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Development of a Reconfigurable Wrist Rehabilitation Device with an Adaptive Forearm Holder*

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Abstract—This paper presents the development of a new and reconfigurable wrist rehabilitation device (WReD). This device can be reconfigured for various hand orientation trainings, including wrist flexion/extension, radial/ulnar deviation, and a combined motion of them. The WReD employs a motor for actuation of a single degree of freedom (DOFs). Its sensing components consist of an angle sensor and a torque sensor. An adaptive forearm holder is also proposed to compensate potential misalignment between the human wrist and the rotation axis of the device. Preliminary tests were conducted with healthy subjects to evaluate the WReD design and potential as a clinical tool for wrist rehabilitation. Quantitative and qualitative results were obtained from each participant. Results show that the WReD is able to deliver therapy training of wrist flexion/extension, radial/ulnar deviation, or a combined motion of them, with positive feedback from all participants. This demonstrates the great potential of the WReD for wrist rehabilitation in multiple orientations.

I. INTRODUCTION

There are around 15 million people worldwide suffering from cerebrovascular accidents or stroke each year [1]. An estimated 60,000 stroke survivors live in New Zealand and many of them have mobility impairments [2]. In the United States, approximately 700,000 people suffer from stroke each year, and approximately two-thirds of these individuals survive and require rehabilitation [3].

Professor Caplan from Harvard Medical School describes stroke as a kind of brain impairment result from abnormal blood supply in a portion of the brain [4]. Patients following a stroke are significantly restricted in their daily activities, such as walking, eating, wearing, and speaking. It is widely recognized that an appropriate rehabilitation therapy is needed for recovering patients' lost abilities [5, 6]. The goals of rehabilitation are to help these survivors improve the plasticity of the nervous system and promote functional outcomes and return to their normal daily lives.

Traditional physical therapy is a classical rehabilitation method and is generally implemented by the therapist. Though this has been demonstrated as an effective way for motor rehabilitation [7, 8] , it is labor intensive and as a consequence expensive. Also, the rehabilitation effectiveness significantly relies on the skills of the therapist. Therefore, there is a great need to develop new enabling technology that can deliver intensive and objective therapy training to patients with physical dysfunction.

In the past few decades, robot-assisted rehabilitation techniques have been widely researched worldwide [9-13]. It was expected to deliver an overdue transformation of the rehabilitation center from labor-intensive operations to technology-assisted operations [14]. Engineers, working together with clinicians, are making enormous efforts to make rehabilitation devices much safer and more compliant for interaction comfort [15,16]. The robot can record a rich stream of data to facilitate patient diagnosis, customization of the therapy, and maintenance of patient records, through built-in or embedded sensors. This enables its objective assessment and training protocols.

Upper extremity function is of paramount importance to carryout various activities of daily living[17], in which the human wrist plays a vital role when orienting of an object. A variety of robot-assisted devices have been developed for the rehabilitation of human wrists in the past a few decades [18-20]. Some rehabilitation robots have been developed by combining the motion of human forearms with the wrist. Krebs, et al. [21] developed a wrist rehabilitation robot with three rotational degrees-of-freedom (DOFs), which are Flexion/Extension (F/E), Radial/Ulnar Deviation (RD/UD) for wrist joint and Pronation/Supination for forearm joint. This wrist device can be operated stand-alone or mounted at the tip of the MIT-MANUS [22]. Faghihi, et al. [23] developed a three-DOF wrist robot by using a similar structure as the work by Krebs, et al. [21]. However, they only presented the design and fabrication of the wrist robot without the introduction of a control system. Oblak, et al. [17] developed a universal haptic device that enables rehabilitation of either arm or wrist movement depending on locking or unlocking of a passive universal joint.

Some devices were developed with the focus on rehabilitation of the wrist joint. CR2-Haptic was developed to meet the requirements of low cost and portable design, with

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only one DOF [24]. However, it only permits a specific wrist motion at a time and can be manually reconfigured to different wrist motions if needed. Some other robots, such as the Bi-Manu-Track [10] and the Supinator Extender [25], these systems help to achieve 2-DOF rehabilitation exercise.

To sum up, the number of wrist joint DOFs depends on specific rehabilitation requirements. Achieving multiple DOFs within a unique robot can make the device complex, expensive, and bulky, from the view of structure design. Rehabilitation devices with appropriate design can be low-cost and portable enabling more patients to afford and even use independently at home. Taking all into consideration, this paper proposes a wrist rehabilitation device (WReD) with one actuator to realize a single rotation DOF. Meanwhile, the WReD can be reconfigured for various hand orientation trainings, including wrist F/E and RD/UD, or a combined motion of them. This paper is organized as follows. Following the introduction, the development of the WReD is given, including the mechanical design, electrical design and control system. Experimental results are presented and analyzed next, following that is the discussion and conclusion.

II. WRIST REHABILITATION DEVICE

Based on anatomical knowledge, the human wrist joint possesses two DOFs: F/E and RD/UD [26]. During wrist movements, the rotational axes of F/E and RD/UD are distally apart by 5 mm [19, 26] to 20 mm [27]. What's more, due to the complex joint structure, axes of rotation are not fixed [28]. This requires the WReD to be flexible and adaptive to the wrist axis variation, ensuring the training safety and comfort.

A. Mechanical Design

Fig. 1 (a) shows the proposed structure design of the WReD, including parts as below: the support unit, the actuation unit, and the handle holder. The support unit is the basic of total structure, and consists of a baseboard, three vertical support bars and a forearm holder. Two vertical support bars support the actuation unit and the mechanical stop, while the other one offers a virtual restraint to make the structure more stable. The forearm holder mounted on the baseboard provides a support to the forearm. The handle holder is connected to the actuation unit though two connection links.

The actuation unit is used to transmit the power for the motion. A gear box with a ratio of 1:74 is chosen to obtain an adequate torque output and minimum backlash. An elastic coupling is adopted in order to overcome the concentricity error due to the manufacture error. Meanwhile, a static torque sensor is placed between the coupling and the output axis, an angle sensor mounted on the vertical support bar on the left side together to record the real time value during the motion. The mechanical stop is designed to prevent the motion parts from exceeding to the specific range for safety. Besides, some bearings are set to minimize the friction between the rotational axis and the base unit.

The forearm holder mounted on the baseboard though bolts, is mainly composed of a forearm cuff, a horizontal slider, a vertical slider, a support base, two springs and a tightening screw, shown in Fig. 1 (b). The open design of mechanical structures permits the simple placement of the human forearm to suit the cuff, without guiding it through rings or other narrow structures that might complicate the procedure. This module can achieve two DOFs motion, sliding along with horizontal axis and vertical axis separately. At the beginning of training, patients forearm will be secured into the cuffs by

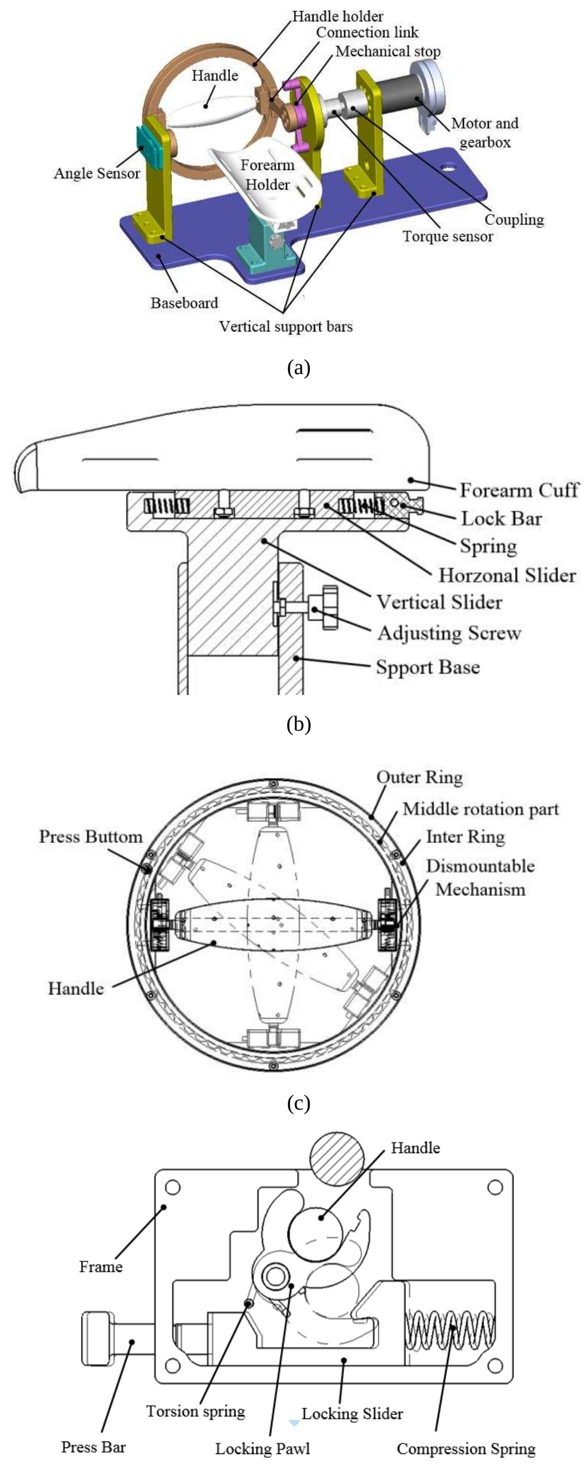


Figure 1. Structure designs of key parts. (a) WReD. (b) Forearm Holder. (c) Handle Holder with three locations. (d) Dismountable Mechanism with released and locked states.

means of Velcro straps, thus the physiatrician will help to adjust the vertical height though the tight screw to make sure the wrist rotation axes align with the actuation axis visually. In Fig. 1 (b), the horizontal slider can translate back and forth along the dovetail groove with the resistance from the two springs to make a misalignment compensation due to the eccentric distance between the two axes of F/E and RD/UD adaptively, thus the discomfort or pain felt by patients can be reduced. The translation rigidity of the horizontal slider can be changed depending on the spring stiffness. An appropriate spring stiffness can lead to comfort and safety.

The handle holder mounted with the actuation unit though two connection links, consists of an outer ring part, an inner ring part, a middle rotation part, a handler and a dismountable mechanism. Fig. 1 (c) shows the detail structure design of the handle holder. The handle is grasped by the fingers, and Velcro straps are usually used to fix the handle so that the wrist can be rotated with the WReD motion and keep static relatively during the training. The handle holder is designed to be reconfigurable to simplify the mechanical structure of the multiple DOFs wrist rehabilitation device. When considering the grasping posture of the patients after stroke, the handle can rotate with the middle rotation part at the specific angle from 0 to 90° with 6° interval in the closed space formed by the outer ring and the inner ring. Fig. 1 (c) also shows three different locations with 0°, 42° and 90°. Actually, when the middle rotation part locates at 0°, it represents patients training at F/E direction training, 90° means switching to the RD/UD direction training, while 42° represents one of a specific grasping posture.

Fig. 1 (d) shows the mechanical design of the dismountable mechanism. The handle mounted on the dismountable mechanism can be mounted or dismounted rapidly through a slight toggling on the press button to replace handles with different shapes. For some stroke patients, it’s difficult for them to grasp the handles like the healthy man due to the seriously deformed fingers, which results in the requirement of handles with different shapes. Thus, the dismountable characteristics can expand the application community well.

B. Electrical Design

The electrical components of the WReD consist of a DC motor (EC 90, Maxon), a controller (ESCON 50/5, Maxon), a static torque sensor (JNNT 50 Nm, Zhongwan), a magnetic rotary encoder (AS5048A, AMS) and an embedded controller (myRIO-1900, NI). The motor EC 90 outputs 0.533 Nm, through a gear box with reduction ratio 1:74, thus there is an estimated torque output of 39.44 Nm. With the consideration of the transmission efficiency being 0.75, thus the WReD can has the torque output of 29.58 Nm at the end effector (also the handle). The torque sensor is installed between the output shaft of the actuation module (through a coupling) and the handle holder for measuring the human-robot interaction torque. A magnetic rotary sensor is applied on the symmetrical shaft for measuring the angular position of the wrist motion in real time. An emergency stop is also set to ensure training safety. Predefined data and those from the electrical components of the WReD communicate with a computer through the myRIO-1900.

C. Control System

Patients implementing the trajectory tracking with the WReD is the basis robot-assisted rehabilitation exercise. It is generally used for passive training on patients to help improve the range of motion (ROM) [8]. It is proved that tracking desired trajectories is not only a simple but also an effective method for rehabilitation training [29]. Trajectory tracking control can be divided into two methods: open loop and closed loop. In this paper, we proposed the open-loop control method to the WReD, to validate the feasibility and reliability of the mechanical design. In the high level, the myRIO 1900 controller sends the position command to the Maxon Controller (ESCON 50/5) for open loop position control. In the low level, a closed loop system is implemented to achieve the speed control by comparing desired speed from the high level controller and actual speed feedback from the rotary encoder embedded in the motor.

III. Experimental Results

A. Quantitative results on three healthy subjects

To make a preliminary validation of the development of the WReD, experiments were conducted, as shown in Fig. 2. Three volunteers with healthy wrist joints participated in this test in a lab environment. The participants are all males with the age of 32, 29, 28 years old, the height of 185, 170, 168cm, and the weight of 75, 70, 65kg, which are marked as P1, P2, P3, respectively. The corresponding experiments are named Exp1, Exp2 and Exp3. Each participant was verbally encouraged to keep relaxed for passive training during the experiments.

Figure 2. The WReD prototype with a healthy subject

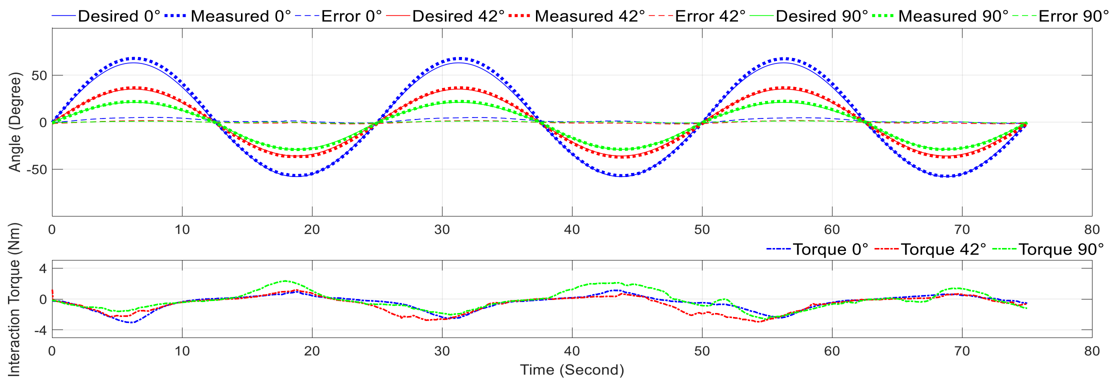
To evaluate the device design for specific hand orientation training, an open loop control strategy is used to deliver passive training to each participant along predefined trajectories. Table 1 shows a preliminary evaluation of appropriate ROMs for each participant before training. The desired trajectory is designed as a sinewave piecewise function which can be described as Eq. (1), this function allows the training to be slow at wrist limited position for comfort and safety. Here flexion and ulnar deviation is defined as negative, extension and radial deviation as positive. Each participant conducted three types of training, wrist F/E (0°), RD/UD (90°) and a specific grasping posture (42°).

$$\theta_r(t) = \begin{cases} A_p \sin(2\,\mathrm{pi} \cdot f \cdot t), \theta_r(t) \geq 0, A_p = \mathrm{Angle}+ \\ A_n \sin(2\,\mathrm{pi} \cdot f \cdot t), \theta_r(t) < 0, A_n = \mathrm{Angle}- \end{cases} \quad (1)$$

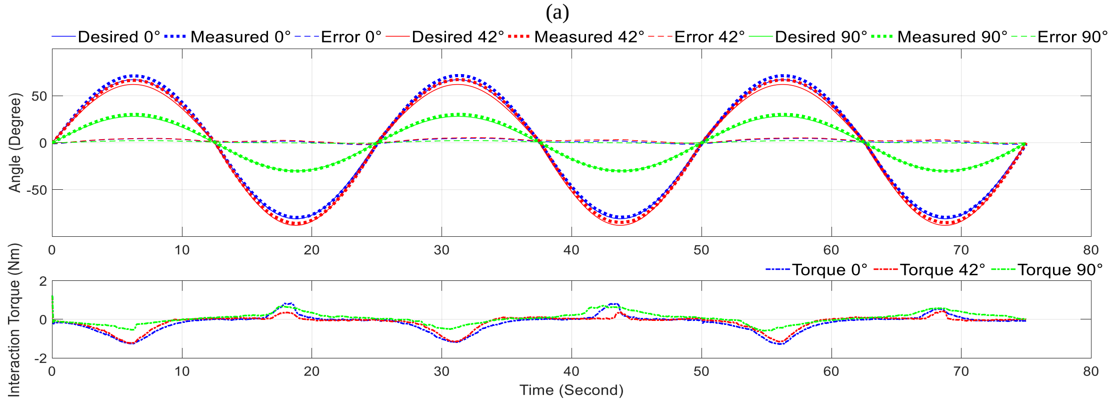
TABLE 1. DEMOGRAPHIC DATA OF THE THREE PARTICIPANTS

No.	**Age**	**Height** (cm)	**Weight** (kg)	**F/E** (0°)		**RD/UD** (90°)		**Grasping posture** (42°)	
				Angle+ (°)	**Angle-** (°)	**Angle+** (°)	**Angle-** (°)	**Angle+** (°)	**Angle-** (°)
P1	32	185	75	67	-81	28	-30	65	-88
P2	29	170	80	66	-83	29	-31	55	-84
P3	28	168	65	63	-58	21	-29	35	-36

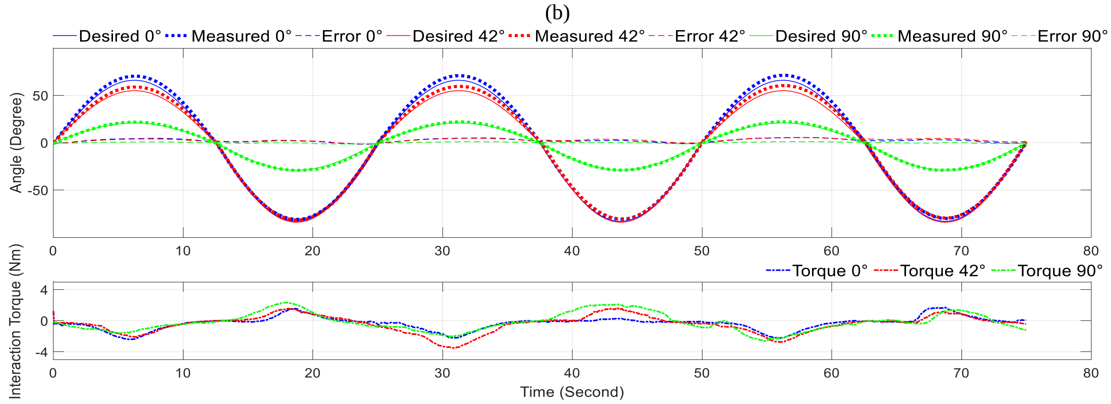
Note: Angle+: the angle in the positive direction, i.e., extension or radial deviation; Angle-: the angle in the negative direction, i.e., flexion or ulnar deviation.



(a)



(b)



(c)

Figure 3. Experiment results. (a) Exp 1. (b) Exp 2. (c) Exp 3.

TABLE 2. STATISTICAL RESULTS OF THE EXPERIMENTS

No.	**MinError** (°)	**MaxError** (°)	**Root Mean Square Deviation** (°)	**Normalized Root Mean Square Deviation** (%)	**Maximum absolute interaction torque** (Nm)	**Mean absolute interaction torque** (Nm)
Exp1	-1.46	4.12	2.18	1.81	1.28	0. 25
Exp2	-1.44	4.15	2.25	1.81	3.51	0.81
Exp3	-1.57	2.64	1.46	1.64	3.05	0.87

Fig. 3 (a), (b), (c) present the trajectory tracking responses corresponding to the Exp.1, Exp.2, and Exp.3, where the solid line sinewave is the desired trajectory, the dotted line is the measured trajectory, the dashed line is the error, and the hidden line in the bottom plot is the measured torque from the torque sensor. All the curves are chosen with three cycles for analysis.

In each figure, three specific hand orientation training data are marked with different colors to make the quantitative analysis of the trajectory tracking performance under the open loop control method. As shown from figures, the measured trajectory follows well with the desired trajectory. Table 2 shows the response results for these three experiments. To help understand, here we cite the Exp.1 for example. It's measured that the following error ranges from -1.46° to 4.12°, the root mean square deviation (RMSD) is 2.18°, and the normalized root mean square deviation (NRMSD) is 1.81%. Fig. 3 also shows an obvious torque variation throughout the training. When the angle is close to the limits of ROM, the maximum of absolute torque value is 1.28 Nm, and the mean of absolute torque value is 0.25 Nm. This is caused by the resistance when the wrist is at limited joint position. From the Table 2, it's obviously seen that the experimental results vary from person to person, however, the results reflect good tracking performance of this device.

B. Quantitative feedbacks from three healthy subjects

To qualitatively make a comprehensive evaluation of the WReD, in the aspects of comfort, ease of use, level of user acceptance, etc., a questionnaire survey for the three healthy subjects are designed. Three participants accomplished the survey after the section A training.

Feedbacks were obtained from the questionnaire. All participants stated that they understood the instructions very well and had no confusion while training by using the WReD. When questioned about whether it was comfortable during the whole training, two participants felt that the forearm placing and fingers grasping were 'very comfortable', without any painfulness or tightness, while one participant considered as 'good'. This might be caused due to the Velcro straps looseness. When asked about the easiness to apply this device, all three participants felt that it was 'very easy', which was evident in the scores each of them achieved. This might be attributed to the fact that the Velcro straps were easy to fix, meanwhile the reconfigurable mechanism and the dismountable mechanism were convenient for reconfiguration and handle replacing. Two participants felt that the forearm often moved back and force during the experiments, which they expected to avoid. This suggests that the springs stiffness chose in the forearm holder may not be suitable to each participant. Furthermore, this might result from that the current mechanism design to compensate the misalignment between the F/E and RD/UD axes needs to be optimized in the future. There was a general feeling that this robot-assist device in a day to day scenario to rehabilitate patients with wrist injuries was accepted gradually.

IV. Discussion and Conclusion

This paper presents the development of the reconfigurable WReD with an adaptive forearm holder. The WReD is portable and cost-effective due to the reconfigurable structure. Since wrist training therapy along F/E direction is more common than that of RD/UD, in this study, the WReD is configured for the rehabilitation training of wrist flexion and extension, as in case 1 in Fig. 1 (c). Meanwhile, it's worth mentioning that the WReD can be easily reconfigured for training in other directions. For example, case 3 in Fig. 1 (c) is configured for RD/UD by rotating the handle to a vertical posture along the handle holder.

The misalignment issue is common on a variety of wrist rehabilitation devices. It can be caused by several reasons, such as the axes eccentric distance between wrist F/E and RD/UD [19, 26, 27], the improper placement of forearm, and the varying rotation axes of the wrist joint. Without a correct axis alignment the rehabilitation device may be uncomfortable and even unsafe for human users [30, 31]. Manual axis alignment is a challenging task in practice since it requires visual observation or even the help of imaging devices. Also, constant adjustment during therapy leads to the low repeatability [32, 33] and brings bad user experience. Thus, a self-alignment function of the human-robot axes is greatly desirable, which has been a hotspot in recent years.

In this study, the WReD employs an adaptive forearm holder with potential for compensating misalignment. The forearm may have to move back and forth theoretically when inconsistent axes exist. However, from the experiment results and the feedbacks of the questionnaire, the effectiveness proves to be not ideal as expected in practice. As discussed in the section of experiment results, one of the reasons is that the properness of spring stiffness varies from person to person, thus sometimes not self-alignment due to the relatively high stiffness. To achieve better self-alignment performance, an optimized self-alignment mechanism needs to be further developed to be used in a three dimensional space. The connection links being flexible rather than grid will be taken into consideration in the next generation of the WReD.

Future work will also focus on the improvement of the WReD in terms of its functionality and clinical evaluation. While the WReD can be reconfigured for various hand orientation trainings, including F/E, RD/UD, and combined motion of them, its clinical significance and task-oriented training strategies need to be further investigated.

In summary, this study presents the development of the reconfigurable WReD and the experiments to evaluate its design with three healthy subjects. The trajectory tracking performance is good with the NRMSD values no greater than 1.81% even under real-time disturbance and interaction between the participant and the device. Qualitative feedbacks were obtained by using questionnaires. Results show that the WReD is able to deliver therapy training with different hand orientations, and all participants gave a positive feedback in using this device. These findings suggest that the proposed robot-assisted wrist rehabilitation technique has great potentials for clinical applications.

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