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Performance Evaluation of a Powered Variable-stiffness Exoskeleton Device for Bilateral Training

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Abstract – **Bilateral rehabilitation training has been proposed to help patients of hemiplegia who have partial impairment of the upper limb to regain the ability of daily living (ADL). In this paper, a bilateral training method by means of a novel power-assist exoskeleton device is presented to help post-stroke patients to improve rehabilitation effects. In order to provide appropriate power assistance during home-based rehabilitation, a variable stiffness actuator (VSA) was applied to regulate the output stiffness of the exoskeleton device. This paper presents the performance evaluation of the integrated VSA. The results related to the performance demonstrated that high stiffness could rapidly force the elbow joint to the initial equilibrium position to ensure precise trajectory movement, while low stiffness could allow relatively large deviations from the desired trajectory thus inherently guaranteeing the patient's safety. In addition, a preliminary elbow rehabilitation trial is performed to evaluate the proposed bilateral rehabilitation strategy. The results show that the proposed bilateral training method can allow the exoskeleton device to smoothly drive the user's right arm to follow the movements of his left arm.**

Index Terms – Bilateral training method, exoskeleton device, variable stiffness, home-based rehabilitation

I. INTRODUCTION

With the sustained growth of aged people all over the world, the incidence of the stroke becomes more and more common as well in recent years [1]. Stroke, which is one of the main reason for long-term loss of motor ability, tends to cause the impairment of upper limb and disabilities of performing activities of daily living (ADLs) [2]. Further, hemiparesis is the most common sequela after stroke. It is reported as high as 85% of post-stroke patients suffer partial impairments of the upper limb [3]. Bilateral rehabilitation training is proposed for hemiplegic patients to perform the simultaneous movements of both arms in order to repair the impaired nuero-muscular system [4]. The clinical results reported the muscle activation is more synchronized with limb motion in bilateral robot-assisted movements [5]. Several bilateral rehabilitation strategies have been proposed for upper extremity hemiparesis [6]. Mirror therapy is a typical bilateral rehabilitation method which utilizes the movements of the intact arm to offer the visual stimulation of the impaired limb [7].

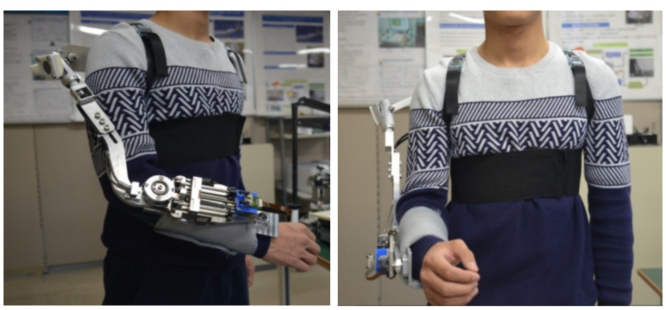
A Prolonged and effective rehabilitation process is extremely significant for post-stroke patients. However, it requests intensive efforts from therapists and health care workers. In order to provide intensive and periodical self-rehabilitation training as well as reducing the expense of medical resources, robot-aided rehabilitation systems have been developed in recent years [8-11]. In addition, robotic devices can evaluate the patient's motor function recovery by collecting some physical and biological parameters of human motion (e.g., joint speed, joint force, and electromyographic signals, etc.) from the integrated sensors. Rehabilitation devices have been developed as the hardware platform to achieve different rehabilitation strategies [12-17]. They can be divided into 2 main categories: end-effector type and powered exoskeleton type. Different from the multi-joint movements for end-effector type, exoskeleton type can provide independent assistance to each target joint, which significantly improve the impaired muscle strength [18]. Especially, wearable power-assist exoskeletons are suitable for home-based self-rehabilitation due to their characteristics of compact structure and light weight. To facilitate home-based rehabilitation, Song et al. designed a light-weight rehabilitation device ULERD which has 3 active degrees of freedom (DoFs) to provide elbow and wrist rehabilitation training [19]. In the following study, Zhang et al. proposed a bilateral rehabilitation training system in which integrated a 6-DoF Phantom Premium (3D Systems, Inc., U.S.A.) and the developed ULERD to perform coordinative motions involved both of the upper limbs [20]. In this system, a VR-based graphic interface is developed to provide cues for task-oriented bilateral training thus enhancing rehabilitation effects.

Most of the current researches focus on the enhancement of vision and haptic feedback for the purpose of improving rehabilitation effects, while the assisting or resisting force provided by the exoskeleton device is constant. However, the human muscle impedance is varied with respect to the upper limb postures and the interaction of related muscles during motions [21]. In order to provide appropriate power assistance for each individual subject, the joint stiffness of the exoskeleton device is expected to be adjusted based on the physical condition of the patient. Variable stiffness actuators (VSAs) can independently adjust the actuated output stiffness of the exoskeleton device [22]. Further, the induced stiffness doesn't rely on the complicated closed-loop interaction control strategies, which is an intrinsic property of the hardware system [23]. Therefore, this characteristic can effectively avoid any risks caused by the control loop. In addition, VSA-based rehabilitation robot can achieve appropriate power assistance in accordance with the specific impairment level of the patient's upper limb, which is beneficial for chronic post-stroke patients with prolonged rehabilitation process.

In this paper, we present a bilateral rehabilitation strategy which is applied an exoskeleton device (PVSED) to implement home-based rehabilitation training. The proposed PVSED utilizes an embedded VSA to regulate the output joint stiffness. Its working principle was introduced and we carried out related experiments to evaluate the characteristics of the integrated VSA. Furthermore, a bilateral rehabilitation training method in which the subject uses his intact upper limb to perform elbow training as a reference to control the equipped exoskeleton on the impaired upper limb. The results show that the subject can use his left hand to control the movement of PVSED equipped on his right hand thus completing home-based bilateral rehabilitation training. The rest of this paper is organized as follows: the powered variable-stiffness exoskeleton device and control method of bilateral training is presented in Section II. In Section III, characteristics of the integrated VSA are presented and a bilateral elbow rehabilitation trial is performed on a healthy subject. Finally, conclusions and future work are drawn in Section IV.

II. Methods

A. Prototype of the Novel Exoskeleton Device



(a) Lateral view (b) Front view

Fig. 1. Physical Prototype of the Powered Variable-stiffness Exoskeleton Device

The physical prototype of the proposed PVSED with a wearer is shown in Fig. 1. It is designed as a wearable and portable power-assist exoskeleton for elbow rehabilitation [24]. In order to facilitate its usage of home-based daily rehabilitation, the main exoskeletal frame and connection parts are mainly made of aluminium alloys and Acrylonitrile Butadiene Styrene (ABS), which results in improvements of exoskeleton structure and weight. The control unit Arduino Mega 2560 (Weight: 37 g, Size: 101.52 mm length x 53.3 mm width, 54 digital input/output pins, Arduino cc., Italy) is designed to be mounted on a compact back frame. A 3000 mAh Lipo-battery pack is mounted on the back frame and provides power for motors and microprocessors. As a result, the device can be equipped on the patient's back via two shoulder straps and a belt. These features enable its use outside of home. To improve the comfortability and wearability of the device, the lengths of back and upper limb parts are adjustable thus making allowances for different wearers who have different body sizes. In addition, there are other 3 revolute joints including internal/ external rotation of the upper limb, shoulder adduction/ abduction, shoulder flexion/ extension designed in the PVSED. By means of the 3 passive degrees of freedom (DoFs), the patient's natural joint range of motion will not be limited by the exoskeleton device. Additionally, the proposed PVSED can provide power assistance for the patient's upper limb to complete elbow rehabilitation training. More importantly, the actuated elbow joint stiffness is regulated in order to meet different task requirements. The stiffness is regulated by the aid of the integrated VSA. As shown in Fig. 2, it mainly consists of a pair of antagonist springs, a slider driven by a DC motor (Maxon RE-30 Graphite Brushes Motor, Switzerland) to move a pivot, an actuated output link which is worn on the subject's forearm. The schematic of the proposed VSA is simplified as shown in Fig. 3. Due to the gravity of the subject upper limb, a contact force is generated on the output link. The force exerted on the output link is balanced by the spring forces based on the equilibrium of moments. As seen from Eq. 1, the transmission ratio L_1/L_2 depends on the pivot position. Therefore, we can move the pivot position to regulate the exerted force.

$$F_{output} = \frac{F_{spring} \cdot L_1}{L_2} \quad (1)$$

where F_{spring} is the force generated by the spring elongation, while L_1 and L_2 are the distance from the current pivot position to spring side and output link side respectively.

The relationship between the pivot distance and the output elbow joint stiffness can be approximated by a 2^{nd} polynomial fitting, which is described by

$$K = 0.1443 \cdot d^2 + 2.287 \cdot d + 16.95 \; (0 \leq d \leq 20 \; mm) \quad (2)$$

where K is the elbow joint stiffness of the exoskeleton device, while d is the pivot position moved from 0 to 20 mm.

By the aim of the integrated VSA, the characteristic of stiffness variation is only related to the pivot position without any other control loop, which is more reliable and avoids the instabilities result from the impedance control system.

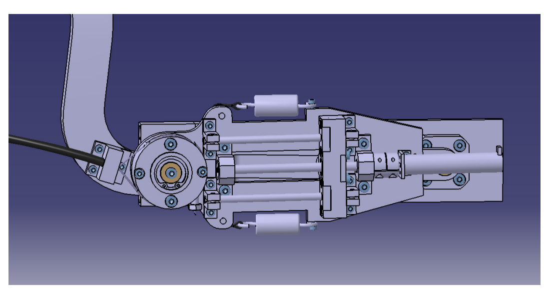


Fig. 2. CAD Model of the Proposed VSA

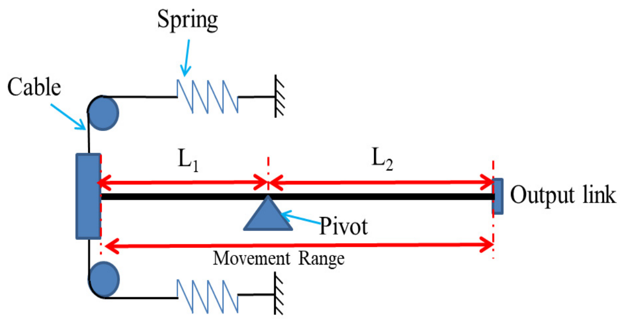


Fig. 3. Schematic Diagram of the Stiffness Variation

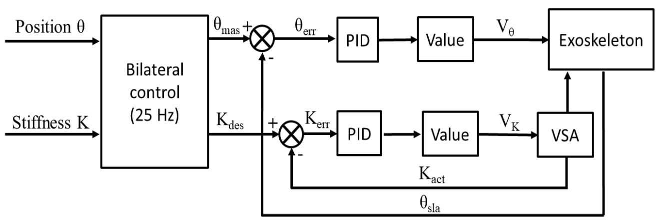


Fig. 4. Block Diagram of the Proposed Bilateral Control Strategy

B. *Bilateral Control Strategy*

For a wearable upper extremity exoskeleton device aimed at safe home-based rehabilitation, it should provide appropriate power assistance to the patient in accordance with their impairment levels of upper limbs. To achieve this target, we proposed a bilateral control method which combines stiffness variation and elbow power assistance. As shown in Fig. 4, the elbow movement of the user's intact side is collected by a GY-25 tilt angle module as the reference of the bilateral elbow movements. Meanwhile, a desired actuated elbow joint stiffness based on the patient's physical condition is sent to the controller. The predefined parameters are transmitted to the Arduino Mega 2560 micro-controller board at a frequency of 25 Hz. The elbow angle θ_{mas} recorded in the master side and the desired actuated joint stiffness K_{des} are respectively sent to the PID controller.

$$V_\theta(i) = K_p \cdot \theta_{err}(i) + K_i \cdot \int_0^i \theta_{err}(i)di + K_d \cdot \frac{d}{di}\theta_{err}(i) \quad (3)$$

$$\theta_{err}(i) = \theta_{mas}(i) - \theta_{sla}(i) \quad (4)$$

where $V_\theta(i)$ is the input variable for elbow position control, θ_{mas} is the recorded elbow position of the intact arm in the master side, θ_{slav} is the actual elbow position of the impaired arm in the slave side, θ_{err} is the angle difference between θ_{mas} and θ_{slav}. K_p, K_i and K_d are corresponding parameters of the proportional, integral and derivative component respectively, which are obtained by the experiments.

For the joint stiffness control, a desired joint stiffness is given according to the patient's impairments and rehabilitation requirements. A typical PID controller is used to control the motor to move the pivot position in order to adjust the output stiffness of the VSA.

$$V_K(i) = K_p \cdot K_{err}(i) + K_i \cdot \int_0^i K_{err}(i)di + K_d \cdot \frac{d}{di}K_{err}(i) \quad (5)$$

$$K_{err}(i) = K_{des}(i) - K_{act}(i) \quad (6)$$

where K_p, K_i and K_d are defined as above, $V_K(i)$ is the input variable for the motor control, K_{des} is the desired elbow joint stiffness, K_{act} is the actual joint stiffness of the exoskeleton device. K_{err} is the stiffness error between the desired and actual joint stiffness.

The most important issue for home-based rehabilitation training is to ensure the user's safety even emergencies such as spasms occur. In our proposed control strategy, the subject's elbow movement is monitored by the GY-25 tilt module angle. If the device exceeds the movement range of human elbow joint or the elbow movement is larger than 150°/s, the controller will immediately turn off the actuation system and adjust the elbow joint stiffness to the minimum value. By this method, a safety control loop is implemented on the exoskeleton device.

III. Experiments and Results

A. *Performance Evaluation of VSA*

VSA can independently adjust the actuated joint stiffness thus adapting to different environmental requirements. In order to characterize the features of the proposed VSA, a pilot trial is carried out to simulate the situation when the VSA device meets a sudden impaction due to the environment. Figure 5 shows the equilibrium position of the VSA, where there is no deflection between the output link and the main frame. The equilibrium position is defined as 0° in the trial. A counterclockwise deflection of 12.5° between the output link and the main frame is set by exerting a force. Then, the force is released and the output link swings. An MTx sensor is used to record its oscillation trajectories. It is noted that the minimum elbow rotation is limited to the equilibrium position in order to avoid any inverse motion of the human elbow joints. The experiments are respectively carried out for 3 different levels of joint stiffness by moving the pivot position to 0 mm, 10 mm and 20 mm.

Figure 6 reported the experimental results, which shows that as the increase of joint stiffness, the oscillation cycle of the output link is gradually weak. In addition, the time return to the stable equilibrium position is decreased. As a result, low stiffness allows relatively large deviations from its equilibrium position thus avoiding excessive interaction forces and passively ensure the user's safety, while high stiffness can make precise trajectory tracking control easier. Hence, the rehabilitation intensity can be improved by increasing the joint stiffness. By means of changing the pivot position, the actuated elbow joint stiffness can be adjusted to adapt to the patients with a specific impairment of the upper limb.

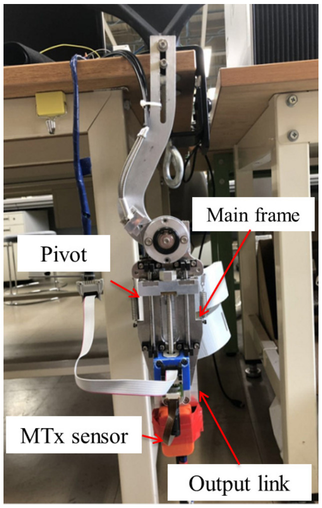
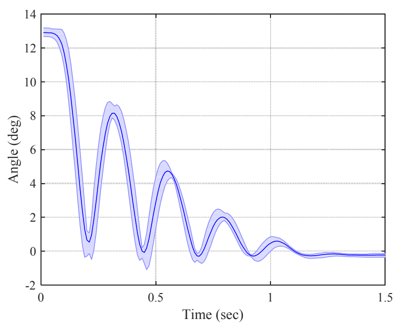
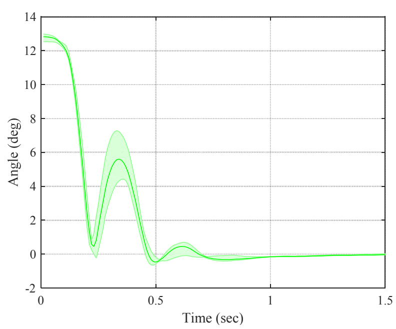


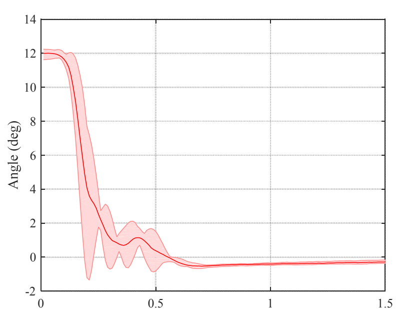
Fig. 5. Experimental Setups



(a) Low Stiffness



(b) Medium Stiffness



(c) High Stiffness

Fig. 6. Experimental Results of Oscillation in Different Stiffness Conditions

B. Bilateral Rehabilitation Trial

A preliminary bilateral rehabilitation trial has been designed and tested on a healthy subject. In this trial, the left upper limb of the participant was assumed as the intact side and can move freely. The right upper limb was assumed as the impaired side and driven by the exoskeleton. The subject was asked to use his left hand to control the movements of the exoskeleton. A GY-25 sensor is attached to the subject's left hand to detect the movements of the master side. Meanwhile, the exoskeleton would drive the user's right hand to track the movements of the user's left side. An MTx sensor was applied to record the movement trajectories of the slave side. During the experiment, the subject was asked to complete elbow flexion and extension successively by the aid of his left arm at a moderate pace (around 15°/s).

A continuous movement of elbow flexion and extension for 3 times was carried out and the trajectories are shown in Fig. 8. It is easy to be noticed that the envelopes of the trajectory in the master side and the slave side have similar shapes, which means the slave side could track the movements of the master side successfully. In addition, the motions of the slave side can

(a) Starting position (b) Horizontal position (c) End position

Fig. 7. Procedures of Bilateral Rehabilitation Trials

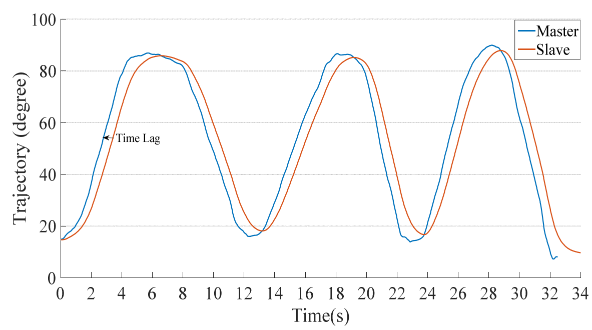


Fig. 8. Recorded Elbow Trajectories

TABLE I
PARAMETERS OF THE BILATERAL REHABILITATION TRIAL

Elbow F/E		*3 times*
Motion range	*Master*	*7.3°↔ 89.9°*
	Slave	*9.4°↔ 86.8°*
Amplitude	*Master*	*82.6°*
	Slave	*77.4°*
Time Lag		*0.6 s*

keep pace with the master side. However, as reported in Table I, a time lag appeared between the master side and the slave side appeared. One of the main reasons is time consumption used to send the data of the movements from the master side to the slave side. The time lag caused by data transmission is a common issue in the teleoperation and master-slave systems. The other reason is that the cable-driven is not in tension enough at the beginning. After the motor rotated a certain degree, the cable becomes in tension and then can start to drive the movements of the forearm part. Limited by this phenomenon, the range of motion for the slave side is nearly 7.2° smaller than that for the master side. The average time lag is nearly 0.6 s, which doesn't affect the effect of rehabilitation training. Although the gentle jitter of movements exists in the master side, the exoskeleton can provide a smooth pace of the elbow movements for the user, which is beneficial for the user's safety and can avoid drastic variation in a short time.

IV. Conclusions

In this paper, we proposed a bilateral rehabilitation control strategy which is applied on a powered variable-stiffness exoskeleton device for safe home-based rehabilitation training. Firstly, the performance of the VSA is evaluated by an oscillation trial. The experimental results show that with the increase of joint stiffness, the device forces the position of the elbow joint and the allowed deviations from its predefined trajectory are decreased. Further, a preliminary elbow rehabilitation test is performed on a healthy subject to evaluate the proposed bilateral rehabilitation control strategy. The results show that the exoskeleton equipped in the impaired side can smoothly track the movements of the intact side although there is a time lag of 0.6 s between them. By the aid of the proposed bilateral rehabilitation control method, the powered variable-stiffness exoskeleton device has the potential to help patients of hemiplegia to complete home-based self-rehabilitation.

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References

[1] D. Mozaffarian, E. J. Benjamin, A. S. Go, D. K. Arnett, M. J. Blaha, M. Cushman, *et al.*, "Executive summary: Heart Disease and Stroke Statistics-2016 update: A report from the American Heart Association", *Circulation,* vol. 133, no. 4, p. 447, 2016.

[2] Y. Hsieh, T. Shih, K. Lin, and C. Wu, "Upper-extremity robot-aided rehabilitation after stroke: A comparison of the arm and wrist robots," *Journal of the Neurological Sciences,* vol. 381, p. 599, 2017.

[3] S. Barreca, S. L. Wolf, S. Fasoli, and R. Bohannon, "Treatment interventions for the paretic upper limb of stroke survivors: a critical review", *Neurorehabilitation and neural repair,* vol. 17, no. 4, pp. 220-226, 2003.

[4] S. M. Waller and J. Whitall, "Bilateral arm training: why and who benefits?," *NeuroRehabilitation,* vol. 23, no.1, pp. 29-41, 2008.

[5] E. Akdoğan, M. E. Aktan, A. T. Koru, M. S. Arslan, M. Atlıhan, and B. Kuran, "Hybrid impedance control of a robot manipulator for wrist and forearm rehabilitation: Performance analysis and clinical results," *Mechatronics,* vol. 49, pp. 77-91, 2018.

[6] A. E. van Delden, P. J. Beek, M. Roerdink, G. Kwakkel, and C. E. Peper, "Unilateral and bilateral upper-limb training interventions after stroke have similar effects on bimanual coupling strength," *Neurorehabilitation and neural repair,* vol. 29, no. 3, pp. 255-267, 2015.

[7] M. Simkins, N. Byl, H. Kim, G. Abrams, and J. Rosen, "Upper limb bilateral symmetric training with robotic assistance and clinical outcomes for stroke: A pilot study," *International Journal of Intelligent Computing and Cybernetics,* vol. 9, no.1, pp. 83-104, 2016.

[8] J. M. Veerbeek, A. C. Langbroek-Amersfoort, E. E. van Wegen, C. G. Meskers, and G. Kwakkel, "Effects of robot-assisted therapy for the upper limb after stroke: a systematic review and meta-analysis," *Neurorehabilitation and neural repair,* vol. 31, no. 2, pp. 107-121, 2017.

[9] N. Smania, N. Valè, E. Dimitrova, S. Mazzoleni, M. Filippetti, C. Depaoli, *et al.*, "Effects of high-intensity robot-assisted training in hand function recovery and adl independence in individuals with multiple sclerosis: A randomized controlled single-blinded trial," *Gait & Posture,* vol. 57, p. 16, 2017.

[10] Y.-w. Hsieh, C.-y. Wu, W.-e. Wang, K.-c. Lin, K.-c. Chang, C.-c. Chen, *et al.*, "Bilateral robotic priming before task-oriented approach in subacute stroke rehabilitation: A pilot randomized controlled trial," *Clinical rehabilitation,* vol. 31, no. 2, pp. 225-233, 2017.

[11] C. Lauretti, F. Cordella, E. Guglielmelli, and L. Zollo, "Learning by Demonstration for planning activities of daily living in rehabilitation and assistive robotics," *IEEE Robotics and Automation Letters,* vol. 2, no. 3, pp. 1375-1382, 2017.

[12] Z. Song, S. Guo, M. Pang, S. Zhang, N. Xiao, B. Gao, *et al.*, "Implementation of resistance training using an upper-limb exoskeleton rehabilitation device for elbow joint," *J. Med. Biol. Eng,* vol. 34, no. 2, pp. 188-196, 2014.

[13] S. Zhang, S. Guo, B. Gao, H. Hirata, and H. Ishihara, "Design of a Novel Telerehabilitation System with a Force-Sensing Mechanism," *Sensors,* vol. 15, no. 5, pp. 11511-11527, 2015.

[14] S. Zhang, S. Guo, B. Gao, Q. Huang, M. Pang, H. Hirata, *et al.*, "Muscle Strength Assessment System Using sEMG-Based Force Prediction Method for Wrist Joint," *Journal of Medical and Biological Engineering,* vol. 36, no. 1, pp. 121-131, 2016.

[15] S. Zhang, S. Guo, Y. Fu, L. Boulardot, Q. Huang, H. Hirata, *et al.*, "Integrating Compliant Actuator and Torque Limiter Mechanism for Safe Home-Based Upper-Limb Rehabilitation Device Design," *Journal of Medical and Biological Engineering,* vol. 37, no. 3, pp. 357-364, 2017.

[16] Y. Liu, S. Guo, S. Zhang, and L. Boulardot, "A novel sEMG control-based variable stiffness exoskeleton," in *Proceedings of 2017 IEEE International Conference on Mechatronics and Automation (ICMA)*, pp. 1444-1449, 2017.

[17] Z. Song, S. Guo, and Y. Fu, "Development of an upper extremity motor function rehabilitation system and an assessment system," *International Journal of Mechatronics and Automation,* vol. 1, no. 1, pp. 19-28, 2011.

[18] N. Vitiello, T. Lenzi, S. Roccella, S. M. De Rossi, E. Cattin, F. Giovacchini, *et al.*, "NEUROExos: A powered elbow exoskeleton for physical rehabilitation," *IEEE Transactions on Robotics,* vol. 29, no. 1, pp. 220-235, 2013.

[19] Z. Song and S. Guo, "Design process of exoskeleton rehabilitation device and implementation of bilateral upper limb motor movement," *Journal of Medical and Biological Engineering,* vol. 32, no. 5, pp. 323-330, 2012.

[20] S. Zhang, Q. Fu, S. Guo, and Y. Fu, "Coordinative Motion-Based Bilateral Rehabilitation Training System with Exoskeleton and Haptic Devices for Biomedical Application," *Micromachines,* vol. 10, no. 8, doi:10.3390/app9081710 , 2019.

[21] R. Gopura, D. Bandara, K. Kiguchi, and G. K. Mann, "Developments in hardware systems of active upper-limb exoskeleton robots: A review," *Robotics and Autonomous Systems,* vol. 75, pp. 203-220, 2016.

[22] S. S. Groothuis, G. Rusticelli, A. Zucchelli, S. Stramigioli, and R. Carloni, "The variable stiffness actuator vsaut-ii: Mechanical design, modeling, and identification," *IEEE/ASME transactions on mechatronics,* vol. 19, no. 2, pp. 589-597, 2014.

[23] L. C. Visser, R. Carloni, and S. Stramigioli, "Energy-efficient variable stiffness actuators," *IEEE Transactions on Robotics,* vol. 27, pp. 865-875, 2011.

[24] Yi Liu, Shuxiang Guo, Hideyuki Hirata, "Development of a powered variable-stiffness exoskeleton device for elbow rehabilitation", *Biomedical Microdevices*, vol.20, no.3, DOI: 10.1007/s10544-018-0312-6, 2018.