Design of a Compliant Upper-Limb Rehabilitation Exoskeleton based on Novel Series Elastic Actuators

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Abstract— This paper proposes an Upper-Limb Exoskeleton actuated by a novel Series Elastic Actuator (SEA) for the purpose of rehabilitation training. In design, the exoskeleton features 7 Degrees of Freedom (DOFs), 4 of which are actuated by SEAs, so as to cover most of the human motion trajectories at the time of rehabilitation training. The elastic component of SEA includes the tension springs intended for circumferential arrangement. Showing a linear torque-deformation characteristic within its working range, the elastic component retains consistent rotary stiffness in both directions. In order to evaluate the dynamic performance of the exoskeleton, the experiment of a single joint force and position control is conducted in this exoskeleton. The result of the compliant joint's bandwidth reaches 6.1 Hz in force control and the tracking error is 0.3 Nm with a sinusoidal input torque with an amplitude of 3 Nm and a frequency of 1.5 Hz. Our result demonstrates an accurate force control and position regulation behavior that meets the requirement placed on rehabilitation training.

I. INTRODUCTION

In general, upper limb motor dysfunction is attributable to the impairment of central nervous [1-3]. Fortunately, it has been found out in some studies that the loss of mobility is reversible for most patients [4]. Thus, adequate and proper rehabilitation training is essential for patients to regain their mobility [3].

Up to now, plenty of researches on robotics for medical rehabilitation have been conducted to assist patients with their activities in daily life (ADL), reduce the work intensity of therapists, and develop the approaches to rehabilitation training that are integrated with robotics.

Despite the wide variety of rehabilitation robots, they can be categorized into the following 3 types [5]. The first one is endpoint manipulator [6-9]. The robots of this type make contact only with the endpoint of patients’ upper-limb, such as hands or wrist. The second one is cable driven [10-14]. The wire is actuated by the actuators mounted on a fixed platform and connected to the limb of patients. The last one is wearable exoskeleton. Capable to mimic and utilize the laws of human motion, the robots of this type possess a kinematic chain that is aligned with human’s. Its active joints are actuated to assist patients with rehabilitation training [15] [16].

Despite its complexity, exoskeleton has demonstrated a significant potential in rehabilitation since each joint of it can move independently, which allows patients to do specific training. Compared with the directly driven conventional exoskeletons, the motors are mounted on active joints for delivering force to patients without buffering. It possesses a comparatively simple structure and its high stiffness is conducive to applying precise control. Due to the lack of elasticity, however, it is possible for the unexpected impulse like the sudden launch of motors to cause harm.

On the other hand, there is a lack of necessary DOFs for a large proportion of existing upper-limb exoskeletons and they are not aligned well with human motion law. For example, the upper limb exoskeleton described in [17] consists of as few as 3 DOFs and it misses the DOF of shoulder’s intra/extra rotation. Due to the deficiency of DOFs, it is unlikely to reach some of the poses in the activities of daily life (ADL).

Besides, it is necessary to develop flexible, compact, economical yet reliable actuators for integration into each active joint. Ways to reach compliant actuation diverge. Pneumatic actuation is a popular research direction for this purpose. It usually exhibits high compliance and adaptability to environment. However, due to its comparatively low reliability, natural nonlinearity and compressibility, it introduces complexity as well as limited speed of response to the control system.

An alternative method is to add an elastic component in series inside the actuator, which is called Series Elastic Actuator (SEA). This kind of compliant actuator have a compact size and higher reliability and response speed, which meet the different requirements in different stages of recovery better, compare to the pneumatic systems. Therefore, SEA is adopted in this design for its compact structure and simplicity of force control [18-21].

In terms of structure of SEA’s elastic component, structural spring such as spiral beam is a kind of typical design [22]. This kind of elastic component features a compact structure and short length in axial direction. At the time of design, however,
it is difficult to estimate its rotary stiffness. It even performs inconsistently in different directions. In addition, spiral springs deeply depend on material properties, which means they are sensitive to environmental factors such as temperature. Because of their sophisticated shapes, they are quite difficult to manufactured and machining errors are more likely to affect structural springs’ performance. To avoid these problems, an elastic component is introduced to the novel SEA, which utilizes a circumferential arrangement of linear tension springs.

The motivation of this paper is to design a compliant upper-limb exoskeleton for rehabilitation purpose. The design should have following distinctive characters:

1) The exoskeleton is compliantly driven by novel design SEAs, which are utilized in each active Degrees of Freedom(DOFs) joints.
2) The exoskeleton contains 7 DOFs of which 4 DOFs are active. To simulate an analogous spherical hinge structure, three compliant actuators whose axes are mutually orthogonal are deployed in exoskeleton’s shoulder. The remaining one active DOF is allocated to elbow. Therefore, the exoskeleton can reach most of positions and poses within human’s range of motion(ROM).
3) Wrist mechanism contains 3 passive DOFs for flexibility.
4) Rather than using spiral springs or structural springs like spiral beams, a novel SEA utilizing set of translational springs is purposed. Forming a hexagon structure, 3 pairs of tension springs are mounted on the circumference of two coaxial components. Translational stiffness of springs is converted to rotary stiffness with high consistency corresponding to wide range of angular deformation.

The rest of the paper is organized as follows. In Section II, the mechanical design of our exoskeleton and the novel SEA are elaborated on. In Section III, the experiments on recording the performance of the actuator will be presented.

II. MECHANICAL DESIGN

Compared with the rigid exoskeleton, a significant advantage of this design is reflected in applying high-performance SEAs in each of its actuated joints. The flexibility allowed by the SEA is conducive to avoiding the potential harm caused by unexpected impulses [23]. Furthermore, the SEA with consistent stiffness can act as the torque sensor and provide the feedback signals required for interactive torque control [24], which is significant to rehabilitation. The studies in [25][26] also demonstrate the positive effect of using SEA in different environments.

A. Overall Structure

The motion of human’s shoulder can be described by a kinematic chain which harmonize the motion of distant shoulder segments including Clavicle, Scapula and Humerus. The principle followed by the design of an upper-limb exoskeleton’s shoulder is to align the intersection point of three mutually orthogonal axes with the center of the human shoulder GH joint to simulate the motion of human shoulder.

As shown in Fig.1, the anatomical structure of humans’ upper limb can be modeled as a kinematics chain consisting of three spherical hinges. The three spherical hinges are interconnected in series in the order of sternoclavicular joint (SC), acromioclavicular joint (AC), and glenohumeral joint GH. In consideration of the links between SC, AC, and AC, and given that GH is relatively short, The DOFs of SC and AC joint are discounted from the design of a shoulder joint to avoid the unnecessary complexity of the mechanism [3][27].

In our design, consideration is given to three rotary DOFs of GH joint, including flexion/extension (GHI/E), abduction/adduction (GHA/A), and intra/extra rotation (GHI/E). They are all designed as active DOFs actuated by our novel SEAs. Their axes are mutually orthogonal and converge at a point aligned with the center of the GH joint. As shown in Fig. 2, the exoskeleton is assembled to the lifting column to ensure that the actuator for GHI/E is moved upward sufficiently to avoid collision with its axis kept in alignment with the corresponding axis of humans. The elbow mechanism is relatively simple as it involves only elbow flexion/extension (EF/E) DOF. It is also an active DOF with SEA integrated. Fig. 3 shows motions of the 4 active DOFs. The exoskeleton can reach most of positions and poses within human’s ROM without facing structural interference. Besides, due to the arrangement of the shoulder mechanism, right arm and left arm modes are made interchangeable. To illustrate this process, the exoskeleton is shifted from the left-arm mode to the right-arm mode. The procedures are detailed in Fig.4 (b). The first step is to rotate 180° around the axis of GHI/E. The second step is to rotate the upper arm link around the axis of GHA/A in the presented direction. The third step is to rotate the forearm link around the axis of EF/E in the presented direction. The last step is to rotate 180° wrist mechanism around the axis aligned with the forearm.
Fig. 3. Motions of the 4 active DOFs. a) Shoulder’s flexion/extension. b) Shoulder’s intra/extra rotation. c) Shoulder’s abduction/adduction and elbow’s flexion/extension. The 4 active DOFs are able to function both independently and collaboratively without introducing mechanical interference.

Fig. 4. Steps of transformation from left arm mode to the right. a) Original state (left arm mode). b) Specific procedures. c) Final state (right arm mode).

Wrist mechanism includes three passive DOFs, the axes of which are mutually orthogonal and converge at the center of wrist. They are designed to facilitate poses adjustment without actuation. Its structure is presented in Fig. 5. The wrist mechanism acts as a spherical hinge. When wearing the exoskeleton, user should put his/her hand through the ring like structure and hold the grip. In summary, the platform consists of 7 DOFs. Its model and prototype are shown in Fig. 6.

Considering the variation in the length of upper arm from one individual to another, a simple length adjustable mechanism is incorporated into the upper arm structure. Besides, the angular position constraining mechanism is adopted in each actuated joint to avoid the prospect of hyperextension. The following table shows the range of motion (ROM) for the aforementioned DOFs and the ROM of the actuated joints is restricted accordingly. The ROM of shoulder and GH joint for ADL is obtained from [28][29][30]. The recommended speed and torque in ADL are obtained from [31].

<table>
<thead>
<tr>
<th>DOF</th>
<th>ROM (human’s)</th>
<th>ROM (actuator’s)</th>
<th>Speed(°/s)</th>
<th>Torque (N*m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHF/E</td>
<td>[0°, +90°]</td>
<td>[0°, +80°]</td>
<td>172</td>
<td>10</td>
</tr>
<tr>
<td>GHA/A</td>
<td>[-45°, +90°]</td>
<td>[-40°, +80°]</td>
<td>172</td>
<td>10</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GHI/E</td>
<td>[-80°, +25°]</td>
<td>[-80°, +20°]</td>
<td>141</td>
<td>3</td>
</tr>
<tr>
<td>EF/E</td>
<td>[0°, +145°]</td>
<td>[0°, +140°]</td>
<td>173</td>
<td>4</td>
</tr>
</tbody>
</table>

B. SEA Design

The design of SEA actuator proposed in this paper consists of a harmonic driving motor comprised of the speed reducer, elastic component, angular position sensor, and the position constraining mechanism, as shown in Figure 7. In order to measure the relative rotational angle between the two pairs of spring and of the forearm of the exoskeleton against that in the vertical standard direction, two encoders are assembled in between the two spring mounting frames and the output shaft separately. The input torque exerted by the motor is transferred through the elastic spring to the output shaft for the motion of the forearm of the exoskeleton.

At the neutral position, each three pairs of springs will be pre-extended and fixed in the Spring Mounting Frame to connect the two frames forming a regular hexagon pattern. The mate of concave and the convex in the two frames will be limited to a 10-degree rotation angle in both directions from the neutral. The bearing is positioned in between to improve the rotational performance by reducing friction. The motor exerts the input torque to rotate frame 1. With the spring extended, the elastic extension force applied to each pair of
springs will drive frame 2 to rotate the robotic arm. The torque exerting in the elastic element is calculated according to the angular deformation of the elastic element. Output torque will be measured and monitored by a force sensor.

In order to prevent the patient from suffering hyperextension in the joint as a result of the unexpected mechanical and electrical malfunctions, position constraining mechanism is developed. A ring of threaded holes is machined on the casing. Screws can be mounted on certain threaded holes to act as position constraints corresponding to allowed ROM.

III. EXPERIMENTS AND RESULT

A. Physical Implementation

All active joints share similar design so we only picked up the elbow joint for performance evaluation as shown in Fig. 9. The forearm and wrist mechanisms are removed. A torque sensor denoted as SRI M2210E is mounted onto the load side of elbow’s SEA for measuring the actual output torque. In order to fix the forearm link for torque measurement, fixation support is adopted. With a resolution of 1024 pluses per revolution, absolute rotary encoders are employed to measure the angular deformation suffered by the elastic component and the joint angle.

B. Control Design for Experiments

For force control experiments, we adopted a PD controller with gravity compensation as shown in Fig. 10. Because of the consistent rotary stiffness, the elastic component can act as a torque sensor. Feedback torque can be obtained by multiplying the angular deformation, which can be measured by rotary encoder, with equivalent rotary stiffness of the elastic component. In addition, gravity term in exoskeleton’s dynamic model is added for gravity compensation. Position control is achieved by a basic PID controller.
component is a significant parameter for SEA and it plays an equally important role in torque control. In this experiment, the forearm link is fixed onto the base (upper arm link). When output torque changes steadily from -8 Nm to 8Nm, the corresponding angular deformation of elastic component is measured. The torque-deformation is illustrated in Fig. 12. The torque-deformation characteristic exhibits a typical linearity and the rotary stiffness remains unchanged in both directions. The recursive line of data indicates a rotary stiffness of 0.9533 Nm/degree.

2) Rotary stiffness measurement: The rotary stiffness of elastic component is a significant parameter for SEA and it plays an equally important role in torque control. In this experiment, the forearm link is fixed onto the base (upper arm link). When output torque changes steadily from -8 Nm to 8Nm, the corresponding angular deformation of elastic component is measured. The torque-deformation is illustrated in Fig. 12. The torque-deformation characteristic exhibits a typical linearity and the rotary stiffness remains unchanged in both directions. The recursive line of data indicates a rotary stiffness of 0.9533 Nm/degree.

3) Interactive force control experiment. The accuracy of interactive force is of vital importance to rehabilitation training. An investigation was conducted into the performance of an active joint in force control. In the experiment, a torque sensor (M2210E, produced by Sunrise Instrument) was applied to collect the accurate torque data. In this experiment, interactive force is consistent with reference value. a) Step response. The compliant joint shows rapid and accurate performance in step response with the rise time of less than 1 second and 0.1 Nm overshoot. b) Ramp response. In this experiment, interactive force is consistent with reference value. c) Sinusoidal response. The frequency of input signal is 1.5 Hz and its amplitude is 3 Nm with +4 Nm excursion from 0. The maximum deviation exists near crests d) Positional error exists near crests, where the direction of motion shifts. This phenomenon is attributed mainly to the gap between the component in the transmission system.

4) Position control experiment. Position control mode is considered suitable for early-stage rehabilitation when patients retain only limited mobility. Exoskeleton is capable to guide the wearer on how to engage in training. In this paper, an investigation was conducted into the performance of an active joint in position control. In the experiment, the fixation support was removed and a rotary encoder with a resolution of 1024 pluses per round was applied to measure the angular position of the joint. Step response, ramp response and sinusoidal response were recorded, as shown in Fig. 13. The system shows rapid and stable performance in step response and ramp response experiments. In the case of sinusoidal experiment, a minor deviation with amplitude of approximately 0.5 Nm occurred near the crests of the sinusoidal wave, which is attributed mainly to the gap between the component in the transmission system.

C. Experiments

1) Bandwidth measurement: Bandwidth is a critical indicator of the dynamic performance produced by the system. The sinusoidal force signals with an amplitude of 1 Nm and varied frequencies are inputted into the elbow joint system and its corresponding steady responses are measured. The bode diagram is presented in Fig. 11. According to the experimental result, the bandwidth is 6.1 Hz.

2) Rotary stiffness measurement: The rotary stiffness of elastic component is a significant parameter for SEA and it plays an equally important role in torque control. In this experiment, the forearm link is fixed onto the base (upper arm link). When output torque changes steadily from -8 Nm to 8Nm, the corresponding angular deformation of elastic component is measured. The torque-deformation is illustrated in Fig. 12. The torque-deformation characteristic exhibits a typical linearity and the rotary stiffness remains unchanged in both directions. The recursive line of data indicates a rotary stiffness of 0.9533 Nm/degree.

IV. CONCLUSION

In this paper, an upper-limb rehabilitation exoskeleton applying novel series elastic actuators is proposed. The elastic component of SEA relies on translational springs to realize consistent rotary stiffness. The geometrical structure of the elastic component ensures the linear and consistent torque-deformation characteristic of SEA. The prototype performance is demonstrated in rotary stiffness and bandwidth measuring experiments. As for future study, the focus will be placed on investigating the advanced control strategy applied to multi-joint collaboration.
REFERENCES


