Study on a Novel Home-based Tele-rehabilitation System

by

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Abstract

Along with the globally growing life expectancy, the incidence of age-related diseases including stroke is rapidly increasing. Acute stroke is the beginning of a long-term struggle with physical damages and subsequent disabilities. This situation creates a massive demand for stroke rehabilitation. However, conventional rehabilitation therapy still remains focused on the in-hospital phase, with its emphasis on intensive manual therapy by the physical therapist, which is a labor-intensive process and consumes significant medical resources. In order to reduce the therapists' burden as well as delivering meaningful restorative therapy to stroke patients, robot-assisted rehabilitation has been deployed in the recovery process. Whereas, there are some issues that need to be addressed. Firstly, most of the existing rehabilitation systems are bulky and heavy, which are not suitable for home-based rehabilitation. Secondly, the comfortability and safety of patient-robot interaction are major concerns for rehabilitation robots. Thirdly, robotic systems lack the practical experience of a skilled therapist who is trained well to perform appropriate force field.

In this research, a home-based tele-rehabilitation system is proposed in order to provide comfortable and safe human-robot interaction to the patient and allow the therapist to remotely help the patient perform efficient and supervised home-based upper limb rehabilitation. In the proposed tele-rehabilitation system, a novel powered variable-stiffness exoskeleton device (PVSED) is firstly designed and evaluated by performance trials.

The PVSED is light-weight and portable, which is suitable for in-home use. Additionally, it can adjust the output stiffness using an integrated variable stiffness actuator (VSA) to adapt to the training requirements and individual's physical condition. Secondly, an sEMG-based real-time stiffness control was proposed to promote comfortable home-based bilateral rehabilitation. With the aid of the proposed sEMG-based stiffness control method, the PVSED is capable of providing appropriate power assistance based on the patient's motion intention. Thirdly, a novel home-based tele-rehabilitation system is developed to allow the therapist to remotely deliver effective rehabilitation to the patient. The proposed tele-rehabilitation system provides alternative control methods for rehabilitation, i.e., therapist-in-charge mode and patient-in-charge mode. In the former mode, a haptic-enabled guided training method is proposed to allow the therapist to guide the patient to perform rehabilitation movement by means of a haptic device. Meanwhile, the contact force on the patient side is delivered to the therapist by the haptic device and used as a reference for therapists to adjust the training parameters. In the latter mode, an sEMG-based supervised training method is proposed to allow the patient to perform robot-assisted bilateral rehabilitation at home independently. Meanwhile, the therapist can feel how the patient is performing based on his/her biological signals and further evaluate the patient's recovery process. Benefitting from the proposed home-based tele-rehabilitation system, the stroke patients may perform effective rehabilitation with the therapist's remote guidance.

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

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Chapter 1Introduction

1.1 Background

The contingent of aged people is going to expand rapidly in the following decades. 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. Particularly in Japan, the ratio of people aged over 65 years old to the total population reaches 29.1% in 2020 and is predicted to rise to about 40% around the year 2065.

With this growth comes an increased incidence of age-related maladies and diseases such as stroke. Acute stroke is the beginning of a long-term struggle with physical damage and the subsequent disability. It is reported that 15% of stroke survivors need long-term healthcare, while over 70% are left with a significant functional impairment in performing the activities of daily living (ADLs). This situation creates a massive demand for stroke rehabilitation.

Fast access to rehabilitation saves lives and improves recovery. However, numerous stroke patients cannot get regular and effective rehabilitation training due to the limitation of medical resources. Additionally, it is a significant challenge for patients with physical difficulties to move from their home to rehabilitation centers or hospitals. All of these problems place a tremendous burden on our healthcare system, and that would result in delayed and insufficient rehabilitation.

1.2 Robotics for Rehabilitation and Literature Review

Conventional rehabilitation therapy still remains focused on the in-hospital phase, with its emphasis on intensive manual therapy by the physical therapist. It is a labor-intensive process and consumes significant medical resources. This situation creates an urgent need for new approaches to improve the effectiveness and efficiency of rehabilitation. As a result, robot-assisted rehabilitation is an alternative to hospital-based therapy that aims to reduce the therapist's workload and improve the effectiveness of training, on the basis that the use of robot has the potential to offer intensive and repetitive rehabilitation practices with less therapist assistance. Additionally, the embedded sensors in robots augment the therapist's toolbox and facilitate a quantitative evaluation of the patient's recovery. Relevant studies have shown positive outcomes of robot-assisted therapy on improving the motor function of stroke patients.

1.3 Research Purposes and Approaches

Although robot-assisted rehabilitation has been deployed to deliver meaningful restorative therapy to stroke patients, some key issues need to be addressed to facilitate the rehabilitation process. Firstly, most of the existing rehabilitation systems are bulky and heavy, which are not suitable for in-home use. Secondly, the comfortability and safety of patient-robot interaction are major concerns for rehabilitation robots. Thirdly, robotic systems lack the practical experience of a skilled therapist who is trained well to perform appropriate force field.

In order to address these issues, the research approaches are described as follows:

1) Design a novel portable exoskeleton device that integrates a variable stiffness actuator to provide adjustable power assistance for home-based rehabilitation

2) Propose an sEMG-based stiffness control that achieves real-time adjustment of the robotic stiffness based on each individual's movement dynamics in order to improve safety and comfortability of human-robot interaction

3) Develop a tele-rehabilitation system that allows skilled therapists to remotely guide the patient's rehabilitation and evaluate their recovery based on real-time biofeedbacks.

1.4 Thesis Contributions

In this research, a novel home-based tele-rehabilitation system is proposed, in which the therapist can remotely provide efficient and supervised upper limb rehabilitation to the patient at home. The principal contributions of this thesis are:

1) *Develop a novel powered variable-stiffness exoskeleton device*

   The proposed PVSED is light-weight and portable, which is suitable for home-based rehabilitation. Additionally, it can adjust the output stiffness using an integrated variable stiffness actuator (VSA) to adapt to the training requirements and individual's physical condition.

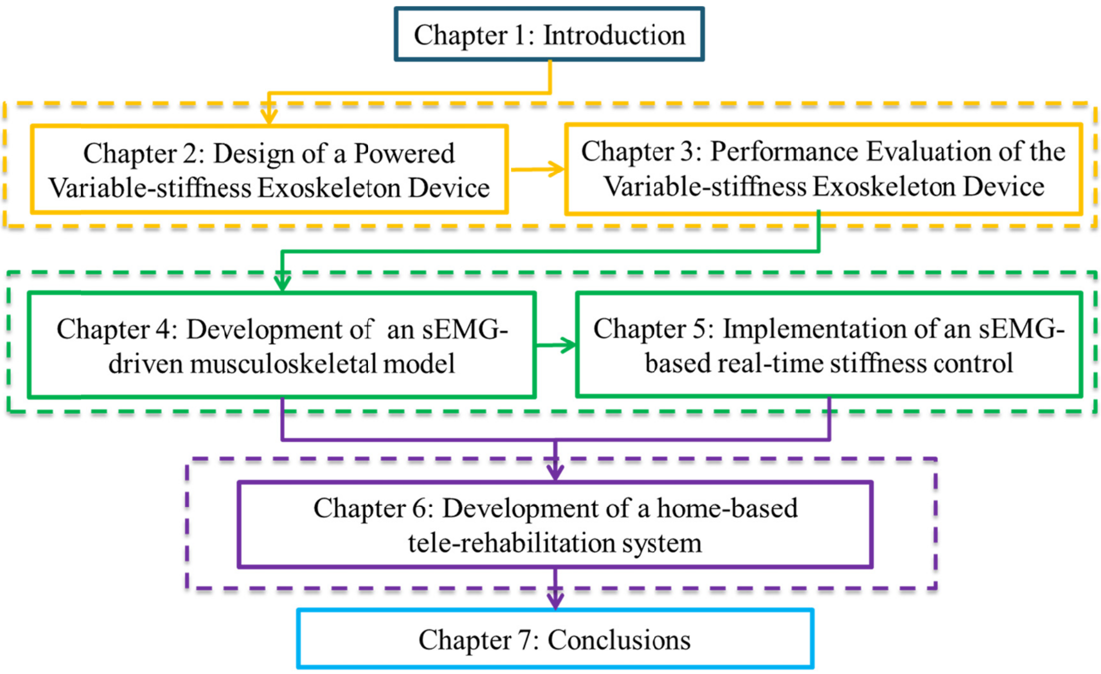
2) *Propose an sEMG-based stiffness control for bilateral rehabilitation*

With the aid of the proposed sEMG-based real-time joint stiffness control, the PVSED is capable of providing appropriate power assistance based on the patient's motion intention. Benefitting from this characteristic, the PVSED has the potential to provide task-oriented and individual-specific rehabilitation to the patient.

3) *Develop a tele-rehabilitation system for safe and effective home-based rehabilitation*

The proposed tele-rehabilitation system provides alternative training modes (therapist-in-charge mode and patient-in-charge mode) that allow skilled therapists to guide and supervise the patient's home-based rehabilitation remotely.

1.5 Thesis Structure



Chapter 2 Development of a Powered Variable-stiffness Exoskeleton Device (PVSED)

2.1 Introduction

Robot-assisted movement training employing exoskeleton devices has been proven to be an effective method for post-stroke patients to recover their motor function. However, in order to be used in home-based rehabilitation, the kinematic structure of a wearable exoskeleton device should provide portability and make allowances for the natural joint range of motion (ROM) for the user. Additionally, the actuated stiffness of the target joint is desired to be adjustable based on the specific impairment level of the patient's upper limb. In this chapter, a novel portable exoskeleton device is developed to provide adjustable assistance to stroke patients with the aid of an integrated variable stiffness actuator in the elbow joint. It has five passive degrees of freedom to guarantee the user's natural joint ROM and intra-subject variability. Moreover, an integrated variable stiffness actuator (VSA) is integrated into the forearm part to independently adjust the stiffness of the elbow joint. An elbow power-assist trial with different actuated joint stiffnesses was tested on a healthy subject to evaluate the functionality of the proposed device. By regulating the joint stiffness, the proposed device could provide variable power assistances for the wearer's elbow rehabilitation.

2.2 Mechanical Design of the PVSED

The device mainly consists of a back section, an adjustable upper limb section integrated with a VSA, and several joint parts used to connect the back section and the upper limb section. A control board and a battery pack are mounted on the back section to achieve fully portable application. The PVSED is equipped with a compact DC motor which provides power assistance for elbow movements. In order to reduce the inertia of the human joints, the power motor is fixed to the back section, away from the upper limb joints, and uses pulleys and cables to drive the exoskeleton device. There is a belt and two shoulder straps allowing the wearer to carry the device on his/her back like carrying a backpack. The elbow joint is connected to the driving cable. A VSA is integrated into the forearm and can be used to adjust the elbow joint stiffness independently. It mainly consists of a pair of antagonist elastic elements, a slider along with a movable pivot, a forearm supporter, and a DC motor.

As a wearable rehabilitation device designed for home-based rehabilitation, the PVSED has a light and compact mechanical structure. The main exoskeletal frames are made of aluminum alloys, and several connection parts were manufactured by a 3D printer to reduce the weight as well as the cost. The total weight of the PVSED is only 3.1 kg. The motors and control boards are supplied by a rechargeable battery pack with a capacity of 3000 mAh, which could allow nearly 1 hour of continuous elbow rehabilitation training. These features help facilitate home-based rehabilitation but also allows for its use outside of the home.

2.3 Kinematic Analysis of the PVSED

he PVSED has 6 degrees of freedom (DOFs) in total, including 3 human-motion controlled passive DOFs to be rotated freely in order to cater to the patients' active movements, two passive length adjustment DOFs to fit different body sizes and 1 active elbow DOF actuated by the power motor. The kinematic structure of a wearable rehabilitation device should take into account the subject's natural joint range of motion (ROM) and the intra-subject variability of the body size. Denavit-Hartenberg (D-H) parameters draw an available methodology for the kinematic analysis of robotic systems. In this method, each link frame is completely described by four parameters associated with a convention matrix.

To explore the maximum available area when using the device, it is assumed that the passive shoulder DOFs are moved by human power while the elbow DOF is actuated by the cable-driven mechanism of the PVSED. To prevent any robot-driven movements exceeding the ROM of human joints, the joint ROM of the PVSED is limited to be slightly smaller than that of human joints, but its range meets most requirements of ADLs.

2.4 Control Apparatus of the PVSED

The elbow movement is powered by a Maxon RE-30 Graphite Brushes Motor. A Maxon Planetary Gearhead GP 32C gearhead with a reduction ratio of 190:1 is assembled with the motor. They are mounted on the back section of the exoskeleton device. In order to control the device, sensors are required to measure the states of the motors. The rotation angle of the driving motor is measured by an incremental optical encoder (Maxon MR L-512, Maxon Motor AG, Switzerland) which is assembled with the driving motor concentrically.

A Maxon RE-13 Graphite Brushes Motor is equipped in the VSA to drive the ball screw for moving the pivot position. The helical pitch of the ball screw is 1 mm. A Maxon Planetary Gearhead GP 13A gearhead with a reduction ratio is 67:1 is assembled with the motor. Additionally, a Maxon MR L-256 incremental optical encoder with 256 counts per revolution is used to measure the current count number of the motor.

Arduino Mega 2560 (Arduino, Italy), as the embedded control unit of the device, is used to regulate the elbow rotation and pivot position by sending corresponding orders to the motor controller. Both of the two motors are controlled by a 50/5 ESCON motor controller (Maxon Motor AG, Switzerland).

2.5 Principle of Variable Stiffness

There is an actuated load at the end of the lever, while the other side is tensioned with a pair of antagonistic springs via steel cables. Due to spring elongation, the force exerted at the end of the lever can be balanced. As long as the pivot position is changed, the transmission ratio between the exerted load and the antagonistic forces generated by the elastic elements would be changed as well thereby allowing the variation of the output stiffness. As a result, the stiffness variation is an inherent property with respect to the pivot position.

2.6 Summary

In this chapter, the design of a powered variable-stiffness exoskeleton device PVSED was described. It has the following notable features. Firstly, the portable, compact structure enables its use in daily living without undue burden. Secondly, passive human-motion controlled DOFs and frame adjustment DOFs ensure a desired kinematic compatibility between the exoskeletal and human joint for the people with different body sizes. Thirdly, the PVSED is capable of adjusting the assistance levels for the patients' elbow rehabilitation training by means of an integrated VSA.

The PVSED focusing on home-based elbow rehabilitation is expected to assist neurological patients with impaired arms to perform safe and comfortable rehabilitation training as well as improving their ADLs. The portable design facilitates home-based rehabilitation setups and allows for use outside of the home. In order to adapt to those patients with specific upper limb impairment levels, the PVSED can regulate the actuated joint stiffness to provide appropriate assistance for elbow rehabilitation. Benefitting from this variable-stiffness characteristic, the PVSED also has the potential to gradually promote the intensity of rehabilitation training for chronic hemiparetic stroke survivors.

Chapter 3 Performance Evaluation of the Powered Variable-stiffness Exoskeleton Device

3.1 Characterization of the VSA

In order to explore the relationship between the pivot position and the resulting stiffness of the VSA, the simulation and experiments were conducted respectively.

3.1.1 Simulation of Stiffness Variation

Five pivot positions (from 0 mm to 20 mm with an increment of 5 mm) were selected to simulate its corresponding elbow joint stiffness respectively. A force is exerted on the end of the output link from 0 N to 25 N with a constant increment of 1 N per second. The friction and gravity were neglected for simplification. It can be observed that the deflection angle between the main frame and the output link becomes larger with the increase of simulated force.

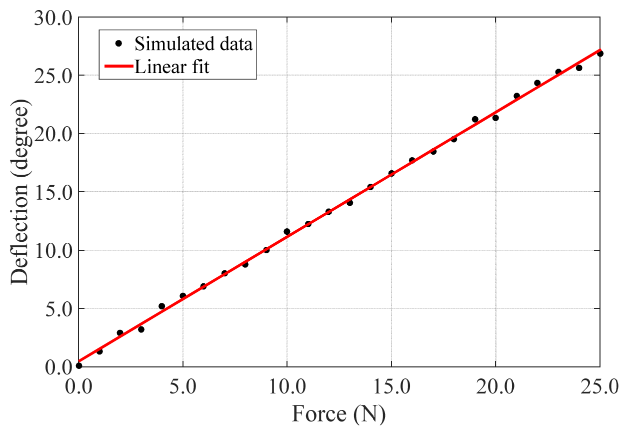


Fig. 3.1: Simulation results of the pivot position at 0 mm

3.1.2 Experimental Results

In the experiment, the force of output link was measured by a 6-axis force sensor (MINI 4/20, BL AUTOTEC. Ltd.). An inertial sensor (MTx sensor, Xsens Technologies B.V., the Netherlands) was attached to the elbow joint to measure the output deflection from its equilibrium position. Five pivot positions, namely 0 mm, 5 mm, 10 mm, 15 mm, 20 mm, are the same with those selected in the simulation. The measurements were iterated 5 times for each pivot position in the positive direction (clockwise) and the negative direction (anticlockwise).

The experimental results are shown in Fig. 3.2. The dash lines represent the results of linear fitting for the five pivot positions. It can be observed that for rotating the same deflection, the measured force became larger with the increase of the pivot position. As the pivot position increased from 0 mm to 20 mm, the slope of the force-deflection diagram became larger, which means a stiffer actuated joint was achieved.

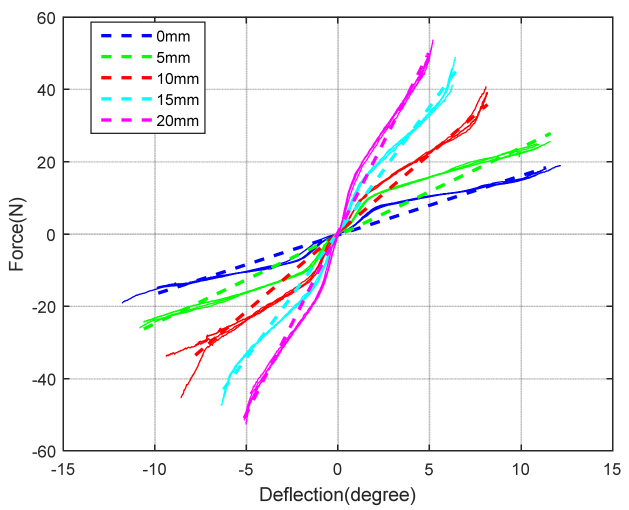


Fig. 3.2: Joint force versus deflection for different pivot positions. The dashed lines show the results after linear fitting.

In order to validate the VSA model and estimate the relationship between the pivot position and the elbow joint stiffness, the joint stiffness versus pivot position diagram is plotted in Fig. 3.3. Compared with the simulated stiffness, the measured stiffness is higher since the initial stage suffered the backlash effect caused by the driving cable in the experiment. The compensated stiffness curve shows an approximated value with the simulation results, although there are small differences that resulted from the energy dissipation (e.g., friction) in the physical system. It indicates that the proposed model properly represents the stiffness property of the VSA. Although a more accurate approximation can be achieved by adding the insertion points of the pivot position, all three of the curves show a significant tendency for the actuated joint stiffness to become higher with the increase of the pivot position.

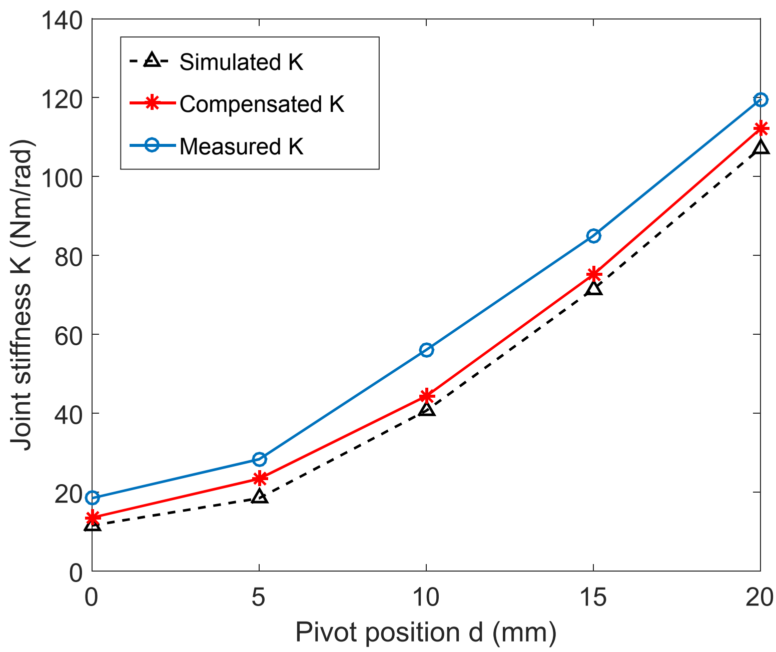


Fig. 3.3: Joint stiffness versus pivot position

3.2 Functional Evaluation of the PVSED

To evaluate the functionality of the proposed PVSED, an elbow power-assist trial was tested on a healthy subject (Male, 28 years old, 175 cm, 67 kg). Five different levels of joint stiffness were selected by moving the pivot position to 0, 5, 10, 15, 20 mm, respectively. The elbow power-assist movement was tested for each level of stiffness. This trial was repeated 10 times to obtain the mean angular error between the reference and the actual trajectory for 5 different levels of joint stiffness.

The trajectory results of the first elbow power-assist trial for five different levels of joint stiffness are shown in Fig. 3.4. The amplitude of elbow angle was varied with respect to the actuated joint stiffness. The angular error was apparent in low joint stiffness. With increasing elbow joint stiffness, the actual trajectory got closer to the reference trajectory. The mean values of the angular error for ten trials are reported in Fig. 3.5. By regulating the pivot position from 0 mm to 20 mm to increase the joint stiffness, the angular error was reduced from 16.97° to 1.68°.

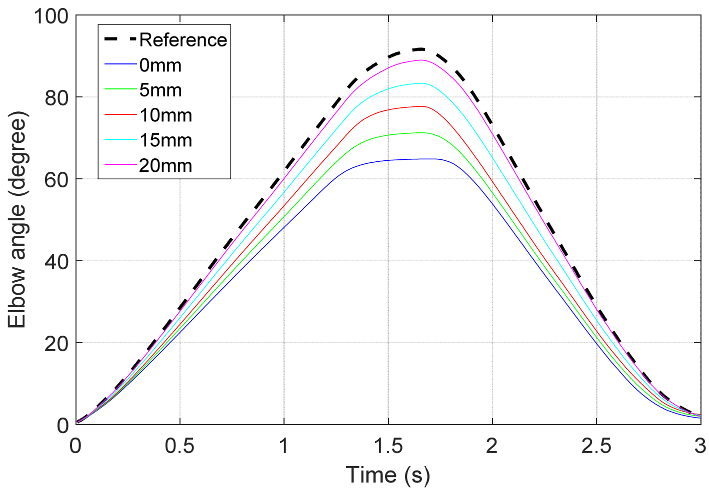


Fig. 3.8: Elbow rehabilitation task

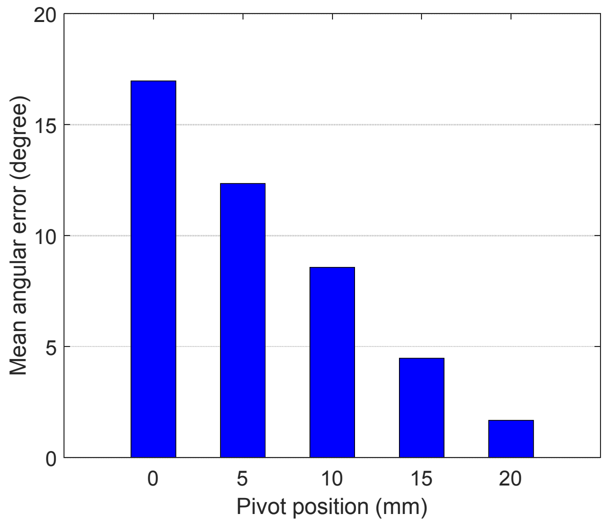


Fig. 3.5: Trajectory error between the reference and actual trajectory

3.3 Summary

In this chapter, preliminary experiments were carried out to characterize the integrated VSA and evaluate the functionality of the proposed PVSED. The VSA characteristic experiment showed that by moving the pivot position, the actuated elbow joint stiffness could be adjusted independently. Furthermore, elbow power-assist testing for different levels of joint stiffness was carried out on a healthy subject. The trajectory results showed that different angular error levels with respect to the desired trajectory appeared for the five levels of joint stiffness. More importantly, the angular error was reduced by applying a higher joint stiffness. With the proper choice of joint stiffness, the PVSED can provide suitable assistance for the patient with specific upper limb impairment levels.

Chapter 4 Development of an sEMG-driven Musculoskeletal Model

4.1 Introduction

In biology, joint stiffness is assumed as an outcome of muscular co-contraction. Surface electromyography (sEMG) was presented as a non-invasive measurement method to describe human muscle properties. In this chapter, an sEMG-driven musculoskeletal model is developed to characterize the physical properties of the human elbow joint, in which not only the muscle activation but also the muscular contraction dynamics are taken into consideration. Firstly, the muscle activation is obtained from sEMG signals and used to estimate the muscle force based on the hill-type muscle model. Furthermore, the joint torque and stiffness can be estimated by analyzing muscle contraction dynamics.

4.2 Measurement of Muscle Activation

In our study, the EMG signals are collected by a commercial EMG device (Personal-EMG, Oisaka Electronic Equipment Ltd., JAPAN). The sampling rate is 1000 Hz, with a differential amplification of 1000 and a common- mode rejection of 104 dB. Firstly, the sampled signals are 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. Thirdly, a digital filter (1^{st}-order, low-pass Butterworth filter with a cut-off frequency of 2 Hz) is applied to extract the envelope of the EMG signals. After the signal pre-processing, the filtered signals EMGα is linearly normalized to a value between 0 and 1 by dividing its peak value EMG_{MVC} obtained from the maximum voluntary contraction (MVC) test, i.e., $u=EMG\alpha/ EMG_{MVC}$. Finally, the normalized signals are transformed to the muscle activation level by applying the following nonlinear normalization:

$$a(u) = \frac{e^{Au} - 1}{e^{A} - 1} \tag{4-1}$$

where u denotes the processed sEMG signals, and A is a nonlinear shape factor between 0 and -3.

4.3 Muscle Contraction Dynamics

Referencing the working principle of muscle units, the Hill-type muscle model was proposed to describe the muscle properties. A conventional Hill-type muscle model consists of an active contractile element (CE), a passive parallel elastic element (PE), and a series elastic element (SE). Elbow flexion and extension in the sagittal plane are principally accomplished by the concentric/eccentric contraction of an antagonistic muscle pair: Biceps brachii (BB) and Triceps brachii (TB). In this study, a musculoskeletal model is developed to describe muscle contraction dynamics during human elbow movements. The upper limb is represented by a pair of antagonistic muscle-tendon units with bones for simplification. As shown in Fig. 4.1, the muscle-tendon units of BB and TB are respectively described by the Hill-type muscle model, while the bones are regarded as the rigid elements.

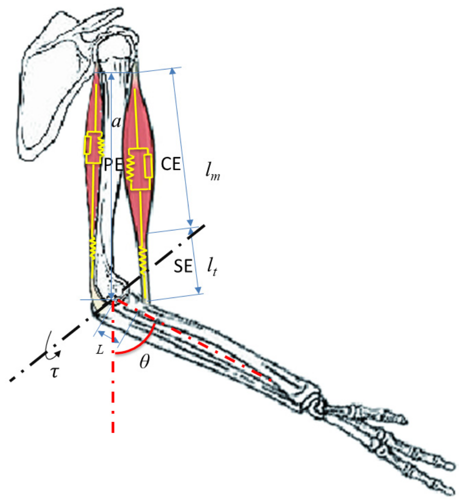


Fig. 4.1: Musculoskeletal model of the upper limb. The biceps brachii and triceps brachii are a pair of antagonistic muscles for elbow flexion/extension in the sagittal plane. Each muscle is modeled as an active contractile element (CE) in parallel with a passive elastic element (PE), while the tendon is modeled as a series elastic element (SE). θ is the elbow angle from the initial position oriented perpendicular to the ground.

The muscle-tendon force can be represented by

$$F^{mt} = F^{t} = F^{m} \cdot cos\varphi \tag{4-2}$$

where φ is the pennation angle.

The pennation angle of BB is nearly 0° and that of TB is smaller than 10°. Therefore, the effect of the pennation angle is ignored, i.e., $F^{mt}=F^{m}$.

Since the muscle fiber can be represented by a CE in parallel with a PE, the muscle force is described by

$$F^{m} = F_{CE} + F_{PE} \tag{4-3}$$

The CE is assumed to produce an active contractile force and the PE is assumed to produce a passive elastic force, which can be calculated by

$$F_{CE} = F_{max} \cdot f_L(l) \cdot f_V(v) \cdot a(u) \tag{4-4}$$

$$F_{PE} = F_{max} \cdot f_P(l) \tag{4-5}$$

where F_{max} is the maximum isometric muscle force, *a(u)* is the muscle activation obtained by *Eq. (4-1)*. $f_L(l)$ and $f_V(v)$ represent the normalized active force-length and force-velocity relationship respectively, and $f_P(l)$ denotes the normalized passive force-length relationship.

To simplify biomechanical parameters in the calculation, a 2nd-order polynomial fitting is applied to obtain $f_L(l)$, which is expressed by

$$f_L(l) = \begin{cases} q_0 + q_1 \cdot l + q_2 \cdot l^2, 0.5 \leq \ l \ \leq 1.5 \\ 0, \qquad\qquad\qquad otherwise \end{cases} \tag{4-6}$$

where q_0=-2.06, q_1=6.16, and q_2=-3.13 are set as constants. $l = l^m / l_o^m$ is the normalized muscle length, and l_o^m denotes the optimal muscle fiber length.

The normalized force-velocity relationship $f_v(v)$ is given by

$$f_V(v) = \frac{0.1433}{(0.1074 + e^{-1.3\, sinh(2.8v+1.64)})} \tag{4-7}$$

where $v = v_m / v_{max}$, v_m is the muscle contraction velocity, which is the derivative of the muscle fiber length l_m. It is reported that the maximum muscle contraction velocity v_{max} is nearly equal to $10 l_o^m / s$ [56], which far exceeds v_m. As a result, $f_V(v)$ can be set to 1 for simplification.

The $f_P(l)$ in *Eq. (4-5)* was derived from a normalized passive force-length curve [57], which is calculated by

$$f_p(l) = e^{10 \cdot l - 15} \tag{4-8}$$

Deduced from *Eq. (4-5) - (4-8)*, the muscle force F^m is expressed as a function of the real-time muscle activation level *a(u)* and muscle fiber length l^m.

The muscle-tendon length consists of the muscle fiber length and the tendon length, i.e.,

$$l^{mt} = l^m \cdot cos\varphi + l^t \tag{4-9}$$

where l^m represents the muscle fiber length, l^t represents the total length of the tendon, and φ is the negligible pennation angle as stated above.

The muscle-tendon length of the biceps brachii acting on the elbow joint can be obtained by

$$l_{BB}^{mt} = \sqrt{a^2 + L^2 - 2aLcos(\pi - \theta)} \tag{4-10}$$

where *a* is the length of the upper arm, *L* is the distance from the axis of the elbow joint to the bone-tendon junction in the forearm, and *θ* is the elbow angle.

Considering the bone-tendon junction of the triceps brachii is much near the elbow joint, the muscle-tendon length of the triceps brachii can be simplified by a 1^{st}-order polynomial of the elbow angle *θ*:

$$l_{TB}^{mt} = b_0 + b_1\theta \tag{4-11}$$

where b_0 and b_1 are constants.

The moment arm of a muscle-tendon unit can be obtained by

$$r = \frac{\partial l^{mt}(\theta)}{\partial \theta} \tag{4-12}$$

Thus, the torque contributed by a single muscle-tendon unit is given by

$$\tau = F^{mt} \cdot r \tag{4-13}$$

Since elbow flexion and extension are principally performed by a pair of antagonistic muscles (BB and TB), the net torque acting on the elbow joint is

$$\tau_{elbow} = |\tau_{BB}| - |\tau_{TB}| = |F_{BB}^{mt} \cdot r_{BB}| - |F_{TB}^{mt} \cdot r_{TB}| \tag{4-14}$$

The stiffness trend index (STI) is defined as

$$STI = |\tau_{BB}| + |\tau_{TB}| \tag{4-15}$$

The STI is linearly mapped to the robot stiffness K, which is written as

$$K = \alpha \cdot STI + \beta \tag{4-16}$$

where α (rad-1) and β (Nm/rad) are constants depending on the task requirements and individual physical condition. For a patient with an altered intrinsic joint stiffness due to spasticity, the robot stiffness may be set to an appropriate range by adjusting the proportional parameter α.

4.4 Model Identification and Validation

The experiments were conducted in isometric and dynamic muscle contraction, respectively. This study was approved by the Institutional Review Board (IRB) in the Faculty of Engineering, Kagawa University (*Ref. No. 01-011*). Ten healthy subjects (males, average age: 25.6 ± 3.7 years old; average weight: 69.4 ± 10.2 kg; average height: 178.1 ± 7.1 cm) were enrolled in this study after signing a written consent.

4.4.1 Isometric Contraction

A bipolar surface electrode (Oisaka Electronic Equipment Ltd., Japan) was attached to BB and aligned parallel to the muscle fibers on the subject's left arm to sample the sEMG signals. Moreover, a 6-axis force sensor (MINI 4/20, BL AUTOTEC. Ltd., Japan) was fastened to a fixed bracket. In the experiment, the subjects were instructed to exert a gradually increasing force on the fastened force sensor to his/her maximum and then return to the related state. Throughout the process, subjects maintained their forearms horizontally without elbow rotation and used their fingertips to push the force sensor along Y axis.

This trial was repeated ten times for each subject. A 3-minute interval was set between every two trials in order to avoid muscular fatigue. The average correlation coefficient ($p<0.01$) of all validation trials for each subject are reported in Table 4.1. It is observed that the correlation coefficient for Subject A is 86.7%, while that for Subject F is 97.7%. This difference partly resulted from the inter-subject variability of sEMG signals. Also, the simplified physiological parameters in the established musculoskeletal model may have effects on this. Overall, the results among all subjects showed that the proposed musculoskeletal model has a satisfying performance for real-time muscle force estimation in isometric contraction.

Table 4.1 Correlation coefficient ($p<0.01$)

Subject	A	B	C	D	E	F	G	H	I	J
R^2	86.7%	96.9%	93.2%	89.3%	92.2%	97.7%	90.4%	96.3%	96.5%	97.0%

4.4.2 Dynamic Contraction

o further evaluate the performance of the proposed musculoskeletal model for dynamic contractions, one healthy subject (Male, Height: 175 cm, Weight: 75 kg) participated in a trial to perform continuous elbow flexion/extension in the sagittal plane. An MTx angle sensor is attached to the subject's upper limb to record the elbow angle θ. Meanwhile, the raw sEMG signals from BB and TB were sampled by a pair of dry electrodes and subsequently processed to obtain the muscle activation $a(u)$. The muscle activation $a(u)$ and elbow angle θ were substituted to the musculoskeletal model to estimate the real-time joint torque.

The reference torque applied to the subject's elbow joint can be deduced from a kinematic and dynamic model of the upper limb, which is presented by

$$\tau = I \cdot \ddot{\theta}_e + \tau_g \tag{4-17}$$

where I is the inertia moment of the forearm, $\ddot{\theta}_e$ is the angular acceleration of the elbow joint, and τ_g is the gravitational torque caused by the mass of the forearm.

Given that the elbow movement in rehabilitation is allowed to perform with a relatively low angular velocity, the resulting angular acceleration is negligible. Thus, the joint torque τ can be represented by

$$\tau = \tau_g = m_f \cdot g \cdot l_f \cdot \sin\theta_e \tag{4-18}$$

where m_f is the total mass of the forearm, l_f is the length from the center of mass of the forearm to the elbow joint, and θ_e is the elbow angle.

The m_f and l_f may be estimated based on the individual's physical parameters [64], which are written as

$$m_f = m \cdot 0.6\% + m \cdot 1.9\% \tag{4-19}$$

$$l_f = \frac{m \cdot 0.6\% \cdot \left(\frac{10.4\% \cdot H}{2} + 15.7\% \cdot H\right) + m \cdot 1.9\% \cdot 15.7\% \cdot \frac{H}{2}}{m \cdot 0.6\% + m \cdot 1.9\%} \tag{4-20}$$

where m and H are the individual's weight and height, respectively. Substituting the subject's physical parameters (75 kg/1.75 m) to the formula above, we can obtain the m_f and l_f (1.875 kg/ 0.1922 m).

In the experiment, the subject was instructed to perform continuous elbow flexion-extension ten times. For evaluating the proposed sEMG-driven musculoskeletal model, the root mean square error (RMSE) between the reference torque τ_r and the estimated torque τ_e was calculated by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\tau_r(i) - \tau_e(i))^2}{n}} \tag{4-21}$$

The average RMSE for all trials was 0.6408 Nm. Furthermore, the normalized root mean square error (NRMSE) was obtained by

$$NRMSE = \frac{RMSE}{\tau_{e\_max} - \tau_{e\_min}} \tag{4-22}$$

where τ_{e_max} and τ_{e_min} are the maximum and minimum estimated torque, respectively.

The NRMSE is equal to 12.52%. Considering the effects of the inherent instability of sEMG signals and the neglected factors (e.g., the moment of inertia) in deducing the reference torque, this error is still acceptable.

4.5 Summary

Since the stiffness of the human elbow joint varies during movement, an sEMG-driven musculoskeletal model that incorporates the muscle activation and muscular contraction dynamics was developed to describe the dynamic properties of the upper limb. The proposed musculoskeletal model was subsequently validated in both isometric contraction (static force estimation - Fig. 4.5) and dynamic contraction (continuous torque estimation - Fig. 4.7).

Based on this model, the reference signals including the real-time elbow angle and stiffness profiles are provided to guide the operation of the exoskeleton device in order to achieve natural and comfortable human-robot coordinated movements.

Chapter 5 Implementation of an sEMG-based Stiffness Control for Bilateral Rehabilitation

5.1 Introduction

Robot-assisted bilateral rehabilitation involving both arms has been proposed in order to improve rehabilitation efficiency and facilitate the individual's recovery. Although various research has made progress in promoting synchronized robot-assisted bilateral movement, few studies have focused on addressing the varying joint stiffness resulting from dynamic motions.

In this chapter, an sEMG-based stiffness control that allows real-time stiffness adjustment of the exoskeleton device is proposed for robot-assisted bilateral rehabilitation. The proposed method can capture the user's real-time motions on the contralateral side and generate a motion-related stiffness variation to adapt to the user's dynamic motions.

5.2 sEMG-based Stiffness Control for Bilateral Rehabilitation

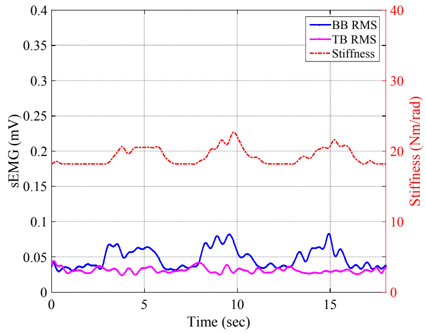
During bilateral exercise, the affected side is desired to follow the movement pattern of the contralateral side with the aid of the rehabilitation robot. In order to achieve natural and comfortable coordinated movements, an sEMG-based real-time joint stiffness control that makes use of the sEMG signals and the elbow angle on the contralateral side as input to dynamically adjust the stiffness of the exoskeleton device during bilateral movement was proposed.

An inertial measurement unit (GY-25 tilt angle module) is attached to the subject's contralateral side to track his/her voluntary elbow movements. The sampled elbow angle θ_{mas} is sent to the PID controller for master-slave position tracking. Meanwhile, the raw sEMG signals on the same side are collected by dry electrodes and subsequently processed to obtain the real-time muscle activation u of the biceps brachii (BB) and the triceps brachii (TB) respectively. Based on the musculoskeletal geometry of the upper limb, the muscle-tendon length l can be calculated according to the measured elbow angle. Once the muscle activation u and muscle-tendon length l are known, the corresponding muscle force and torque can be estimated using the musculoskeletal model. Furthermore, the elbow joint stiffness is deduced from the antagonistic muscle torques and used as reference signals to guide the stiffness regulation of the VSA.

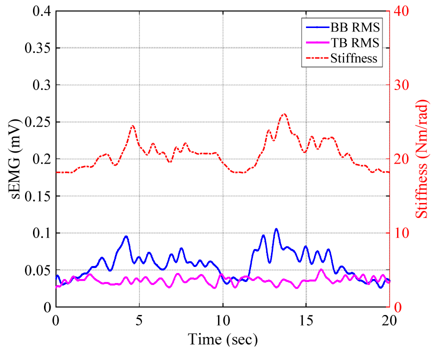
5.3 Experiment and Characteristic Evaluation

5.3.1 Characterization of the sEMG-based Variable Stiffness

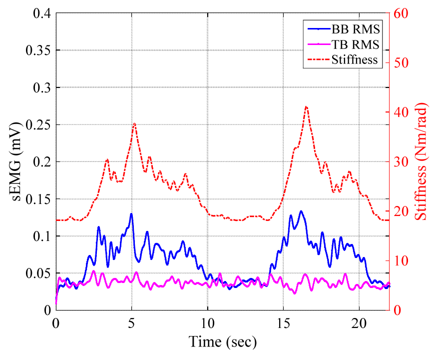
A weight lifting task was designed and performed by ten subjects. In the trial, the subjects were instructed to lift a dumbbell in the sagittal plane with different weights (0 kg, 1 kg, and 2 kg), which simulates different intensities of rehabilitation training. Two dry electrodes were attached to BB and TB to collect the sEMG signals. Fig. 5.1 shows the RMS of sEMG signals from Subject A, along with the real-time stiffness of the VSA at each level of intensity. As we can see, the stiffness of the VSA continuously varied with respect to the RMS of sEMG signals, by following the relationship described in the musculoskeletal model. Moreover, with the increase of the lifting load, the RMS values were also augmented due to the increased muscle contraction. The stiffness amplitude of the VSA was accordingly enlarged in order to provide enhanced assistance to the user for completing the laborious task. Similar outcomes were observed in other participants.



(a) 0 kg



(b) 1 kg



(c) 2 kg

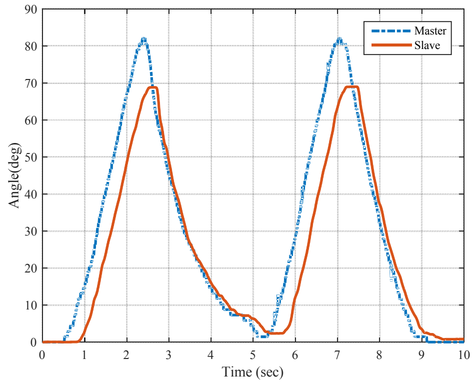
Fig. 5.1: Real-time stiffness control with different loads

5.3.2 Performance Evaluation of the Exoskeleton Device with sEMG-based Real-time Stiffness Variation

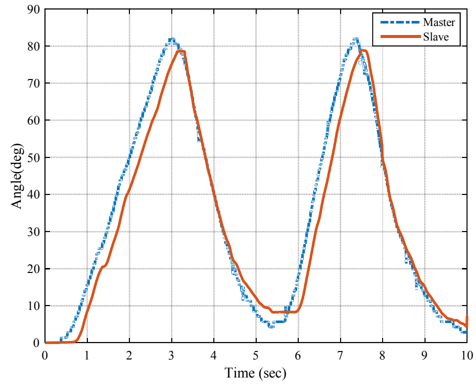
A rehabilitation task involving the participation of both arms was designed and conducted on ten subjects. A miniature inertial measurement unit (GY-25 tilt angle module) was attached to the subject's left hand to capture the active elbow movements. Meanwhile, the trajectory of the subject's right arm with the PVSED was recorded by an attached MTx angle sensor. In addition, a small-size force sensor (FS03, Honeywell Ltd., U.S.A) was placed into the upper support frame to measure the contact force during elbow movement. In the experiment, the subjects performed voluntary elbow motion on the left side. Meanwhile, the subject's elbow movements on the right side were completely powered by the PVSED to track the elbow movement of the left side.

The tracking accuracy of the proposed rehabilitation system was evaluated in four stiffness settings, including a minimum stiffness of the VSA (pivot position d= 0 mm, K= 18.48 Nm/rad) as low stiffness (LS), a maximum stiffness of the VSA (pivot position d= 20 mm, K= 119.49 Nm/rad) as high stiffness (HS), an average joint stiffness measured in human elbow flexion/extension (pivot position d= 5 mm, K= 28.33 Nm/rad) as medium stiffness (MS), and an sEMG-based variable stiffness (VS).

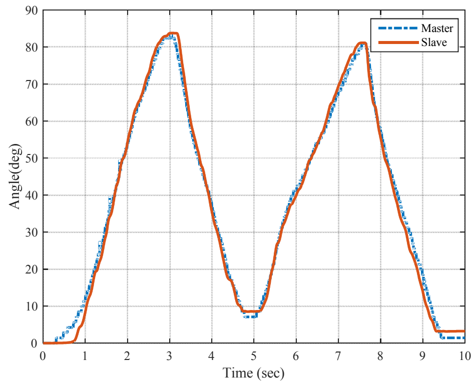
A segment of the experimental results for Subject A is plotted in Fig. 5.2. The tracking error was principally caused by the gravitational torque from the weight of the forearm, and its range varied due to the stiffness settings. For the trials with constant stiffness, the tracking error increased in the ascending phase while decreased in the descending phase. It is of considerable interest that in the trial with sEMG-based real-time stiffness variation, the system allowed the slave side to deviate from the reference trajectories, while it attempted to minimize the scale of the deviations throughout the process. The average tracking error along with standard deviation (SD) of the ten subjects in each stiffness setting was calculated. It is seen that the average tracking error in the VS case was comparable with that in the MS case (4.05° versus 3.63°), although the SD in the former case was more significant (±1.09° versus ±0.47°) owing to the inter-subject variability of sEMG signals.



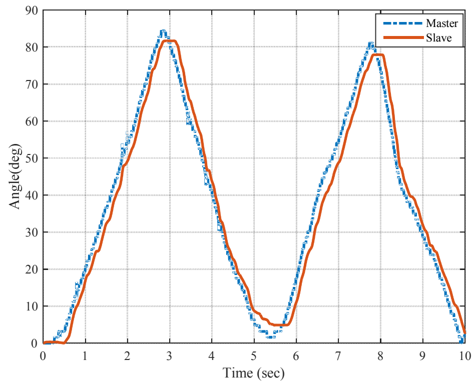
(a) LS



(b) MS



(c) HS



(d) VS

Fig. 5.2: Trajectories of the elbow bilateral rehabilitation task

To further evaluate the comfort of the proposed rehabilitation system, a trial to compare the contact force in the MS and VS settings was conducted. In the experiment, a bilateral movement task including ten cycles of elbow flexion/extension was completed by ten subjects.

Although the contact force varied slightly among subjects due to the minor shift of detection position on each individual, a general trend of lower contact force was seen in the VS trial, in which the value decreased by 47.2% (from 2.29 N to 1.21 N) on average compared with that in the MS trial.

5.5 Summary

In this chapter, an sEMG-based real-time stiffness control was proposed to facilitate efficient and comfortable robot-assisted bilateral rehabilitation. Preliminary experiments were carried out to evaluate the feasibility of the proposed sEMG-based joint stiffness control and characterize the performance of the novel bilateral rehabilitation system. In the lifting trial with different load weights, the experimental results showed that the proposed sEMG-based joint stiffness control method allowed the subjects to real-time adjust the stiffness of the VSA by their sEMG signals to adapt to different task requirements. Furthermore, the subsequent bilateral rehabilitation task showed that with the aid of the sEMG-based real-time stiffness variation, the proposed bilateral rehabilitation system achieved promising results in both tracking accuracy and comfortability.

Chapter 6 Development of a Home-based Tele-rehabilitation System

6.1 Introduction

Due to the shortage of therapists and limited medical resources, numerous stroke patients cannot get regular and expert rehabilitation training. Further, it is a significant challenge for stroke patients with physical difficulties to move from their home to rehabilitation centers or hospitals. All of these problems place a heavy burden on our healthcare system and that would result in delayed and insufficient rehabilitation. As a result, home-based tele-rehabilitation system is proposed as an alternative to hospital-based therapy to reduce the therapist's workload and facilitate an individual's recovery, on the basis that a robotic system is an ideal tool for intensive and repetitive rehabilitation.

6.2 Overview of the System Framework

The framework of the proposed tele-rehabilitation system consists of two separate sides, including a master side for the therapist and a slave side for the patient. The therapist can operate a haptic device to remotely guide the patient wearing the exoskeleton to perform home-based rehabilitation. In addition, the proposed tele-rehabilitation system allows the therapist to monitor the patient's motion and dynamically adjust training parameters based on the real-time physical and biological feedbacks from the slave side.

6.3 Teleoperation Interface

In order to facilitate teleoperation, user interfaces, including the master side and the slave side, were designed. On the master side, the therapist may remotely assist the patient to perform rehabilitation and adjust training parameters based on the task requirements and patient's physical condition. In addition, the real-time data streaming such as the joint angles and force on the slave side can be observed from this panel. On the slave side, the patient's real-time muscle activity and contact force can be observed on the program windows.

6.4 Control Architecture

In order to adapt to the individual physical conditions, the proposed tele-rehabilitation system provides alternative control methods for rehabilitation, i.e., therapist-in-charge mode and patient-in-charge mode. In the former mode, a haptic-enabled guided training is proposed to allow the therapist to tune the strategy and intensity of the therapy in real-time based on awareness of the contact forces applied to the patient's upper limb. In the latter mode, an sEMG-based supervised training method is proposed to allow the patient to perform robot-assisted bilateral rehabilitation at home independently.

6.5 Stabilization Algorithm

For a tele-rehabilitation system, the highest priority must be given to the user's safety. Time-varying delays in tele-communication may lead to energy accumulation, thus causing major challenges in the stability of the tele-robotic system and the safety of the human-robot interaction.

To address these issues, a stabilization algorithm is presented using the embedded force and angle sensors to monitor the potential risk. Firstly, the received data from the master side is compared with the preset threshold to avoid exceeding the range of motion of human. Moreover, once the measured force exceeds 12 N, or the robotic angular velocity is larger than 150°/s, the safety loop will be triggered to switch off the power motor immediately. Meanwhile, the VSA motor will drive the pivot to return to its original position, where has the minimum stiffness.

6.6 System Evaluation

6.6.1 Experimental Setups

The experiment was carried out in the faculty of engineering, Kagawa University. The master side is set in Room 6903, 9th floor, Building No. 6, while the slave side is set in Room 1201, 2nd floor, Building No. 1. This study was approved by the Institutional Review Board (IRB) at the Faculty of Engineering, Kagawa University. Two healthy subjects (assumed as the therapist and the patient separately) were enrolled in this experiment after signing a written consent. In the trial, the therapist operated the haptic device HD^2 to assist the patient wearing the exoskeleton device PVSED to perform home-based tele-rehabilitation training.

6.6.2 Fidelity of Data Transmission

The fidelity of data transmission in the tele-rehabilitation was evaluated in the master-slave angle tracking and stiffness tracking respectively. The slave side could preciously track the angle and stiffness trajectories of the master side although there was an inevitable time delay during the process.

6.6.3 Implementation of Safety Loop

To evaluate the effectiveness and response speed of the safety loop, a preliminary test was conducted on a healthy subject for haptic-enabled guided training and sEMG-based supervised training respectively.

In the former mode, the therapist operated the HD^2 to remotely control the PVSED to assist the patient to perform elbow motions. However, when the received angle from the master side exceeded the preset safety threshold, the angle of the PVSED was limited under the threshold in order to avoid exceeding the range of motion of human, which may pose a risk to the patients. In the latter mode, the subject's right upper limb was passively driven by the PVSED to perform robot-assisted bilateral elbow flexion. Then, the subject suddenly exerted an opposite force on the mounted support frame against the movement trend, which mimics the typical symptoms of spasms. During this procedure, the subject's elbow trajectory on the slave side, interaction force with the upper support frame, the sEMG signals from the contralateral arm and the real-time stiffness of the VSA were simultaneously recorded. It is evident that when the interaction force exceeded the threshold, the safety loop was automatically triggered and the actuation motor of the PVSED was switched off immediately. Regardless of the sEMG signals variation, the stiffness of the VSA was regulated to the lowest level to prevent uncomfortable or even painful interaction.

6.7 Summary

In this chapter, a home-based tele-rehabilitation system was proposed to facilitate home-based upper limb rehabilitation and subsequently evaluated by experiments. In the trial of the fidelity of data transmission, the tele-communication between the master side and slave side demonstrated satisfying performance in both angle and stiffness tracking. Then, the response of the safety loop in the proposed system was tested by simulating an emergency, and the results showed it enabled fast switching of actuation to protect the user’s safety. With the aid of the safety loop, the proposed tele-rehabilitation system is capable of taking immediate measures to ensure the patient’s safety even in case of emergency.

Chapter 7 Conclusions

7.1 Thesis Summary

Robot-assisted rehabilitation employing exoskeleton devices has been proven to be an effective method for stroke patients with disabilities to recover impaired motor function. Although robot rehabilitation systems have been deployed to deliver meaningful restorative therapy to stroke patients, some key issues need to be addressed to facilitate the rehabilitation process. Firstly, most of the existing rehabilitation systems are bulky and heavy, which are not suitable for in-home use. Secondly, the comfortability and safety of patient-robot interaction are significant concerns for rehabilitation robots. Thirdly, robotic systems lack the practical experience of a skilled therapist who is trained well to perform appropriate force field. In this research, a novel home-based tele-rehabilitation system has been proposed in order to provide comfortable and safe human-robot interaction to the patient and allow the therapist to remotely help the patient perform efficient and supervised home-based upper limb rehabilitation. Firstly, a novel powered variable-stiffness exoskeleton device (PVSED) was designed and evaluated by performance trials. The proposed PVSED is light-weight and portable, which is suitable for home-based rehabilitation. Additionally, it can adjust the output stiffness using an integrated variable stiffness actuator (VSA) to adapt to the training requirements and individual's physical condition. Then, an sEMG-based real-time stiffness control was proposed to promote comfortable home-based bilateral rehabilitation. With the aid of the proposed sEMG-based real-time joint stiffness control, the PVSED is capable of providing appropriate power assistance based on the patient's motion intention. Finally, a novel home-based tele-rehabilitation system was developed to deliver effective rehabilitation and supervise the patient remotely. The proposed tele-rehabilitation system provides alternative control methods for rehabilitation, i.e., therapist-in-charge mode and patient-in-charge mode. In the former mode, a haptic-enabled guided training method is proposed to allow the therapist to guide the patient to perform rehabilitation movement by means of a haptic device. Meanwhile, the contact force on the patient side is delivered to the therapist by the haptic device and used as a reference for therapists to adjust the training parameters. In the latter mode, an sEMG-based supervised training method is proposed to allow the patient to independently perform robot-assisted bilateral rehabilitation at home. Meanwhile, the therapist can feel how the patient is performing based on his/her biological signals and further evaluate the patient's recovery process. Benefitting from this characteristc, the stroke patients may perform effective rehabilitation with the remote guidance of the therapist. By fusing the therapist's skills and robotic capabilities, the proposed tele-rehabilitation system has the potential to provide task-oriented and individual-specific rehabilitation to facilitate the recovery process.

7.2 Research Achievements

The main research achievements can be summarized as

1) Designed a novel portable and wearable exoskeleton device which integrates a variable stiffness actuator to provide adjustable power assistance.
2) Proposed an sEMG-based real-time stiffness control to improve the safety and comfortability of human-robot interaction for each individual patient.
3) Developed a tele-rehabilitation system that allows skilled therapists to remotely guide and supervise the patient's home-based rehabilitation.

7.3 Recommendations for Future Work

Some limitations of this study need to be noted and addressed in the near future. Firstly, the backlash of cable-driven mechanism caused hysteresis in elbow-assisted motion. An adaptive backlash compensation control strategy is preferred to minimize this negative effect. Secondly, the proposed bilateral rehabilitation system only achieved passive rehabilitation training thus far. The assisted-as-needed torque control may be a promising approach to encourage active rehabilitation practice. Thirdly, the preliminary evaluation of the proposed rehabilitation system was only conducted on healthy subjects. Rehabilitation trials with stroke patients are expected to be involved in the near future for further evaluation.

Publication List

International Journal Papers

1. **<u>Yi Liu</u>**, Shuxiang Guo, Ziyi Yang, Hideyuki Hirata, et al., "A Home-based Bilateral Rehabilitation System with sEMG-based Real-time Variable Stiffness", *IEEE Journal of Biomedical and Health Informatics*, 2020. DOI: 10.1109/JBHI.2020.3027303.
2. **<u>Yi Liu</u>**, Shuxiang Guo, Hideyuki Hirata, et al., "Development of a powered variable-stiffness exoskeleton device for elbow rehabilitation", *Biomedical Microdevices*, 2018. DOI: 10.1007/s10544-018-0312-6.
3. Ziyi Yang, Shuxiang Guo, **<u>Yi Liu</u>**, Hideyuki Hirata, et al., "An intention-based online bilateral training system for upper limb motor rehabilitation", *Microsystem Technologies*, 2020. DOI: 10.1007/s00542-020-04939-x.

International Conference Papers

1. **<u>Yi Liu</u>**, Shuxiang Guo, et al., "Preliminary Design of a Novel Teleoperation Interface for Home-based Upper Limb Rehabilitation ", *Proceedings of 2020 IEEE International Conference on Mechatronics and Automation,* pp. 1553-1557, October 13-16, Beijing, China, 2020.
2. **<u>Yi Liu</u>**, Shuxiang Guo, et al., "Performance Evaluation of a Powered Variable-stiffness Exoskeleton Device for Bilateral Training ", *Proceedings of 2019 IEEE International Conference on Mechatronics and Automation,* pp. 2163-2167, August 4-7, Tianjin, China, 2019.
3. **<u>Yi Liu</u>**, Shuxiang Guo, et al., "Modeling and Analysis of a Variable

Stiffness Actuator for a Safe Home-based Exoskeleton", *Proceedings of 2018 IEEE International Conference on Mechatronics and Automation*, pp. 2243-2248, August 5-8, Changchun, China, 2018.

4. **Yi Liu** and Shuxiang Guo, "Design of a Novel Wearable Power-assist Exoskeleton Device", *Proceedings of 2018 13th World Congress on Intelligent Control and Automation*, pp.131-134, July 4-8, Changsha, China, 2018.
5. **Yi Liu**, Shuxiang Guo, et al., "A Novel sEMG Control-based Variable Stiffness Exoskeleton", *Proceedings of 2017 IEEE International Conference on Mechatronics and Automation*, pp. 1444-1449, August 4-7, Takamatsu, Japan, 2017.
6. Shuxiang Guo, **Yi Liu**, et al., "A VR-based Self-rehabilitation System", *Proceedings of 2016 IEEE International Conference on Mechatronics and Automation*, pp. 1173-1178, August 7-10, Harbin, China, 2016.
7. Ziyi Yang, Shuxiang Guo, and **Yi Liu**, "Comparison of Isometric Force Estimation Methods for Upper Limb Elbow Joints", *Proceedings of 2020 IEEE International Conference on Mechatronics and Automation,* pp. 1558-1563, October 13-16, Beijing, China, 2020.
8. Ziyi Yang, Shuxiang Guo, and **Yi Liu**, "EMG-based Continuous Prediction of the Upper Limb Elbow Joint Angle Using GRNN", *Proceedings of 2019 IEEE International Conference on Mechatronics and Automation,* pp. 2168-2173, August 4-7, Tianjin, China, 2019.

Biographic Sketch

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