Supinator Extender (SUE): A Pneumatically Actuated Robot for Forearm/Wrist Rehabilitation after Stroke

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Abstract—**The robot described in this paper, SUE (Supinator Extender), adds forearm/wrist rehabilitation functionality to the UCI BONES exoskeleton robot and to the ArmeoSpring rehabilitation device. SUE is a 2-DOF serial chain that can measure and assist forearm supination-pronation and wrist flexion-extension. The large power to weight ratio of pneumatic actuators allows SUE to achieve the forces needed for rehabilitation therapy while remaining lightweight enough to be carried by BONES and ArmeoSpring. Each degree of freedom has a range of 90 degrees, and a nominal torque of 2 ft-lbs. The cylinders are mounted away from the patient's body on the lateral aspect of the arm. This is to prevent the danger of a collision and maximize the workspace of the arm robot. The rotation axis used for supination-pronation is a small bearing just below the subject's wrist. The flexion-extension motion is actuated by a cantilevered pneumatic cylinder, which allows the palm of the hand to remain open. Data are presented that demonstrate the ability of SUE to measure and cancel forearm/wrist passive tone, thereby extending the active range of motion for people with stroke.**

I. INTRODUCTION

STRATEGIES for optimizing robotic therapy include improved exercise protocols, developing more sophisticated control algorithms, and improving the mechanical design of the robots. This paper focuses on the last strategy: improved mechanical design. Previous robotic therapy devices targeted toward the forearm and wrist are typically complex and heavy, making it difficult to incorporate them into spatial robotic devices [1-4]. The device described here, SUE (Supinator Extender) seen in Fig. 1, is conceived with a strong focus on simplicity, resulting in a lightweight, compact design.

Traditional robot wrists that attach to the end of a serial robotic chain resemble the human arm with a wrist attached between the forearm and the hand. The problem with copying this natural design is that a rehabilitation robot must fit around the human wrist. The robotic joints and links must physically avoid the human joints and links while mimicking their motion.

This paper presents the design of a new robot that extends the functionality of BONES (Biomimetic Orthosis for the Neurorehabilitation of the Elbow and Shoulder), a 4-DOF therapy robot at UCI [5]. The serial attachment of SUE creates a 6-DOF mechanism. The SUE wrist was also adapted for use with the ArmeoSpring rehabilitation device, produced by Hocoma based on work from our lab on T-WREX [6]. We report preliminary results with a force compensation control mode designed to work with ArmeoSpring.

II. DESIGN

A. Requirements

Hand and wrist exercises are an important part of the rehabilitation process after stroke [2]. A key design requirement for SUE was that the actuators be mounted away from the subject to minimize the required limitations to the overall workspace. Also, the seated position of the subject imposed the requirement that the actuators not be mounted below the forearm to prevent a collision with the legs.

A common choice for wrist actuation is electric motors. Electric motors typically must be highly geared in order to provide forces that are large enough to move the human wrist through a desired trajectory. The disadvantage of using motors with gears is that back-driving the motors is difficult, necessitating the use of force feedback. The high impedance

Fig. 1. Solid model of SUE and picture of device attached to ArmeoSpring.

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of the gear train also limits the bandwidth of the robot. To circumvent these problems, SUE uses small lightweight pneumatic cylinders constructed mostly of aluminum. The lightness of these actuators also contributes to the low impedance of the wrist design. The actuators use low fiction seals running against a self-lubricating composite cylinder wall.

Another design constraint was that the device be easy to don and doff. For SUE the forearm cuff that attaches the robot to the subject may open and close while the wrist is aligned to any angle within the supination-pronation workspace, a feature useful for users with spasticity.

B. Forearm Supination-Pronation

The first link in the SUE wrist serial chain attaches to the forearm of the BONES or ArmeoSpring exoskeleton. The human forearm rotates in supination-pronation by the relative motion of the radius and ulna, resulting in a rotation axis inside the forearm. Some exoskeletons have used ring bearings to enclose the forearm [1, 4], allowing the rotation axis to lie within the forearm envelope. We desired to avoid the use of a ring bearing because of the added workspace volume such a bearing occupies. Inspiration came from noting that if one places their hand flat on a table with the palm down, and rolls to the palm up position while the little finger stays in place on the table, then one can achieve supination. Although the motion is no longer a pure rotation about an internal axis of the forearm, this motion feels quite natural and justifies the placement of the forearm rotation axis outside the human forearm.

C. Wrist Flexion Extension

The rehabilitation therapists working with the BONES robot desired that the subject be able to grasp an object while wearing SUE. This requires any robotic attachments be made to the back of the hand. This requirement is also a design aspect of the HWARD robot [2]. A cantilever design is used for its simplicity, improving reliability and manufacturability. The position of the driving cylinder allows a safe workspace for the BONES robot by placing the flexion-extension mechanism away from the subject's face.

D. Seal Stiction

Although pneumatic cylinders are compliant and backdrivable, they have nonlinear seal friction forces that are difficult to eliminate with feedback control [7]. We designed the linkage and cylinder in a way that minimizes the effects of stiction felt at the output.

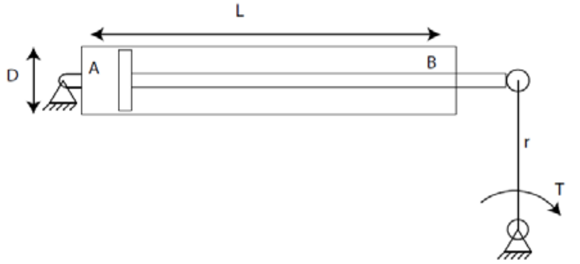

Fig. 2. Simplified model of pneumatic cylinder mechanism.

Assume a pneumatic cylinder (Fig. 2) of diameter D is attached to a moment arm of length r to produce a torque given by

$$\tau_{\text{cyl}} = \frac{P_A \pi D^2 r}{4}, \tag{1}$$

where P_A is the gauge pressure in cylinder chamber A, and cylinder chamber B is unpressurized. The seal friction force is assumed to be proportional to the length of the seal [8],

$$F_{friction} = \mu_{seal} \frac{\pi D}{4}. \tag{2}$$

the torque at the output shaft from $F_{friction}$ is then

$$\tau_{friction} = F_{friction} r = \mu_{seal} \frac{\pi D}{4} r, \tag{3}$$

which is proportional to D. However the output torque τ_{cyl} from (1) is proportional to D^2. The ratio $\tau_{friction}/\tau_{cyl}$ decreases with a larger diameter cylinder. This knowledge is useful for design purposes since it demonstrates that a cylinder with a large diameter and a small stroke reduces the effects of seal friction felt at the output.

E. Components

1) On-Off Valves: SUE uses on-off solenoid valves to control air flow into and out of each cylinder. Solenoid valves are lightweight, and in the closed state there is zero leakage. The drawback to using on-off solenoid valves is that they are designed to be only on or off. A haptic device that has a good "feel" requires smooth control of force which necessitates fine control of airflow. But on-off valves provide step functions for airflow making smooth force control difficult. To achieve fine airflow control, the valves must open and close rapidly. The valve manufacturer [9] offers a spike and hold circuit called "speed-up" for this purpose. The Matrix 821 valves used with SUE can switch in 1 ms. The fast switching of the valves creates an audible sound that is mitigated by a muffler on the exhaust outlets. The clicking sound that remains is minimal and indicative of the amount of robot actuation, which is useful for subject feedback.

2) Power Source: SUE requires peak airflow of 0.4 Nm^3/hr (14 SCFH) at 586 kPa (85 psi); standard industrial air outlets, compressed air bottles, or a small quiet compressor meet this requirement.

3) Safety: Protrusions that extend in the direction of the subject are eliminated. The mechanical range of motion is comparable, but slightly less than human range of motion. The danger of a dynamic instability is covered by an emergency stop button wired in series with the valve power supply, which cuts power to the normally exhausting solenoid supply valve. By exhausting the pneumatic supply, the robot goes quickly and smoothly to rest.

III. CONTROL

A. Sliding Mode Controller

There are two control modes for SUE, position control or force control. Both control modes use a sliding control approach [10] to take advantage of the fast on-off solenoid valves. The controller is implemented using xPCTarget in standalone mode running at 1000 Hz.

1) Position control mode: The second order sliding surface used for the position controller is defined by

$$s = \ddot{e} + 2\zeta\omega\dot{e} + \omega^2 e, \tag{4}$$

where

$$e = \theta - \theta_d. \tag{5}$$

The details of the sliding mode position controller are described in [10]. The control law that drives the system to the sliding surface $s(t) \approx 0$ is achieved by using a feedback potentiometer to estimate the error signals in (4) in order to obtain s at each sample time. Based on s, the control signals for each valve are obtained as follows:

$$\begin{aligned} s > \varepsilon &: u = [0110] \\ s < -\varepsilon &: u = [1001], \\ else &: u = [0000] \end{aligned} \tag{6}$$

where ε is a deadband and u is a control vector for the state of each valve.

$$u = [A_S\ A_E\ B_S\ B_E], \tag{7}$$

where A and B denote the side of the cylinder the valve is connected to as in Fig. 2 and the subscript S and E denote whether the valve is connected to the supply pressure or atmosphere respectively. The valve states 1 and 0 indicate open or closed respectively. The deadband included reduces chattering when the system is near the desired state. Furthermore, within the deadband, $|s| \leq \varepsilon$, the system is in an energy conserving state with all 4 valves closed.

2) Force control mode: The force controller uses the valves to control the air pressure separately in each chamber. Given a desired net cylinder output force F_d, the force levels required for each chamber must be defined. The difference in these forces creates the actual output $F = F_A - F_B$. The desired values for the forces in chambers A and B are given by

$$\left.\begin{aligned} F_{dA} &= F_{\min} + F_d \\ F_{dB} &= F_{\min} \end{aligned}\right\} F_d > 0 \qquad , \qquad \left.\begin{aligned} F_{dA} &= F_{\min} \\ F_{dB} &= F_{\min} - F_d \end{aligned}\right\} F_d \leq 0 \tag{8}$$

where F_{min} is a small constant force level that maintains a positive pressure difference between each cylinder chamber and the atmosphere. A high value of F_{min} leads to a fast force response since exhaust air will flow quickly to atmosphere. However, a high value leads to higher seal friction and to wasted energy.

Given a desired chamber force level, the valves are adjusted by the controller as follows. Consider chamber A: the force error is

$$e_{fA} = F_{dA} - F_A, \tag{9}$$

where F_A is the measured force in chamber A. The sliding surface for the force control law is then

$$s = e_f. \tag{10}$$

The error is driven to within a deadband ε by the control law

$$\begin{aligned} s > \varepsilon &: u = [01];\ \textit{exhaust cylinder} \\ s < -\varepsilon &: u = [10];\ \textit{pressurize cylinder} \\ else &: u = [00];\ \textit{cylinder force is within range} \end{aligned} \quad , \tag{11}$$

where the 1 or 0 values are for the inlet and exhaust valve commands for cylinder chamber A. A similar controller is used for chamber B.

B. *Tone Compensation for ArmeoSpring with SUE*

We had previously developed a passive arm exoskeleton, T-WREX (commercialized as ArmeoSpring), which uses springs to provide arm weight support so that patients with limited strength may perform movement therapy that would otherwise be too difficult [6]. A therapist can set the spring tension to compensate for the weight of a patient's arm. We added SUE to the end of ArmeoSpring to provide similar force compensation for the forearm and wrist.

Compensation of passive tone and gravitational forces at the forearm and wrist would be impossible to achieve by a tensioned spring. We therefore designed a controller for SUE to record the passive restraint forces that may limit a patient's motion. Compensation forces are provided to counteract the restraint forces thus allowing the subject a greater range of forearm and wrist motion. An advantage of such "counterpoise control" [11] is that it does not require a desired trajectory, thus allowing the patient to move their forearm and wrist at will. In addition, a counterpoise controller requires the patient to be active for the forearm/ wrist to move, preventing patient slacking and passivity.

To identify the restraint forces, the patient is first asked to relax their wrist while SUE steps through a set of positions that cover the robot range of motion, defined in a spiral pattern (Fig. 3). The force required to reach each point is recorded to the control computer memory. The grid is tested again, by spiraling in the opposite direction to ensure that only static forces are compensated. By approaching each point from the opposite direction frictional forces will cancel out after taking the mean of both recording sweeps. Fig. 4 shows the compensation forces measured for one subject with stroke. These forces are then replayed using the force controller described above. A single control knob allows the supervising therapist to use SUE to cancel only a fraction of the restraint forces if desired.

IV. RESULTS

We tested eight subjects with a chronic stroke to determine if the restraint force compensation mode increased forearm and wrist active range of motion (ROM). Active ROM measurements were taken with and without force compensation. ROM was measured by a therapist using a goniometer. Fig. 5 shows that wrist total flexion/extension increased by a mean of 15° and forearm total supination/pronation by a mean of 10° with 100% force compensation; both increases were significantly different from zero (paired t-test, $p < 0.05$). Some subjects were capable of reaching the limits of the robot without compensation (7 reached the flexion limit, 2 reached the supination limit and 3 reached the pronation limit). In these cases no improvement was observed. The limited robotic workspace is a safety feature, which prevents the robot from causing harm in the case of a malfunction.

V. CONCLUSION

SUE is a lightweight (0.56 kg (1.23 lb)), compact yet powerful, and backdriveable robot that provides forearm/wrist capability for two arm rehabilitation exoskeletons. SUE is an excellent example of why pneumatic actuation is attractive for exoskeleton design: pneumatic actuators can generate large, compliant forces without adding excessive weight, an especially important consideration for distally mounted exoskeletal components. However, effective use of pneumatic actuation requires careful design considerations, as outlined here, including: kinematic design to place actuators on the outside of the arm; minimization of the nonlinear effects of seal stiction by appropriate cylinder sizing; and use of four solenoid valves per cylinder for reduced friction and improved energy efficiency.

We also described here how SUE can measure and compensate for restraint forces at the forearm and wrist due to stroke, resulting in improved active range of motion for people with heightened passive tone. The coupling of such "counterpoise" control with SUE and the arm counterbalancing function of ArmeoSpring provide a comprehensive upper extremity rehabilitation training device that extends active range of motion of the patient, while also preventing patient passivity during training, as the device will not move unless the patient drives movement. We are currently testing whether this approach improves the therapeutic efficacy of training with ArmeoSpring.

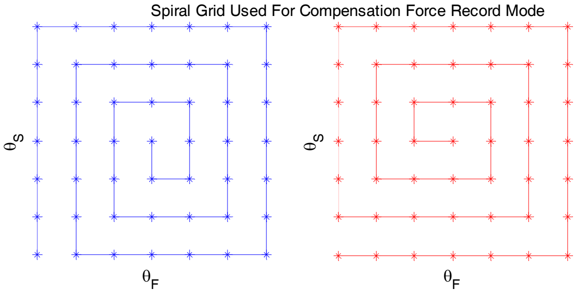

Fig. 3. Paths used for force compensation record mode.

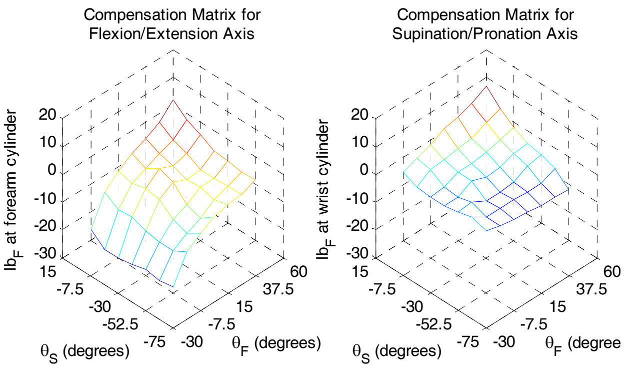

Fig. 4. Actual compensation values for subject age 78, 6 weeks after stroke.

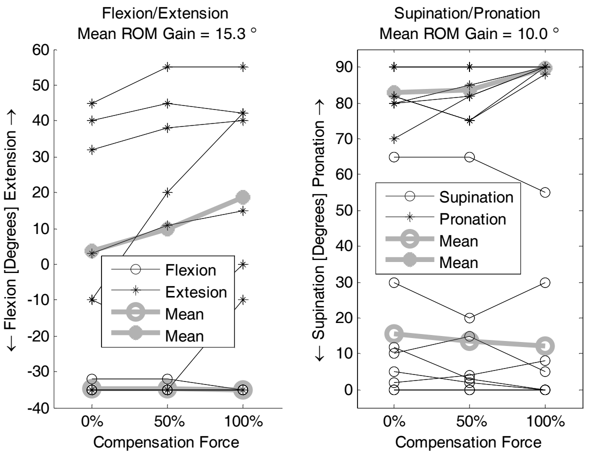

Fig. 5. Participants with a stroke on average showed an increased wrist flexion/extension range of motion (left) and increased forearm supination/pronation range of motion (right) with compensation turned on at 100%. 0° supination was defined as the thumb pointing vertical and 90° pronation was defined as palm down. 0° flexion/extension was defined as the wrist straight out in neutral; wrist flexion is defined positive, and extension is defined negative.

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