

A Novel Variable Stiffness Actuator-based Exoskeleton Device for Home Rehabilitation

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Abstract –Most exoskeleton devices for upper-limb rehabilitation are heavy and bulky. The present study develops a light and wearable exoskeleton device for passive and resistance training that can potentially be used in home rehabilitation. Stroke patients may prefer to rehabilitate at home considering the inconvenience of regularly attending rehabilitation centres. In this paper, a novel training device combined with a variable stiffness actuator (VSA) is developed with safe-consideration. First, compared with traditional actuators with very high mechanical impedance, actuators with adaptive compliances can guarantee patients' safety, especially spasm happen. Second, it is composed of 4 degrees of freedom to move and 2 others degrees to adjust to the patient. Moreover it allows you to put the weight of the system on shoulders because this device can be wear just like a bag, so the patients can create a fully portable device, and very low cost. The processed EMG signals can be used to verify that the rehabilitation device could provide the power assist to the patients.

Index Terms –Rehabilitation device, Compliant actuator, Series elastic actuator, Variable stiffness actuator

I. INTRODUCTION

Approximately 795,000 people suffer from a new or recurrent stroke every year according to the statistics [1]. Stroke can lead to upper and lower limbs and activities of daily living significantly impaired, and the impact of the patient's own control for actions. For this reason, perform highly intensive treatment for every stroke patient, it has become a huge health care amount of work. An effective and stable rehabilitation process can be offered by robot-assisted therapy [2]. Most existing therapeutic robots fit into one of these categories: endpoint manipulator [3], cable suspension [4], and powered exoskeleton [5]–[7]. Although home-based rehabilitation devices have been developed [8], Caregivers often relatively the lack of professional care for the patient's knowledge and work skills. In order to reduce the losses caused by the time delay, while improving the stability of the system telerehabilitation, some other control strategies have

also been designed [9]–[10].The traditional exercises should be considered as a standard during intensive rehabilitation [11]. Based on the robotic technology has been investigated by many research groups and can be separated into three types: end-effector [3], cable suspension [12], and exoskeleton [13]. Among them, the exoskeleton device proposes a solution to the problem of control and measurement of angle and torque on each joint of impaired limbs [14].In our previous study, Z. Song et al. designed a human upper-limb exoskeleton rehabilitation device (ULERD) as shown in (Fig. 1) [15]. This is the task of training activities typical exoskeleton devices in activities of daily living (ADL), it is possible to support patient rehabilitation cooperative control strategy the whole arm. As the same, a previous study developed a portable exoskeleton device [15]–[16], as part of the patient's family rehabilitation device. Compared with previous devices, the variable stiffness actuator (VSA) has not been a very high kinetic energy. It can ensure patient safety, because the stiffness can be adjusted, this allows adjust for a specific patient trauma and recovery specific. The adjustable compliant behavior of VSAs is an inherent hardware property [17]–[18], thus a mechanism for varying the stiffness is needed. Moreover, there is no latency due to the stiffness control is fully mechanical without any sensor.

In the rehabilitation related study , that the variable stiffness actuator (VSA) need the response times required for adjustment, from a high to a low level of stiffness equipment; the torque limiter provided to the patients which further security. Based on previous explanation, it's understandable that if the patient want to move a lot compared to the initial angle, Based on previous interpretations, which is understandable, if a patient want to move lot of to compare with the initial angle, the force required could be very strongly ($Force=k \cdot \Delta angle$). Therefore, in some circumstances, such as spasms in the variable stiffness actuators torque limiter it may not be enough, which is why a torque limiter that the action is engaged by the cutting between the device and the

motor , allowing freely movable without any resistance is a useful way.

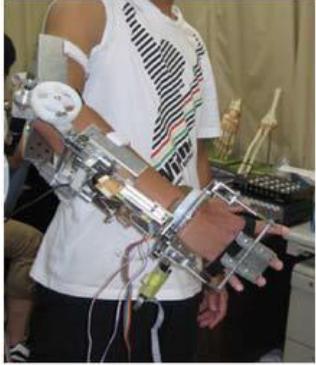


Fig.1 Human upper limb exoskeleton rehabilitation device (ULERD).

With the sEMG technology development, the sEMG signal has been applied to the body movement of pattern recognition. In recent decades, the relationship between muscle force and sEMG signals has been extensively investigated [19]. However, due to the complexity of the EMG signals, an important requirement for application is to improve the accuracy of pattern classification. A non-linear normalization method proposed by Potvin et al. [20] has also been applied [21]–[25]. There are many methods presented number of years ago. The processing of EMG signal mainly includes four phases: signal acquisition, signal segmentation, feature extraction and classification. In general, they can be separated into three types: time domain, frequency domain and time-frequency domain according to analysis methods. The Electromyographic signal, which represents the nature of the skeletal muscle activation potential, can be activated to whether or not the state of the muscle provides direct indicators. Because of this, the sEMG signal processing may be used to verify which rehabilitation device may provide power assisted for stroke patients.

This paper is organized as follows. In the section I, some background and related research will be introduced first. In the section II, the novel variable stiffness actuator-based exoskeleton for home-based rehabilitation will be analyzed. In the section III, it presents the sEMG experiment and experiment results are introduced in this part. At the last part of this paper, some conclusions and future works are carry out.

II. OVERVIEW OF THE DEVICE DEVELOPMENT

A. Working Principle of VSAs

The working principles of the SEA and VSA are shown in (Fig. 2) [26]–[27]. Usually, a gearbox is added to the motor which can realize a high weight-to-torque ratio performance and reduce the overall weight of the device. However, a large reduction ratio reducer unavoidable problem is the result of the non-back drivability highly reflective inertia and friction caused. To obtain flexible joints variable impedance, the elastic member is added between the motor shaft and the output of the apparatus. Variable stiffness elastic element, so that VSA inherent hardware performance standard behavior.

Therefore, need the mechanism for adjusting the stiffness. By comparison, a closed loop control method to achieve a strategic interaction, to yield a low impedance elastic member has a constant stiffness.

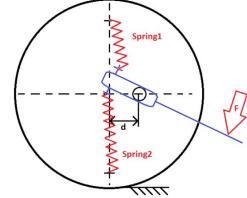


Fig.2 The different upper limb training device

B. Mechanical Design

Most of the exoskeleton devices for upper-limb rehabilitation had a very complicated system to change the stiffness so it was difficult to integrate and bulky. Generally these devices had two main motors , one against the others, which are expensive and very high power consumption to keep a position. Also many devices designed with no-linear springs, are difficult for dimensioning and to order a suitable one. And finally there is device without springs but with more exotic system like magnetic/hydraulic VSAs, but these solutions weren't retained due to the complexity and the cost.



Fig.3 The 3D view of the novel variable stiffness actuator-based exoskeleton for home-based rehabilitation

The designed prototype of the VSA-based exoskeleton device is shown in Fig. 3. Stiffness control section from the position control section independently. Forearm stent is a commercial product, it is easy to wear and range of motion can be adjusted manually. In the position control unit, the torque limiter mechanism is designed to ensure patient safety. The torque limiter can provide more protection for patients. The power for the flexion/extension motion is provided by a Maxon motor (12V 60W RE-30 dc-motor) combined with a planetary gearbox (Maxon GP32C). Power is transmitted via a steel wire rope with a diameter of 1.0 mm to the turntable. The rotation of the turntable will cause the rotation of the device, thus the patients' forearm will move together. And one side of the turntable is connected to a bearing holder with bearing (BEM-6005ZZ; MIYOSHI, Japan) with a low friction. The rotation motion of the device can be measured with a contact-less Hall-IC angle sensor (CP-20HB; Midori Precisions Co., Ltd., Japan). For obtaining a smooth control signal, a low-pass Butterworth filter with a cutoff frequency of 5 Hz was used further. Because we know that the stiffness exoskeleton device variable drive-based, it has some advantages, such as safe, smooth, elastic and adaptable. At the

same time, the Titan Arm also has some advantages, such as lot of DOFs, low cost, fully portable, weight on the shoulders. During the development of research, the novel variable stiffness actuator-based exoskeleton device chose to make a mix between the Titan Arm and a VSA near from the one of add the advantages of the VSA to the Titan Arm device.

C. Characteristic Evaluation for the Proposed Device

There are two kinds of passive and active training proposed alternative control strategy for the device. A typical proportional-integral-derivative (PID) algorithm was used for position control for passive training in which a pre-defined trajectory is programmed. Stiffness output, open loop control in order to adjust the current position of the pivot. Torque limiter in the absence of any control algorithm, the work can be passively. Interactive closed loop control method may be used to generate a variable impedance is active training. In this study, we focused on passive training at different levels have different stiffness and impaired function of the torque limiter mechanism evaluation. The control system used for the training device comprises two parts: a high-level control system (Windows 7 Professional system with a 3.0-GHz AMD Processor and 4.0-GB random-access memory) and a low-level actuator control system (DSP28335 processor inside controller). The two systems can communicate by a series port. A user interface in the high-level control system was programmed in Visual C++ 2010 (Microsoft Co., Redmond, WA, USA). Accordingly, at the interface of the control panel can be used to select parameters by the therapist training and record data for further remote evaluation. In our assessment of the project in remote design can remotely determine the training parameters and know the state of recovery.

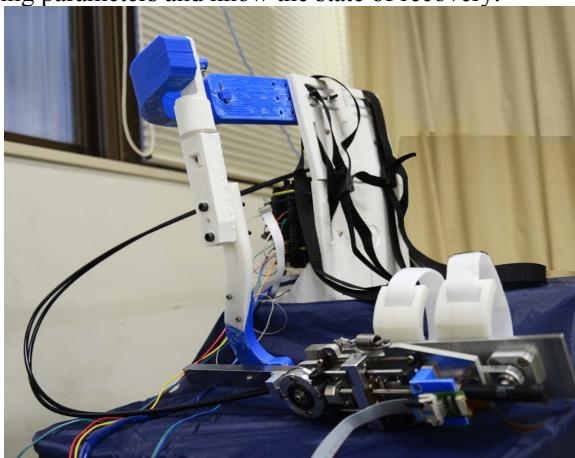


Fig.4 The real device view of the novel variable stiffness actuator-based exoskeleton for home-based rehabilitation

After 3D modeling design, we did some virtual testing to the device in CATIA software. In the initial design of the VSA device, we also made for this one a kinematic and dynamic analysis, using hand computations and verified with Adams. About the Adams, we make a very precise model by adding gravity and friction CAD model. The main goal of this step was to verify the preliminary dimensioning and be able to adjust the 3D model to have exactly what the researcher designed. Constantly modified lot of problems on the design

details and structural components, after that the researchers carried out the device manufacturing process stage. The most important part on this new device is the VSA, so in this step, to give the dimension of the main parts which are the springs and the lever length to elevate a human arm with a very accuracy and strong security structure design. On the important VSA structural parts, we used traditional manufacturing: milling, water-cutting, etc. In order to better control the costs and portability of device, we used the 3D-Printer manufacturing to other parts of the device (Fig. 4).

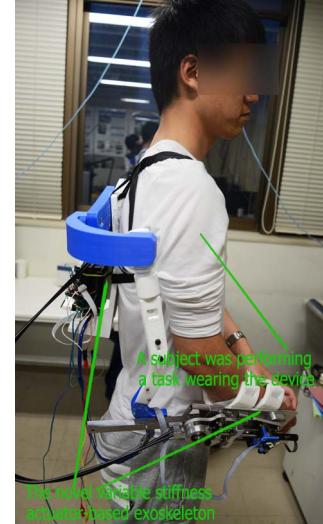


Fig.5 The experimenter being wear the device of the novel variable stiffness actuator-based exoskeleton for home-based rehabilitation

During manufacturing the entire device, we used 3D-Printer to prototype some secondary part, such as attach cables and the supporting shoulder and elbow parts and so on. After manufacturing the novel Variable Stiffness Actuator-based exoskeleton for home-based rehabilitation device, it is the using status shown in Fig.5.

III. EXPERIMENTS AND EXPERIMENTAL RESULTS

A. Signal acquisition



Fig.6 The sEMG experimental devices

The signal acquisition system used in our research (Fig. 6), the Personal-EMG equipment was developed by Japan's company in Osaka. It has eight channels used to extract the EMG signal. Surface EMG is chosen, since it is non-invasive and can be conducted by personnel other than technical medical doctors. Personal Electromyographic also provides a hardware filtering. For the experiment, we mainly consider

several important actions related to activities of daily living, this is used to refer to a daily self-care activities of individuals in a residence in medical terminology, in the outdoor environment, or both. sEMG signals were collected using bipolar surface electrodes which is 12mm long and located 18mm apart , as shown in Fig.6. The sampling rate was 1000Hz with differentially amplified (gain 1000) and common mode rejection (104dB). The used 4th order Butterworth filter was implemented in the software which was programmed using C++. The user interface was programmed using Visual C++ 2010 (Microsoft Co. USA) which can collect A/D data from the AD board through the application programming interface and process the data with MATLAB (Math Works Co. USA) via a communication from the custom interface to the commercial software running on a person computer with a 2.8GHz quad-core processor (Intel Core i7 860) and 4GB RAM.

Five healthy volunteers (age: 24.60 ± 1.67 , height: 1.70 ± 0.07 (m), weight: 67.66 ± 9.54 (kg), all male, one left-handed and four right-handed) participated in the experiments(Fig. 7). Which were placed parallel to the muscle fibers than in muscles of the abdomen before the electrodes, and the skin is shaved to reduce skin impedance cleaned with alcohol. In order to maintain the rotational speed of the upper limb movement and general volunteers, their movement is limited by the practice before the experiment such as requiring.

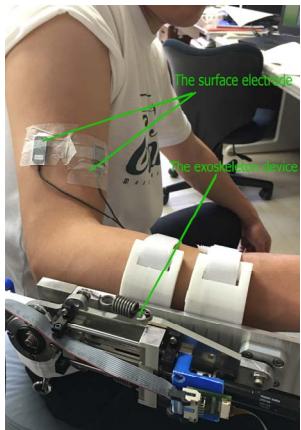
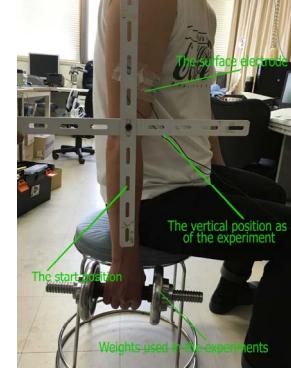


Fig.7 A performance test with the exoskeleton device and the sEMG experimental devices

In the experiment of upper limb flexion and extension in vertical plane, the volunteers were asked to sit on a chair started with upper limbs relaxed vertically; the right hand holed the 5 kg of weight, and then flexed their upper forearms by 90 degree. After a short stop keeping forearms to the horizontal position (0.5—1.0 seconds), the volunteers were asked to extend forearms to the initial vertical position. Flexion and extension in the upper level of the experiment, the volunteers put their upper limbs horizontal and repeat the same motions as in the vertical experiments.

In order to generalization the upper limb movement of the volunteers, their motions were restricted as requirement directing by a video. In the experiment of upper arm flexion

and extension, the volunteer were asked to sit on a chair started with upper limbs relaxed vertically fitting to the vertical pillar of the benchmark apparatus and then contracted their experimental upper forearm to the horizontal beam, as shown in Fig.8. After a short stop keeping the forearm to the horizontal position, the volunteer was asked to extend the forearm to the initial vertical position. In the experiment of forearm pronation and supination, the upper arm kept vertical and volunteer only pronated with his forearm, keeping the upper arm still. There is a cross mark on the ground to be the benchmark for pronation and supination, as shown in Fig.9. In the experiment of palmar flexion and dorsiflexion, volunteer kept his forearm horizontal and flexed or dorsiflexed to the contracted bounds. Each volunteer repeated each experiment ten times.



The vertical position as of the experiment the keeping position in the experiment, from which forearm moves upward and downward.

Fig.8 Experimental procedure A.



The cross mark as of the experiment the keeping position in the experiment, from which forearm moves upward and downward.

Fig.9 Experimental procedure B.

B. Experimental Results

After several series of experiments to verify and prepare the preliminary work, the entire research team recorded and analysed the data of this experiment. The above graph shows the normalized muscle activation horizontal from four muscles. Previous research has addressed the linear relationship between the musculotendon force (F_T) and the

muscle activation level ($a(t)$), as defined in Eq. (4), where c_T denotes the constant coefficient [28]:

$$F_T = c_T a(t) \quad (1)$$

Autoregressive AR model function is used to extract the filtered raw sEMG signal. In statistics and signal processing, AR model is the natural phenomenon's of various types are often used for modelling and prediction of random processes. And AR model was first introduced to represent the muscle activation electrical behaviour since 1975 [29]. The AR model is defined as following:

$$X_t = c + \sum_{i=1}^p \varphi_i X_{t-i} + \varepsilon_t \quad (2)$$

Where p is the order of the AR model; X_t is the value of the data; φ_i is the coefficients; c is a constant and ε_t is a white noise. Based on AR model, which is to predict the future based on the previously detected input output system function, which is the order of the input data is reasonable considering the coefficients certain representative.

The different motions are labelled in the medium plot. The inputs were muscle activation levels of the two muscles (Fig. 10). The outputs of the classifier were binary representation for four motions, which are relaxing, reaching, exerting force, and moving back motion. Fig. 10 shows the result filtered by Butterworth. The red curve described the filtered signals process by Butterworth filter. The peak of the signals is connected with the action of moves upward to the highest point when the hand holding with the weights.

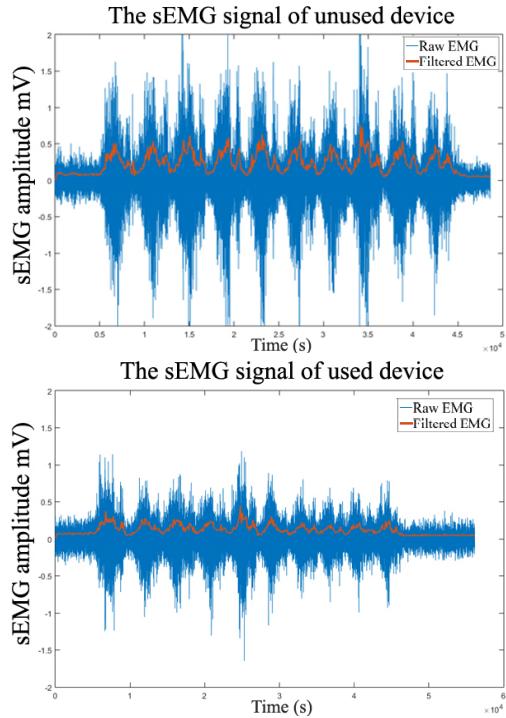


Fig.10 The sEMG signal of wearable device compared to not wearing the device.

The processed EMG signals can be used to verify that the rehabilitation device could provide the power assist to the

patients. The neural network contains one hidden layer with eight neurons. The training process was conducted using MATLAB neural network recognition tools (Version 7.10.0.499, Math Works, Inc., USA) and the on-line recognition was calculated by a modified C++ program in which the parameters involved were obtained from the ANN training results from MATLAB. After finishing the collection of the initial data, we asked each subject to perform the proposed rehabilitation training for 10 times in the morning everyday (before breakfast) and the training cycle is a period of 2 days. When the training program is completed, the experimental results were recorded once. In this experiment, the 100 sets experimental data from 5 subjects were collected. After that, analyzed and calculated the recording sEMG average value of the subjects from each subject 10 sets data, and compared with the average between the used of the device and the unused. Table I shows the average value of the normalized muscle activation level from the two muscles.

Table I
THE RECORDING sEMG AVERAGE VALUE OF THE SUBJECTS

Subject	The sEMG amplitude (mV)	
	Unused Device	Used Device
A	0.0823	0.0609
B	0.2248	0.1209
C	0.1004	0.0645
D	0.1929	0.0534
E	0.2055	0.0999

Each subject's the average value of the normalized muscle activation level from the two muscles is different, it is not difficult to observe that using the exoskeleton device the muscle activation level has been reduced, that shows the upper limb of the subject when lift the same weight, the use of force has been reduced.

IV. DISCUSSION AND FUTURE WORKS

Compliant actuator is one of the main requirements for a rehabilitation device. Both the SEA and VSA have been applied to many rehabilitation devices. In this paper, the device of the novel Variable Stiffness Actuator-based exoskeleton for home-based rehabilitation was introduced. Type of visiting rehabilitation centers, it is not convenient rehabilitation is expected to create demand for home-based growth. This paper presents a being wear the device of the novel variable stiffness actuator-based exoskeleton for home-based rehabilitation for patients' use. It's easy to achieve a device is absolutely for the home Rehabilitation. In particular, if the device is acting as a proxy for the therapist, it must be able to exercise a passive and active training necessary to switch between the impedance near zero impedance necessary high articulation and strong mobility. Patient safety is the rehabilitation process of the most critical issues. The device can be controlled in the proposed method, a low output impedance. Required output impedance may be obtained by

setting the virtual impedance. During the mechanical design, there are two passive DoFs designed for solving the misalignment between the human joint and device joints during the training. A torque limiter was designed for ensuring the patients' safety. Experiments for testing the rehabilitation device could provide the power assist to the patients.

In the future, more experiments should be carried out to find the relationship between the external feedback and the training effect. Manufacturing method using 3D-Printing, binding allowed more reasonable with a device, after the design will be improved.

ACKNOWLEDGMENT

This research is partly supported by National Natural Science Foundation of China (61375094), Key Project of Scientific and Technological Support of Tianjin (15ZCZDSY00910), National High Tech. Research and Development Program of China (No.2015AA043202), and SPS KAKENHI Grant Number 15K2120.

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