. In addition, a frame structure was used to support the middle part of the pneumatic muscle actuator preventing unwanted contact between the actuator and the wrist. Flexible pneumatic structures have the advantages of simple structure, avoiding the problem of misalignment between the rotational axis of the robot and the rotational axis of the wrist. Nevertheless, accurate control becomes difficult for flexible wrist rehabilitation robots. Furthermore, pneumatic actuation requires devices such as air sources increasing the size of the overall system. Moreover, hysteresis of soft materials makes the design of the controller difficult [29].

Considering that pure rigid structures have risks to cause second damage to patients' wrist and pure flexible structure is hard to be accurately controlled, Higuma et al. [4] proposed a wrist exoskeleton mechanism consists of two elastic elements and two linear actuators. The inherent flexibility due to the elastic structure is the greatest advantage of this design. However, some parts their design need to be improved. First, the two sharp steel blades were not covered which is dangerous. Second, bearings were not used at their passive rotational joints which may add friction and influence the smoothness of the motion. In our study, we adopted a similar design and made some modifications to tackle the aforementioned problems.

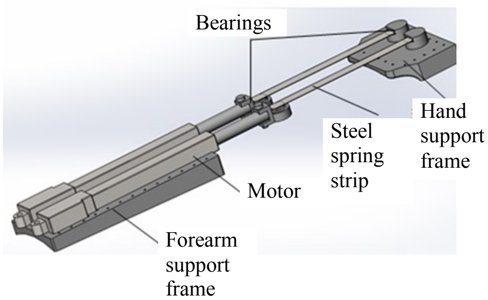
2) Exoskeleton design

Fig. 4 (a) illustrates the overall design of the wrist exoskeleton. This wrist exoskeleton consisted of 5 parts, including a forearm support frame, two linear motors, several connection structures, a hand support frame, and two spring strips. The structure was connected to the arm and the back of the hand through the support frames. The linear motors pulled or pressed the steel spring strips, and then the steel spring strips transmitted the force to the back of the hand. Extension/flexion and ulnar deviation/radial deviation of the wrist could be achieved using different state combinations of the two motors. As depicted in Fig. 4 (b), when the elongations of steel spring strips were different, the wrist could be driven to ulnar deviation or radial deviation.

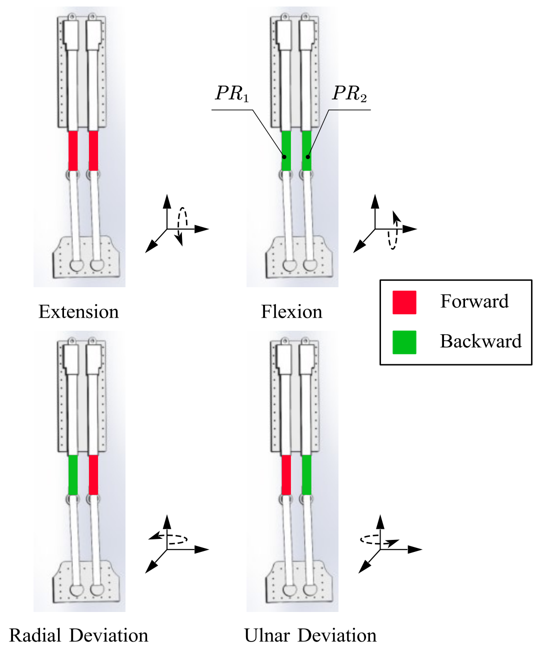
Two L12-100-100-6-I linear motors (Actuonix Motion Devices Inc., Canada) with maximum force of 42N, back drive force of 22N, maximum side load of 30N, and stroke of 100mm were used in this wrist exoskeleton. A steel spring strip with thickens of 0.3mm, width of 8mm, and length of 120mm was connected to each motor. The spring strip material selected in this paper was 65Mn. The overall length of the wrist exoskeleton was 325mm.

As shown in Fig. 5 (a), bearings were used in the connectors between the spring strip and the motor as well as the hand support frame to achieve smoother rotation. The top end of the push rod and the bearing tray were fixed using screws; the bearing was placed inside the tray; the bolt was matched with the inner hole of the bearing; one end of the steel spring strip closely adhered to the upper surface of the bolt. The overall dimensions of the connector were 24 mm long, 16 mm wide and 13 mm high, respectively. The structure shown in Fig. 5 (b) was designed for the connection between the steel spring strip and the hand support frame. The bearing was placed in the inner hole; the spring strip was inserted into the upper plane hole, and then bonded with super glue. The bearing sleeve belonged to the hand support frame structure. The bearing sleeve is approximately a cylinder with a diameter of 16 mm and a height of 8.5 mm.

The function of the wearable structure was to fix the exoskeleton to the human hand preventing slide between the exoskeleton and the human hand. In addition, it should allow some customization to hand size. Fig. 5 (c) displays the wearable part made of fabric and Velcro. The relative position of the Velcro straps and the base surface could be adjusted at the arm to adapt to the thickness of different human hands. The needle face was cut into four pieces to fit the conical shape of the arm. The user could adjust the Velcro strap on the back of the hand and the two straps surrounding the thumb to fit different hand sizes.



(a)



(b)

Fig. 4. Conceptual design shown in (a) and movement strategy of the wrist exoskeleton shown in (b): red color highlights the forward of push rod (PR) and green color highlights the backward of PR.

Fig. 5 (d) illustrates the design of forearm support frame. The two grooves of the upper forearm fitted the shape of the motor to fix the motor, and curved back was to fit the outline of arm. In addition, a trapezoid-structure (different thicknesses along the arm) was applied to compensate the height changes of the

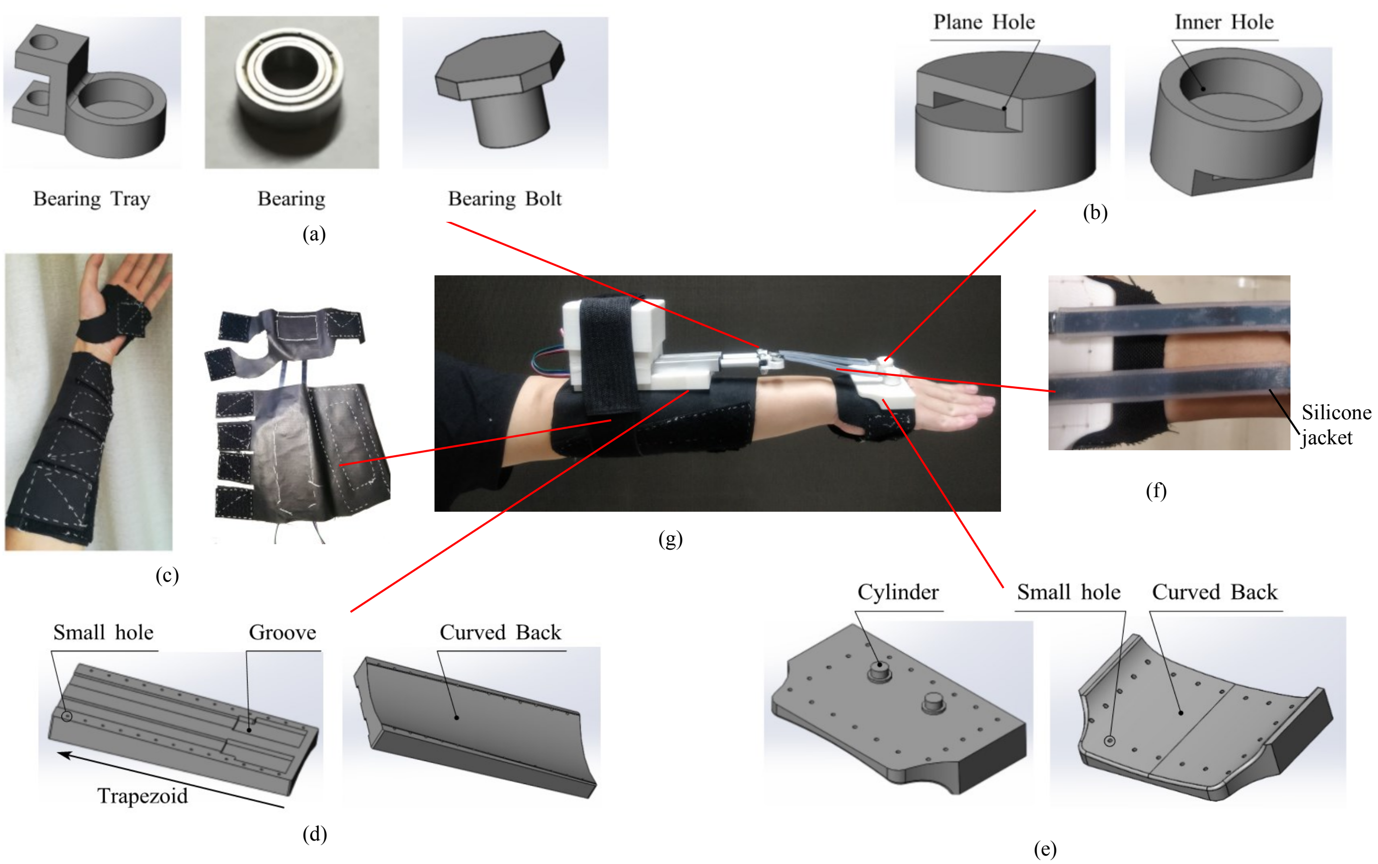


Fig. 5. Design details of the exoskeleton: (a) the connector between the spring strip and the push rod of the linear motor, (b) the connector between the spring strip and the hand support frame depicted from different directions, (c) the wearable structure, (d) the forearm support frame, (e) the hand support frame, (f) the silicone jacket of the steel strip, and (g) the assembly of the exoskeleton.

forearm to make sure that the two linear motors were parallel to each other. Small holes were fixedly connected with the wearable structure. The forearm support frame was 152mm long, 58mm wide and 13mm thick (maximum), respectively. As depicted in Fig. 5 (e), the hand support frame was curved to fit the hand back. Those small holes were used to be stitched to the fabric structure. The height of the two cylinders on the upper side was 3 mm, and the inner hole of the bearing was matched with the inner hole by transition fit. The hand support frame was 80mm long and 50mm wide, respectively.

The designed parts were 3D printed using polylactic acid material (PLA) in a rapid prototyping machine (D3020, Shenzhen Sundystar technology co. Ltd, China). As shown in Fig. 5 (f), the steel strip was cladded by a silicone rubber jacket with thickness of 1mm (Excoflex^{TM} 0030, Smooth on Inc.) to protect the user from the sharp steel strip blade. The wrist exoskeleton weighted 259g (415g including the controller).

D. System integration

Fig. 6 shows the system of brain-controlled wrist rehabilitation with visual guidance. The BrainLink device transmitted data to a MATLAB program via a Bluetooth connection. An Arduino UNO (Arduino, Ivrea, Italy) was used as the controller of the device. Bluetooth connection was also used between the Arduino and the computer. The Arduino UNO controlled the linear motors using the 0-5V interface mode of the linear motors. The 0-5V input voltage to the motor had a linear relationship to its 100mm stroke.

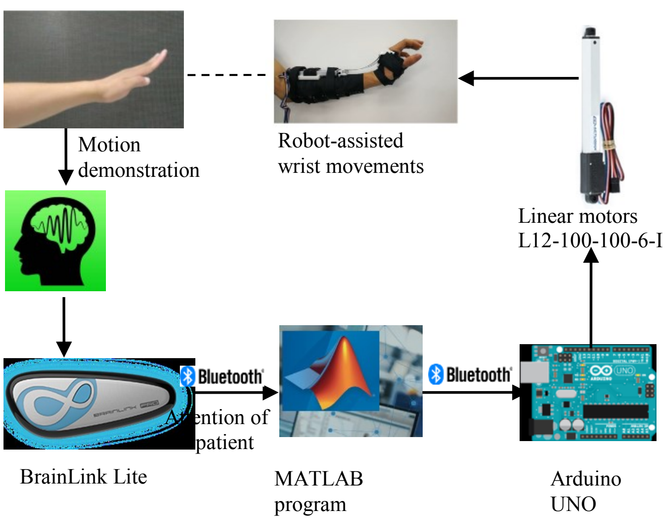


Fig. 6. System integration of brain-controlled wrist rehabilitation with visual guidance.

III. EXPERIMENTS AND RESULTS

A. Exoskeleton experiments

For wrist flexion/extension, the typical ranges of motion are 70° and 60°; for ulnar and radial deviation, the typical ranges of motion are 35° and 25° [30]. A patient suffering deficiencies in the wrist might not be able to achieve the full range of motions. Therefore, the target ranges of the motion of the wrist exoskeleton were set to be flexion/extension: 50°/50°, radial deviation: 18°, ulnar deviation: 30°. The performance tests of the exoskeleton include extension/flexion angle measurement and ulnar/radial deviation angle measurement.

TABLE Ⅱ shows the different angles of deviation when the two rods were pushed out with different length.

TABLE Ⅱ
THE ANGLE OF DEVIATION

Length difference between the two rods (mm)	Angle of Radial Deviation (°)	Angle of Ulnar Deviation (°)
10	7.0	19.1
20	11.0	35.1
30	19.9	39.6

As depicted in TABLE Ⅲ, the rods were pushed out or back with different lengths, angles would change correspondingly.

TABLE Ⅲ
THE ANGLE OF EXTENSION AND FLEXION

Length (mm)	Angle of Extension (°)	Angle of Flexion (°)
10	14.5	8.7
20	20.2	23.0
30	30.8	34.1
40	40.7	40.7
50	53.5	50.5

The maximum observed angle of flexion was 50.5°, that of extension was 53.5°, that of ulnar deviation was 39.6°, and that of radial deviation was 19.9°. The results show the range of motion fulfilled the requirement. The range of motions in flexion and extension can be further extended by a linear motor with a larger stroke.

B. Attention threshold experiment

An appropriate threshold of the attention level should be set for the proposed system. If the exoskeleton is switched on when the patient has not paid much attention to the rehabilitation exercise, active rehabilitation training cannot be achieved. On the other hand, if the threshold is very difficult for the patient to achieve, the rehabilitation exercise initiative of the patient will be reduced. Therefore, experiments were conducted to investigate the attention level threshold for the proposed brain-controlled wrist rehabilitation system.

The study involved twelve participants consisting of seven males and five females with an average age of 23.2 years (age range: 22-25). They were volunteers from Xi'an Jiaotong University. All subjects had normal vision and nervous system. This study was approved by the institutional review board of Xi'an Jiaotong University. All experiment participants provided a signed consent form before the experiment. The experiments were conducted in a quiet room. During the experiment, human subjects were seated in a chair wearing a BrainLink Lite device in front of a laptop computer. Before the experiment, participants had time to get familiar with the BrainLink device. The experiment included three parts including focusing, focusing with visual guidance, and disturbing. In the experiment of focusing, the participant was asked to focus on the user interface with no demonstration motion. At the same time, the attention level was measured and recorded. In the experiment of focusing with visual guidance, the participant was asked to focus on the demonstration motion shown on the user interface. In the experiment of disturbing, the attention level was measured when subjects were disturbed by four videos playing on a computer screen, music, and random questions from the experimenter. Each part of experiment lasted about 1 minute. Between every two parts of the experiment, the participant took a 1 to 2 minutes' break. These three experiment parts were performed in a pseudo-random order. The experiment was repeated five times.

An average attention level was calculated for each trial from a 30s long data when the attention level reaches a stable status. As shown in Fig. 7, the mean attention level of those subjects was 69 (SD=13.1), 37 (SD=11.8), and 74 (SD=14.2), for the experiment of focusing, disturbing, and focusing with visual guidance. The sample size was 60 (12 subjects ×5 repeats). Shapiro-Wilk test was used to check the sample normality. The test results showed that the attention level of each experiment part had a normal distribution (Focusing: W=0.967, p=0.108, disturbing: W=0.984, p=0.604, focusing with visual guidance: W=0.976, p=0.283). Then a student t-test with Bonferroni correction was applied for pairwise comparisons. The experiment of disturbing had significantly less attention level than the other two ($p=7.83\times10^{-23}<0.05/3$, $p=2.12\times10^{-26}<0.05/3$). The average of attention level of experiment of focusing with visual guidance and that of the experiment of focusing also had difference (p=5.84×10-3<0.05/3) significantly.

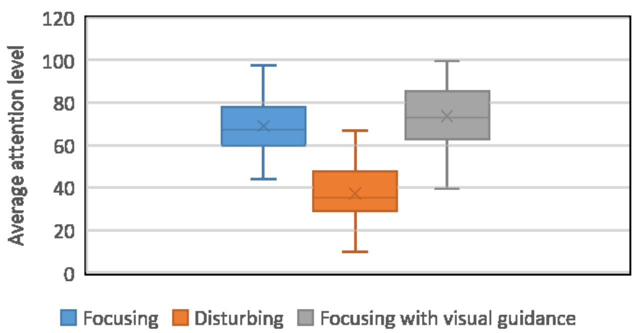


Fig. 7. The average attention levels in the attention threshold experiment

C. System evaluation

Two parts of the system evaluation experiment were conducted including wrist rehabilitation control with a general attention level threshold and with customized attention level thresholds. Since the average attention level achieved in experiment of focusing with visual guidance was higher than that of the experiment of focusing, visual guidance was applied in this experiment. A general attention level threshold of 74 was set according to the average attentional level result in the attention level experiment. The customized attention level for each subject was set according to the average level of each subject acquired in the attention level experiment. The same volunteers as in the attention threshold experiment conducted this system evaluation experiment. They were required to look at the motion demonstration shown on the computer monitor and imagine the same wrist motion. Their attention level values were acquired from the BrainLink sensor. If the attention level reached the threshold, the exoskeleton was activated to conduct the same wrist motion. If the exoskeleton could not be activated within 30s, this trial was marked as failure. During the entire experiment, the number of activated rehabilitation actions and the time took before reaching the threshold were recorded. The subjects had a one-minute break after one rehabilitation exercise. The two parts of the experiment were carried out alternately and the experiment was repeated ten times. After the experiment, participants were asked to give a subjective score out of 10 to assess whether the thresholds were appropriate and whether the attention-based control for the hand exoskeleton feels natural.

The sample size was 120 (12 subjects×10 repeats). The wrist robot was actuated during the wrist rehabilitation control experiment with customized thresholds 112 times (success rate 93.33%). The wrist robot was actuated during the wrist rehabilitation control experiment with a general threshold 116 times (success rate 96.67%). In general, the actuation success rate was 95.00%. Wilson score intervals was used to test the difference of two proportions (CI=0.029, Δp = 0.033, $CI < \Delta p$). This proved that there was significant difference between the two thresholds. The general threshold performed better.

As shown in Fig. 8, the average time before actuation was 4.62s (SD=4.98) and 4.04s (SD=4.08) for wrist rehabilitation control with a general attention level threshold and with customized attention level thresholds, respectively. Shapiro-Wilk test was used to check the sample normality. The test results showed that the time before actuation of each experiment part did not have a normal distribution (Focusing: W=0.703, $p=2.897\times10^{-13}$, disturbing: W=0.984, p=0.604, focusing with visual guidance: W=0.725, $p=8.677\times10^{-13}$). Therefore, a Mann-Whitney U test was applied to compare the time difference between the two experiment parts. The time difference between the two experiment parts was not significant (W = 5431.5, p = 0.764).

As shown in Fig. 9, the average subjective scores marked to the general threshold and the customized threshold by those subjects were both 7.5 (SD=1.36 for customized threshold, SD=2.64 for general threshold). The participants considered the performance of wrist rehabilitation robot control with a general attentional level threshold and customized attentional level threshold were similar.

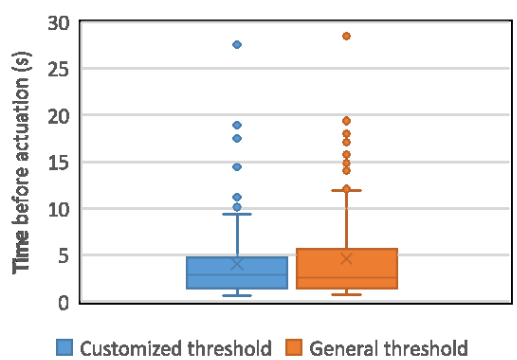


Fig. 8. Time before actuation of the wrist rehabilitation control experiment.

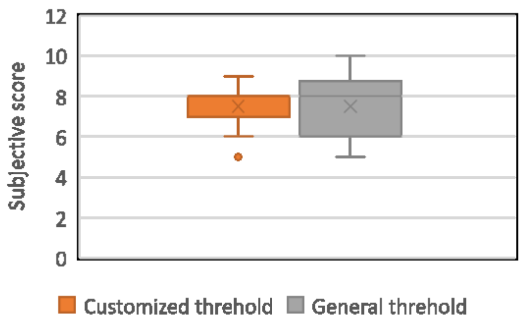


Fig. 9. Scores marked to experiment parts with the general threshold and the customized threshold by human participants.

D. Discussion

The proposed mechanism combined the advantages of rigidity and flexibility. Moreover, the cost of the product was controlled under the premise of ensuring the rehabilitation effect compared to the BCI-controlled wrist exoskeleton design [13] in which use traditional EEG acquisition equipment and complete contraction and extension. Our system adopted cheaper extremely device and accomplish four motions, which may be more easily introduced by rehabilitation agencies and even families. Compared to the previous wrist exoskeleton described in [4], Although similar mechanical structures were employed, BCI control was added to our system, which was a closed loop system to increase the patient's enthusiasm for participating in the rehabilitation process and improve the rehabilitation effect.

It was noted that in the evaluation experiment the electrodes of the EEG sensor were accessible to be abraded when we cleaned the electrodes for the convenience of the next experiment participant. The service life of this EEG sensor will be much shorter than other expensive ones. However, consider the much lower price of this sensor, it would not be a big problem.

According to the success rates in the system evaluation experiment, the general threshold performed slightly better. However, the time used before the robot actuation in the system evaluation experiment showed there was no significant difference. Moreover, the participants also considered the performance of wrist rehabilitation robot control with a general attentional level threshold and customized attentional level threshold were similar according to the subjective scores. Therefore, we believe that a general threshold of a certain group of users can be utilized in the wrist robot control rather than a customized threshold to simplify the procedure.

To further improve the effectiveness of the equipment, it is necessary to further explore the attention of different people, such as age, gender, etc. The mechanism of human attention may be more clearly understood in the future. Personalized customisation can be applied according to the specific situation of the patient via modifying the parameters of the piece and so on due to different defect level of hand.

IV. Conclusion

This paper introduced a brain-controlled wrist rehabilitation method using a low-cost EEG sensor. The attention-based control solution for the wrist exoskeleton was inexpensive and convenient to use either for a rehabilitation hospital environment or at-home rehabilitation training. The feasibility of the attention-based control was proven with the overall actuation success rate of 95% and the subjective score of 7.5 out of 10 given by the participants to assess whether the attention-based control for the wrist exoskeleton felt natural. Although the general threshold performed slightly better in the system evaluation experiment regarding the success rates, the time used before the robot actuation and the subjective scores showed no significant difference on the performance using a general threshold and using customized threshold. A general threshold of a certain group of users can be utilized in the wrist robot control rather than a customized threshold to simplify the procedure.

In future studies, more experiments with stroke patients are needed to further prove the clinical feasibility of the method.

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