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AVSER—Active Variable Stiffness Exoskeleton Robot System: Design and Application for Safe Active-Passive Elbow Rehabilitation

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Abstract—**The paper introduces an active variable stiffness exoskeleton robotic system (AVSER) with the active variable stiffness elastic actuator (AVSEA), which improves the safety for human-robot interaction and produces unique adjustable stiffness capacity to meet the demand for safe active-passive elbow rehabilitation. The AVSEA consists of two DC-motors. One is used to control the position of the joint, and the other is used to adjust the stiffness of the system. The stiffness is generated by a leaf spring. By shortening the effective length of the leaf spring, the AVSEA is able to reduce the stiffness automatically, which makes the AVSER from active (assistive) motion to passive (resistance) rehabilitation during the process of therapy. In the paper, the mechanical design, modeling, and control algorithms are described in details. The capacity of the proposed AVSER with electromyogram (EMG) signal feedback is verified by rehabilitation exercise experiments for the subject to demonstrate the efficacy of the developed system.**

I. Introduction

Rehabilitation robotics emerges from mechatronics as a focused effort to design rehabilitation systems, since successful motor rehabilitation of traumatic brain-injured, spinal cord-injured, and stroke patients usually require a task-specific therapy approach. In reality, budget constraints and therapist shortages limit a hand-to-hand therapy approach throughout the world. Thus, intelligent machines not only offer a good solution to promote motor recovery, but also provide a better understanding of motor control [1-3].

Achieving the intensive automatic treatment must employ manifold strategies, involving all aspects of the mechatronics system design, such as the mechanical, electrical, and control and software architectures. In general, two different kinds of rehabilitation robots, **active assistive robots** and **passive constrained robots** are developed as successful rehabilitation tools. An active assistive robot serves as a force source, transmitting power to a body segment to actively guide a patient passively following the desired rehabilitative motions. Assistive robots in [4][5], prosthetic devices in [1][6] and even exoskeletons in [7][8] fall into this category. On the other hand, a passive constrained robot serves as a passive constraint. The robot can actively change preset constraints of a patient's motions to allow the patient to move spontaneously according to the given motion pattern of the passive treatment. The devices and robots proposed in [9][10] are passive constrained robots. Determining to utilize what kind of robots to improve motor capacity depends upon quantitative evaluation of different rehabilitation training for different patients. For instance, in the early stages of therapy, passive rehabilitation is often the preferred method for reducing swelling, alleviating pain, and restoring range of motion [11].

Up to now, most of robotic systems, consisting of rigid components, are heavy, fast, strong and powerful. Most of them are without any capacity for interaction with humans under safe constraints. In order to work, cooperate, assist, and interact with human, the new generation of safe robot systems have been devised to efficiently build a robot with intrinsically safe robot actuation, such as series elastic actuators (SEA) [12]–[15] or Safe joint mechanism (SJM) [16][17]. However, the safe robot actuators, SEA and SJM, cannot generate a desired stiffness to satisfy specified tasks in advance. In order to obtain the ideal stiffness to satisfy the functions of human-robot interaction, active variable stiffness actuators used a variable stiffness transmission mechanism to actively vary mechanical stiffness of the given system were proposed. The active variable stiffness actuators can be classified into several groups. (1) Antagonistic actuation with nonlinear spring: two actuators connect same block [18]–[20]. (2) Antagonistic actuation using a pneumatic artificial muscle [21]–[24]. (3) Serial actuation: most implementations used two actuators to control the position and stiffness of the joint [25]–[28]. (4) Serial actuation with leaf springs: leaf springs were also used to vary mechanical stiffness [29][30]. These active variable stiffness actuators are advantageous to dexterous manipulation and their compliant components are good for interaction safety. However, for antagonistic actuation, the control theory for synchronous movement of two antagonistic motors is complex, and the size of air compressor for pneumatic artificial muscle is huge.

In this paper, a new active variable stiffness mechanism, the Active Variable Stiffness Elastic Actuator (AVSEA) is developed. With a special AVSEA actuator design, the particular Active Variable Stiffness Exoskeleton Robot (AVSER) system is applied to safe active-passive elbow rehabilitation, as shown in Fig. 1. The AVSER is defined as a robotic system using the concept of the AVSEA. Herein, the AVSER is designed and applied to elbow rehabilitation to generate either directly positive actuation force to guide the

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human user or indirectly negative resistive force to resist the human user to achieve versatile desired motion patterns.

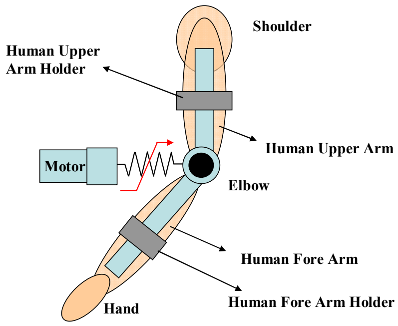

Fig. 1. The Active Variable Stiffness Exoskeleton Robot System

To sum up, the AVSER has the following characteristics and advantages:

- Energy efficiency: The leaf spring structure of the AVSEA has solved the energy waste problem because of dispensable dynamic adjustment.
- Functionality: The AVSER has elastic elements and functions of variable stiffness to meet the demand for safe active-passive elbow rehabilitation.
- Safety: The elastic elements are used to improve the safety and security for human-robot interaction. Beside, the bounded joint limited and the emergency stop are used to prevent an abnormal or uncomfortable elbow rehabilitation.
- Cheap: With the AVSER, the torque/force sensor can be replaced with a potential meter to lower costs.
- Portable: The convenient AVSER is small enough to carry easily.
- Convenient: The complete rehabilitation robot system (with computer user interface, control system, and AVSER) is developed for users to set it up and use it more conveniently.

The paper is organized as follows. Section II presents an overview of the AVSER. The AVSEA, its properties, and the design topology are introduced in Section III. The design and principle of the proposed AVSER based on the Active Variable Stiffness Elastic Actuator (AVSEA) is addressed in Section IV. Experiments are provided to demonstrate that the proposed AVSER can provide different rehabilitation exercises. The results are given in Section V. Finally, the conclusions are made in Section VI.

I. New Rehabilitation Robot System—Active Variable Stiffness Exoskeleton Robot (AVSER)

As a possible application, an AVSER using an Active Variable Stiffness Elastic Actuator (AVSEA) provides an adjustable stiffness capacity to execute the particular tasks for active-passive elbow rehabilitation.

Considering that EMG signals of human muscles are crucial to understanding a patient's intention of movement, this AVSER is also integrated with EMG signal feedback capacity. This signal feedback can be used as important information to investigate the patient's muscle condition with

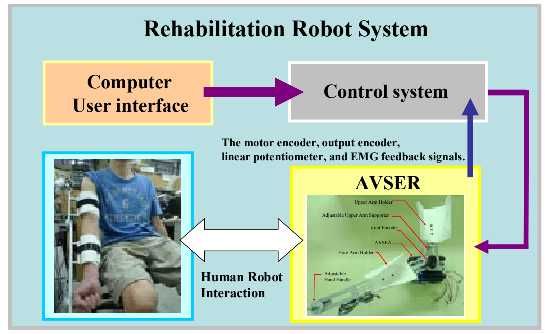

Fig. 2 Rehabilitation Robot System

other quantity signal feedback for the control system to generate suitable training strategies, whereas we only use EMG signals to allow occupational therapists to investigate the muscle condition with other feedback signals in this work. In short, we use two encoders, one linear potentiometer, and two active electrodes as the feedback sensors for the AVSEA. Two encoders are used to measure the motor angle and the elbow angle; the linear potentiometer is used to measure the deflection of linear springs; two active electrodes are used to measure EMG signals. The overall Rehabilitation Robot System using AVSER is shown in Fig 2.

II. Property of the Active Variable Stiffness Elastic Actuator (AVSEA)

A. Motor-Ball screw Drive System

To keep the ability of the actuator to make precise position movements and trajectory tracking control easier, a Motor-Ball screw Drive System was used in this paper. In order to shorten the length of the ball screw to reduce the size of the Motor-Ball screw Drive System, a block assembly with propelling shave and fixed pulley is used, as shown in Fig. 3. In the block assembly, $X_P{}'$ is the position of the propelling shave, and X_P is the position of the propelling shave before the external force is generated. $X_E{}'$ is the position of the end point of the cable, and X_E is the position of the end point of the cable before the external force is generated. The movement distance between the propelling shave and the end point of the cable is given by:

$$-2(X_P{}' - X_P) = X_E{}' - X_E \qquad (1)$$

By combining Motor-Ball screw Drive System and block assemblies, the New Motor-Ball screw Drive System is presented in this paper. It is shown in Fig. 4. The ball-screw is driven and rotated by a DC-motor01. The moving plant which is fixed on the ball screw will advance or draw back in its own axial direction, and the propelling shave fixed on the moving plant will advance or draw back, too. Finally, by the block assembly, the output link of New Motor-Ball screw Drive System (with block assembly) will be rotated.

B. Active Variable Stiffness Serial Configuration

The design of an active variable stiffness serial configuration can be expressed by the series combination. A simple beam system can be used to explain the properties of the active variable stiffness serial configuration. However, in this paper a leaf spring is used instead of the beam. In order to obtain the ability to control the deflection at the end point of the leaf spring, an active variable stiffness serial configuration is designed, as shown in Fig 5. In the active variable stiffness serial configuration, a screw is rotated by a DC-motor02, and a moving plant02 is placed on the screw. When the screw is rotated by the DC-motor02, the moving plant advances or draws back in its own axial direction. By changing the position of the moving plant, the active variable stiffness serial configuration has ability to obtain the effective length of leaf spring (l), the change of the effective length of the leaf spring results in changing stiffness.

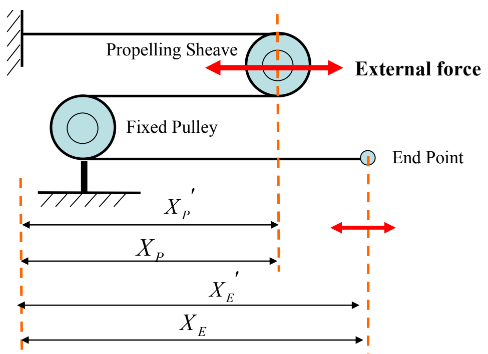

Fig. 3 A block assembly (with propelling shave and fixed pulley).

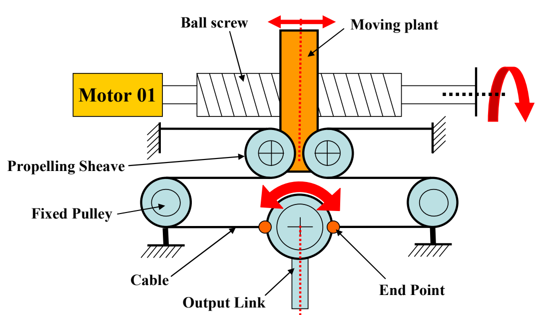

Fig. 4 New Motor-Ball screw Drive System (with block assembly)

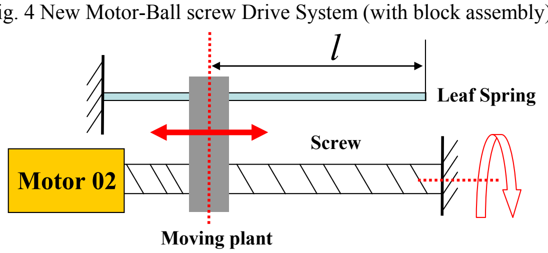

Fig. 5. Schematic of active variable stiffness serial configuration.

C. Active Variable Stiffness Elastic Actuator (AVSEA)

The new motor-ball screw drive system makes precise position movements, and the active variable stiffness serial configuration has the ability to minimize large impact forces due to shocks, thereby safely interacting with the user. In this paper, the main idea of the AVSEA design and application for safe physical human-robot interaction is based on these two important properties: precise positioning and minimizing impact force.

III. Principle and Design of the Active Variable Stiffness Elastic Exoskeleton Robot (AVSER)

Based on the results in the previous section, an Active Variable Stiffness Elastic Actuator (AVSEA) is built. The design, modeling, and analysis of the AVSER (AVSEA with exoskeleton structure) will be explained in this section.

A. Mechanism Design and Working Principle of the AVSEA

The two main mechanisms, the new motor-ball screw drive system and an active variable stiffness serial configuration, are designed to obtain the two desired characteristics of AVSEA, i.e., accurate movement and safe human-robot interaction. The 3-D model of AVSEA is shown in Fig. 6.

The key feature of the AVSEA mechanical structure is the relation between the input shaft and the ball screw. The actuation principle of the AVSEA is illustrated in Fig. 7. Fig. 7(a) shows the working concept. In the drive system, an input shaft passes through the center of the ball screw. When the input shaft is driven and rotated by the DC-motor 01, the ball screw will be driven and rotated then the moving plant, which is fixed on the ball screw, advances or draws back in its own axial direction. There is a time belt fixed on the moving plant and connected to the output link. Then the output link is rotated since the time belt, which is connected to the moving plant with the output link, is moved. According to the abovementioned moving principle, the AVSEA is able to make precise position movements or trajectory tracking control easier. Fig. 7(b) is the cross-section diagram, and the detailed structure of the Motor-Ball screw drive system of AVSEA is shown in Fig. 7(c). In addition, when external forces, impacts or shocks are exerted on the output link, the external forces will push/pull the moving plant through the time belt, and then all of the structure, including ball screw and moving plant, will be moved. Because the input shaft passes through the center of the ball screw, the ball screw will slide in the same axial direction as the input shaft, as shown in Fig. 7(d). In all cases, the AVSEA can minimize large impact forces due to shock and safely interact with the user.

B. Mechanism Design of the AVSER

In order to satisfy individual needs of the elbow rehabilitation, a level arm with a forearm holder is designed to move with a subject's forearm, and an adjustable reference with an upper-arm holder is designed to allow a subject to change the posture from lying down to sitting, The 3D model of AVSER is shown in Fig. 8.

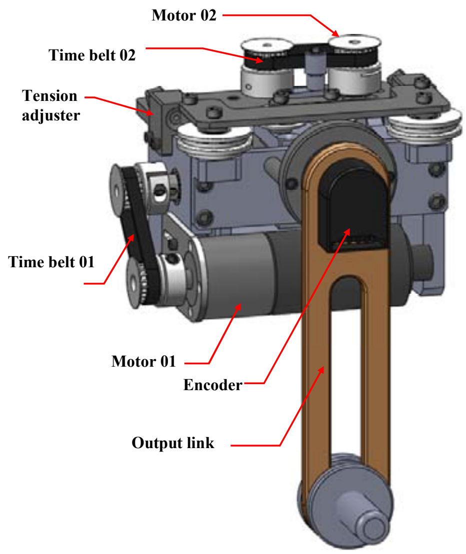

Fig. 6. 3D model of AVSEA

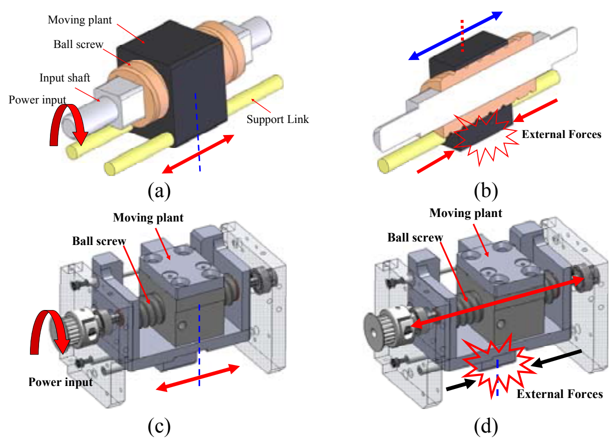

Fig. 7. 3D model of the Motor-Ball screw drive system of AVSEA

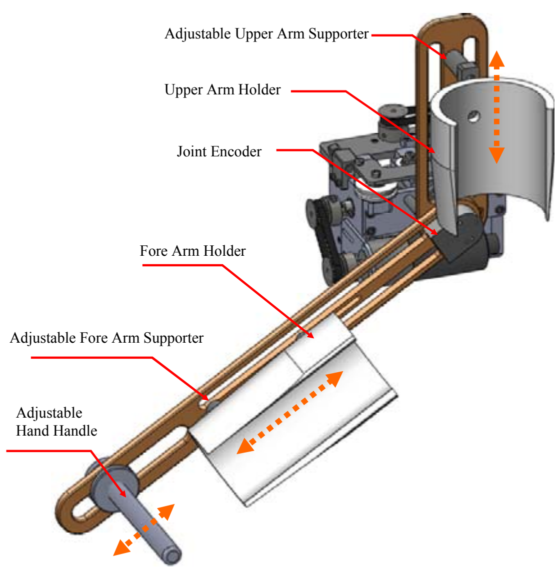

Fig. 8. 3D model of AVSER.

IV. System Experiment Evaluation

In this section, experiments are conducted to evaluate the properties and abilities of the Active Variable Stiffness Exoskeleton Robot System (AVSER), as shown in Fig. 9. The rotation of the axis is measured by an encoder which is fixed on the output link. The dimension of the AVSER, design parameters and some detailed specification are listed in Table I. In the following experiments, EMG signals from two muscles, the biceps and triceps, were measured from a 34-year-old subject. Active surface electrodes were placed on the biceps and triceps by an occupational therapist. Those data were sampled at 8000 Hz by a NI sbRIO-9642 and filtered with a band-pass fourth-order Butterworth filter in which the low cutoff frequency is 100 Hz and the high cutoff frequency is 1000 Hz. The rehabilitation exercise setup is shown in Fig. 10.

TABLE I
The Specifications of AVSER

Parameters	Value
Mass (include two motors)	1.6 kg
Length*Width*Height	120*110*90 mm
DC-motor	2
Max. Output Torque	29 Nm
Max. Output Speed	60 rpm
Max. Stiffness	Equivalent to rigid joint stiffness
Min. Stiffness	0.085Nm/deg
Motion Space	$\pm 150^o$
Leaf spring (thickness* width)	3*10 mm
Max. Output Link Deflection	$\pm 40^o$

* The input motors used in this prototype design are Faulhaber DC-micromotor 3863W024CR with 38/2 gear head of which reduction ration is 1:14. and 3257W024CR.

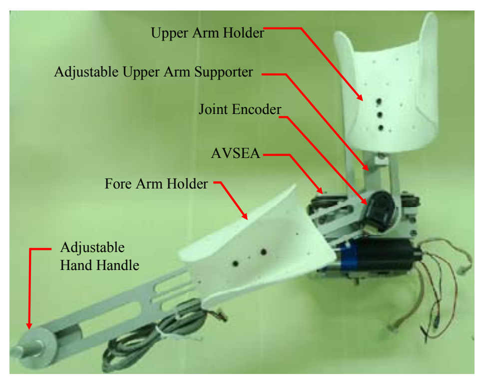

Fig. 9. Active Variable Stiffness Exoskeleton Robot System (AVSER).

AVSER is able to demonstrate its capacity of realizing different rehabilitation exercises. Four kinds of rehabilitation exercise modes—(a)Active rehabilitation, (b)Active-assistive rehabilitation, (c)Passive-resistance rehabilitation, and (d)Zero resistance—are examined, as shown in Fig. 11. Experimental results of the elbow angle, assistive torque, resistance torque, and EMG signals from biceps and triceps during each test are shown in Fig. 12.

Active rehabilitation

Fig. 12(a) shows that in the range-of-motion exercise mode and under joint position control, the muscles are relaxed and the EMG signals are flat. In this active training, the movement will be entirely induced by the AVSER and the subject will not exert any force.

Active-assistive rehabilitation

Fig. 12(b) shows that in active-assistive rehabilitation mode and under force control, the AVSER provides assistive torque in the same direction during the elbow flexion and the biceps are relaxed. On the other hand, this exercise mode can be seen as an interactive mode in that the subject can induce the movement by himself without any side effects when the AVSER assists.

Passive-resistance rehabilitation

In passive-resistance rehabilitation mode and under force control, as shown in Fig. 12(c), biceps contract in the elbow flexion motion because of the direction of the set resistive torque. With the resistive torque, triceps will contract more in the elbow resistance rehabilitation motion. The results show that the AVSER can generate constant load torque while a subject spontaneously moves.

Zero resistance

In zero resistance and under force control, as shown in Fig. 12(d), the EMG signals of biceps are induced by the gravity component generated by the weight of the level arm and the subject.

In those experiments, EMG signals implying the subject's intention provide therapists a better understanding of the subject's motor condition, and can be used to modify the therapy with other information, like elbow angles, elbow torque, etc. It could be used to automatically provide physical therapy for different rehabilitation exercises in the future as well.

Fig. 10. Rehabilitation exercise setup.

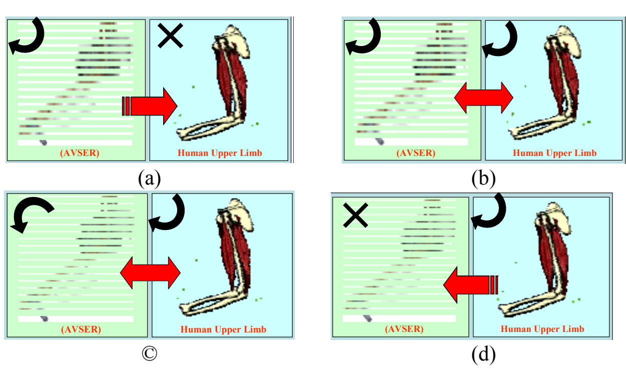

Fig. 11. Four kinds of rehabilitation exercises.

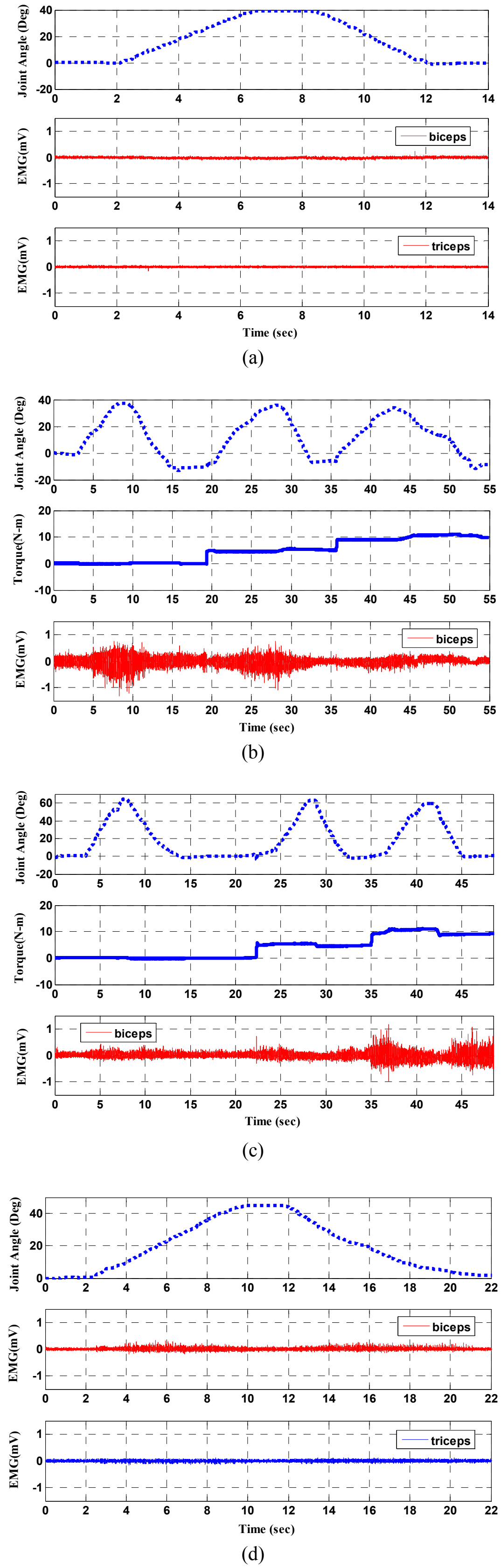

Fig. 12. Experiment results of different rehabilitation exercise modes.

V. Conclusion

This paper presents the rehabilitation system (AVSER) with the safety component (AVSEA). The working principle, construction, properties, and the possible application of the AVSER are provided as well. The AVSER improves the safety for human-robot interaction and produces unique adjustable stiffness capacity to meet the demand for safe active-passive elbow rehabilitation. Compared with other rehabilitation systems, the proposed AVSER possesses several important advantages, such as energy efficient, safe, cheap, portable, and convenient. The experimental results show that the AVSER is capable of realizing different rehabilitation exercises.

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