An Industrial Robot-based Rehabilitation System for Bilateral Exercises

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This work was supported by the International S&T Cooperation Program of China (ISTCP) under grant no.2016YFE0121700, the Science and Technology Development Fund of Macao S.A.R (FDCT) under MoST-FDCT joint grant no.015/2015/AMJ, the Faculty Research Development Fund of the University of Auckland under grant no.3717395 and China Sponsorship Council under grant no. 201508250001.

ABSTRACT Robot-assisted rehabilitation devices can provide intensive and precise task-based training that differs from clinician-facilitated manual therapy. However, industrial robots are still rarely used in rehabilitation, especially in bilateral exercises. The main purpose of this research is to develop and evaluate the functionality of a bilateral upper-limb rehabilitation system based on two modern industrial robots. A 'patient-cooperative' control strategy is developed based on an adaptive admittance controller, which can take into account patients' voluntary efforts. Three bilateral training protocols (passive, active, and self) are also proposed based on the system and the control strategy. Experimental results from 10 healthy subjects show that the proposed system can provide reliable bilateral exercises: the mean RMS values for the master error and the master-slave error are all less than 1.00 mm and 1.15 mm respectively, and the mean max absolute values for the master error and the master-slave error are no greater than 6.11 mm and 6.73 mm respectively. Meanwhile, the experimental results also confirm that the recalculated desired trajectory can present the voluntary efforts of subjects. These experimental findings suggest that industrial robots can be used in bilateral rehabilitation training, and also highlight the potential applications of the proposed system in further clinical practices.

INDEX TERMS Adaptive admittance controller, bilateral upper-limb rehabilitation system, industrial robot, patient-cooperative control strategy.

I. INTRODUCTION

Stroke is one of the leading causes of disability [1], with many stroke survivors suffering from complications such as paralysis of the limbs on one side of the body, or difficulty speaking and understanding words [2]. About 50% of them will suffer from upper-limb disabilities after the subacute stage (6 months from stroke onset), limiting their abilities to perform Activities of Daily Living (ADLs) [3]. This affects survivors and their families physically, emotionally, financially and socially. Bilateral upper-limb training has been widely researched as a new rehabilitation intervention in clinical practices [4-6]. According to the theory of neuroplasticity, neural networks in a damaged hemisphere could be reconstructed by an undamaged hemisphere through symmetrical movements [7, 8]. The possibility of voluntary muscle contractions in an affected limb could also be increased via the activation of the primary motor cortex and the supplementary motor area of an unaffected limb during symmetrical movements [9].

Compared to traditional manual therapy, robot-assisted training has been developed as an effective rehabilitation intervention which can provide precise training for a sufficiently long timeframe, regardless of physiotherapists' experience and fatigue level [10, 11]. A similar trend has been occurring amongst bilateral upper-limb robots/systems. For example, Mahoney et al. [12] developed the ARCMIME system for elbow extension/flexion and shoulder adduction/abduction exercises. The system consists of linear slides and aluminium extrusions of which arm supporters are mounted onto, allowing bilateral planar movements along with the linear slides. Four different training modes (passive, active-assisted, active-constrained and master/slave) has been tested by 4 stroke survivors and 2 healthy subjects with this system. Recently, some industrial robots have been employed for rehabilitation interventions, with high safety and reliability are their advantages, verified by clinical practices [13, 14]. Toth et al. [15] developed the REHAROB system consisting of two industrial robots (the IRB 140 and 1400H from Asea Brown Boveri Ltd, Zurich, Switzerland) to help with the recovery of patients with spastic hemiparesis. Moreover, a new industrial robot named the 'KUKA lightweight robot' (LBR iiwa, KUKA AG, Augsburg, Germany) provides built-in force/torque measurement with adjustable stiffness and damping for each joint [16]. Experimental results show that the LBR iiwa is safe and back-drivable, making it useful as a potential platform for rehabilitation interventions [17, 18]. However, these industrial robot-involved systems cannot be counted as bilateral systems since they only focus on one arm of patients. To date, only one industrial robot has been used in bilateral training: the PUMA 560 robot (Unimation Inc, Danbury, USA) of the MIME system [19] (Mobile DESIRE platform [16] includes two LBRs, but it is not designed for rehabilitation purpose).

In addition, the motion path is also important for bilateral systems as it is the foundation for applying different exercises. Normally, bilateral systems can be classified into two types with differing motion paths. The first type is systems with fixed motion paths, such as the Bi-Manu-Track system [20] and the Reha-Slide system [21], which focus on specific joints of the upper limb. The former provides two fixed exercises (forearm pro-/supination and wrist flexion/extension), and the latter provides three fixed exercises (wrist flexion/extension, elbow extension/flexion, and shoulder adduction/abduction). The other type is systems with continuous motion paths, which can deliver planar or three-dimensional (3D) workspaces for training multiple joints of the upper limb. For example, Kim et al. [22] developed the EXO-UL7 which consists of two 7-DoF (degree of freedom) exoskeletons. The EXO-UL7 supports most ADLs since each exoskeleton has seven single-axis revolute joints. However, the training trajectories in these two kinds of systems have to be predefined before the exercise, and cannot be adjusted in real time. This could be a safety problem for affected limbs when made to follow unaffected limbs during bilateral exercises, especially for systems with a continuous motion path [23] as the workspace of an affected limb is less than that of an unaffected limb [24]. Recently, a new control strategy named 'patient-cooperative' has been proposed by Riener et al. [25] and revised by Trlep et al. [26] and Zhang et al. [27]. This control strategy can adjust trajectories in real time by taking into account the patients' intentions and voluntary efforts, which has been proved to be more effective for motor and functional improvements than predefined or inflexible trajectories [25, 26]. However, this kind of control strategy has not been used by existing industrial robot-based bilateral systems so far.

Therefore, the purpose of this research is to develop and evaluate a bilateral upper-limb rehabilitation system based on two modern industrial robots. Specifically, a prototype will be developed based on two 'Universal Robot' (UR) robots, the 'patient-cooperative' control strategy would be realised based on an adaptive admittance controller, and related bilateral training protocols will also be proposed. It is hypothesized that the proposed bilateral system can provide a reliable bilateral training environment, and could be used as a platform for further clinical practices.

II. SYSTEM DESIGN AND METHODS

A. ROBOT DESIGN

An industrial robot-based bilateral rehabilitation system (IRBRS) has been developed (Fig. 1(b)) to be able to train multiple joints in the upper limbs within a continuous 3D workspace to meet the requirements of most ADLs. The system is mainly composed of two off-the-shelf industrial robots (UR5 and UR10, Universal Robots A/S, Denmark), two six-axis force sensors (SRI M3713C and SRI M3715C, Sunrise Instruments LLC, China) and two customised handlebars. Each robot includes one UR arm and one UR controller (the touchpad, Fig. 1(a)), and a built-in program "PolyScope" is used to manipulate the UR arm via the UR controller [28]. The UR arm is a 6-DoF device, which meets the movement requirements of arm rehabilitation (≥5 DoFs) [29], and the safety of the UR arm (the UR10) has been confirmed through kinematic and dynamic analyses conducted in our previous research [30]. The velocities and poses of the UR arm' joints can be easily acquired in real time via built-in functions based on the robot's original industrial design. The pose of the tool centre point (TCP, the tip of the UR arm) is expressed by a vector of six arguments {X, Y, Z, Rx, Ry, Rz} in relation to the base of the UR arm. The {X, Y, Z} coordinates represent the TCP's pose in a 3D space whereas the {Rx, Ry, Rz} coordinates indicate the rotation of the TCP. Meanwhile, in order to acquire real-time interaction forces between patients and robots, a force sensor is mounted between the TCP and the customized handlebar of each robot. Furthermore, each customized handlebar includes a supporter for patients' hands and wrists, as well as Velcro straps to attach patients' hands to the grip, making it suitable for the affected arms of patients. Safety measures have been implemented in both the hardware and software levels of the system. The robots stop if velocity or movement magnitudes exceed predefined limits. Operators can also terminate the robots using the stop command or the emergency button at any time.

In this research, the UR10 and UR5 are treated as master and slave robots respectively, since the UR10 can provide a larger working radius (1.3 m and 0.85 m for the UR10 and UR5 respectively). The two robots are linked to a PC (i7 processor, Windows™ 10) through a router based on a LabVIEW program (National Instruments Corporation, Austin, USA). The master robot can send commands to, and receive feedback from, the slave robot through the Modbus TCP/IP protocol (Fig. 2(a)). Therefore, the proposed system could become a platform for bilateral exercises as the unaffected and affected arms of patients can use the robots for real-time communication, and the roles of the master and slave robots can be conveniently switched. The relation of two robots' base frame can be seen in the previous research [23] which provided detailed information about the construction of bilateral rehabilitation system (e.g. the basic parameters of the system, reference trajectory generation).

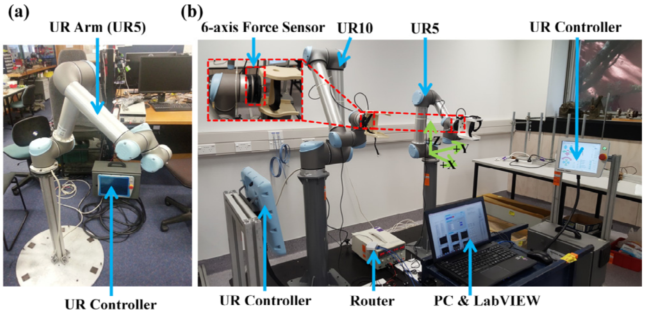

FIGURE 1. **The diagrammatic hardware. (a) The UR5. (b) Prototype of the proposed bilateral system.**

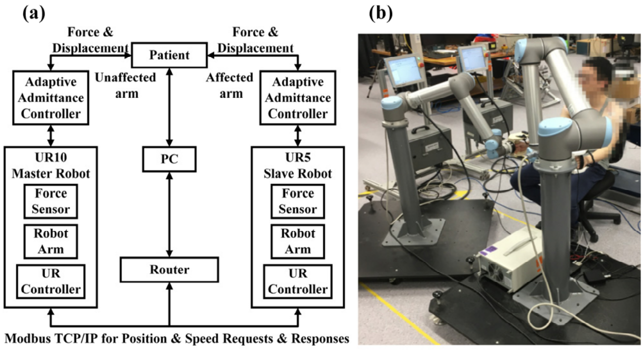

FIGURE 2. **The proposed bilateral system. (a) Block diagram of the bilateral system. (b) A healthy subject with the bilateral system.**

B. 'PATIENT-COOPERATIVE' CONTROL STRATEGY

As discussed in the introduction, the 'patient-cooperative' control strategy can enhance the level of voluntary involvement of patients, which are more effective for motor and functional improvements than predefined or inflexible trajectories [25, 26]. An adaptive admittance controller is therefore designed to address this purpose. The robots will present the behaviour of admittance accordingly, and their movements will be determined by the interaction forces exhibited by patients. The proposed controller consists of two parts: an admittance control scheme and an adaptation scheme, which have been shown in Fig. 3. The admittance control scheme is used to realise the 'patient-cooperative' control strategy, that is, the robots will deviate from the reference trajectory in the presence of 'patient-cooperative', but otherwise they will follow the reference trajectory. The adaptation scheme is used to tune the parameters of the admittance control scheme based on interaction forces, which can adjust the compliance of the robots in real time. A fuzzy logic approach is adopted to realise the purpose of real-time adaptation. The input and output of the controller are the interaction force $\boldsymbol{f}$ from patients and the desired trajectory $\boldsymbol{p}_d$, respectively (Fig. 3). The desired trajectory can be obtained by equation (1)

$$\boldsymbol{p}_d = \boldsymbol{p}_r + \triangle \boldsymbol{p} \tag{1}$$

where $\boldsymbol{p}_d$ is the desired trajectory for the robots to perform, $\boldsymbol{p}_r$ is the reference trajectory predefined on a computer, and $\triangle \boldsymbol{p}$ is the trajectory change calculated by the admittance control scheme based on real-time interaction forces.

There are two conditions should be considered: 1) If there is no force applied in the current loop, the trajectory change $\triangle \boldsymbol{p}$ would be zero, and the desired trajectory $\boldsymbol{p}_d$ would be the same as the reference trajectory $\boldsymbol{p}_r$. This means that the robots would follow the reference trajectory. 2) If there is force applied in the current loop, the trajectory change $\triangle \boldsymbol{p}$ would be non-zero, and the desired trajectory $\boldsymbol{p}_d$ would be adjusted based on interaction forces in real time. Therefore, the intentions and voluntary efforts of patients can be reflected (interaction forces can be treated as the 'guidance' for the robot).

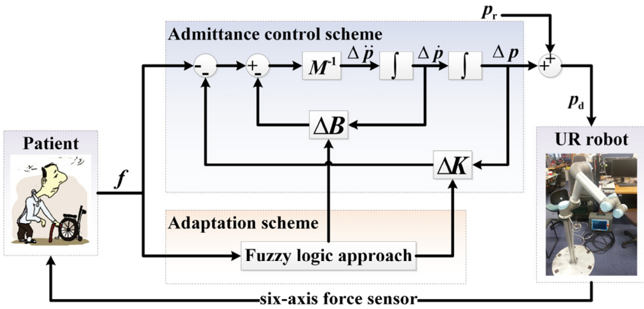

FIGURE 3. **Adaptive admittance controller implemented on the UR robot with a patient. *f* is the interaction force; *M* is the mass inertia matrix; $\triangle B$ is the change of the damping matrix; $\triangle K$ is the change of the stiffness matrix; $\triangle p$ is the trajectory change; p_r is the reference trajectory; p_d is the desired trajectory.**

ADMITTANCE CONTROL SCHEME

The admittance control scheme is referred to as the interaction control scheme proposed by Hogan firstly [31], which is the inverse of the impedance control scheme. Several control strategies have been proposed based on the impedance control scheme such as 'assist-as-needed' [32, 33]. However, the impedance control scheme is challenging to be used on industrial robots due to the high requirement of the model precision. Considering the system in this research, two industrial robots plus subjects' time-varying dynamics will become very complex, causing an accurate system model to be hardly available in practice [34]. Therefore, we have focused on only the high-level admittance control and have left some low-level inner-loop controls (e.g. position control, velocity control) for each joint to be completed by the UR robots themselves. A similar method has been tested on a compliant parallel ankle robot [27, 35], which is robust and fast-response. As for the admittance control scheme, the system receives force inputs and produces displacement outputs. In this research, the force input is provided by patients, and the displacement output is the trajectory change $\triangle \boldsymbol{p}$. The admittance control law is proposed in

$$\boldsymbol{f} = -(\boldsymbol{M}^{-1}\Delta\ddot{\boldsymbol{p}} + \Delta\boldsymbol{B}\Delta\dot{\boldsymbol{p}} + \Delta\boldsymbol{K}\Delta\boldsymbol{p}) \tag{2}$$

where $\boldsymbol{M}$, $\triangle\boldsymbol{B}$ and $\triangle\boldsymbol{K}$ represent the mass inertia matrix, the change of the damping matrix, and the change of the stiffness matrix, respectively. $\triangle\boldsymbol{p}(t)$, $\triangle\dot{\boldsymbol{p}}(t)$, and $\triangle\ddot{\boldsymbol{p}}(t)$ are the trajectory change, velocity change and acceleration change respectively. The $\triangle\boldsymbol{B}$ and $\triangle\boldsymbol{K}$ are the outputs of the adaptation scheme (the fuzzy logic approach), which would be updated based on real-time interaction forces. Equation (2) can be rewritten as

$$\Delta\boldsymbol{p} = -(\boldsymbol{M}^{-1}\Delta\ddot{\boldsymbol{p}} + \Delta\boldsymbol{B}\Delta\dot{\boldsymbol{p}} + \boldsymbol{f})/\Delta\boldsymbol{K} \tag{3}$$

and equation (1) can be then rewritten as

$$\boldsymbol{p}_d = \boldsymbol{p}_r - (\boldsymbol{M}^{-1}\Delta\ddot{\boldsymbol{p}} + \Delta\boldsymbol{B}\Delta\dot{\boldsymbol{p}} + \boldsymbol{f})/\Delta\boldsymbol{K} \tag{4}$$

Meanwhile, the utilised robots are serial industrial manipulators (6 DoFs) whose mass inertia matrix $\boldsymbol{M}$ can be calculated based on [30, 36]

$$\boldsymbol{M} = \sum_{i=1}^{n}\left(\mathrm{m}_i \boldsymbol{J}_{v_i}\boldsymbol{J}_{v_i}^T + \boldsymbol{I}_i\boldsymbol{R}_i\boldsymbol{R}_i^T\boldsymbol{J}_{w_i}\boldsymbol{J}_{w_i}^T\right) \tag{5}$$

where m_i, $\boldsymbol{I}_i$ and $\boldsymbol{R}_i$ represent mass, inertia tensor matrix, and rotational transformation matrix of robot's each link, respectively. $\boldsymbol{J}_{v_i}$ and $\boldsymbol{J}_{w_i}$ represent the linear part and angular part of the Jacobian matrix of robot's each link, respectively.

ADAPTATION SCHEME

A fuzzy logic approach is used to regulate the parameters of the admittance control scheme based on interaction forces. The advantage of applying the fuzzy logic approach is its ability to cope with nonlinear systems and systems with uncertain parameters [37-39], which is suitable for processing interaction forces. According to the design of the controller (Fig. 3), the input of the fuzzy logic approach is the interaction force $\boldsymbol{f}$, and the outputs of the fuzzy logic approach are the damping matrix change $\triangle\boldsymbol{B}$ and the stiffness matrix change $\triangle\boldsymbol{K}$.

The block diagram of the fuzzy logic approach is shown in Fig. 4(a), and the detailed data processing has been concluded as follows. 1) The interaction force $\boldsymbol{f}$ is normalized to become the fuzzy input (E) as mentioned above, and the first derivative of $\boldsymbol{f}$ is normalized to become the other fuzzy input (EC) based on the standard procedure of the fuzzy logic approach (Fig. 4(a)). 2) In the fuzzification, E and EC are mapped to seven Gaussian curve membership functions (Fig. 4(b)), namely, Positive Large (PL), Positive Middle (PM), Positive Small (PS), Zero (O), Negative Small (NS), Negative Middle (NM) and Negative Large (NL), respectively. The membership degree of each mapped input is obtained from these membership functions. 3) Each combination of membership degrees of mapped inputs (E and EC) activates one fuzzy rule based on a fuzzy rule table (Table 1). A total of 49 different fuzzy rules are included in Table 1. These fuzzy rules are employed by the Mamdani-type inference method, which are based on the if-then-else structure [40]. 4) The fuzzy output is calculated in the defuzzification based on the centre of gravity method [38]:

$$U = \sum_{i=1}^{n} W_i \cdot B_i \Big/ \sum_{i=1}^{n} W_i \tag{6}$$

where U is the fuzzy output, B_i is ith activated fuzzy rule, W_i is the minimum of E and EC's membership degrees, and i stands for PL, PM, PS, O, NS, NM, and NL. 5) The output U is then denormalized to the crisp output which is the final output of the fuzzy logic approach. In this research, the fuzzy rules are initially determined based on the empirical knowledge of the domain experts and the suggestions of literature [41, 42]. Then these initial fuzzy rules are filtered by the algorithm of clustering to get the final fuzzy rules [43], one of the standard procedures for determining the fuzzy rules. Because the suitable fuzzy rules are placed according to grid-like partitions in the input space, while the redundant fuzzy rules are scattered in the input space. These final fuzzy rules have been tested to be effective and stable in our previous research based on the same robot [44].

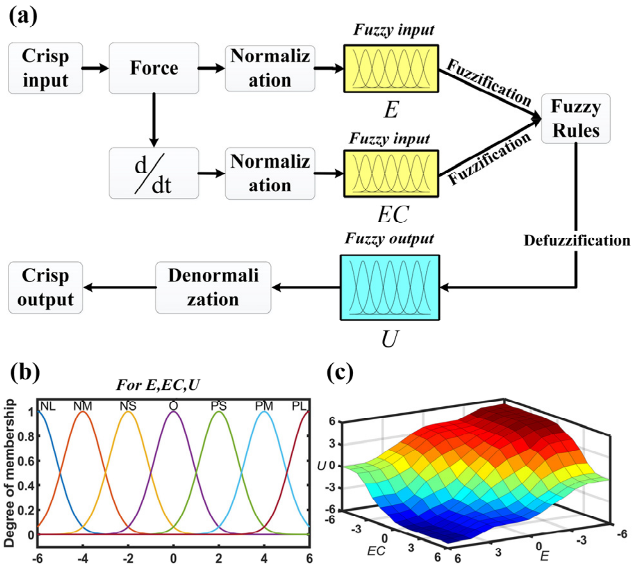

FIGURE 4. **The fuzzy logic approach. (a) Block diagram of the fuzzy logic approach. (b) Membership functions for *E*, *EC* and *U*. (c) Surface of fuzzy rules.**

TABLE 1. Fuzzy rules.

E \ EC	NL	NM	NS	O	PS	PM	PL
NL	PL	PL	PL	PL	PM	O	O
NM	PL	PL	PL	PL	PM	O	O
NS	PM	PM	PM	PM	O	NS	NS
O	PM	PM	PS	O	NS	NM	NM
PS	PS	PS	O	NM	NM	NM	NM
PM	O	O	NM	NL	NL	NL	NL
PL	O	O	NM	NL	NL	NL	NL

PL=Positive Large, PM=Positive Middle, PS=Positive Small, O=Zero, NS=Negative Small, NM=Negative Middle and NL=Negative Large.

C. BILATERAL TRAINING PROTOCOLS

A commonly used method in bilateral exercises is to ensure that the slave robot (affected arm) follows the master robot (unaffected arm) at all times [23]. In this research, three different bilateral training protocols are developed to actualise the bilateral exercises, which are determined based on literature [19, 45], the Brunnstrom approach (from Stage 5 to Stage 7, Table 2) [46], and the neuroplasticity theory mentioned in the introduction. The master force (MF, created by unaffected arms) is used for describing a force applied on the master robot, and the slave force (SF, created by affected arms) is used for describing a force applied on the slave robot. The interaction forces and their directions (xyz directions) will be measured by the force sensors and processed by the controllers on both robots in real time. There would be four conditions for the desired trajectory (Fig. 5) in each loop (10 Hz):

$$\mathrm{DT} = \begin{cases} \mathrm{RT}, & \mathrm{MF} = 0, \mathrm{SF} = 0 \\ \mathrm{RT} + \mathrm{MT\ change}, & \mathrm{MF} \neq 0, \mathrm{SF} = 0 \\ \mathrm{RT} + \mathrm{ST\ change}, & \mathrm{MF} = 0, \mathrm{SF} \neq 0 \\ \mathrm{RT} + \mathrm{MT\ change} + \mathrm{ST\ change}, & \mathrm{MF} \neq 0, \mathrm{SF} \neq 0 \end{cases} \quad (7)$$

where DT is the desired trajectory (the same as the $\boldsymbol{p}_d$), RT is the reference trajectory (the same as the $\boldsymbol{p}_r$), MT change is the master trajectory change, and ST change is the slave trajectory change. These four conditions all follow the control rule in bilateral exercises where the slave robot follows the master robot at all times.

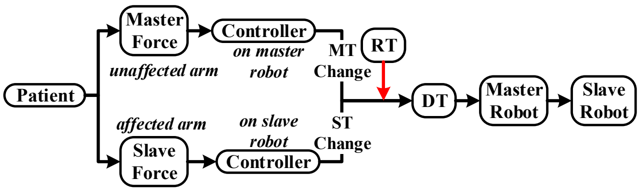

FIGURE 5. Block diagram of the bilateral training protocols.

1) BILATERAL-PASSIVE TRAINING PROTOCOL
This protocol is designed for the primary stage of recovery (Stage 5, Table 2), in which patients' affected arms are moved carefully by the slave robot if they lack mobility. The objective of this protocol is to help in the recovery of force within patients of high disability levels.

2) BILATERAL-ACTIVE TRAINING PROTOCOL
This protocol is designed for the middle stage of recovery (Stage 6, Table 2), and is performed when patients can provide a medium level of force upon the robots. The objective of this protocol is to encourage patients to involve themselves in the exercises, and so, patients are asked to provide a comfortable amount of force upon the robots instead of passively following the reference trajectory.

3) BILATERAL-SELF TRAINING PROTOCOL
This protocol is designed for the final stage of recovery (Stage 7, Table 2), in which patients should then be able to perform almost all ADLs with normal motor functions. Therefore, a 'self-training' protocol is proposed, where the reference trajectory is not provided (Fig. 5, red line), and all trajectories are to be created by themselves. The protocol contains two sub-exercises: the bilateral-self-mimic exercise, in which the trajectories of the master and slave robots are the same; and the bilateral-self-cooperative exercise, in which the trajectories of the master and slave robots are reversed in one direction (e.g. the Y-direction is reversed whereas the other directions are the same). The objective of this protocol is to maximise the degree of patients' involvement. It should be noted that the bilateral-self training protocol is developed for testing with the proposed bilateral system and the control strategy only, and should not be used for clinical practices without further analyses and tests. The future applications of this protocol are discussed later.

TABLE 2. Recovery stages of the Brunnstrom approach [46].

Stage	Characteristics
5	• More difficult combinations are mastered. • Spasticity continues to decline.
6	• Individual joint movement becomes possible. • Coordination approaches normalcy. • Spasticity disappears: individual is more capable of full movement patterns.
7	• Normal motor functions are restored.

III. EXPERIMENT
The purpose of the experiment was to evaluate the functionality of the proposed system, control strategy and training protocols. It was not a clinical or medical practice to evaluate the biological response of patients, therefore, only healthy subjects were recruited. All experimental procedures were approved by the University of Auckland Human Participants Ethics Committee (reference 015256).

A. SUBJECTS
Ten healthy subjects (mean age: 27.9±1.1 years, height: 178.6±5.4 cm, weight: 73.9±10.6 kg, arm's length: 89.0±3.1 cm) were recruited in this research, with all having no known nervous system diseases or upper-limb disorders. The demographics of the subjects are listed in Table 3.

TABLE 3. The demographics of the subjects.

Subjects	Gender	Age	Height (cm)	Weight (kg)	Arm's length (cm)
1	Male	26	168	58	83.5
2	Male	26	180	85	91.1
3	Male	27	182	72	90.3
4	Male	28	175	70	86.3
5	Male	28	181	83	90.1
6	Male	28	176	67	87.8
7	Male	29	183	69	91.6
8	Male	29	183	90	92.0
9	Male	29	186	85	92.8
10	Male	29	172	60	84.7
Mean		27.9	178.6	73.9	89.0
SD		1.1	5.4	10.6	3.1

B. EXPERIMENTAL PROTOCOL
Before the experiment, all subjects gave their written informed consent, and their demographic information was collected. A brief demonstration of the system and an instruction on how to terminate the system were given to them as well. They were invited to sit on a height-adjustable chair in front of the bilateral system where they could grasp the handlebars of the robots to perform exercises (Fig. 2 (b)). Four different exercises were used in the experiment: shoulder flexion/extension, shoulder adduction/abduction, self-mimic and self-cooperative exercises. The first two

exercises are commonly used physiotherapy exercises based on a guide from the National Stroke Association [47], which were used for the bilateral passive and active training protocols. The last two exercises were developed based on the concept of self-training, which were used for the bilateral-self training protocol.

The detailed experimental procedure can be seen in Fig. 6. Specifically, for protocol 1 (passive training) and protocol 2 (active training), subjects performed the shoulder flexion/extension exercise 4 times, with an angle range of [-60º to +60º] at a speed of 10º/s (Fig. 6(b)), and the shoulder adduction/abduction exercise 4 times with an angle range of [0º to +60º] at the same speed as the first exercise (Fig. 6(c)). For protocol 3 (self-training), subjects were asked to stand in front of the proposed system to allow the generation of greater forces upon the robots. During the self-mimic exercise, subjects moved the robots (without reference trajectory) to draw a square-shaped trajectory 5 times, with the trajectories of the master and slave robots being the same (Fig. 6(d)). During the self-cooperative exercise, the protocol was the same as the self-mimic exercise protocol, but the trajectories of the master and slave robot were reversed in the Y-direction (Fig. 6(e), other directions are the same). Meanwhile, throughout the experiment, 3-minute breaks and 5-minute breaks were given after each exercise and protocol respectively to avoid muscle fatigue. The training time of all exercises would take approximately 40 minutes for each subject, excluding acclimation phases. It should be noted that in the protocol 1, subjects were asked not to exhibit forces upon the robots, whereas in the protocol 2, subjects were asked to exhibit a comfortable amount of force upon the robots. In addition to this, the reasoning behind the development of the bilateral-self training protocol is that we wanted to mimic some ADLs based on the proposed system and the control strategy, which could be addressed through incorporating virtual reality (VR) games in the future [48]: for self-mimic exercises (the same motion of hands and arms), VR games could include 'wash face' or 'wear pants'; for self-cooperative exercises (the cooperative motion of hands and arms), VR games could include 'pick up a basketball and shoot' or 'pick up watermelon and eat'. Kate et al. [49] reported that VR games might be beneficial in improving the functions of upper limbs and ADLs after reviewing 37 trials with 1019 participants. Normally, VR game-based trials will ask subjects to finish tasks without reference trajectories. For example, Dario et al. [50] designed VR game-based arm reaching movements in which subjects were asked to reach targets by themselves with the help of verbal prompts. In other words, no reference trajectory was provided to subjects during movement. However, as a pilot study, the functionality of the proposed protocols will be tested, and further analyses on their safety and reliability, along with the collaboration with VR games, are planned for future studies.

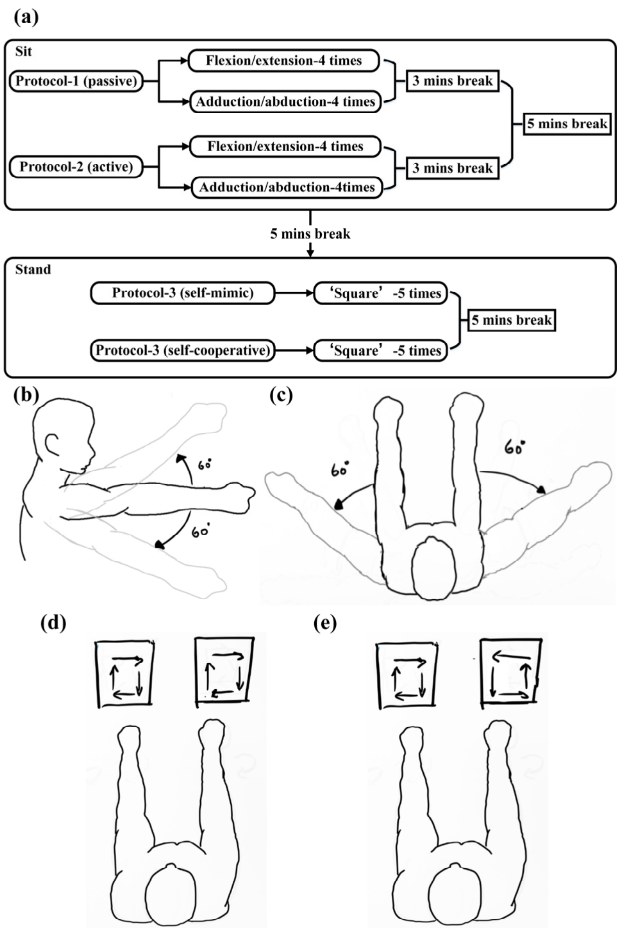

FIGURE 6. The detailed experimental procedure. (a) Flow diagram of the experimental protocol. (b) Shoulder flexion/extension exercise. (c) Shoulder adduction/abduction exercise. (d) Bilateral self-mimic exercise. (e) Bilateral self-cooperative exercise.

C. STATISTICAL ANALYSIS

Experimental data are analysed in three aspects: master trajectory tracking error (master error for short), master-slave trajectory tracking error (master-slave error for short), and trajectory deviation. Specifically, the master error is computed by comparing the desired trajectory and the measured trajectory of the master robot, which can show the performance of the robot. Master-slave error is computed by comparing the measured trajectories of the master and slave robots. The reason for using the master-slave error is that the commonly used method in bilateral exercises is to ensure the slave robot follows the master robot at all times. Trajectory deviation is computed by comparing the reference trajectory and measured trajectory of the master robot, which can reflect the level of voluntary involvement of subjects. It should be noted that there is no trajectory deviation in the bilateral-self training protocol since there is no reference trajectory in that protocol. Root mean square (RMS) and maximum absolute value are used as the statistical methods to analyse these three evaluation criteria. Pearson's correlation coefficient [51] has also been used to explore the correlations between the master error, the master-slave error, and the trajectory deviation in the active training protocol. The significance was set at $p \leq 0.05$.

IV. RESULTS

The results are presented according to the bilateral training protocols: 1) the bilateral-passive training protocol, 2) the bilateral-active training protocol, and 3) the bilateral-self training protocol.

A. BILATERAL-PASSIVE TRAINING PROTOCOL

In the bilateral-passive training protocol, subjects were asked not to exhibit forces upon the robots during both the flexion/extension and adduction/abduction exercises. The experimental results are presented in Fig. 7 and Tables 4 and 5. The performance of the proposed system is satisfactory in both exercises. As shown in Fig. 7, the reference trajectory, the desired trajectory, the measured master robot and slave robot trajectories are almost all the same in both exercises. Statistical results are summarized in Tables 4 and 5. For the flexion/extension exercise (Table 4), the mean RMS values for the master error and master-slave error are 0.35 mm and 0.49 mm respectively, and the mean max absolute values for the master error and master-slave error are 2.06 mm and 2.31 mm respectively. Meanwhile, the level of voluntary involvement of each subject can be reflected by the trajectory deviation. Due to no interaction forces exhibited by subjects in this training protocol, the values of subjects' trajectory deviations are small. The mean RMS value and mean max absolute value of the trajectory deviation are 1.12 mm and 2.35 mm, respectively. A similar result can be found in the adduction/abduction exercise (Table 5): the mean RMS values for the master error, master-slave error, and trajectory deviation are 0.34 mm, 0.63 mm and 0.90 mm, respectively. The mean max absolute values for the master error, master-slave error, and trajectory deviation are 2.37 mm, 3.10 mm and 2.53 mm, respectively. It should be noted that Fig. 7 is drawn based on the mean values of all subjects' trajectories.

TABLE 4. Quantitative comparisons of the flexion/extension exercise in the bilateral-passive training protocol.

Subject	RMS value/mm			Max absolute value/mm		
	Master	M-S[a]	D[b]	Master	M-S[a]	D[b]
S1	0.36	0.52	1.27	1.82	2.25	2.16
S2	0.38	0.54	1.33	2.17	2.25	2.62
S3	0.34	0.52	0.99	1.95	2.51	2.62
S4	0.39	0.52	1.22	2.15	2.63	2.53
S5	0.41	0.52	1.11	2.21	2.24	2.34
S6	0.35	0.48	1.14	2.06	2.25	2.51
S7	0.28	0.38	0.88	1.82	2.00	2.00
S8	0.36	0.49	1.24	2.12	2.15	2.11
S9	0.33	0.49	1.02	1.90	2.42	2.07
S10	0.32	0.46	0.97	2.35	2.35	2.58
Mean ±SD	0.35 ±0.04	0.49 ±0.04	1.12 ±0.14	2.06 ±0.17	2.31 ±0.17	2.35 ±0.23

M-S[a] means tracking error between the master and slave robots, D[b] means trajectory deviation.

TABLE 5. Quantitative comparisons of the adduction/abduction exercise in the bilateral-passive training protocol.

Subject	RMS value/mm			Max absolute value/mm		
	Master	M-S[a]	D[b]	Master	M-S[a]	D[b]
S1	0.30	0.59	0.87	1.32	2.78	2.12
S2	0.41	0.60	0.94	3.26	2.78	2.97
S3	0.32	0.60	0.87	2.97	3.01	2.69
S4	0.28	0.74	0.88	1.17	3.67	2.10
S5	0.37	0.55	0.93	3.04	2.73	2.82
S6	0.31	0.60	0.83	1.41	2.78	2.20
S7	0.36	0.74	0.88	2.85	3.75	2.75
S8	0.36	0.65	0.96	1.95	3.41	2.44
S9	0.41	0.60	0.97	3.84	3.05	3.03
S10	0.31	0.60	0.90	1.86	3.07	2.17
Mean ±SD	0.34 ±0.04	0.63 ±0.06	0.90 ±0.04	2.37 ±0.89	3.10 ±0.36	2.53 ±0.35

M-S[a] means tracking error between the master and slave robots, D[b] means trajectory deviation.

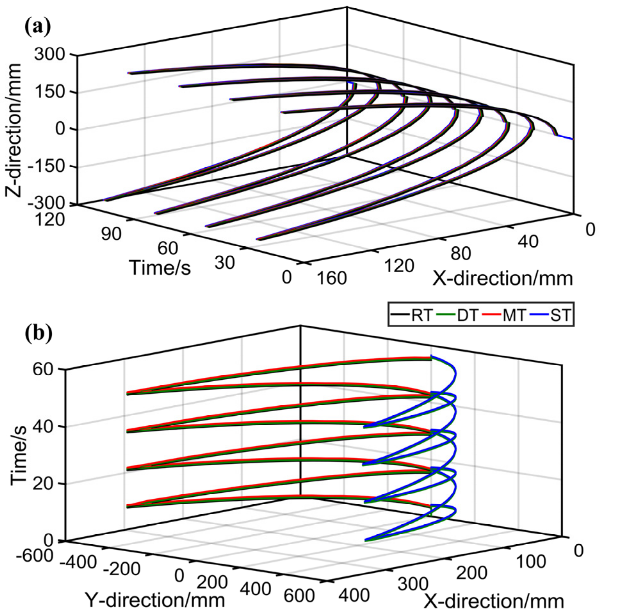

FIGURE 7. Results of the bilateral-passive training protocol. (a) Results of the flexion/extension exercise. (b) Results of the adduction/abduction exercise.

B. BILATERAL-ACTIVE TRAINING PROTOCOL

For the bilateral-active training protocol, subjects were asked to exhibit forces upon the robots during both the flexion/extension and adduction/abduction exercises. The results of these two exercises are shown in Figs. 8 and 9, respectively. The planar results are also given for clarity (Figs 8b, 8c, 9b and 9c). Statistical results are summarized in Tables 6 and 7. From Fig. 8, we can see that the desired trajectory (green line) is adjusted according to the interaction forces of the subject. For example, during the period of the 40th and 50th seconds, the subject interaction forces in +Z-direction, the desired trajectory was then adjusted along the corresponding direction (+Z). A similar situation can be found during the period of the 70th to 75th seconds. Meanwhile, the performance of the proposed system is satisfactory in this exercise (Table 6): the mean RMS values for the master error and master-slave error are 0.90 mm and 1.15 mm, respectively. The mean max absolute values for the master error and master-slave error are 5.47 mm and 6.70 mm, respectively. Accordingly, due to the interaction forces exhibited by subjects, the values of trajectory deviations are increased a lot. The mean RMS value and mean max absolute value of the trajectory deviation are 8.94 mm and 43.13 mm, respectively. On the other hand, for the adduction/abduction exercise, a similar result can be found in Fig. 9, in which the desired trajectory can be adjusted in real time based on the interaction forces. The performance of the proposed system is also encouraging (Table 7): the mean RMS values of the master error and master-slave error are less than 1.05 mm, and the mean max absolute values of the master error and master-slave error are less than 6.73 mm. Meanwhile, the mean RMS value and mean max absolute value of the trajectory deviation are 9.39 mm and 46.93 mm, respectively. It should be noted that the presented trajectories are not the mean values of all subjects' trajectories since different subjects have different trajectories. Figs. 8 and 9 are the results of subject 7, which are neither the best nor the worst.

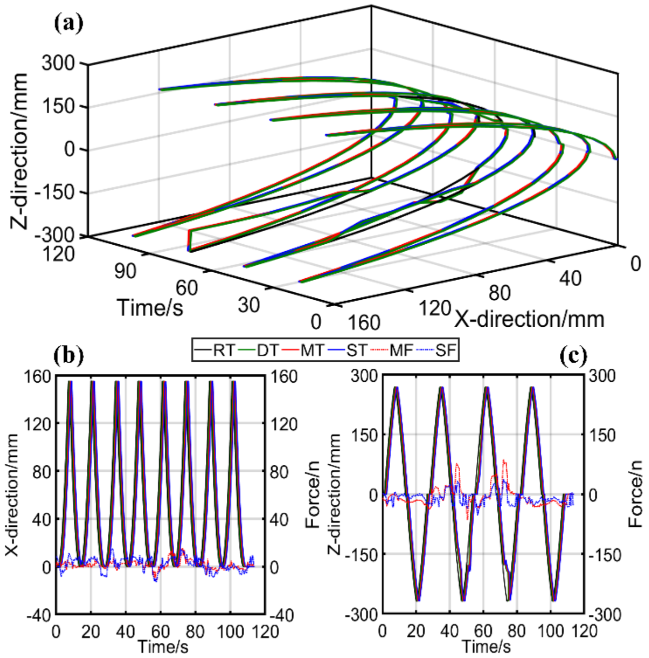

FIGURE 8. **Results of the bilateral-active training protocol during the flexion/extension exercise. (a) Results of the flexion/extension exercise. (b) Results of the flexion/extension exercise in the X-direction. (c) Results of the flexion/extension exercise in the Z-direction.**

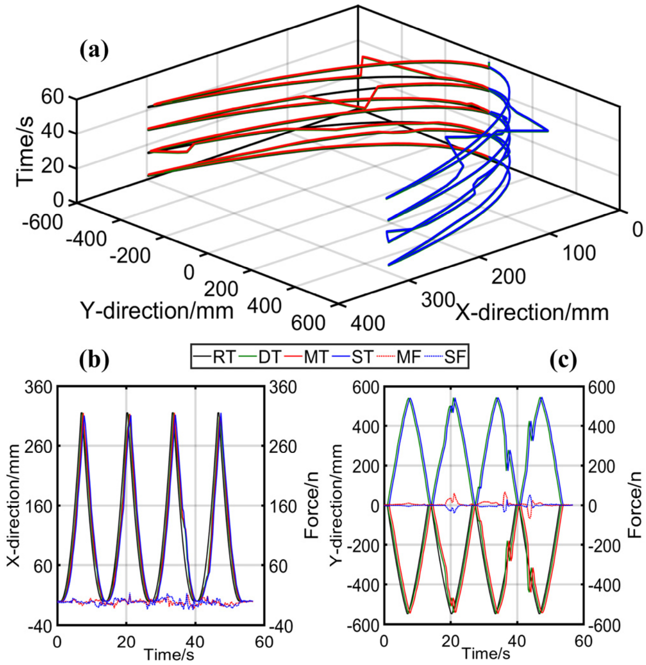

FIGURE 9. **Results of the bilateral-active training protocol during the adduction/abduction exercise. (a) Results of the adduction/abduction exercise. (b) Results of the adduction/abduction exercise in the X-direction. (c) Results of the adduction/abduction exercise in the Y-direction.**

TABLE 6. Quantitative comparisons of the flexion/extension exercise in the bilateral-active training protocol.

Subject	RMS value/mm			Max absolute value/mm		
	Master	M-S[a]	D[b]	Master	M-S[a]	D[b]
S1	1.46	1.92	10.97	7.58	10.04	53.67
S2	1.30	1.60	10.33	7.66	8.77	52.51
S3	1.26	1.71	10.65	7.66	9.73	54.09
S4	0.74	0.99	8.49	4.08	5.33	35.97
S5	0.21	0.47	7.30	1.99	2.60	25.96
S6	1.69	1.97	11.94	10.65	11.95	70.17
S7	0.70	0.78	8.35	4.72	4.91	42.16
S8	0.38	0.49	6.38	3.12	2.80	25.73
S9	0.89	1.16	8.19	5.09	7.15	39.33
S10	0.36	0.39	6.82	2.13	3.69	31.73
Mean	0.90	1.15	8.94	5.47	6.70	43.13
±SD	±0.48	±0.58	±1.81	±2.69	±3.14	±13.58

M-S[a] means tracking error between the master and slave robots, D[b] means trajectory deviation.

TABLE 7. Quantitative comparisons of the adduction/abduction exercise in the bilateral-active training protocol.

Subject	RMS value/mm			Max absolute value/mm		
	Master	M-S[a]	D[b]	Master	M-S[a]	D[b]
S1	0.70	0.74	8.14	3.68	3.83	36.14
S2	1.32	1.27	10.19	7.45	7.71	54.14
S3	0.33	0.33	6.87	1.90	2.15	24.85
S4	1.26	1.60	11.17	9.24	9.87	62.23
S5	1.36	1.22	11.65	7.03	7.30	52.77
S6	1.41	1.40	10.93	8.01	8.87	56.53
S7	1.03	1.04	9.25	7.25	7.63	52.76
S8	0.62	0.63	8.31	3.54	4.20	33.67
S9	0.87	1.07	8.41	5.35	6.88	40.64
S10	1.05	1.24	8.94	7.66	8.83	55.52
Mean	1.00	1.05	9.39	6.11	6.73	46.93
±SD	±0.34	±0.36	±1.47	±2.25	±2.38	±11.57

M-S[a] means tracking error between the master and slave robots, D[b] means trajectory deviation.

C. BILATERAL-SELF TRAINING PROTOCOL

For the bilateral-self training protocol, subjects were asked to perform exercises without the reference trajectory. The results of the self-mimic and self-cooperative exercises are shown in Fig. 10, and the statistical results are summarized in Table 8. As shown in Fig. 10, the square-shaped trajectory can be drawn by the subject in both exercises via his own forces, and the smoothness of the trajectories are acceptable, especially that of the trajectories of the self-cooperative exercise (Fig. 10b). The performance of the proposed system is also encouraging: for the self-mimic exercise, the mean RMS values for the master error and master-slave error are no greater than 0.87 mm, and the mean max absolute values are no greater than 5.18 mm; for the self-cooperative exercise, the mean RMS values are less than 1.00 mm, and the mean max absolute values are less than 5.66 mm. As mentioned above, there is no trajectory deviation in this training protocol due to the lack of the reference trajectory. The presented trajectories (Fig. 10) are the results of subject 5, which are neither the best nor the worst.

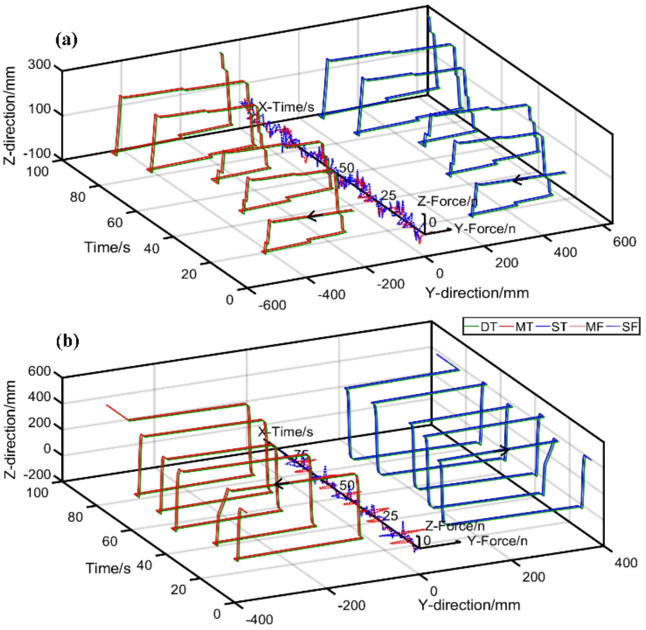

FIGURE 10. Results of the bilateral-self training protocol. (a) Results of the bilateral-self-mimic exercise. (b) Results of the bilateral-self-cooperative exercise.

TABLE 8. Quantitative comparisons of the bilateral-self training protocol.

Index	Subject	Self-Mimic		Self-Cooperative	
		Master	M-S[a]	Master	M-S[a]
RMS value /mm	S1	1.30	1.51	1.33	1.53
	S2	0.46	0.50	1.15	1.48
	S3	1.17	1.38	0.35	0.44
	S4	0.67	0.75	0.81	0.92
	S5	0.68	0.86	1.29	1.53
	S6	0.45	0.62	1.03	1.25
	S7	0.49	0.61	0.36	0.56
	S8	0.30	0.37	1.04	1.18
	S9	1.15	1.59	0.40	0.59
	S10	0.51	0.55	0.33	0.56
	Mean	0.72	0.87	0.81	1.00
	±SD	±0.34	±0.43	±0.39	±0.42
Max abs. value /mm	S1	6.54	7.21	7.16	8.00
	S2	3.01	3.36	7.88	8.35
	S3	7.08	7.99	2.37	2.77
	S4	4.11	4.52	4.70	5.02
	S5	4.25	4.72	8.15	8.81
	S6	3.22	3.82	6.36	6.74
	S7	3.58	3.85	2.97	3.70
	S8	2.08	2.96	6.45	6.74
	S9	8.27	9.33	2.98	3.50
	S10	3.77	4.03	2.48	3.01
	Mean	4.59	5.18	5.15	5.66
	±SD	±1.90	±2.08	±2.19	±2.22

M-S[a] means tracking error between the master and slave robots.

V. DISCUSSION

In this research, a bilateral rehabilitation system based on two modern industrial robots is proposed. A 'patient-cooperative' control strategy is also realised based on an adaptive admittance controller. An experiment with 10 healthy subjects was therefore conducted based on three bilateral training protocols to evaluate the functionality of the proposed system. To the authors' knowledge, two industrial robots used simultaneously in a bilateral rehabilitation system has not yet been reported in the literature. The implementation of the 'patient-cooperative' control strategy in an industrial robot-based bilateral rehabilitation system may also be the first of its kind.

A. THE BILATERAL REHABILITATION SYSTEM

Recently, with the development of technology, some modern, low-cost industrial robots have been used for rehabilitation purposes. Tóth et al. [15] proposed the REHAROB Therapeutic System, which consisted of two synchronized robotic arms (IRB 140 and 1400H from Asea Brown Boveri Ltd, Zurich, Switzerland). However, this system was only designed for single-arm use, making it unideal for bilateral exercises. Lum et al. [19] proposed the MIME system, which consisted of one self-made device and one robotic arm (PUMA 560 robot, Unimation Inc, Danbury, USA). However, the arrangement of the master and slave robots were fixed, and so the master and slave sides could not be swapped. In this research, we propose a bilateral rehabilitation system based on two off-the-shelf industrial robots. Both utilized robots come from the 'Universal Robot' lineup, which are designed to mimic the motion of the upper limbs and can be easily controlled through their built-in robotic language. Compared to existing industrial robot-based systems, the advantages of the proposed system can be concluded as follows. Firstly, the utilized UR robots can provide sufficient DoFs with high precision (+/- 0.1mm) [28], which is the foundation of precise bilateral exercises. Secondly, the utilized six-axis force sensors can measure real-time data from subjects, making the 'patient-cooperative' control strategy possible. Thirdly, the cost of the system is low (Table 9), but it can support most ADLs in a continuous 3D workspace. Fourthly, the master and slave sides of the system can be swapped, which may be more suitable for practical applications. The statistical results summarized in Tables 4 to 8 suggest that 3D bilateral exercises can be performed reliably based on the proposed system, and the low-level inner-loop controls (e.g. position control, velocity control) completed by the UR robots themselves can provide a stable operating environment for implementing the proposed 'patient-cooperative' control strategy. It should be noted that the effectiveness of the proposed high-level admittance control can be directly influenced by the low-level inner-loop controls. The largest errors out of all exercises occurred in the active training protocol, with the mean RMS value and the mean max absolute value of the master error being 1.00 mm and 6.11 mm, respectively. It means that the UR robots (industrial robot) can be successfully used for 3D bilateral exercises. Meanwhile, the mean RMS value and the mean max absolute value of the master-slave error are 1.15 mm and 6.73 mm, respectively. It means that the slave robot closely follows the master robot at all times, and therefore 3D bilateral exercises can be performed precisely. These errors are very small when compared to the whole trajectory (e.g. 565 mm for the flexion/extension exercise). One interesting finding is that the master error and master-slave error in the active training protocol are greater than those in other training protocols. The possible reason for this finding could be that in the active training protocol, the desired trajectory was changing drastically. In other words, during the passive training protocol, the desired trajectory was almost the same as the reference trajectory (changed slightly), and during the self-training protocol, the desired trajectory was created by the trajectory change (no reference trajectory has to be followed). It should be noted that the measured decoupled loads can be treated as pure interaction forces between subjects and robots, which has been proven in our previous research [52]. Other forces such as inertia and friction forces are considered negligible due to the lightweight of the handlebar (around 0.2kg) and the slow speed of the movements (10º/s). The weight of the force sensors, the handlebars, and the subjects' hands and wrists are also compensated for at the beginning of each exercise.

TABLE 9. The cost of industrial robot-based rehabilitation devices [14, 53].

Device	Manufacturer	Degree of Freedom	Cost (USD)
InMotion 2 (MIT-MANUS)	Interactive Motion Technologies, Inc.	2 DoFs	>50,000
InMotion 3	Interactive Motion Technologies, Inc.	5 DoFs	>50,000
HapticMASTER	Moog FCS Robotics, Inc.	3 DoFs	>50,000
WAM™	Barrett Technology, Inc.	3 DoFs	>50,000
REHAROB	ABB, Inc.	2*6 DoFs	308,000
IRBRS (current device)	Universal Robot, Inc.	2*6 DoFs	43,000

Include both unilateral and bilateral rehabilitation devices.

B. THE 'PATIENT-COOPERATIVE' CONTROL STRATEGY

The 'patient-cooperative' control strategy is implemented in this research based on the adaptive admittance controller, which is supposed to take into account patients' voluntary efforts. The same control strategy with similar controllers has been tested by many researchers. Riener et al. [25] firstly proposed the 'patient-cooperative' control strategy to enhance the degree of subjects' involvement during robot-aided treadmill training. Trlep et al. [26] then used this control strategy to provide coordinated training protocols for bimanual exercises. Zhang et al. [27] latterly used this control strategy to enhance training safety for an ankle rehabilitation robot. In fact, the control proposals of Riener and Zhang are the same. Large interaction forces are treated as patients' voluntary efforts which are represented via the modified desired trajectory. Small interaction forces are treated as excessive interaction forces (may be created by the patients' limited workspace), which urge the desired trajectory to be modified to prevent secondary injuries of patients and therefore enhancing training safety. Compared to the existing approaches, the innovation of this research could be concluded as the first attempt to implement the 'patient-cooperative' control strategy in industrial robots for bilateral rehabilitation training. The functionality of the implemented control strategy and three different bilateral training protocols have been tested with 10 healthy subjects. The satisfactory results have been represented in Figs 7 to 10, showing that the desired trajectories can be created by the voluntary efforts of subjects. For example, it is shown in Fig. 8c that the recalculated desired trajectory deviates from the reference trajectory towards the +Z-direction when the master and slave forces are in the positive direction for 40-50 seconds. The robots deviate and move toward the negative Z-direction for 55-58 seconds when negative master and slave forces are applied. In addition, the criterion of the trajectory deviation has been proposed to reflect the level of voluntary involvement of subjects. It can be concluded that the values of trajectory deviation in the active training protocol are much greater than those in the passive training protocol, which indicates that the subjects put more efforts into the active training protocol. It can also be concluded from Table 6 or Table 7 that the greater trajectory deviation is accompanied by the increased master error and master-slave error. The correlation analysis also confirms this finding that there are very strong correlations between the trajectory deviation and the master error, and between the trajectory deviation and the master-slave error. The r values (Table 10, Pearson's correlation coefficient) in the active training protocol are all greater than 0.87, which are belong to the very strong grade (0.80 to 1.00). The possible reason could be the same as the discussion for the performance of the active training protocol: the desired trajectory would be changed drastically with the increase of the trajectory deviation, which further increases the master error and the master-slave error. However, these errors are still very small when compared to the whole trajectory. In summary, all experimental results indicate that the 'patient-cooperative' control strategy can be successfully implemented in the proposed bilateral rehabilitation system, and the level of voluntary involvement of subjects can be successfully reflected by the trajectory deviation.

TABLE 10. Pearson's correlation coefficients for the active training protocol.

Criteria	Flexion/Extension			Adduction/Abduction		
	Master	M-S[a]	D[b]	Master	M-S[a]	D[b]
Master	1.00	0.99	0.97	1.00	0.93	0.94
M-S[a]	0.99	1.00	0.97	0.93	1.00	0.87
D[b]	0.97	0.97	1.00	0.94	0.87	1.00

M-S[a] means tracking error between the master and slave robots, D[b] means trajectory deviation, r value: very weak-0.00-0.19, weak-0.20-0.39, moderate-0.40-0.59, strong-0.60-0.79, and very strong-0.80-1.00 [51], the significance level is 0.05.

C. LIMITATION AND FUTURE WORK

As a pilot study, the limitations are that only healthy subjects were recruited to do the experiment, and only three evaluation criteria have been used to evaluate the proposed system, control strategy and training protocols. Future work could be done to address these limitations in three aspects: 1) testing the system, control strategy and training protocols with healthy subjects of different genders, race, age and degrees of healthiness and stroke survivors against different evaluation criteria; 2) utilizing other control strategies (e.g. the deterministic algorithm, the iterative feedback tuning algorithm); and 3) developing VR games to collaborate the proposed training protocols. As introduced above, the proposed bilateral training protocols could be incorporated with VR games, especially the bilateral-self training protocol. VR games could be ADLs-based tasks that require the bilateral cooperation of two hands/arms, such as 'wash face' or 'pick up watermelon and eat'. In addition, kinematic measures can also be used to do the quantitative assessment of different subjects (healthy persons or stroke survivors) such as 'inter-joint correlation' and 'joint range of motion'. These kinematic results can provide deep information about the bilateral recovery process.

VI. CONCLUSION

This research proposes a bilateral upper-limb rehabilitation system based on two modern industrial robots. The 'patient-cooperative' control strategy is realised based on an adaptive admittance controller. Three bilateral training protocols are then proposed based on the system and control strategy. Preliminary results with 10 healthy subjects show that different bilateral exercises can be successfully performed based on the proposed bilateral rehabilitation system: the mean RMS values and mean max absolute values of the master error are all no greater than 1.00 mm and 6.11 mm respectively; the mean RMS values and mean max absolute values of the master-slave error are all less than 1.15 mm and 6.73 mm respectively. The experimental results also support that the proposed 'patient-cooperative' control strategy has the ability to represent the voluntary efforts of subjects via the recalculated desired trajectory, and the level of voluntary involvement of subjects in training can be successfully reflected by the trajectory deviation. Overall, the proposed bilateral system could be a potential platform for clinical practices, which can provide a reliable bilateral training environment. The next step is to develop VR games for the proposed bilateral training protocols, which would be evaluated further by kinematic measures.

ACKNOWLEDGMENT

The authors would like to thank Lynette Lulich, Yi Lin Huang and Hui Jun Wang for the technical support, and Oscar Moosman, Sabina Nanna Yang and Yujiao Qiao for the manuscript proofreading.

ETHICAL APPROVAL

The ethical approval has been approved by the University of Auckland Human Participants Ethics Committee (reference 015256).

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