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A Hybrid Motion Stiffness Control of Variable Stiffness Actuator for Upper Limb Elbow Joints Rehabilitation

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***Abstract* –The variable stiffness actuator (VSA) can be integrated into the robotics to improve the inherent compliance characteristics of robotics for the safe physical human robot interaction (pHRI). The output stiffness of the VSA is excepted to be independently controllable during the rehabilitation training processing. Furthermore, the motion and stiffness control of VSA can be independently controlled by VSA for rehabilitation application scenario. In this paper, a hybrid motion stiffness control strategy for achieving assist-as-needed control and suitable patient-robot interaction was proposed utilizing the compliance characteristic of VSA. The elbow joint output stiffness could be adjusted by a linear mapping method to obtain controllable assistant level, which is based on the real-time bilateral position tracking error. It is noted that the linear mapping scaler could be regulated for different patient injury-levels. The preliminary experimental results show that the proposed method can adjust the elbow joint stiffness for patients according to the real-time bilateral position errors.**

Index Terms – Stiffness Control, Upper limb elbow joint, and physical human robot interaction

I. Introduction

Recently, with the global aging processing, the stroke is becoming the most common illness leading to the disability of the elder people [1]. For post-stroke patients, the hemiplegia can be assorted as a specific kind, which can lead to the one side disability of body [2]. To reduce the medical source pressure, the rehabilitation robotics are widely applied in recovery training and daily life assistance [3]-[10]. Especially, the bilateral rehabilitation robotics have been developed for hemiplegia patients, which focus on the coordination movement assistance and synchronic motor skill relearning [11]-[15].

To improve the recovery effect, the rehabilitation robotics should have the ability of provide suitable motor assistance [16]. This suitable motor assistance can be categorized as the physical human robot interaction (pHRI) control of robotics research fields [17]. For the rigid robotics, some control algorithms have been successfully proposed for achieving the compliant pHRI, such as impedance control [18] and admittance control [19]. These compliance control algorithms take the external load as input to adjust the robotic behaviors for improving the safety of pHRI. On the other hands, the most inherent compliance realization is that the compliant elements could be implemented into the robotics mechanisms to realize the inherent mechanical compliant characteristics [20]. Therefore, the compliant robotics are proposed for improving compliant performance of pHRI, which is integrated with compliant elements for variable stiffness or variable damping characteristics [21]-[25]. The variable stiffness robotic is the most common type as the high performance on increasing control bandwidth and low-cost, which has been applied in the robot-aided rehabilitation. Liu et.al developed a variable stiffness actuator MeRIA for lower limb rehabilitation, which combines a linear quadratic regulator (LQR) technology-based stiffness control algorithm for compliant pHRI of VSA-integrated-robotics [26]. Zhang et. al proposed an end-effector type VSA robotic for upper limb rehabilitation, which can realize real-time stiffness regulation for variable compliance [27]. Liu. Et. al also developed a VSA-integrated robot for upper limb rehabilitation [28], [29]. This robot can track the stiffness trajectory from dynamic biomedical signals for high comfortable wear-ability.

From the above-mentioned researches, the high compliant pHRI can be achieved by combining the compliant control algorithms into the compliant robotics. However, how the stiffness variation can improve the safety of the pHRI and the rehabilitation effect is still an open issue. Furthermore, the rehabilitation of hemiplegia requires the robotics can provide bilateral task skill relearning, especially the coordination of bilateral side limbs. In this study, a hybrid motion stiffness control of the VSA-integrated robotics is proposed for realizing task-oriented compliant pHRI for bilateral rehabilitation. Motivated from the mechanical characteristic of the VSA, that the independent stiffness variation with respect to the joint motion, the proposed hybrid motion stiffness control can be separated into independent joint tracking and independent stiffness regulation. The desired motion trajectory and stiffness variation trends can be transferred to the affected side limb of hemiplegia for bilateral synchronic and symmetric movements.

The remainder of this paper is as follows; In Section II the VSA-integrated robotic system is descripted. In Section III, the

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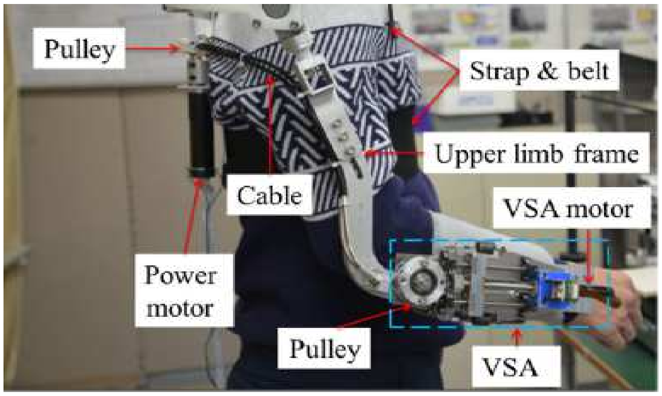

Fig. 1. The PVSED overall

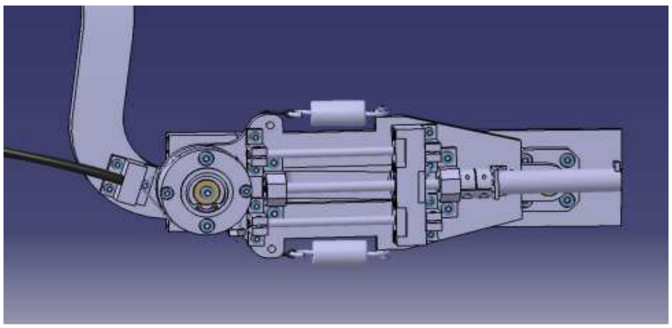
Fig. 2. The CAD mechanical design of the PVSED.

proposed hybrid motion stiffness control method will be introduced. In Section IV, the preliminary experiments are carried out, and the experimental results are analyzed. In Section V, the conclusion is drawn.

II. System Description

A. Overall of the PVSED

The powered variable-stiffness exoskeleton device (PVSED), purposed in our previous research [29], is a light wearable rehabilitation robot for upper limb bilateral training, shown in Fig. 1. There are 3 passive degree of Freedoms (DoFs) in shoulder joint and 1 passive DoF in elbow joint, which are designed for wear-comfortability. The flexion/extension movements of elbow joint in vertical plane can be powered by a main joint actuator. The main joint actuator includes a cable-driven transmission mechanism linked to the pulley on the mainframe and a brushless motor (Maxon RE-30 Graphite Brushes Motor). Furthermore, the PVSED integrated with an independent VSA, coupled by the pulley on the mainframe, for providing variable stiffness output to elbow joint. This VSA consisted of a slider screw, a compact motor (Maxon RE-13 Graphite Brushes Motor), pivot and a pair of antagonistic springs. The mechanism of the PVSED in CAD is shown in Fig. 2.

B. Principle of Variable-stiffness Actuator

Benefited from the mechanism design of the PVSED, the pivot can be driven by the RE-13 motor along within the slider screw to actively regulate the ratio of leverage. The external load, usually refers to the patient robot interaction force, can be

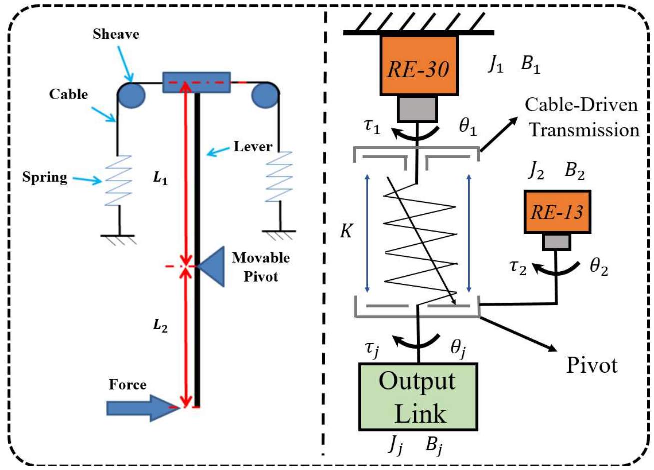

Fig. 3. The working principle of the VSA

added to the output link of the PVSED. On the other side of the leverage, the pair of antagonistic springs is linked to provide the compliant assistant force. As the leverage effect, the controllable variable stiffness can be achieved independent to the main joint motion by the motor-driven pivot. The working principle of the VSA is explained in Fig. 3. As the Fig. 3, the equilibrium of moment can be written as follows:

$$\boldsymbol{F_{spring} \cdot L_1 = F \cdot L_2} \tag{1}$$

where the L_1 is the lever of the spring force, and the L_2 is the lever of the external torque. According to the Hooke's Law:

$$F_{spring} = K \cdot \theta_d \tag{2}$$

where the θ_d is the deviation angle of the VSA. For the PVSED, the elasticity coefficient of spring is set as 19.6 N/mm.

$$K = \frac{F_{spring} \cdot l}{\theta_d} \cdot \frac{L_1}{L_2} \tag{3}$$

The L_1/L_2 represents the transmission ratio which represents the position of the pivot. The relationship between the output stiffness and the pivot position can be fit as a 2-order polynomial relationship as follows:

$$K = 0.1443 \cdot d^2 + 2.287 \cdot d + 16.95 \quad (0mm \leq d \leq 20mm) \tag{4}$$

As the RE-13 motor was driven by a position controller, the position of pivot can be transferred by the parameter of the ball screw and the motor rotation. Therefore, the output stiffness can be actively adjusted through the motor-driven pivot position.

III. Hybrid Motion Stiffness Control

A. Overall

In this study, a hybrid motion stiffness control was proposed for the VSA-integrated robotics, shown in Fig.4. As the independent variable stiffness characteristic of the PVSED, the joint motions of the PVSED can be separated into two parts, the main joint tracking and compliant dynamic interaction, respectively. The main joint control refers to the position of the mainframe of the PVSED. It can bring the rough elbow joint assistance to the training task accuracy. On the other hand, the compliant dynamic interaction always refers to the compliance characteristics of the robotics during patient-robot interaction.

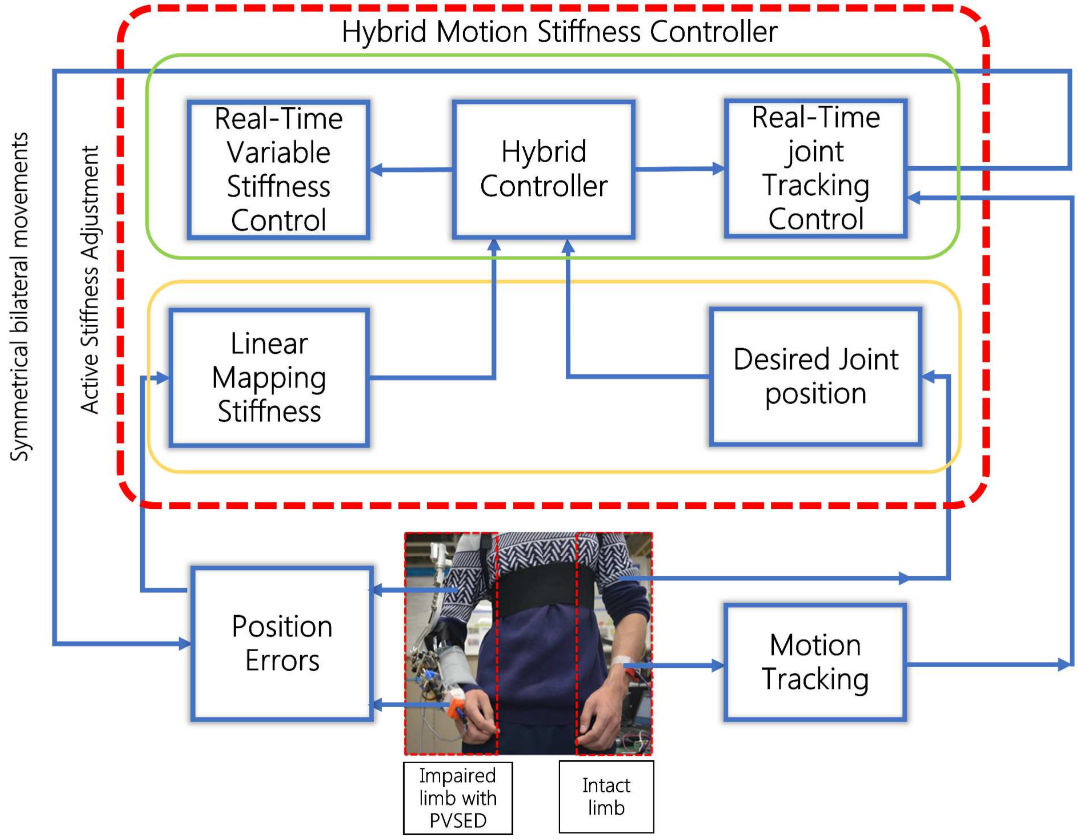

Fig. 4. The Control diagram of the proposed hybrid motion stiffness control.

In our previous study [25], the dynamics of 1-DoF VSA-integrated robotics is modeled as follows shown in Fig. 3.

$$J_m\ddot{\theta}_j + B_m\dot{\theta}_j + G(\theta_j) = \tau_j + \tau_{ext} \tag{5}$$

$$\tau_j = K(\theta_2)\cdot(\theta_j - \theta_1) \tag{6}$$

where the J_m is the moment of inertia of the output link of the joint. The B_m is the damping coefficient of the output link, τ_j represent the output torque of the joint. The τ_{ext} is the external force applied on output link. Consider about the rehabilitation scenario, the elbow joint motion should be performed in a relatively low velocity. So that the velocity and acceleration of angular can be ignored. Therefore, the whole system modelling can be simplified as

$$G(\theta_j) = \tau_j + \tau_{ext} \tag{7}$$

From the furmula 13, the function of the desried stiffness can be calculated when the system was applied a interaction force which leads to the deviation angle between the main frame and the output link.

B. Motion Control of Joint Position Tracking

Due to the disability of the hemiplegia patients, the bilateral movements are always not sufficient and not synchronic. So in the real rehabilitation training processing, the main evaluation metric is the training accuracy of the predefined bilateral movements. Therefore, the rehabilitation robotic should have the ability of accurate movement assistance for providing the synchronic and coordinated bilateral motor skills to the affected side limb. In this study, the motion control of the main joint of the PVSED aims to grantee that the mainframe position can track the movements of the contralateral side limb. To achieve this control goal, the motion tracking control is designed as a PID controller implemented position control loop. The control input is designed as the desired trajectory of the contralateral side limb, and the mainframe positions are selected as the control output. This intuitive tracking control can fast correct the huge motion errors during the rehabilitation training, but the motor errors are still remained because of the inherent compliant characteristic of the PVSED. This joint tracking control is aiming to provide rough assistance to affected limb for flexible training intensity and safety consideration.

C. Stiffness Control of Compliant dynamic Interaction

As the independent variable stiffness characteristic of the PVSED, the real time stiffness regulation of the PVSED can be achieved for compliant dynamic interaction. The real time stiffness variation can provide human-like motor patterns to the affected side limb. These human-like motor patterns are important to the bilateral motor skill transfer, which contain the dynamic motor information adaptive to the specific task. Therefore, the robotic stiffness is expected to be adjusted according to the dynamic task. To achieve dynamic adaptive stiffness control, the motor errors between the affected-side limb and the contralateral side limb are selected as control input.

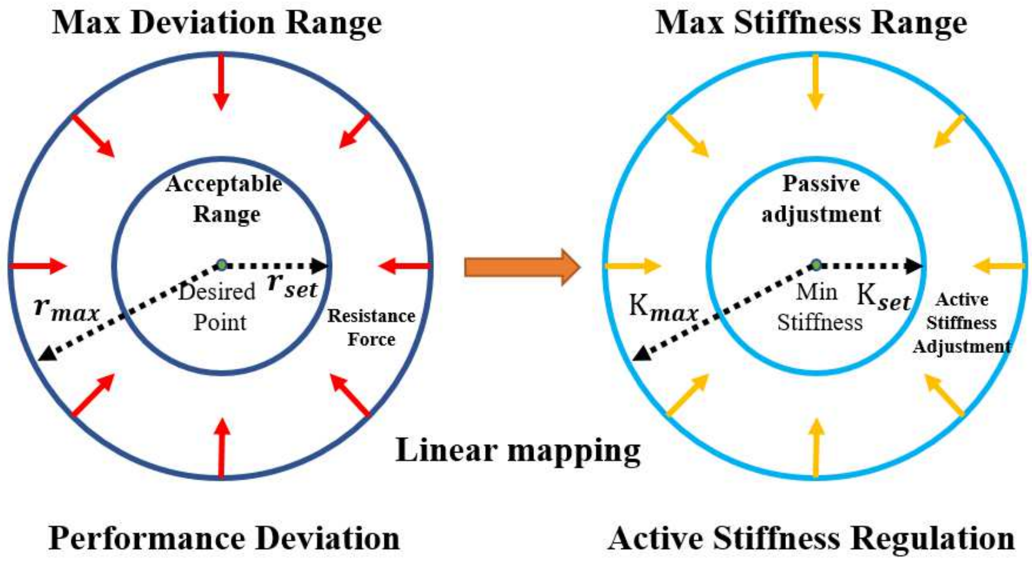

Fig. 5. The linear mapping from the position errors to robotic stiffness.

As Fig.5 shows, the linear mapping is implemented to map the tracking errors to the stiffness variation, as follows:

$$K_d = \alpha \cdot \theta_e \quad (8)$$

where the α is the scalar factor for linear mapping, which can be determined by the desired assistance level. The linear mapping comparison results is shown in Fig. 6. After obtaining the desired stiffness K_d, the VSA should track the desired stiffness trajectory. In in the stiffness control, the position control loop is implemented with a PID controller. Using (1), the desired stiffness can be transferred to the desired position of the RE-13 motor.

IV. EXPERIMENTS AND RESULTS

A. Experimental Setup

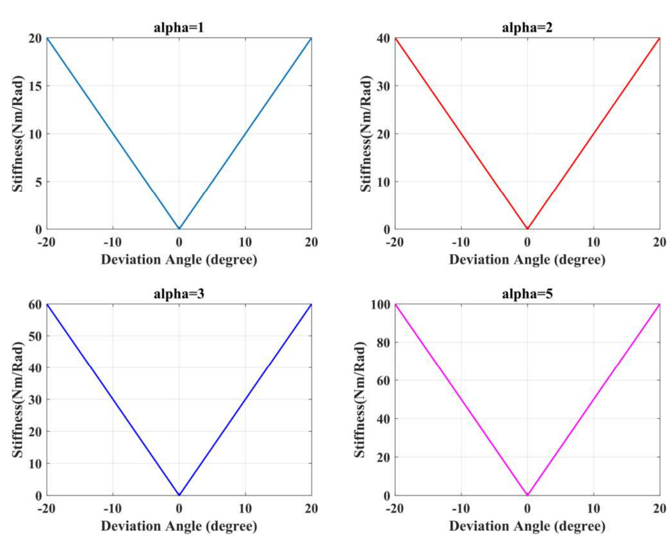

Fig. 6. The comparison results of different α.

In the experiments, the fixed situation of the PVSED was selected to evaluate the control performance. An inertial measurement unit (GY-25T) was attached on the operator's limb for recoding the desried limb movements θ_d. In the whole PVSED system, there are two inertial measurement units (GY-25T) are implemented on the output link and mainframe for obtaining θ_j and θ_1. And a thin film interaction force sensor (FSR-402) was placed on the forearm holder of the PVSED against the fixed link to obtain the interaction force. In these experiments, the stiffness was set as the max level, min level, and linear variation level to compare the different stiffness effects on the patient robot interaction.

B. Preliminary Results

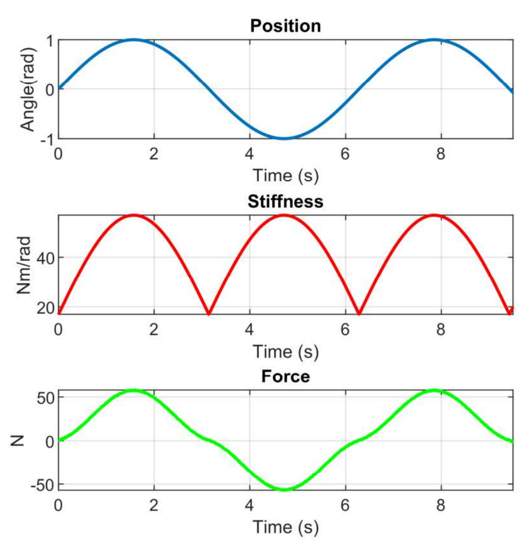

Fig. 7. The experimental results of interaction condition.

In order to evaluate the dynamic patient robot interaction of the proposed control method, a preliminary evaluation experiments were carried out. The comparison results of the different α are shown in Fig.6. In this experiment, 4 different α were selected including α=1, α=2, α=3, and α=4, for explaining the linear stiffness variation. And the linear variable stiffness control could real time adjust the stiffness according to the task statements, which leads to the changing contact force level, shown as Fig. 7. In the experimental results of the fixed interaction case, the stiffness was changing and so that the contact force was relatively increasing. The stiffness can be linearly increased when the deviation angle increasing. According to the different α, the desired assistant level can be achieved. This property can be utilized for therapists to rapidly regulate the assistance levels for adapting individual-specific and task difficulties during the rehabilitation training processing.

V. CONCLUSIONS

In this paper, a hybrid motion stiffness control was proposed for variable stiffness robotic to achieve dynamic compliant interaction assistance. The stiffness can be regulated according to the dynamic task conditions using the linear mapping. The experimental results show that with the increase of joint stiffness, the lower deviation angle would reduce at the same interaction force level. By the aid of the proposed performance-based stiffness control method, the powered variable-stiffness exoskeleton device has the potential to help the patients complete homebased self-rehabilitation training in different intension.

REFERENCES

[1] G. Bao, L. Pan, H. Fang, X. Wu, and H. Yu, "Academic Review and Perspectives on Robotic Exoskeletons," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. November, pp. 2294–2304, doi: 10.1109/TNSRE.2019.2944655, 2019.

[2] Z. Yang, S. Guo, H. Hirata and M. Kawanishi, "A Mirror Bilateral Neuro-Rehabilitation Robot System with the sEMG-Based Real-Time Patient Active Participant Assessment," *Life*, 11, 1290, 2021, doi: 10.1109/ICMA49215.2020.9233869, 2020.

[3] J. Narayan, B. Kalita and S. K.. Dwivedy, "Development of Robot-Based Upper Limb Devices for Rehabilitation Purposes: a Systematic Review," *Augmented Human Research,* vol,6. No.1, pp.11-17, 2021.

[4] J. Jiang, W. Li, and Kok-Meng Lee, "A Novel Pantographic Exoskeleton based Collocated Joint Design with Application for Early Stroke Rehabilitation," *IEEE/ASME Transactions on Mechatronics*, DOI: 10.1109/TMECH.2020.2992993, 2021,

[5] Yaxi Wang, and Qingsong Xu, "Design and testing of a soft parallel robot based on pneumatic artificial muscles for wrist rehabilitation," *Scientific Reports.*, doi: 10.1038/s41598-020-80411-0. 2021,

[6] E. Barjuei, M. Ardakani, D. G. Caldwoll, M. Sanguineti, and J. Ortiz, "Optimal Selection of Motors and Transmissions in Back-Support Exoskeleton Applications," *IEEE Transactions on Medical Robotics and Bionics,* doi: 10.1109/TMRB.2020.3010611, 2020.

[7] T. Chen, R. Casas, and P.S. Lum, "An Elbow Exoskeleton for Upper Limb Rehabilitation with Series Elastic Actuator and Cable-Driven Differential," *IEEE Transactions on Robotics,* DOI: 10.1109/TRO.2019.2930915, 2019.

[8] Q. Chen, B. Zi. Z. Sun, Y. Li, and Qingsong Xu , "Design and Development of a New Cable-Driven Parallel Robot for Waist Rehabilitation," *IEEE/ASME Transactions on Mechatronics*, DOI: 10.1109/tmech.2019.2917294. 2019

[9] E. Trigili. Et. al, "Design and Experimental Characterization of a Shoulder-Elbow Exoskeleton With Compliant Joints for Post-Stroke Rehabilitation," *IEEE/ASME Transactions on Mechatronics*, doi: 10.1109/tmech.2019.2907465, 2019.

[10] X. Cui, W. Chen, X. Jin and Sunil K. Agrawal., "Design of a 7-DOF Cable-Driven Arm Exoskeleton (CAREX-7) and a Controller for Dexterous Motion Training or Assistance," *IEEE/ASME Transactions on Mechatronics*, doi: 10.1109/TMECH.2016.2618888, 2017.

[11] B. W. Gasser et. al, "Preliminary Assessment of a Hand and Arm Exoskeleton for Enabling Bimanual Tasks for Individuals with Hemiparesis," *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* vol,28. No.10, pp.2214-2223, 2020.

[12] B. Sheng, Shane Xie, Lihua Tang, Chao Deng, and Yanxin Zhang, "An Industrial Robot-Based Rehabilitation System for Bilateral Exercises," *IEEE Access*, DOI: 10.1109/ACCESS.2019.2948162, 2019.

[13] 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*, doi: 10.3390/mi10010008, 2018.

[14] Z. Yang, S. Guo, Y. Liu, H. Hirata, and T. Tamiya, "An intention-based online bilateral training system for upper limb motor rehabilitation," Microsyst. Technol., vol. 0123456789, doi: 10.1007/s00542-020-04939-x, 2020.

[15] Z. Song, S. Guo, N. Xiao, B. Gao, and L. Shi, "Implementation of human-machine synchronization control for active rehabilitation using an inertia sensor," Sensors, vol. 12, no. 12, pp. 16046–16059, doi: 10.3390/s121216046, 2012.

[16] A. U. Pehlivan, D. P. Losey, and M. K. Omalley, "Minimal Assist-as-Needed Controller for Upper Limb Robotic Rehabilitation," *IEEE Transactions on Robotics*, vol. 32, no. 1, pp. 113–124, 2016.

[17] X. Li, Y. Pan, G. Chen, and H. Yu, "Adaptive Human-Robot Interaction Control for Robots Driven by Series Elastic Actuators," *IEEE Transactions on Robotics*, vol. 33, no. 1, pp. 169-182, 2016.

[18] T. Sun, L. Peng, L. Cheng, Zeng-guang Hou, and Y. Pan, "Stability-guaranteed variable impedance control of robots based on approximate dynamic inversion," *IEEE Transactions on System, Man, and Cybernetics: Systems*, vol. 51, no. 7, pp. 4193-4200, 2021.

[19] F. Ferraguti, et al. "Avariable admittance control strategy for stable physical human–robot interaction," *International Journal of Robotics Research*, vol. 38, no. 6, pp. 747-765, 2019.

[20] S. Wolf et al., "Variable Stiffness Actuators: Review on Design and Components," *IEEE/ASME Transactions on Mechatronics*, vol. 21, no. 5, pp. 2418–2430, 2016.

[21] B. Vanderborght, A. Albu-schaeffer, A. Bicchi, E. Burdet, and D. G. Caldwell, "Variable impedance actuators: A review," *Rob. Auton. Syst.*, vol. 61, no. 12, pp. 1601–1614, 2013.

[22] H. Yu, S. Huang, G. Chen, Y. Pan, and Z. Guo, "Human–Robot Interaction Control of Rehabilitation Robots with Series Elastic Actuators," *IEEE Transactions on Robotics*, vol. 31, no. 5, pp. 1089–1100, 2015.

[23] J. Zhang and C. C. Cheah, "Passivity and Stability of Human-Robot Interaction Control for Upper-Limb Rehabilitation Robots," *IEEE Transactions on Robotics*, vol. 31, no. 2, pp. 233–245, 2015.

[24] X. Li, Y. Pan, G. Chen, and H. Yu, "Adaptive Human-Robot Interaction Control for Robots Driven by Series Elastic Actuators," *IEEE Transactions on Robotics*, vol. 33, no. 1, pp. 169-182, 2016.

[25] Z. Yang, S. Guo, and Yi Liu, " Preliminary Evaluation of a Performance-based Stiffness Control for Upper Limb Elbow Joints Rehabilitation," *in Proceedings of 2021 IEEE International Conference on Mechatronics and Automation*. pp.1280-1285, 2021.

[26] L. Liu, S. Leonhardt, and B. J. E. Misgeld, "Impedance-controlled variable stiffness actuator for lower limb robot applications," IEEE Transactions on Automation Science and Engineering, vol. 17, no. 2, pp. 991-1004, 2020.

[27] S. Zhang et al., "Integrating Compliant Actuator and Torque Limiter Mechanism for Safe Home-Based Upper-Limb Rehabilitation Device Design," *J. Med. Biol. Eng.*, vol. 37, no. 3, pp. 357–364, 2017.

[28] Y. Liu, S., S. Guo, S, Z. Yang, and H. Hirata, "A Home-based Bilateral Rehabilitation System with sEMG-based Real-time Variable Stiffness," IEEE Journal of Biomedical and Health Informatics, vol. 25, no. 5, pp. 1529-1541, 2019.

[29] Y. Liu, S. Guo, H. Hirata, H. Ishihara, and T. Tamiya, "Development of a powered variable-stiffness exoskeleton device for elbow rehabilitation," *Biomed. Microdevices*, vol. 20, no. 3, pp. 1-13, 2018.