A Home-based Tele-rehabilitation System With Enhanced Therapist-patient Remote Interaction: A Feasibility Study

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***Abstract*—As a promising alternative to hospital-based manual therapy, robot-assisted tele-rehabilitation therapy has shown significant benefits in reducing the therapist's workload and accelerating the patient's recovery process. However, existing telerobotic systems for rehabilitation face barriers to implementing appropriate therapy treatment due to the lack of effective therapist-patient interactive capabilities. In this paper, we develop a home-based tele-rehabilitation system that implements two alternative training methods, including a haptic-enabled guided training that allows the therapist to adjust the intensity of therapeutic movements provided by the rehabilitation device and a surface electromyography (sEMG)-based supervised training that explores remote assessment of the patient's kinesthetic awareness. Preliminary experiments were conducted to demonstrate the feasibility of the proposed alternative training methods and evaluate the functionality of the developed tele-rehabilitation system. Results showed that the proposed tele-rehabilitation system enabled therapist-in-the-loop to dynamically adjust the rehabilitation intensity and provided more interactivity in therapist-patient remote interaction.**

***Index Terms*—Home-based rehabilitation, telerobotics and teleoperation, alternative training modes, therapist-patient remote interaction.**

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I. Introduction

According to a report from the United Nations, the global aging population aged 65 and over is expected to double from 703 million to 1.5 billion by 2050 [1]. Along with this growth comes an increasing incidence of age-related diseases including stroke [2]. Currently, there are already over 50 million stroke survivors worldwide, and it is anticipated that over 13 million people will suffer a stroke each year [3]. This situation creates a rapidly growing demand for stroke rehabilitation.

However, conventional rehabilitation therapy still remains focused on the in-hospital phase, with its emphasis on manual therapy by physical therapists. Owing to the shortage of skilled therapists and healthcare resources, a number of stroke survivors have expressed concern about the lack of available long-term support and ongoing unmet rehabilitation needs [4]. In addition to the limited healthcare resources, it is also a laborious and time-consuming process for stroke patients with affected limbs to move from home to rehabilitation centers or hospitals. Notably, due to containment efforts for the COVID-19 pandemic including social distancing and isolation, they are faced with more significant difficulties and risks in visiting the rehabilitation facilities for regular rehabilitation sessions [5]. All of these problems place a heavy burden on the healthcare system and result in delayed and insufficient rehabilitation.

In order to improve the efficiency of treatment and increase accessibility to rehabilitation, rehabilitation robots have been deployed in restorative therapy [6], [7]. Compared with the conventional manual therapy that requires laborious work from therapists, rehabilitation robots are programmable to deliver repetitive and intensive training to stroke patients. As a result, the use of robotics in rehabilitation therapy has potential benefits in reducing the therapist's workload as well as accelerating the patient's recovery process [8]. In addition, the embedded sensors in robotic systems also enrich the therapist's toolbox to promote a quantitative evaluation of recovery based on the collected physical and biomedical signals from the patient [9]. Related studies have shown that robot-assisted rehabilitation promotes positive outcomes for stroke patients in the recovery process [10], [11].

Despite the fact that the use of robotics offers numerous significant advantages, some studies indicate that in certain cases, robot-assisted therapy may be less effective than conventional manual therapy owing to the lack of flexibility in interacting with patients [12], [13]. Considerable research has focused on implementing adaptive and intention-based control strategies to improve human-robot interaction [14], [15]. Lenzi *et al.* presented an intention-based control for a powered elbow exoskeleton NEUROExos [16]. By proportionally scaling the patient's surface electromyography (sEMG) signals without specific calculation, this method only provides a rough estimation of the required torque assistance. To provide assistance as needed, Chen *et al.* implemented an adaptive torque control on a cable-driven elbow exoskeleton CAREX [17].

Although these methods provided some flexibility and improved the performance of robotic systems, they cannot completely replace the role of a therapist who has practical experience and skills in the treatment. Most notably, it is difficult or even impossible to enable a robotic system to behave as well as a human therapist in the aspect of interaction with patients. For instance, a therapist is able to identify the patient's needs and feelings by oral communication and hands-on interaction, thereby delivering appropriate treatment to the patient.

It is believed that the therapist plays an irreplaceable role in adjusting rehabilitation treatment to meet a particular need for each individual patient, while the use of robotics has the potential to augment the therapist's capabilities and facilitate the process of recovery assessment. Aiming to fuse the therapist's guidance and supervision into the robot-assisted rehabilitation process, we develop a home-based therapist-in-the-loop tele-rehabilitation system in this paper, by which the therapist is capable of providing adjustable therapeutic movements to the patient and enhancing the remote interaction with the patient.

The rest of this paper is organized as follows: in Section II, we highlight the novelty and innovation of the proposed system by comparing its characteristics with those of existing tele-rehabilitation systems. Section III is the elaboration of the hardware/software components and control methods of the proposed system. The experimental protocols and obtained results are presented in Section IV. Furthermore, the promising prospects as well as potential concerns regarding the use of tele-rehabilitation systems are discussed in Section V. Finally, conclusions are drawn in Section VI.

II. Related Work

As a promising alternative to in-hospital manual therapy, home-based tele-rehabilitation with the use of robotic systems has attracted a great deal of interest in the past decade [18]. Currently, the research related to tele-rehabilitation can be divided into two main topics: 1) online rehabilitation consultation services based on telecommunication networks and 2) remote implementation of rehabilitation therapy by telerobotic systems. The former mainly includes Internet-based videoconferencing systems [19] and web-based monitoring interfaces [20] for remote consultation and supervision. Although these systems have recently made great progress in "telepresence", many stroke patients still express their needs to receive therapeutic movement training in their own homes. Nevertheless, it is far beyond what a general videoconferencing and monitoring system can provide.

In order to improve accessibility to physical rehabilitation therapy, various telerobotic systems have been developed to implement remote treatment. Brennan *et al.* designed a telerehabilitation-enabled automated platform teleAutoCITE that uses a rehabilitation device to help patients perform constraint-induced movement therapy in their homes with the therapist's remote monitoring [21]. However, the therapist has no way to intervene in the device-generated therapy tasks. To enable therapist-in-the-loop treatment, Zhang *et al.* developed a tele-rehabilitation system that uses a haptic device to remotely control the elbow movements of an exoskeleton worn by the patient [22]. In order to adapt to different rehabilitation tasks, the therapist can either choose to provide assistance or resistance treatment, whereas the amount of assistance applied to the user's elbow joint is fixed. For the purpose of providing more interactivity in tele-rehabilitation, some virtual reality (VR)-based methods have also been integrated into the robotic systems [23], [24]. Atashzar *et al.* presented a computational model to adjust the viscoelastic coupling in the virtual environment to produce variable therapeutic assistances [25]. Nevertheless, the software-generated viscoelastic coupling is achieved by a closed-loop interaction control at a limited bandwidth and depends on the feedback from the sensors.

Despite the efforts to promote remote interaction, the key challenge in tele-rehabilitation systems still remains: how to enable a therapist to *directly* adjust the intensity of therapeutic movements provided by the rehabilitation device and *remotely* assess the patient's kinesthetic awareness (e.g., assessment of muscle force) that is typically achieved through hands-on interaction. To address these issues, two alternative training methods are implemented in the proposed tele-rehabilitation system, including a haptic-enabled guided training that allows a therapist to dynamically adjust the robot-assisted therapeutic movements and an sEMG-based supervised training that explores remote assessment of the patient's kinesthetic awareness.

III. Methods

In this section, we elaborate on the development of the proposed tele-rehabilitation system, including components of the hardware and software, employment of a stabilizer, control loop of the alternative modes, and design of teleoperation interfaces.

A. Overview of the Developed Tele-rehabilitation System

As shown in Fig. 1, the proposed tele-rehabilitation system mainly consists of two parts: a master side for therapists and a slave side for patients. On the master side, a 6-DoF haptic device (HD^2 [26], Quanser Inc., Canada) is employed for the therapist's manipulation. The HD^2 is an advanced teleoperation platform that can provide a high-fidelity haptic interface for the manipulator to interact with remote environments by programmable haptic feedback. Six DC motors with high-resolution optical encoders are equipped to allow for dexterous haptic interaction. For motor control and data acquisition, a high-performance Hardware-in-the-Loop control board (Q8-USB [27], Quanser Inc., Canada) is placed inside the server PC and connected with the HD^2 using the SCSI cable. On the slave side, we developed a powered variable-stiffness exoskeleton device

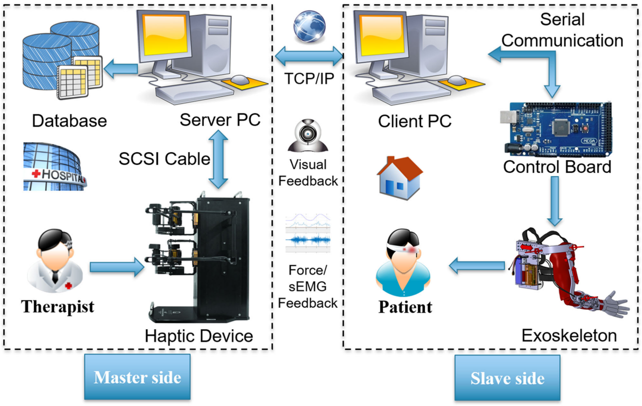


Fig. 1. Schematic diagram of the proposed tele-rehabilitation system. The therapist on the master side operates a haptic device to provide therapeutic movement, while the patient on the slave side performs home-based rehabilitation movements with the assistance of the designed exoskeleton. The proposed system also provides the functions of multimodal feedback and data logging to facilitate the therapist-patient remote interaction.

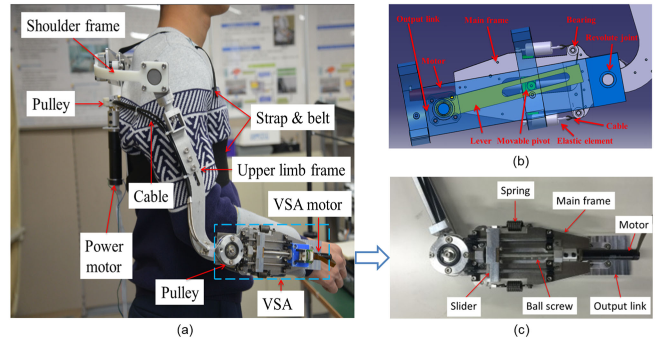


Fig. 2. The PVSED with an intergated VSA. (a) Physical prototype of the PVSED. (b) CAD details of the VSA (Back View). (c) Physical prototype of the VSA (Front View).

(PVSED) for home-based upper limb rehabilitation [28]. The PVSED is a wearable rehabilitation device to assist patients with affected upper limbs in implementing therapeutic elbow movements.

Regarding the software components, the control panels for teleoperation are designed using the LabVIEW graphical development environment (National Instruments Corp., U.S.A). In order to be enabled to interface with the hardware system (the HD^2 and PVSED), the Rapid Control Prototyping Toolkit (RCP [29], Quanser Inc., Canada) is added to the LabVIEW software. Additionally, the data transfer between master and slave sides is performed using a Transmission Control Protocol/Internet Protocol (TCP/IP)-based communication module provided in the RCP, which enables multi-channel data sending and receiving with the property of minimum time latency. For control of the exoskeleton, the client PC receives the control signals from the master side and sends them to the embedded microcontroller board (Arduino Mega 2560, Arduino.cc, Italy) on the PVSED by serial communication [30].

In tele-rehabilitation applications, the capability to interact with the patient needs to be particularly emphasized. For providing more interactivity, the proposed system includes the functions of multimodal feedback and real-time data visualization. The patient's physical and biological parameters (elbow joint angle, contact force, sEMG signals, etc.) are simultaneously transferred to the server PC and graphically displayed on the TV monitor. Moreover, the therapist can visually observe the patient's movements and verbally communicate with the patient through a telecommunication network during the tele-rehabilitation process. By these means, the therapist can remotely monitor the training status and immediately adjust the input parameters in response to the patient's needs. Furthermore, the user's data collected over several therapy sessions are also saved in the database on the server PC, which may provide valuable information to facilitate a comprehensive assessment of recovery.

B. Characteristics of the PVSED

The PVSED is a wearable exoskeleton characterized by the features of high portability and variable-stiffness actuation. As shown in Fig. 2, it can be worn by a user via shoulder straps and belts without undue burden. To expand its support for users with different body sizes, the shoulder breadth and shoulder-elbow length of the PVSED are designed to be adjustable. In addition, there are 3 passive degrees of freedom on the shoulder joint including shoulder abduction/adduction, flexion/extension, and internal/external rotation to make allowance for the user's natural joint range of motion. The resulting high compatibility and portability not only facilitate home-based rehabilitation setups but also greatly expand its usage scenarios.

As a powered exoskeleton for upper limb rehabilitation, the PVSED can assist stroke patients with affected upper limbs in performing elbow movement training. The elbow joint of the PVSED is actuated via a lightweight cable-driven mechanism, in which a compact DC motor (Maxon RE-30 Graphite Brushes Motor, Maxon Motor AG, Switzerland) mounted on the backplate is used to transmit power by a steel cable threaded through a pulley. A gearhead (Maxon Planetary Gearhead GP 32C) with a reduction ratio of 190:1 is assembled coaxially to the driving motor. The rotation angle of the driving motor is measured by an incremental optical encoder (Maxon MR L-512, Maxon Motor AG, Switzerland) with a resolution of 512 pulses per revolution (ppr). Thus, the rotation angle of the elbow joint θ can be obtained by

$$\theta = c \cdot \frac{360}{p \cdot r} \cdot \frac{R_{dp}}{R_e} \tag{1}$$

where c is the count of pulses from its initial position recorded by the encoder, p is the pulses per revolution of the encoder, and r is the reduction ratio of the gearhead. R_{dp} is the radius of the driving pulley connected to the power motor, and R_e is the radius of the driven pulley to rotate the elbow joint.

In order to provide appropriate assistance to the user, a variable stiffness actuator (VSA) is integrated into the forearm part of the PVSED. As shown in its detailed view (Fig. 2(b)), the cable-driven main frame and the output link are linked together by a pair of antagonistic elastic elements (springs). Due to the preload force generated by the springs, they can rotate conjointly to perform synchronized elbow movements. However, once the external force acting on the output link exceeds the spring preload, one of the antagonistic springs will be elongated, thus causing an angle deviation between the main frame and the output link. Benefiting from this characteristic, the PVSED does not force the user's joint to reach the precise position received from the position controller. Instead, it allows a deviation from the reference position to avoid excessive interaction force. The resulting "passive compliance" can be utilized to prevent uncomfortable or even painful human-robot interaction. More importantly, the level of compliance is adjustable by moving a pivot along the longitudinal groove in the lever to change the transmission ratio between the internal elastic elements and the output link [28].

The physical prototype of the VSA is shown in Fig. 2(c), in which the slider is actuated by a Maxon RE-13 Graphite Brushes Motor to move the pivot position through ball screw transmission. The helical pitch of the ball screw is 1 mm. Additionally, the motor is assembled to a Maxon Planetary Gearhead GP 13A gearhead with a reduction ratio is 67:1. A 256-ppr incremental optical encoder (Maxon MR L-256, Maxon Motor AG, Switzerland) is used to measure the motor motion. Therefore, the pivot position can be obtained by

$$d = c \cdot \frac{h}{p \cdot r} \tag{2}$$

where c is the count of pulses from its initial position recorded by the encoder, h is the helical pitch of the ball screw, p is the ppr of the MR L-256 incremental optical encoder, and r is the reduction ratio of the gearhead.

C. Stabilizer

As a home-based tele-rehabilitation system, the highest priority must be given to the user's safety. During the tele-rehabilitation process, the therapist supplies the energy to the teleoperator in order to guide the patient toward the correct path of motion. As the therapist is supposed to deliver varying therapeutic movements, the dynamical behaviors of the therapist are regarded as a nonlinear active network to inject nonpassive energy into the interconnection for providing assistance and coordination [31]. In addition, the time-varying delays during intermittent communication may cause energy accumulation in the telecommunication loop, which results in a hazardous patient-exoskeleton interaction.

The interaction stability during teleoperation needs to be investigated to ensure safety. Since the rehabilitation motion performed by the PVSED is elbow flexion/extension in the sagittal plane, the dynamics of the master and slave sides are respectively described by [32]

$$\begin{aligned} M_m(\theta_m)\ddot{\theta}_m + C_m(\theta_m, \dot{\theta}_m)\dot{\theta}_m + G_m(\theta_m) \\ = u_m + J_m^T(\theta_m) f_m \end{aligned} \tag{3}$$

$$\begin{aligned} M_s(\theta_s)\ddot{\theta}_s + C_s(\theta_s, \dot{\theta}_s)\dot{\theta}_s + G_s(\theta_s) \\ = u_s - J_s^T(\theta_s) f_p \end{aligned} \tag{4}$$

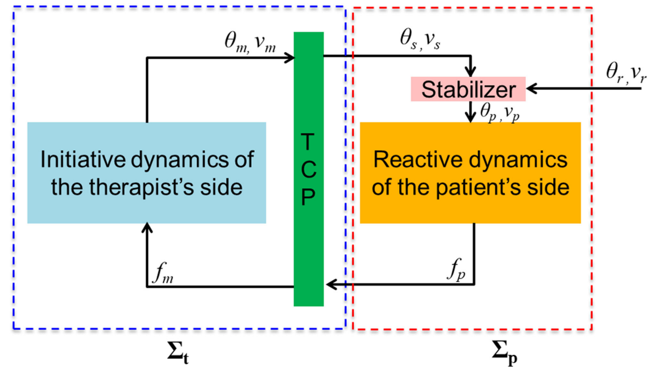


Fig. 3. Telecommunication loop with a stabilizer.

where θ_m and θ_s are the joint angles of the HD[2] and PVSED respectively, $\dot{\theta}_m$ and $\dot{\theta}_s$ are the corresponding angular velocity of each side (i.e., v_m and v_s). M_i is the inertia matrix of the operator i ($i = m,s$), C_i is the Coriolis matrix, and $G_i(\theta_i)$ is the gravity torque term which is compensated in the controllers. $J_i^T(\theta_i)$ is the kinematic Jacobian, f_p is the interaction force between the patient and the exoskeleton, and f_m is the force feedback from the slave side. The u_m and u_s are the initiative dynamics of the therapist's side and the reactive dynamics of the patient's side, respectively.

The u_s in Eq. (4) mainly depends on the θ_s and v_s. In an ideal situation without any disturbances, the θ_s and v_s on the slave side should be equal to θ_m and v_m in Eq. (3), which results from the initiative dynamics of the therapist on the master side and flows to the salve side using TCP as illustrated in Fig. 3. However, the unavoidable latency Δt in telecommunication causes position lags between the master and slave sides, i.e., $\theta_s(t) = \theta_m(t-\Delta t)$. It is indicated that in the implementation of the low-layer position control with a fixed interval T, the significant latency due to intermittent communication may lead to a great position change between two consecutive intervals, thereby generating a large v_s on the slave side.

To evaluate the safety of the patient-exoskeleton interaction, the amount of energy applied to the patient is measured, which is given by

$$E(x) = \int_0^t f_p(x) * v_p(x)\, dx \tag{5}$$

where t is the time interval that is set to 0.1 s in this case.

In order to achieve a stable interaction in the presence of time-varying delays and position lags, the amount of energy applied to the patient should be restricted. For this purpose, a stabilizer is employed in the telecommunication loop to measure the energy flow in/out of the communication loop and appropriately regulate the energy output to affect the reactive dynamics on the patient's side. During a given episode, if the amount of energy remains within the predefined stability boundary, the stabilizer will allow the mechanical energy to flow freely to ensure transparency of teleoperations. Once the therapist's dynamical behaviors or time-varying delays lead to the accumulation of energy exceeding the threshold, the stabilizer will be activated

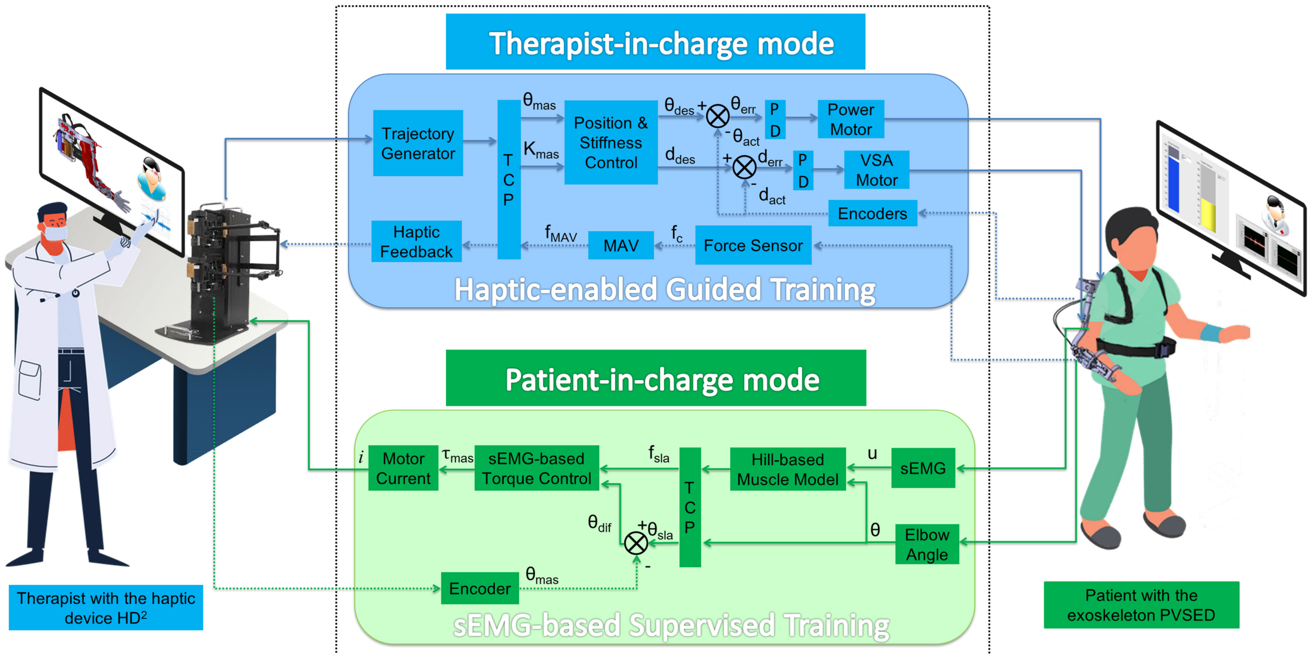


Fig. 4. Alternative training methods. A haptic-enabled guided training (i.e., therapist-in-charge mode) and an sEMG-based supervised training (i.e., patient-in-charge mode) are proposed in order to adapt to each patient's needs in different rehabilitation stages.

to regulate the amount of energy flowing to the patient, thus preventing potential risks.

D. Alternative Training Methods

In order to adapt to the patient's needs in different rehabilitation stages, we propose two alternative training methods, including a haptic-enabled guided training (i.e., *therapist-in-charge mode*) and an sEMG-based supervised training (i.e., *patient-in-charge mode*).

1) Haptic-enabled Guided Training (Therapist-in-charge Mode): In this training mode, the therapist can operate a haptic device to assist the patient wearing an exoskeleton in performing home-based rehabilitation. Compared to conventional manual therapy, a significant challenge regarding the implementation of tele-rehabilitation therapy is how to effectively modulate the intensity of therapeutic movements provided by the rehabilitation device. To address this issue, a remote stiffness control is implemented to enable the therapist's dynamic adjustment. The control loop of the haptic-enabled guided training is illustrated in the top half of Fig. 4. The therapist-led position trajectories and stiffness profiles are simultaneously sent to the slave side via TCP sockets and respectively used as the input of the independent position and stiffness control for the slave exoskeleton. With the regulation of the stabilizer, the desired angular position θ_{des} is used as a reference to control the elbow angle of the PVSED. A proportional-derivative (PD) controller is configured to operate on the error between the desired joint angle θ_{des} and the actual joint angle θ_{act} measured by the embedded encoder on the power motor.

$$\theta_{err}(t) = \theta_{des}(t) - \theta_{act}(t) \quad (6)$$

The input of the PD controller in the loop of stiffness control is the error between the desired pivot position d_{des} and the actual pivot position d_{act}.

$$d_{err}(t) = d_{des}(t) - d_{act}(t) \quad (7)$$

By remotely moving the pivot position of the VSA to regulate the actuating stiffness, the therapist is capable of delivering varying intensities of therapeutic movements to the patient. In addition, the haptic feedback is provided by the HD^2 to cue the therapist for proper adjustment. The contact force between the patient's affected limb and the exoskeletal joint is measured by a force sensor. In order to outline the general trend of the contact force, the mean absolute value (MAV) is applied to process the raw force signals, which is described by

$$f_{MAV}(t) = \frac{1}{n}\sum_{i=1}^{n} |f_i(t)| \quad (8)$$

where n is the sampling number in one period.

The f_{MAV} is delivered to the master side via TCP sockets and used for providing haptic feedback on the therapist's hand. The haptic cues in conjunction with telecommunication network-based services (e.g., oral communication and movement monitoring) can help the therapist remotely assess the patient's status and properly adjust the therapeutic movements.

2) sEMG-Based Supervised Training (Patient-in-charge Mode): In this training mode, the patient wearing the exoskeleton can perform robot-assisted bilateral rehabilitation under the supervision of a therapist. Given that the lack of hands-on interaction leads to a major difficulty in conducting direct kinesthetic supervision [33], an sEMG-based torque control that makes use of the patient's sEMG signals is proposed to enable the therapist to remotely assess the patient's kinesthetic awareness.

As a biological signal generated by muscle contraction, the sEMG signal has been widely used for the assessment of muscle strength [34], [35]. In our previous work [36], an sEMG-driven musculoskeletal model was developed to quantify the relationship between the sEMG signals and the muscle force, by which the muscle force is expressed as a function of the amplitude of sEMG signals and the elbow angle.

$$f_{sla}(t) = F(u, \theta) \tag{9}$$

As shown in the bottom half of Fig. 4, the sEMG signals u from the patient's biceps brachii and real-time elbow joint angle θ are simultaneously collected using the attached sEMG electrodes and the angle sensor. The real-time estimated muscle force f_{sla} is transferred to the master side via TCP sockets and used as the input of an sEMG-based torque control applied to the HD^2, which is described by

$$\tau_{mas}(t) = K \cdot f_{sla}(t) \cdot l \cdot sin((\theta_{sla}(t) - \theta_{mas}(t)) \tag{10}$$

where K is a proportional gain to be adjusted for sensation intensity and l is the arm length of the HD^2.

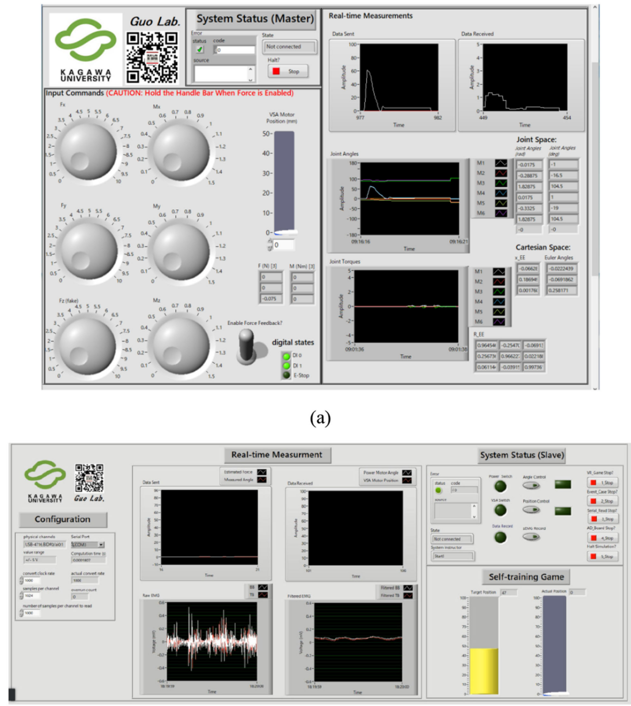
E. Teleoperation Interface

In order to provide a convenient and user-friendly interface when performing the teleoperation, we design a pair of graphics control panels (including a master panel for therapists and a slave panel for patients) to enable the interactive operation and real-time data visualization. As shown in Fig. 5(a), the master panel receives the data from the slave side and real-time plots on the display windows. Meanwhile, it provides remote control buttons that allow the therapist to immediately adjust the control parameters of the exoskeleton during the tele-rehabilitation process.

To motivate patients to participate more actively in the treatment, a target-track game is designed on the slave panel to guide the user through a self-rehabilitation session. As seen on the right bottom of Fig. 5(b), the left yellow bar indicates the target position randomly generated by the program, while the right slider shows the actual elbow angle of the patient measured by an attached angle sensor. The target and the actual elbow angle are simultaneously displayed on the screen. In the game, the patient wearing the PVSED is guided to move his/her elbow toward the target position. Once reached, a new target is generated randomly, and this procedure is repeated until the exercise routine is completed. Throughout the process, the patient's real-time muscle activities can be observed on the slave panel.

IV. Experiment and Performance Evaluation

In this section, a series of experimental trials are conducted for the purpose of determining the feasibility of the proposed tele-rehabilitation system and evaluating its functionality. The experimental protocol was approved by the Institutional Review Board (IRB) at the Faculty of Engineering, Kagawa University (*Protocol Number: 01-011*). Ten healthy subjects were enrolled in this study after signing a written informed consent, five of whom are assumed as therapists (called *therapist subject* below) and the remaining are assumed as patients (called *patient subject* below).



(a)

(b)

Fig. 5. Teleoperation interface. (a) Master panel for therapists. (b) Slave panel for patients.

A. Experimental Set-up

The experimental sites are located in the Faculty of Engineering, Kagawa University, with the master and slave sides set in two separate buildings as depicted in Fig. 6. On the master side, a haptic device HD^2 is provided to the therapist subject for remote movement control of the PVSED worn by the patient subject. Meanwhile, the therapist subject can observe the patient subject's real-time movements through the TV monitor during the tele-rehabilitation process. In addition, the patient subject's physical and biological data (joint angle, contact force, sEMG signals, etc.) displayed on the slave panel are also shared on the TV screen of the master side, which makes it possible for the therapist subject to monitor any minor changes in biomechanics and identifying the abnormal activities of the patient (e.g., *spasm*). Furthermore, an emergency-stop (*E-stop*) button is provided to the therapist subject in case of emergency during teleoperation. All motors can be disabled once the E-stop button is pushed down.

On the slave side, a small-size force sensor (FS03, Honeywell Ltd., U.S.A) is placed into the forearm support brace to measure the contact force between the patient subject and the exoskeletal joint. In addition, an angle sensor (GY-25 tilt module) is attached to measure the patient subject's actual elbow angle. Simultaneously, the sEMG signals from the patient subject's biceps brachii are collected by a commercial EMG device (Personal-EMG, Oisaka Electronic Equipment Ltd., Japan) with a sampling rate

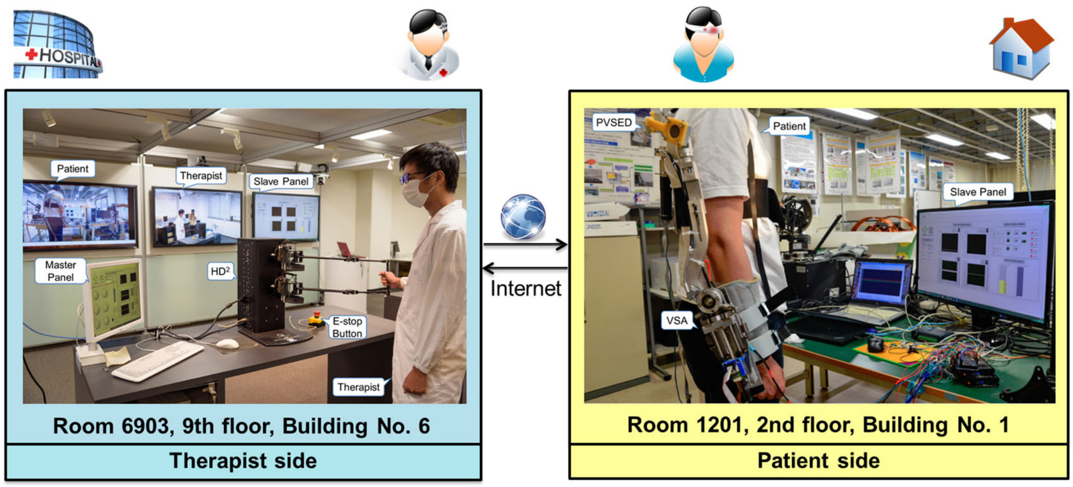


Fig. 6. Experimental sites. The therapist subject manipulates the HD^2 to remotely deliver rehabilitation treatment to the patient subject wearing the PVSED. The real-time movements and interface panel on the patient side are also displayed on the TV monitors of the therapist side.

of 1000 Hz and a differential amplification of 1000. For measuring the real-time muscle activation, the raw sEMG signals are firstly filtered by an accessory high-pass filter box with a cut-off frequency of 10 Hz to remove DC offsets and the noises in the low-frequency range. Then, a full-wave rectifier is used to acquire the absolute value of the EMG signals. Subsequently, a digital filter (1st-order low-pass Butterworth filter with a cut-off frequency of 2 Hz) is applied to extract the envelope of the EMG signals. The sEMG and force signals are sampled by a DAQ card (USB-4716, Advantech Co., Ltd.) with 16-bit resolution and visually displayed on the teleoperation interface of the client PC.

B. Characterization of Data Transmission

For evaluating the proposed tele-rehabilitation system, we first characterized its performance in remote data transmission, which includes the following three aspects:

1) Fidelity: The fidelity of remote data transmission is a key factor in tele-rehabilitation applications emphasizing the master-slave motion synchronization. In this study, the fidelity of data transmission between the master and slave controllers was evaluated by implementing the tasks of master-slave angle and stiffness tracking. In the trial, the therapist subject on the master side operated the HD^2 to control the elbow angle of the PVSED and dragged the slide bar on the master panel to move the pivot position of the VSA. The angle and pivot positions were sent to the slave side via TCP. Fig. 7 shows the control signals from the master side along with the received signals on the slave side. It is seen that both trials achieved satisfactory results in tracking accuracy, although there were minor phase offsets due to the inevitable time delay in telecommunication.

2) Latency: The distribution of latency time during the telecommunication trials is shown in Fig. 8. It is reported that 98.1% of the data transfer in the telecommunication process was completed within 0.6 s and the average latency time was 0.42 s. Although it is expected that the latency time will vary depending on the transmission distance and network bandwidth, a bit longer latency is still acceptable, as the therapeutic movements in rehabilitation therapy are generally performed at a relatively slow pace for safety [37].

3) Jitter: In telecommunication systems, jitter is the deviation from the true periodicity of a periodic signal [38]. Jitter may lead to signal degradation and data loss that impair the interoperability in telerobotics applications. In this study, jitter is defined as the phase difference of the control signals between the master and slave sides on the horizontal time axis. To measure the jitter level in the proposed system, we conducted a simulation test by sending periodic control signals from the master side to

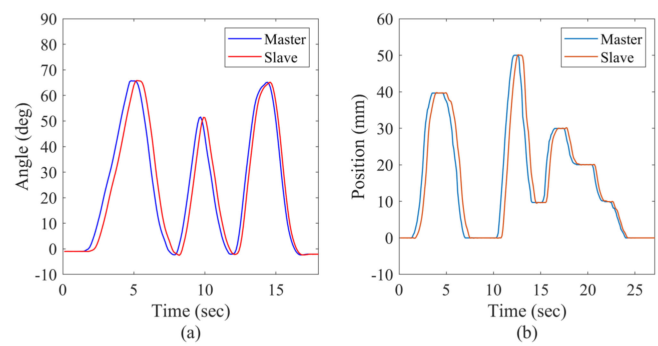


Fig. 7. Fidelity of data transmission between the master and slave sides. (a) Angle tracking. (b) Pivot position tracking.

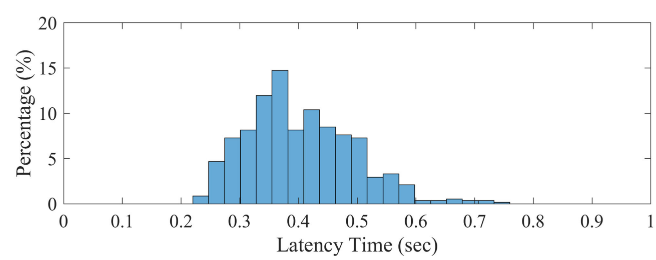


Fig. 8. Distribution of latency time.

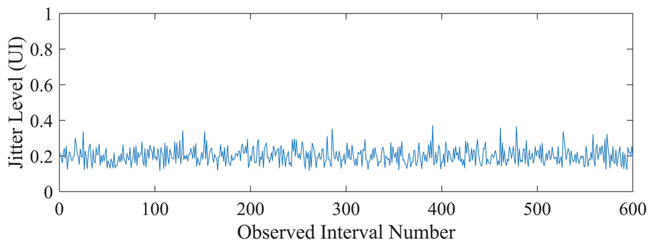


Fig. 9. Measurement of jitter level.

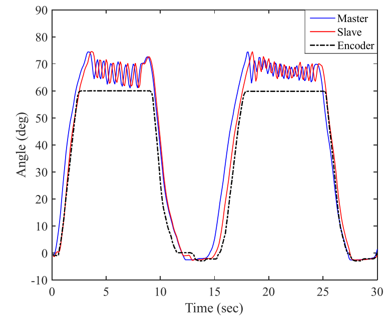


Fig. 10. Implementation of the stabilizer.

the slave side. A continuous sine wave signal with a period of 2 s and an amplitude of 90°, which simulates the frequency and range of an elbow movement training, was used as a reference source to be transferred.

The jitter level is measured in unit interval (UI), which quantifies the jitter in terms of a fraction of the transmission unit period (i.e., $J(i) = \frac{1}{T} \cdot (t_s(i) - t_m(i))$, where T is the transmission unit period, $t_s(i)$ and $t_m(i)$ are the timestamps of the i_{th} sample on the slave side and master side respectively). Fig. 9 shows the variation of the jitter level. The root mean square (RMS) value of the jitter amplitude over the entire observation interval was 0.207 UI, which indicates that the jitter noise power was kept to a relatively low level with limited interference to the telecommunication in the proposed system.

C. Implementation of the Stabilizer

Considering the intermittent communication and dynamics of the therapist's interaction may cause jitter accumulation and pose potential risks to the patient, a stabilizer is implemented in the telecommunication loop to monitor the energy flow and limit the maximum amount of energy.

As seen in Eq. (5), the amount of energy depends on the amplitude of the force and the velocity applied to the patient. Since the interaction force f_p between the user and the PVSED is limited to a given range by means of a sensor-based safety loop [36], in this study we mainly focus on the varying velocity due to the dynamics of the therapist's operation. In the trial, the therapist subject was operating the HD^2 to deliver guided movements to the patients, then he was instructed to perform random motions with a suddenly accelerated frequency to simulate the dynamics and uncertain disturbances that may appear in the tele-rehabilitation process. During this procedure, the angular position of the HD^2 on the master side, the input angular position of the slave controller, and the output angular position of the power motor measured by the encoder were recorded simultaneously and the results are plotted in Fig. 10.

It is evident that when the undesired motions appeared, the stabilizer in the loop was activated to limit the range and frequency of the motor motion in order to guarantee stability at the expense of transparency. With the regulation of the embedded stabilizer in the loop, the exoskeleton on the slave side is capable of guaranteeing safe human-robot interaction, even in the presence of uncertainties caused by the therapist's operation dynamics.

D. Evaluation of the Alternative Training Methods for the Proposed Tele-rehabilitation System

1) Haptic-enabled Guided Training (Therapist-in-charge Mode): To evaluate the characteristic of the haptic-enabled guided training, a therapist-led tele-rehabilitation task was conducted with varying actuating stiffnesses of the PVSED. In the trial, the therapist subject on the master side operated the HD^2 to guide the patient subject to perform elbow movements with the assistance of the PVSED in a low actuating stiffness. After a few cycles, the therapist subject increased the actuating stiffness by remotely moving the pivot to the maximum and then repeated the same pattern of movements. Throughout the process, the elbow movements on the slave sides were fully driven by the PVSED without the patient subject's voluntary motion.

A segment of the experimental results is shown in Fig. 11. The received position of the HD^2 on the slave controller was used as the reference trajectory, while the measured trajectory is the actual elbow angle of the patient subject recorded by the attached angle sensor. It is seen that in the phase of the low-stiffness task (pivot position at 0 mm), the offset between the reference and actual trajectories was significant, most notably in the ascending phase of each motion. The offset was primarily caused by gravitational torque from the weight of the forearm, as indicated by the following observations. Firstly, as stated in Section III.B, if the load exerted on the output link exceeds the spring preload, the output link will deviate from the cable-driven main frame to restrain the excessive interaction force but simultaneously cause an angular deviation. In the ascending phase when the output link raises the forearm to perform elbow flexion, the mass of the patient subject's forearm exerted a gradually increasing gravitational torque on the output link. As a result, the output link was forced to gradually deviate from the cable-driven main frame, thus generating an increasing angle error from the reference position. In addition, the offset in the ascending phase against gravity was more significant than that in the descending phase moving down along the direction of gravity. It needs to be noted that the angle error was minimized after the stiffness adjustment (moving the pivot position to 50 mm). But meanwhile, an increased contact force was observed in Fig. 11(b).

The average angle error and contact force of the five patient subjects in the low-stiffness and high-stiffness tasks are reported in Fig. 12. In comparison to those in high stiffness, the angle

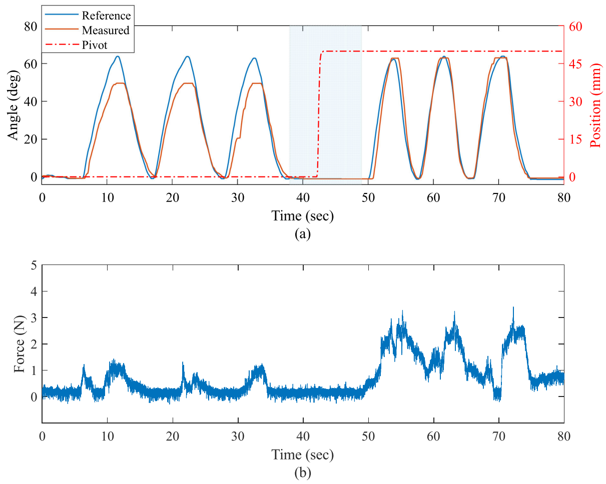


Fig. 11. Experimental results of the haptic-enabled guided training. (a) Position trajectories and actuating stiffness profiles of the PVSED. (b) The measured contact force between the patient's forearm and the forearm support brace. The received HD^2 position on the slave controller was used as the reference trajectory, while the measured trajectory was the patient subject's elbow angle recorded by the angle sensor. The light blue-shaded area in (a) showed the process of the therapist-controlled stiffness adjustment of the PVSED by moving the pivot position of the VSA.

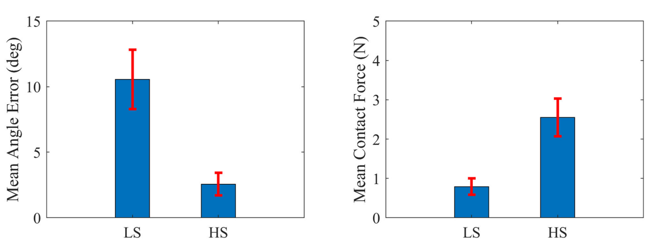


Fig. 12. Average angle error and contact force of the five patient subjects in low-stiffness (LS) and high-stiffness (HS) tasks respectively.

error in low stiffness is more significant, but the contact force is reduced. It is indicated that with a lower actuating stiffness, the PVSED may provide greater comfort that allows relatively larger deviations from the reference position to minimize the interaction force, while a more precise movement control can be achieved by applying a higher actuating stiffness. By remote control of the stiffness, the therapist may dynamically adjust the rehabilitation intensity to adapt to each patient's needs and different task requirements. More importantly, this adjustment is achieved in a continuous manner by moving the pivot position of the VSA. Its ease of operation provides more flexibility for the therapist to enable the provision of individual-specific and task-oriented rehabilitation treatment to the patients in their homes.

2) sEMG-Based Supervised Training (Patient-in-charge Mode): To explore the feasibility of the proposed sEMG-based supervised training, a patient-led rehabilitation task was conducted, in which the patient subject wearing the PVSED performed home-based bilateral rehabilitation under the remote supervision of the therapist subject. The trial process was divided into two sessions: initially, the patient subject performed robot-assisted bilateral elbow movements at a relatively slow pace. After completing a given number of cycles, the patient subject was instructed to start the second session with an accelerated pace of movement.

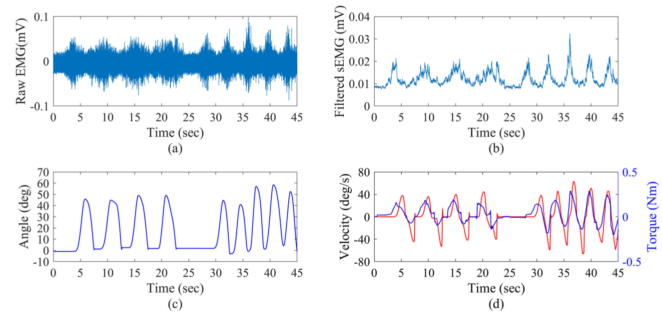


Fig. 13. Experimental results of the sEMG-based supervised training. (a) Raw sEMG signals of the biceps brachii on the slave side. (b) Filtered sEMG signals of the biceps brachii on the slave side. (c) Angle position of the HD^2 on the master side. (d) Motor torque (blue curve) and angular velocity (red curve) of the HD^2 on the master side.

The raw and filtered sEMG signals obtained from the biceps brachii of the patient subject are shown in Fig. 13(a) and (b) separately. The processed sEMG signals were used as input to implement the sEMG-based torque control for supervised training. In the trial, to visually observe the torque variation on the master side, the HD^2 was set in free motion without the manipulation of the therapist subject. The position trajectory of the HD^2 handle is plotted in Fig. 13(c), and the motor torque along with its resulting angular velocity of the HD^2 handle is shown in Fig. 13(d). According to Eqs. (9) and (10), the motor torque applied to the HD^2 on the master side continuously varies with respect to the sEMG signals of the patient subject on the slave side. It is observed in the plotted data that when the patient subject's muscle contractions resulted in the variation of sEMG signals, the torque feedback on the master side and its resulting velocity of the HD^2 were correspondingly varied, which reflected a high correlation between them. Numerically, in the second session (the period from 25s to 45s) that has a larger amplitude variation of sEMG signals (the peak amplitude to root mean square ratio of the sEMG signals was averagely 144.37% of that in the initial session), the corresponding average amplitude of torque feedback on the master side likewise increased to 150.91% of that in the initial session. Therefore, by holding the handle of the HD^2, the therapist may kinesthetically feel the variation and better figure out how the patient is performing the movements. Benefiting from the sEMG-based supervised training provided by the developed tele-rehabilitation system, the therapist has the potential to remotely assess the patient's kinesthetic awareness.

V. Discussion

Tele-rehabilitation therapy is the provision of specialist treatment to the stroke patient living at a remote location [39]. Considering that the therapist's operation dynamics and time-varying delays may cause energy accumulation in the process of tele-rehabilitation therapy, a stabilizer was employed in the telecommunication loop to regulate the amount of energy applied to the patient. The experimental results in Fig. 10 evidenced that in the presence of uncertainties and disturbances during teleoperation, the telecommunication loop with the employment of the stabilizer still guaranteed stability. The capability to handle undesired disturbances during intermittent communication is also beneficial for other remote or cloud-based rehabilitation systems.

Since there is no hands-on interaction during the tele-rehabilitation process, two alternative training methods are proposed to enhance the therapist-patient remote interaction. In the haptic-enabled guided training, the therapist can deliver guided rehabilitation therapies to the patients in their homes using the developed tele-rehabilitation system. In order to provide more interactivity, the developed system allows the therapist to dynamically adjust the intensities of therapeutic movements provided by the PVSED. As depicted in Fig. 11, by moving the pivot position to increase the stiffness, the therapist subject achieved a more precise movement control of the PVSED to drive the subject's affected upper limb, thereby resulting in the reduction of angle errors but meanwhile the increase of interaction force as seen in Fig. 12. By this means, the therapist is capable of flexibly adjusting the intensity of rehabilitation therapy to adapt to each patient's needs and task requirements. The proposed tele-rehabilitation system also includes an sEMG-based supervised training that allows a patient to perform self-rehabilitation under the remote supervision of a therapist. An sEMG-based torque control is implemented to the haptic device on the master side to help the therapist assess the patient's kinesthetic awareness. It is seen in Fig. 13 that the torque feedback applied to the HD^2 varied with respect to the patient's sEMG signals, which provides the possibility to remotely assess the patient's kinesthetic awareness.

While these are significant advantages and promising prospects for home-based tele-rehabilitation, some limitations of this study need to be noted and addressed in the near future. In this paper, we preliminarily explored an sEMG-based supervised training method that allows the therapist to kinesthetically sense the patient's muscle activities. This opens up the intriguing possibility of remote recovery assessment. Nevertheless, the quantitative assessment method has not been developed yet. Future work will focus on exploring new approaches including deep learning-based neural networks to facilitate the remote diagnosis and recovery assessment. Secondly, the experiments were only conducted on healthy subjects in order to demonstrate the engineering feasibility of the proposed system, with results showing that the proposed tele-rehabilitation system enabled therapist-in-the-loop to dynamically adjust the rehabilitation intensity and provided more interactivity in therapist-patient remote interaction. Despite these achievements, we were unable to reach definitive conclusions about its clinical effectiveness due to the lack of participation of post-stroke subjects. Clinical trials involving stroke patients and experienced therapists are expected to be conducted for further rigorous evaluation and exploit the potential advantages as well as limitations of the proposed system in practical use. By then, a Likert scale-based evaluation form will also be included to thoroughly investigate the patient and therapist satisfaction regarding the usefulness of the proposed tele-rehabilitation system. Another primary concern regarding the usage of tele-rehabilitation systems is data privacy. In this study, basic data anonymization has been implemented to remove personally identifiable information from the collected datasets. With the development of remote and cloud-based rehabilitation applications, the related data encryption techniques are also expected to be incorporated to further reduce the risk of unintended disclosure.

Compared with conventional inpatient rehabilitation, the use of tele-rehabilitation systems makes it possible for stroke patients to obtain specialist treatment in their homes, which may simultaneously alleviate the burden of the healthcare system and expand access to expert rehabilitation. In addition, eliminating the need for visiting rehabilitation facilities may also bring some additional benefits, e.g., reduced travel time as well as cost savings. But meanwhile, the challenges associated with tele-rehabilitation systems need to be noted as well. Firstly, it has high demands on the bandwidths of the telecommunication network for delivering real-time support and continuous transfer of multiple data (streaming video, audio, biological data, etc.). Secondly, it requires a learning curve for both patients and therapists to get acquainted with this emerging form of treatment and operation. Moreover, they may be unable to troubleshoot unexpected technical problems. Online tutorials and ongoing technical support are therefore needed. Thirdly, concerns have also been raised regarding the security of data transfer and the confidentiality of patient records [40]. Nevertheless, we believe these issues will be addressed with the employment of new technologies (widespread deployment of the latest fiber-optic communication and 5G network, cloud-based skill training and technical support, enhanced techniques of data encryption, etc.) and the introduction of home-based tele-rehabilitation systems is becoming a promising alternative for individuals who are experiencing a stroke.

VI. Conclusion

In this paper, a home-based tele-rehabilitation system that fuses the therapist-in-the-loop and robotic capabilities was developed to provide specialist treatment to the patients in their homes. Two alternative training methods, including a haptic-enabled guided training and an sEMG-based supervised training, were implemented to enhance the therapist-patient remote interaction. Depending on the rehabilitation stages and goals, the therapist can either lead the patient to perform robot-assisted passive rehabilitation by means of the former mode or adequately supervise the patient's self-rehabilitation using the latter mode. Preliminary experiments were conducted to demonstrate the feasibility of the developed system. The results showed that with the aid of the proposed alternative training methods, the developed tele-rehabilitation system enabled remote control of the robot-assisted rehabilitation interventions with adjustable intensity and provided more interactivity in therapist-patient remote interaction.

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