Mechanical Design and Control Method for SEA and VSA-based Exoskeleton Devices for Elbow Joint Rehabilitation

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Abstract: Robot-aided rehabilitation training allows patients to receive a more effective and stable rehabilitation process. Exoskeleton devices are superior to the endpoint manipulators and cable suspension devices on the aspect that they can train and measure the angle and torque on each joint of impaired limbs. For robotic devices, physical safety should be guaranteed since the robot-assisted training relies on high human-robot interaction especially for exoskeletons. Traditional robotic devices mainly introduce the stiffness actuator, while the high levels of kinetic energy of robots will induce unsafe. For guaranteeing the safety of patients, compliant actuator such as the series elastic actuator (SEA) and variable stiffness actuator (VSA) design has been involved into these devices. The added compliance can make robots intrinsically safe and realize the energy-efficient actuation. The VSA used a variable stiffness elastic component instead of a constant stiffness elastic component, and VSAs is deemed to a kind of SEAs. A closed-loop interaction control method was used for SEAs to generate low impedance. By comparison, the VSA realizes adaptable compliance properties with inherent mechanical design. Thus, for SEAs, an additional mechanism is needed to adjust the output stiffness. In this paper, two kinds of compliant exoskeleton devices designed with the SEA and VSA respectively are introduced. The mechanical design and control method for each device are introduced, especially the design for guaranteeing patients’ safety.

Keywords: Compliant actuator, home-based rehabilitation device, series elastic actuator, variable stiffness actuator, mechanical design, control method.

1. INTRODUCTION

Approximately 795,000 people suffer from a new or recurrent stroke every year according to the statistics [1]. Stroke can lead to impaired motor control of the upper and lower limbs with significant impairment of activities of daily living (ADL). Traditional therapy is labor-intensive and it requires one-to-one therapist-patient interaction [2]. Therefore, it becomes onerous to perform highly intensive treatment for all patients. Given that, treatment based on the robotic technology has been investigated by many research groups and can be separated into three types: end-effector [3], cable suspension [4], and exoskeleton [5]. 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 [6]. For instance, the ARMin robot which is one of typical exoskeleton devices can support the entire arm for rehabilitation with patient-cooperative control strategy during activities of daily living (ADL) training tasks [7].

For robotic training devices, it is necessary to guarantee enough torque performances to perform training while allowing for a safe patient-robot interaction, especially spasmotic happens [8]. For the conventional robot with “stiffness actuator”, the high levels of kinetic energy of robots will induce unsafe; especially the motion is associated with the fast speed. The SEA designed with a new actuator principle has been introduced into the compliant robot design. The SEA is a high weight-to-torque ratio actuator which can decrease the weight while guaranteeing sufficient force performance. The added compliance makes robots intrinsically safe and realizes the energy-efficient actuation. The compliance of the SEA realizes low impedance with an additional control loop and the compliance property is fixed [9]. As an improvement, VSAs added variable stiffness elastic components instead of constant ones. VSAs are capable of varying the apparent output stiffness independently of the actuator output position. The adjustable compliant behavior of VSAs is an inherent hardware property [10, 11], thus a mechanism for varying the stiffness is needed. The VSA is also a trade-off between the compliance and accuracy [12]. For instance, Lenzi et al. proposed a variable impedance powered elbow exoskeleton device named “NEUROExos”. The device used an antagonistic actuation system providing a software-controllable passive compliance [10]. Wang et al. also proposed the active variable stiffness elastic actuator (AVSER), and the compliance was changed by shortening...
the effective length of the leaf spring, thus the transmission ratio between the actuated load and the force from the internal elastic elements can be adjusted [13].

In this paper, two kinds of exoskeleton devices with the principles of SEAs and VSAs respectively are introduced. Both of them were designed according to therapist’s advice. The mechanical and control method for each device are introduced, and the method for ensuring patients’ safety is addressed. The remainder part of this paper is organized as follows. In the section 2, the working principles of SEAs and VSAs are briefly introduced. In the section 3, the mechanical design and control method of the SEA-based exoskeleton device are focused on. In the section 4, the VSA-based exoskeleton device is introduced. The conclusion will be given at last.

2. WORKING PRINCIPLE OF SEAs AND VSAs

The working principles of the SEA and VSA are shown in (Fig. 1) [12, 13]. Usually, a gearbox is added to the motor which can realize a high weight-to-torque ratio performance and decrease totally weight of devices. However, an unavoidable problem with large reduction ratio gearheads is the non-backdrivability resulting from high-reflected inertia and friction. To obtain variable impedances or a compliant joint, elastic elements were added between the motor shaft and output of the device. The dynamic of the load in each actuator can be written as:

\[ m\ddot{x}_2 = k(x_1 - x_2) \]  

where the \( m \) is the mass of the load, \( x_1 \) is the equilibrium controlled by the motor, \( x_2 \) is the displacement of the output, and \( k \) is the coefficient of the elastic element. It can be found that VSAs are differing from SEAs with a controllable stiffness \( k \) [12]. The variable stiffness elastic components make the VSA an inherent hardware property compliant behavior. Thus, a mechanism for adjusting the stiffness is needed. By comparison, the SEA realizes a closed-loop interaction control method to generate low impedance with a constant stiffness elastic component.

\[ \text{(a) Working principle of the SEA.} \]

\[ \text{(b) Working principle of the VSA.} \]

Fig. (1). Working Principles of the SEA and VSA [12, 13].

3. SEA-BASED EXOSKELETON DEVICE AND THE CONTROL METHOD

3.1. Mechanical Design

In our previous study, Z. Song et al. designed a human upper-limb exoskeleton rehabilitation device (ULERD) as shown in (Fig. 2) [14]. The motivation of the ULERD is to provide passive and active training to patients with motor dysfunction to recover the motor function of upper limb. The working principle of this device is relative to the principle of the SEA [14]. The exoskeleton device realizes an ergonomic physical human-robot interface that is convenient to wear and comfortable to operate. The device can provide the training for both elbow and wrist joints and it is easily worn by caregivers or patients themselves. In this paper, we mainly focus on the elbow joint, thus the wrist part is ignored.

Fig. (2). Human upper limb exoskeleton rehabilitation device (ULERD).

The detailed structure of the elbow joint is shown in (Fig. 3). The two passive Degree of Freedom (DoF) mechanisms (rotation and translation) in the elbow joint allow constant alignment between the user’s elbow and robot axes. Otherwise, joint misalignment between the robot and human joints would introduce unwanted translational forces. Patients may feel not comfortable when the translational force happens.

\[ \text{Friction facing} \]

\[ \text{Grooved pulley} \]

\[ \text{Encoder+gearhead+motor} \]

\[ \text{Clamp nut} \]

\[ \text{Shaft sleeve} \]

\[ \text{Spring} \]

\[ \text{Cable} \]

\[ \text{Main pulley} \]

Fig. (3). CAD drawing of the elbow joint structure.

3.2. Torque Limiter for Physical Safety of Patients

Security issues of patients are important caused by robotic devices. A torque limiter mechanism was designed as shown in (Fig. 4). The friction between the axle sleeve of the elbow motor and cable driving part is controlled by adjusting the screw. Therefore, the cable driving part will separate from the motor shaft when overloaded. When external torque is less than the threshold preset, the movement can be trans-
mitted to the cable driving part through a stainless steel wire with a diameter of 0.5mm. The torque threshold of the torque-limiter mechanism can be adjusted to different patients. The design can avoid the suddenly increased force (e.g. spasm).

\[ X_{md} = \int K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \]

where \( K_p, K_i, \) and \( K_d \) are three parameters of the PID controller, \( e \) is the error that can be controlled as a constant value for the compliance. The influence can be partly mitigated by using a direct-drive motor; however, the weight of the device will be increased for generating the same power performance. Therefore, the elastic elements were added between the motor shaft and output of the device. The SEAs have several advantages, including high shock tolerance, low reflected inertia, high energy-storage capacity, and accurate and stable force control [13].

After introducing the SEA into the exoskeleton device, the compliance is actually realized with a closed-loop interaction control strategy. By controlling the deflection of elastic elements in the SEA, the output impedance can be controlled. For generating the desired virtual impedance, the control algorithm can be written as Equation (2),

\[ X_{md} \sim \theta = \frac{K_v \theta_B \dot{\theta}}{K_i} \]  

where \( X_{md} \) is the desired rotation angle of the motor, \( \theta \) is the rotation angle of the device, \( K_v \) and \( B_v \) are the parameters for virtual impedance model, and \( K_i \) is relative to the elastic element. It can be found that for the mechanism of SEA, the stiffness of the actuator is constant. A typical proportional-integral-derivative (PID) algorithm was used for controlling the deflection accurately. The detailed PID algorithm is written as Equation (3) and (4),

\[ v(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \]  

\[ e(t) = X_{md}(t) - \theta(t) \]

where the \( K_p, K_i, \) and \( K_d \) are three parameters of the PID controller. The stiffness control part is fixed to a bearing while rotating with the motion range can be adjusted manually.

In the position control part, a torque-limiter mechanism can help the motor recovery of stroke patients. The torque-limiter can provide patients more protection. 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.

The stiffness control part is fixed to a bearing while rotating with the motion of position control part. For the stiffness control part, the variable stiffness behavior is realized with a variable transmission ratio between the elastic elements and the actuator output. A Maxon motor (6V 8W EC-max-16 dc-motor) combined with a planetary gearbox (Maxon GP16C planetary gearbox) was applied into a hypocycloid mechanism as shown in (Fig. 7). The hypocycloid gear mechanism

\[
\text{Fig. (4). Torque limiter in the elbow joint.}
\]

3.3. Control Method for the ULERD with Non-back drivability

To decrease the totally weight of device, the BLDC motor with high power density was used, and the frame of the device was fabricated with aluminum. After adding a gearbox with a high reduction ratio (231:1), the device can output enough torque performance to perform rehabilitation tasks (with Max. continuous torque 14.2mNm), especially for passive trainings. However, the intrinsic stiffness was increased after adding the reduction gear and a reflected inertia will be added to the elbow joint. Consider that the compliant actuation is claimed to be one of the main requirements for a rehabilitation device [15], the added reflected inertia will influence the compliance. The influence can be partly mitigated by using a direct-drive motor; however, the weight of the device will be increased for generating the same power performance.

The stiffness control part is fixed to a bearing while rotating with the motion of position control part. For the stiffness control part, the variable stiffness behavior is realized with a variable transmission ratio between the elastic elements and the actuator output. A Maxon motor (6V 8W EC-max-16 dc-motor) combined with a planetary gearbox (Maxon GP16C planetary gearbox) was applied into a hypocycloid mechanism as shown in (Fig. 7). The hypocycloid gear mechanism
was designed with a special diameter, thus the rotation motion can be changed to a straight-line motion of the pivot [17].

In more details, the rotation of the motor can be changed into a straight-line motion of the pivot point and the ratio between the elastic elements and the output can be adjusted as shown in (Fig. 8). Thus, the stiffness of the device can be adjusted by the moving distance of the pivot. The stiffness of the device can be calculated by (5),

\[ K = \frac{F}{\delta} \]  

where the \( K \) represents the output stiffness, \( F \) is the applied force and \( \delta \) is the deflection of the output. The output stiffness can be further calculated by (6),

\[ K = 2kl^2 \left( \frac{l_1}{l_2} \right)^2 \cos(2(\delta - \theta_1)) \]  

where the \( k \) is the elastic constant of the spring, \( l \) is the whole length that the pivot can move, \( l_1 \) is the distance that the pivot moves (Fig. 8), and the \( \theta_1 \) is the rotation angle of the frame (Fig. 7) [17].

The idea that brings the hypocycloid mechanism into the stiffness adjustable mechanism was first presented by Groothuis SS et al. [17]. Groothuis SS et al. also proved that by moving the pivot point along the lever arm can minimize the involved forces during the change of stiffness. A similar mechanism is also used in HypoSEA [18]. We directly fixed the arm supporter to the output of the stiffness adjustable mechanism while the rotating center of the device is accordance with that of the arm supporter. Compared with the SEA-based exoskeleton device, the device becomes more complex. However, an easier position controller is enough, to realize the compliance by just control the movement of the pivot point. This device is also designed for the requirements of home-based rehabilitation training; the device is easy to be fixed to a table before the training. And both the passive and active training can be performed with the same device. The variable stiffness is also adapted to special level of impairment of patients by moving the pivot point.
4.2. Torque Limiter for Physical Safety of Patients

A torque limiter clutch mechanism is also designed in the VSA-based exoskeleton device as shown in (Fig. 9). The clutch mechanism is superior to that of the ULERD by using the ball rollers. When the interaction torque between the patients and the device is larger than a preset threshold, the torque limiter will be released, thus the device will rotate regardless of the position of the motor. In detailed, the coupling is used to connect the axis of motor and torque limiter part. The clamp spring restricts the translation motion. The mechanism is similar with a clutch that the compressed force from the coil spring can force four ball rollers insert into the fillister. When the interaction force becomes larger than the preset threshold, the ball roller will be apart from the fillister, so that the safety of patients could be ensured.

Fig. (9). Torque limiter clutch mechanism. (a) CAD design (b) Torque limiter clutch.

4.3. Evaluation of the Compliance of the Device with Different Stiffness

A position controller (PID controller) was used for moving the pivot point to control the output stiffness. The compliance variable device is necessary for adapting to a specific level of impairment of patient. Therefore, the compliance with variable stiffness should be evaluated experimentally.

A force sensor (MINI 4/20; BL AUTOTEC, LTD.) was attached to the output link at 91 mm from the center of rotation. We manually rotate the frame clockwise and an output deflection was caused. The rotation angle of the frame was measured with the angle sensor as shown in (Fig. 10). An inertial sensor (MTx sensor, Xsens, Enschede, the Netherlands) was installed on the output part for measuring its rotation angle. The measured force with force sensor is relative to the deflection between the frame and the output. We selected three parameter (0mm, 4mm, 8mm) which represent distances that the pivot moves from the rotation center and the experimental result is shown in (Fig. 11). It can be found that the measured force increased linearly with the deflection angle, defined as the deviations from its own equilibrium position. Therefore, for the experimental result, with the increase of the selected parameter, the passive joint stiffness was increased. During the rehabilitation training, a suitable stiffness can be selected for a better recovery of impairment of patients.

Fig. (10). Compliance test with different stiffness.

Fig. (11). Relationship between the output deflection and force.

CONCLUSION

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, two kinds of exoskeleton devices which realize the compliance with the SEA and VSA respectively are introduced.

The SEA-based exoskeleton device has a relatively simple structure and the compliance was realized with a closed-loop interaction control method. The device can output low impedance with the proposed control method. A needed impedance output can also 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.
Compared with it, the VSA-based exoskeleton device can realize inherent hardware compliance. The variable stiffness behavior was realized with a variable transmission ratio between the elastic elements and the actuator output. The hypocycloid mechanism was used to move the pivot point along the lever arm for changing the transmission ratio. Especially, for guaranteeing the safety of patients, a torque-limiter mechanism was designed. The performance that the device can change the stiffness was evaluated. With a constant stiffness, the output impedance (force) is relative to the deflection of elastic elements.

Overall, the VSA-based device does not need a complex control loop to realize the compliance; however, an additional mechanism for adjusting stiffness is needed. For obtaining a better recovery of impairment limb, a suitable stiffness can be selected. By comparison, the structure of SEA-based exoskeleton device is relative simple; however, the output stiffness of the SEA-based exoskeleton device is constant. The adequate and inadequate of two kinds of devices for rehabilitation training will be studied in our future work with more clinical evidences.

CONFLICT OF INTEREST

The author(s) confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

This research is partly supported by National High Tech. Research and Development Program of China (No.2015 AA043202), JSPS KAKENHI Grant Number 15K2120 and Kagawa University Characteristic Prior Research Fund 2014.

REFERENCES