Preliminary Study on the Design and Control of a Pneumatically-Actuated Hand Rehabilitation Device

Houcheng Li[1,2] and Long Cheng[1,3]

1. the State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China.
E-mail: long.cheng@ia.ac.cn

2. School of Automation, Beijing University of Posts and Telecommunications.

3. University of Chinese Academy of Sciences

Abstract: In recent years, the robotic devices have been used in hand rehabilitation training practice. The majority of existing robotic devices for rehabilitation belong to the rigid exoskeleton. However, rigid exoskeletons may have some limitations such as heavy weight, un-safety and inconvenience. This paper presents a device designed to help post-stroke patients to stretch their spastic hands. This hand rehabilitation device actuator is fabricated by soft material, powered with fluid pressure, and embedded in one glove surface. The distinguished features of this device are: safety, low cost, light weight, convenience and pneumatic actuation. In clinical practice, rehabilitation therapists should help the post-stroke patients to stretch fingers to a desired joint position. Therefore, the control objective of the proposed hand rehabilitation device is to drive the patient's finger bending angle to a predesigned position. To this end, curvature sensors embedded in the glove are used to measure the finger's bending angle. A commercial data glove is used to collect the actual finger's bending angle for calibrating the curvature sensors based on a three-layer back-propagation (BP) neural network. Then the error between the designed joint position and the actual joint position can be calculated. An error proportional control strategy is adopted for the positioning control objective (the controller's input is the pump speed). Finally, experiments are conducted to validate the effectiveness of control method and the capacity of the proposed hand rehabilitation device.

Key Words: Rehabilitation, hand, pneumatic actuation, control, bending angle.

1 Introduction

Recently, China Stroke Center has reported that stroke is the first cause of death and the leading cause of disability of adults in China. According to one preliminary survey, there are 11.82 million people over 40 suffering from stroke in 2014. Recent data displays that the stroke incidence is increasing at an annual rate of 8.7%, and the recurrence rate (11.2%) is the highest in the world [1]. Hand function is complex, versatile and plays an important role in performing activity of daily living (ADL). However, the hand function is strongly impaired by neurological injury, which reduces the independence of patient's life [2]. In order to improve the life quality of post-stroke patients, regaining hand function is identified as one most critical need [3].
Physical therapy has been shown to be effective on the recovery of hand function [4]. The treatment of paralysis is a long-term process, which will lead to a large number of medical and human resource consumption [5]. However, the number of rehabilitation therapists is insufficient to meet the huge need. Fortunately, using robotic devices to assist therapists to perform hand rehabilitation training for post-stoke patients has been proved to be effective [6, 7, 8]. In the literature, there are a lot of hand rehabilitation devices, while the majority of existing hand rehabilitation devices belong to exoskeleton. There are two design methodologies for exoskeleton: the fixed-frame platform and the portable device [9]. The devices based on the fixed-frame platform design have been successfully applied to stretch the post-stroke patient's hands [10, 11]. These devices are precise and useful, while they are extremely heavy. Another hand rehabilitation devices based on the portable design overcome this issue, which are compact and effective. However, some portable devices have rigid component and complex mechanical structure [12, 13, 14], which makes them uneasily wearable, high-cost, and likely to hurt patient's hands when these devices are out of control. Therefore, these devices are limited in practical use either. In order to design a safer, easier-to-wear and lighter exoskeleton, another approach utilizing soft materials has been adopted [15, 16, 17]. These devices are inherently compliant, lightweight, safe, compact, and have multiple degrees of freedom (DOFs). All above characteristics show that the rehabilitation devices based on the soft material are more preferable for post-stroke patients to do hand rehabilitation training compared to the rigid exoskeleton.

By the above observation, this study aims to develop a safe, low-cost, lightweight, and easy-to-wear hand rehabilitation device for helping post-stroke patients improve the hand function. The actuator of the proposed hand rehabilitation device is fabricated by the soft material, powered with fluid pressure and embedded in one glove surface which makes

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this device easy to wear. The glove and the actuator are connected by inextensible ropes. When the air is pumped into the actuator, the actuator expands, which pulls ropes and stretch the hand passively. When the air is pumped from the actuator, the actuator shrinks and the patient's high flexor activity (because of the hand spasm) makes the hand contracture. In the actual rehabilitation therapy, the post-stroke patient's fingers are usually stretched to a desired joint position under the help of rehabilitation therapists. For this purpose, the proposed hand rehabilitation device needs to drive the patient's finger bending angle to a predesigned position. To this end, curvature sensors embedded in the glove are used to measure the finger's bending angle as the feedback. To calibrate curvature sensors, a commercial data glove is used to collect the finger's actual bending angle, and a three-layer BP neural network is established to realize the curvature sensor calibration. Then the error between the predesigned finger's bending angle and the finger's actual bending angle can be calculated. Based on this error, a proportional control strategy is adopted to realize the closed-loop control. At last, the effectiveness of control method and the capacity of the proposed hand rehabilitation device are validated by experiments.

The rest of this paper is organized as follows. Section 2 mainly introduces the principle of mechanical design and electrical control system design of this device. In Section 3, the calibration of curvature sensors and the error proportional control strategy are presented. Section 4 describes experiments for validating the control method and testing the function of the proposed hand rehabilitation device. Finally, Section 5 concludes this study and suggests the future work plan.

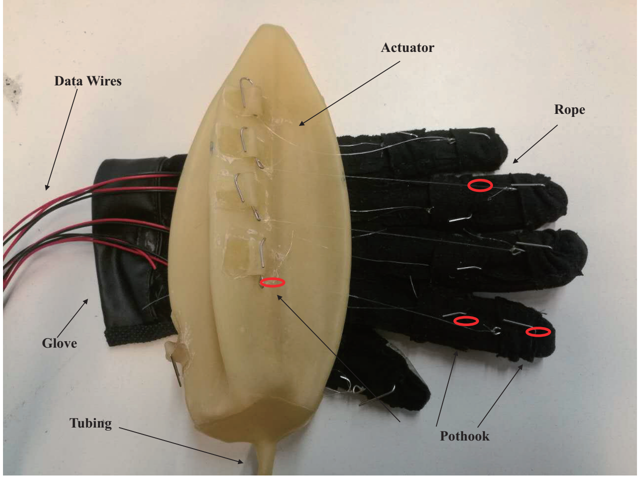
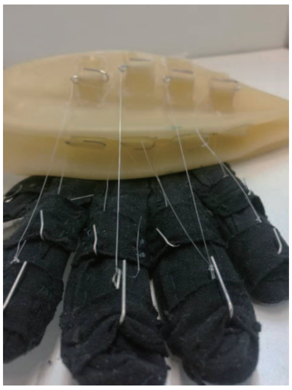


Figure 1: Actuator of the hand rehabilitation device.

(a) Connection with the thumb.



(b) Connection with other four fingers.

Figure 2: Connection between the actuator and the glove.

2 Principle of Mechanical System Design and Electrical Control System Design

2.1 Mechanical System Design

In this study, to make the hand rehabilitation device easy to wear, the actuator is fixed on one glove which can be easily worn by patients. The mechanical system design of the hand rehabilitation device mainly includes three parts: the design of the actuator, the connection between the actuator and the glove, the placement of curvature sensors.

2.1.1 The design of actuator

Hands are flexible and particularly vulnerable. Many existing exoskeletons are heavy and have rigid component and complex mechanical structure, which make the patients feel uncomfortable and make these devices have a high risk of losing control. As a result, these exoskeletons may hurt the patient's hands. Considering the safety and comfort factors, the soft material is considered as one promising choice. In order to reduce the control complexity of the soft material, the actuator is designed into a "ball" shape with a pipeline and is actuated pneumatically. When the actuator is inflated by a pump, spastic fingers are opened through the power of the actuator expansion. Therefore, the selected soft material must have a certain degree of elasticity and tensile strength. Considering the above factors, the latex material is used to fabricate the actuator. This actuator looks like a "carambola" when it is not inflated. This shape design makes it look more compact and occupy less space, which is shown in Fig. 1.

2.1.2 The connection between the actuator and the glove

The most important part in the mechanical system design is the connection between the actuator and the glover. There are three factors that need to be considered, namely, how to open the spastic fingers effectively, how to avoid damaging the patient's fingers, and how to make patient feel comfortable and convenient. At the beginning of the design, the actuator was put in the palm, and the expansion strength of the actuator can stretch the spastic fingers. However, when we consulted the physical therapist with China Rehabilitation Research Center regarding this design, they confirmed that the actuator in the palm could stimulate the hand flexor and this design is not beneficial to relieve the spastic symptom. Taking into account of this important advice, the actuator is put on the back of the hand. This design can ef-

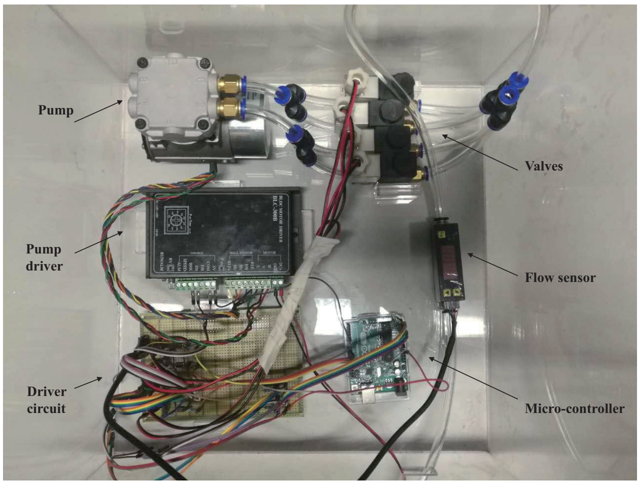
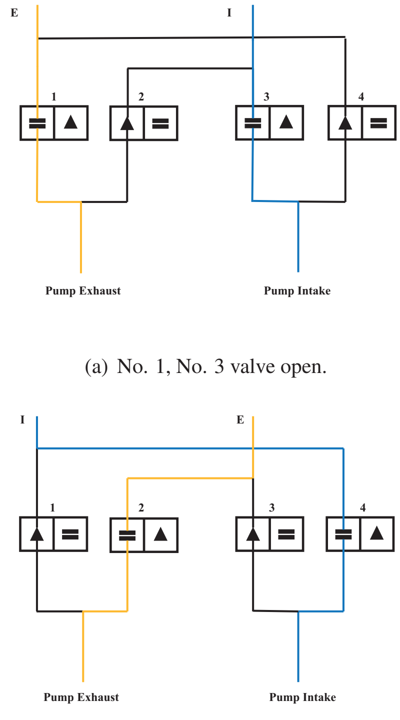


Figure 3: The electrical control system design of the hand rehabilitation device.



(a) No. 1, No. 3 valve open.

(b) No. 2, No. 4 valve open.

Figure 4: The switching of valves.

fectively avoid stimulating the flexor, while it may cause an issue on how to open the spastic hand through the expansion of the actuator. To solve this issue, ropes with two pothooks are used to connect the glove and the actuator. Two positions are selected to fix ropes on each finger. They are located between the finger's first joint and the second joint and the finger tip, respectively. Appropriate connection locations on the actuator surface are selected by several experiments. The final connection form is given in details in Fig. 2.

2.1.3 The placement of curvature sensors

The curvature sensors are used to measure the post-stroke patient's finger bending angle for the feedback control. In order to measure the finger's bending angle accurately and protect the easily broken circuit connectors on the curvature sensors, curvature sensors are embedded in the glove. Figure 1 shows the data wires of curvature sensors.

2.2 Electrical Control System Design

To reduce the noise generated by the air pump and make the device more compact, the pneumatic control system is placed into a box shown in Fig. 3. The pneumatic control system consists of a micro-controller (Arduino UNO), a miniature piston pump (260ZC35/24, Thomas, Germany) which has one intake and one exhaust, air flow sensors (MF4008, Siargo Ltd., USA) for measuring the actuator's volume, four solenoid valves (2V025-08, SUODI, China). The solenoid valve has only two states: fully close and fully open. The valve state is switched by an independent circuit with photoelectric switch which is used to realize the isolation between the valve driven circuit and the micro-controller. Because there is only one pipeline on the actuator, in order to change the direction of air flow, the connection of solenoid valves is designed as the one shown in Fig. 4. As seen from the chart, the intakes of NO. 1 and NO. 2 valves are connected to the pump exhaust. The intakes of NO. 3 and NO. 4 valves are connected to the pump intake. The exhausts of NO. 1 and NO. 4 valves are connected to the pipeline. The exhausts of NO. 2 and NO. 3 valves are left open. Therefore, by appropriate switch between solenoid valves, the actuator's inflation and deflation can be realized. The control details are presented in Section 3.

3 Control Method

3.1 Calibration of Curvature Sensor

In the clinical hand rehabilitation training, rehabilitation therapists should help the post-stroke patients to stretch the fingers to a desired joint position. Therefore, the proposed rehabilitation device should have the ability of driving the patient's finger bending angle to a predesigned position. To this end, the curvature sensor embedded in the glove is used to measure the post-stroke patients finger's bending angle. A commercial data glove (WISEGOLVE15, a product of WONSTAR company) is used to collect the actual finger's bending angle for calibrating the curvature sensors based on a three-layer BP neural network model. The commercial data glove can measure the actual bending angles of the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints, respectively. Due to the placement of the curvature sensor in the experiment, the PIP joint angle is the one for calibrating the curvature sensor.

In the calibration experiment, one healthy male volunteer is recruited. The commercial data glove is worn on the volunteer hand first and then designed glove with curvature sensors is worn outside of the commercial glove. The volunteer is required to move his fingers from the contracture

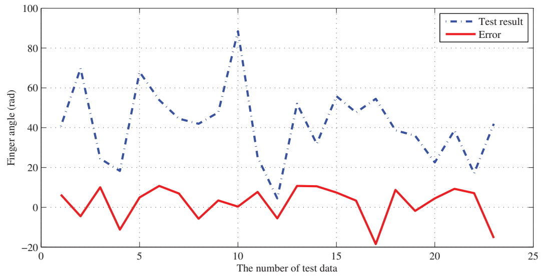


Figure 5: The result of model test.

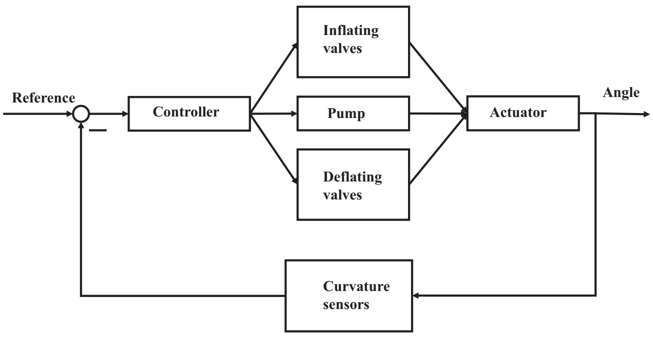


Figure 6: The control block diagram.

state to the stretching state, and then from the stretching state to the contracture state. The commercial data glove collects the actual PIP joint angles of five fingers simultaneously with a 1000Hz sampling frequency. Finally, 123 sets of data are collected for each finger.

In this paper, a three-layer BP neural network is used to calibrate the curvature sensor. The input of the neural network is the readout of the curvature sensor and the neural network's output is the readout of PIP joint angle. The number of neurons in the hidden layer is four. The hyperbolic tangent sigmoid transfer function is chosen as the activation function of each neuron in the hidden layer. The activation functions of the neurons in the output/input layers are the unit function. The collected data is divided into two parts for training the neural network: 80% are used to train the neural network and 20% are used for the model test. In the experiment, error within 10 degree is acceptable. After making the cross validation, the accuracy rate on the test data sets can reach 91.03%. The experimental results are shown in Fig. 5.

3.2 Control Algorithm

The control algorithm is designed based on the error proportion, and the control block diagram is given in Fig. 6. All fingers are controlled by the speed of air pump (volume in the actuator) and the switch between four valves (the air flow direction). The general idea is that the controller pumps the air into the actuator to reduce the finger's bending angle and bleeds the air out of the actuator to increase the finger's bending angle.

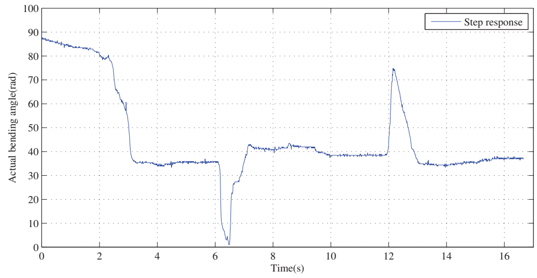


Figure 7: The control of the finger's bending angle .

3.2.1 Control of valves

When the NO. 1 and NO. 3 valves are opened and the NO. 2 and NO. 4 valves are closed, the actuator is inflated by the pump exhaust. When the NO. 1 and NO. 3 valves are closed and the NO. 2 and NO. 4 valves are opened, the actuator is deflated by the pump intake. Figure 4 presents the procedure.

3.2.2 Control of the finger's bending angle

Error-proportional control is employed for controlling the fingers bending angle.

$$u(t) = k_p(r(t) - y(t)) \tag{1}$$

where $u(t)$ is the controller's input, $r(t)$ is the predesigned finger's bending angle, $y(t)$ is the actual finger's bending angle, k_p represents proportional coefficient.The parameter k_p is selected by the trail-and-error approach.

4 Experiment Results and Discussions

4.1 Test of the Proposed Controller

This control algorithm is programmed in the Arduino UNO micro-controller which sends commands to valves and pump. In order to validate the effectiveness of the proposed control algorithm, the rehabilitation device is required to help the finger's bending angle to the predesigned position 37°. The experimental result is shown in Fig. 7. It can be seen that the system can quickly track the desired position under various disturbances, which shows the effectiveness of the proposed algorithm.

4.2 Function Test of the Proposed Hand Rehabilitation Device

The overall appearance of the proposed hand rehabilitation device is showed in Fig. 8. An experiment with one healthy volunteer is conducted to validate the capacity of the hand rehabilitation device. In order to test whether the device can help stoke patients do hand rehabilitation training, the volunteer is asked to generate sufficient force in his hand to prevent the hand stretch for emulating the post-stroke patient's hand. In the experiment, a cycle test is conducted, which makes the hand from the contracture state to the stretching state and then from the stretching state to the contracture state. Figure 9 shows some instant states of the hand. From the experimental results, the proposed device can help patients do the hand rehabilitation training.

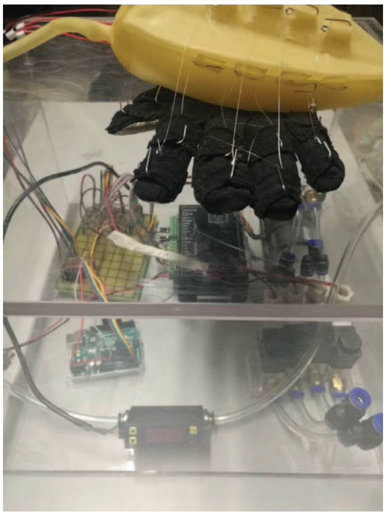
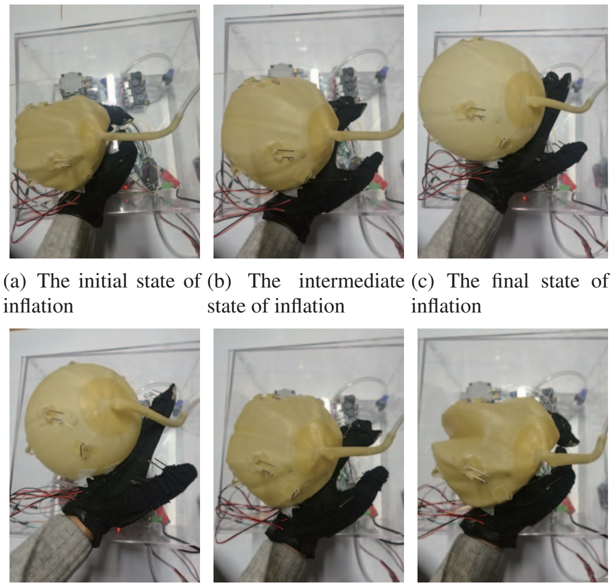


Figure 8: The overall appearance of hand rehabilitation device.



(a) The initial state of inflation (b) The intermediate state of inflation (c) The final state of inflation

(d) The initial state of deflation (e) The intermediate state of deflation (f) The final state of deflation

Figure 9: The separate state of the hand from contracture to stretching and stretching to contracture.

5 Conclusions and Future Work

In this paper, a safe, low-cost, pneumatically-actuated, lightweight, and easy-wearable device has been designed to help stroke patients improve the hand function. The mechanical system design and the electrical control system design are given in details. To control the finger's bending angle to a desired position, curvature sensors embedded in the glove are adopted to measure the finger bending angle. Based on a three-layer BP neural network, a commercial data glove is used for calibrating curvature sensors. An error proportion control strategy is adopted for the feedback control of the finger's bending angle. Finally, experiments are conducted to validate the effectiveness of the proposed control method and the capacity of the proposed hand rehabilitation device.

This is only a preliminary study of the hand rehabilitation device. There are still many challenges in the future work. First, this device can only realize the hand stretch and can not realize the hand contracture actively. Second, the device moves all fingers together and lacks of the capability of moving fingers separately. Third, the accurate control of this device has not been well addressed. It has been shown in experiments that the hysteresis nonlinearity appears in the dynamics of the proposed device. Probably, the model predictive control approach can be employed to achieve the control of this rehabilitation device [18, 19, 20]. Fourth, how to optimally coordinate the control of the five fingers can be investigated based on the multi-agent theory [21, 22, 23, 24, 25]. Finally, this device can only achieve passive hand rehabilitation training rather than the active training (i.e., assistance as needed). The patient's active motion intention is not considered by the proposed device. In the future, more effort is to be made towards solving these challenges by using physiological signals like sEMG [26, 27, 28].

REFERENCES

[1] http://www.cnstroke.com/NewsInfo/News/NewsDetailWeb?Tid=2024.

[2] J.C. Metzger, O. Lambercy, A. Califfi, F.M. Conti, and R. Gassert, "Neurocognitive robot-assisted therapy of hand function," *IEEE Transactions on Haptics*, vol. 7, no. 2, pp. 140-149, April 2014.

[3] S.R. Soekadar, M. Witkowski, C. Gmez, E. Opisso, J. Medina, M. Cortese, M. Cempini, M.C. Carrozza, L.G. Cohen, N. Birbaumer, and N. Vitiello, "Hybrid EEG/EOG-based brain/neural hand exoskeleton restores fully independent daily living activities after quadriplegia," *Science Robotics*, vol. 1, eaag3296, 2016.

[4] P. Polygerinos, K.C. Galloway, S. Sanan, M. Herman, and C.J. Walsh, "EMG controlled soft robotic glove for assistance during activities of daily living," in *Proceedings of 2015 IEEE International Conference on Rehabilitation Robotics*, Singapore, August 2015, pp. 55-60.

[5] D. Epstein, A. Mason, and A. Manca, "The hospital costs of care for stroke in nine European countries," *Health Economics*, vol. 17, no. 1, pp. S21-S31, January 2008.

[6] R. Colombo, F. Pisano, S. Micera, A. Mazzone, C. Delconte, M. C. Carrozza, P. Dario, and G. Minuco, "Robotic techniques for upper limb evaluation and rehabilitation of stroke patients," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 13, no. 3, pp. 311-324, September 2005.

[7] F. Zhang, Z.-G. Hou, L. Cheng, W. Wang, Y. Chen, J. Hu, M. Tan, and H. Wang, "iLeg – a lower limb rehabilitation robot: design, control, and experiments," *IEEE Transactions on Human-Machine Systems*, vol. 46, no. 5, p. 761–768, 2016.

[8] W. Wang, Z.-G. Hou, L. Cheng, L. Tong, F. Zhang, Y. Chen, L. Peng, L. Peng, and M. Tan, "Towards patients' motion intention recognition: dynamics identification of a lower limb rehabilitation robot – an LLRR under motion constraints," *IEEE Transactions on Systems, Man and Cybernetics: Systems*, vol. 46, no. 7, pp. 980–992, 2016.

[9] M. Cempini, M. Cortese, and N. Vitiello,"A powered fingerCthumb wearable hand exoskeleton with self-aligning joint axes," *IEEE/ASME Transactions on Mechatronics*,

vol. 22, no. 2, pp. 705-716, April 2015.

[10] C.N Schabowsky, S.B Godfrey, R.J Holley, and P.S Lum,"Development and pilot testing of HEXORR: hand exoskeleton rehabilitation robot," *Journal of NeuroEngineering and Rehabilitation*, vol. 7, no. 3, pp. 36-51, July 2010.

[11] E.B. Brokaw, I. Black, R.J. Holley, and P.S. Lum,"Hand spring operated movement enhancer (HandSOME): a portable, passive hand exoskeleton for stroke rehabilitation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 19, no. 4, pp. 391-399, August 2011.

[12] N.S.K. Ho, K.Y. Tong, X.L. Hu, K.L. Fung, X.J. Wei, W. Rong, and E.A. Susanto,"An EMG-driven exoskeleton hand robotic training device on chronic stroke subjects: Task training system for stroke rehabilitation," in *Proceedings of 2011 IEEE International Conference on Rehabilitation Robotics*, Zurich, Switzerland, June 2011, pp. 1-5.

[13] T. Chen, P.S. Lum,"Hand rehabilitation after stroke using a wearable, high DOF, spring powered exoskeleton," in *Proceedings of 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Florida, America, August 2016, pp. 578-581.

[14] A. Chiri, N. Vitiello, F. Giovacchini, S. Roccella, F. Vecchi, and M.C. Carrozza,"Mechatronic design and characterization of the index finger module of a hand exoskeleton for post-stroke rehabilitation," *IEEE/ASME Transactions on Mechatronics*, vol. 17, no. 5, pp. 884-894, October 2012.

[15] H.K. Yap, W.K. Benjamin, H.L. Jeong, C.H. James, and C.H. Yeow,"A fabric-regulated soft robotic glove with user intent detection using EMG and RFID for hand assistive application," in *Proceedings of the 2016 IEEE International Conference on Robotics and Automation*, Stockholm, Sweden, May 2016, pp. 3537-3542.

[16] H. Zhao, J. Jalving, R. Huang, R. Knepper, A. Ruina, and R. Shepherd,"A helping hand: soft orthosis with integrated optical strain sensors and EMG control," *IEEE Robotics and Automation Magazine*, vol. 23, no. 3, pp. 56-64, September 2016.

[17] P. Polygerinos, K.C. Galloway, E. Savage, M. Herman, K.O' Donnell, and C.J. Walsh,"Soft robotic glove for hand rehabilitation and task specific training," in *Proceedings of 2015 IEEE International Conference on Robotics and Automation*, Seattle, America, May 2015, pp. 2913-2919.

[18] W. Liu, L. Cheng, Z.-G. Hou, J. Yu, and M. Tan, "An inversion-free predictive controller for piezoelectric actuators based on a dynamic linearized neural network model," *IEEE/ASME Transactions on Mechatronics*, vol. 21, no. 1, pp. 214–226, 2016.

[19] L. Cheng, W. Liu, Z.-G. Hou, J. Yu, and M. Tan, "Neural network based nonlinear model predictive control for piezoelectric actuators," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 12, pp. 7717–7727, 2015.

[20] L. Cheng, W. Liu, Z.-G. Hou, T. Huang, J. Yu, and M. Tan, "An adaptive Takagi-Sugeno model based fuzzy predictive controller for piezoelectric actuators," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 4, pp. 3048–3058, 2017.

[21] L. Cheng, Y. Wang, W. Ren, Z.-G. Hou, and M. Tan, "On convergence rate of leader-following consensus of linear multi-agent systems with communication noises," *IEEE Transactions on Automatic Control*, vol. 61, no. 11, pp. 3586–3592, 2016.

[22] L. Cheng, Y. Wang, W. Ren, Z.-G. Hou, and Min Tan, "Containment control of multi-agent systems with dynamic leaders based on a PI^n-type approach," *IEEE Transactions on Cybernetics*, vol. 46, no. 12, pp. 3004–3017, 2016.

[23] L. Cheng, Z.-G. Hou, and M. Tan, "A mean square consensus protocol for linear multi-agent systems with communication noises and fixed topologies," *IEEE Transactions on Automatic Control*, vol. 59, no. 1, pp. 261–267, 2014.

[24] L. Cheng, Y. Wang, Z.-G. Hou, M. Tan, and Z. Cao, "Sampled-data based average consensus of second-order integral multi-agent systems: switching topologies and communication noises," *Automatica*, vol. 49, no. 5, pp. 1458–1464, 2013.

[25] Y. Wang, L. Cheng, Z.-G. Hou, J. Yu, and M. Tan, "Optimal formation of multi-robot systems based on a recurrent neural network, " *IEEE Transactions on Neural Networks and Learning Systems*, vol. 27, no. 2, pp. 322–333, 2016.

[26] M. Chen, L. Cheng, F. Huang, and Z.-G. Hou, "Towards robot-assisted post-stroke hand rehabilitation: Fugl-Meyer gesture recognition using sEMG," in *Proceedings of the 7th Annual IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems*, Hawaii, USA, July 2017.

[27] L. Peng, Z.-G. Hou, L. Luo, L. Peng, W. Wang, and L. Cheng, "An sEMG-driven neuromuskeloskeletal model of upper limb for rehabilitation robot control," in *Proceedings of the 2016 IEEE Conference on Robotics and Biomimetics*, Qingdao China, December 3–7, 2016, pp. 1486–1491.

[28] D. Zhang, Z.-G. Hou, L. Cheng, G. Bian, X. Xie, and L. Peng, "ϵ-SVR-based estimation for the motion trajectory of human lower limb using acceleration signals," in *Proceedings of the 2016 IEEE Interactional Conference on Information and Automation*, Ningbo China, July 2016, pp. 1278–1283.