Towards a Soft Robotic 3\textsuperscript{rd} Arm for Activities of Daily Living

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1 Background

Limb sensorimotor function plays an important role in activities of daily living (ADLs) and quality of life. Spinal cord dysfunctions, such as cervical spondylotic myelopathy (CSM), often affect limb function and limit independence. In this paper, we apply technologies from the emerging field of soft robotics to develop Soft Robotic 3rd Arms (SR3As) that branch out of the body – thus providing an artificial limb that enables effective execution of ADLs for CSM patients and the like.

Soft robotics is a fairly recent addition to the field of robotics. Differing from traditional, "hard", robotics, soft robotics are made of flexible materials such as silicone rather than stiff materials such as metals. One such soft robotic actuator is the fiber-reinforced actuator (FRA). Fabricated utilizing a combination of silicone bladder(s) and inextensible materials, these actuators are able to perform one of various motions through changes of pressure [1].

Supernumerary limbs (3\textsuperscript{rd} arms), in contrast, are extra robotic limbs that can function cooperatively or independently of the user's own limbs. These differ from exoskeletal robotics, as they are not fixated to the user's limb to augment strength, but rather are placed elsewhere on the body to assist in tasks that would otherwise require multiple people. Examples of such devices include MIT/Boeing's supernumerary arms to assist in the assembly of aircraft fuselage [2] or the supernumerary hand SoftHand [3].

Combining these two concepts, an articulate SR3A was created (Fig. 1). By replacing traditional actuators with soft actuators, the limb is not only lighter, but it also better replicates the equivalent human limb. In addition to these benefits, the SR3A would also need to be less expensive to fabricate and actuate than an arm using rigid body components. This paper presents the design of a proof-of-concept prototype of the actuators used in this design are discussed in greater detail in the Results section.

2 Methods

To determine the functional requirements of the SR3A, the abilities and limitations of the human arm, as well as the functional requirements of other similar devices, were researched. Using this information, the physical dimensions of

<table>
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<th>Shoulder</th>
<th>RoM (deg)</th>
<th>Torque (Nm)</th>
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<td>Adduction</td>
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<table>
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<th>RoM (deg)</th>
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</tr>
<tr>
<td>Extension</td>
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Table 1: Functional Requirements

Figure 1: Wearable backpack view of soft robotic 3\textsuperscript{rd} arm. the arm and the back-mounted interface it is attached to, as well as the strength and range of motion of various motions of the arm (e.g. flexion, adduction), were determined; these are shown in Table 1.

The types of soft robotic actuators used in the design of the SR3A were the previously mentioned FRAs, as well as McKibben or Pneumatic Artificial Muscles (PAMs). Fluid-based actuators were chosen for their typically larger range of motion, higher strength, and easier, safer, and more readily available method of actuation.

PAMs, as their name suggest, exert force through contraction, made using an inflatable bladder surrounded by a braided mesh. When pressurized, the inner bladder expands radially, expanding the surrounding mesh. As this mesh expands, it contracts, thus forcing the inner bladder to contract with it. Depending on the method of fabrication, these actuators can reach contractions of up to 50% [4]. The specific geometry of the actuators used in this design are discussed in greater detail in the Results section.

FRAs, as mentioned before, utilize elastomeric bladders and inextensible materials to perform some type of motion. The FRA used in this design is a three-chambered actuator (3CA), which utilizes three bladders. These silicone bladders are cylindrical in shape with one open end, and wrapped in two opposite helix patterns by an inextensible Kevlar thread. Individually, when unconstrained and without an open end, these bladders expand radially and extend along their lengths; the thread constrains the radial motion. These bladders are then grouped parallel to one another in a triangular shape, bound together using additional elastomeric material, and capped at the other end to create a single actuator with three chambers. The elastomer in the center acts as a semi-inextensible material, turning the extending motion of the individual chambers into a bending motion toward the other two. Varying the pressure all three chambers allows the actuator to bend in any direction.

The shoulder joint of the arm was made using a 3CA, attached to two 3D-printed and carbon fiber rigid components (Fig. 2), which in turn attached to both the back-mounted interface and the upper arm. The elbow joint is actuated via an agonist-antagonistic pair of PAMs mounted on the back of the user and a series of pulleys. The back-mounted interface also held the pneumatic and electrical system used to control the actuation of the actuators.
3 Results

To determine the length, diameter, and orientation of the PAMs for use in the elbow joint, tests were conducted using a tensile testing machine (Instron 5944 Single Column, Illinois Tool Works, Inc., Norwood, MA). To determine the dimensions, multiple PAMs were created that fell into two groups: same diameter with differing lengths and same lengths with differing diameters. For each of these sets, two tests were conducted: one to test contraction against force and another to test pressure against force. For the former, the PAMs were clamped into the machine and pressurized to a constant pressure of 207kPa (about 30PSI), after which the machine allowed the PAMs to slowly contract until force of zero was reached, then returning them to the original position. For the latter, the PAMs were clamped at their unpressurized lengths, and the pressure was increased from 0 to 207kPa, measuring the force, then returning to 0kPa. The results depicted that larger diameters yielded larger forces, and that longer lengths yielded larger contractions, but at the same contraction of 20%.

With the 20% contraction, the actuators needed to be much longer than the back-mounted interface in order to actuate the elbow through its range of motion (0 – 150 degrees). As such, additional tests were conducted to determine how two actuators would act in both series and parallel in an attempt to obtain a larger contraction percentage. Theoretical simulations demonstrated that PAMs in series would be identical to a PAM of twice the length; in other words, would not change contraction percent, while PAMs in parallel would effectively half the load (and increase contraction proportionally). The results matched the predictions, and showed that the amount of contraction gained from parallel PAMs was less than series. As such, the design was built using two 0.295 meter long PAMs.

As for the 3CA, the approximate angle formed, when either one or two chambers were inflated, was determined to be approximately 60 degrees at 207kPa (30PSI), with the two chambers bending at a larger angle. Additionally, as the 3CA changes between angles, the orientation of the arm changes as well. Due to this unique motion, the workspace of the entire arm was plotted using motion capture technology (Nexus software using T20 cameras, Vicon, Oxford, UK). A cyclical pattern of pressures was used to capture an approximation of the motion: The 3CA was moved to one of six positions (with either one or two chambers fully pressurized while the remainder were unpressurized), then one PAM was pressurized, then the other, and this cycle repeated six times. In other words, the shoulder would move, the elbow would flex then extend, then repeat. Figure 3 shows the approximated full range of motion of the soft robotic 3rd arm, the yellow, overlain on top of the gathered data, the black. The range of motion resembles a dome, missing its center. Data on the torques and specific angles of each joint were not gathered.

4 Interpretation

Due to both the overly-long PAMs (which makes them impractical) and the short size of 3CA (which limits the range of bending angle), in future work we aim to replace the elbow joint with another 3CA and make the 3CA of both joints longer. In this way, we can remedy the limited workspace of this design. Not only would this add another degree of freedom, but also it would allow for greater range of motion for each joint. Additionally, this change would simplify the design significantly due to the removal of the pulley system and complicated 3D printed parts, bringing the concept of the soft robotic 3rd arms for activities of daily living closer to realization. Additional future work would be to determine a method of robustly controlling the soft robotic system. Unlike an electric motor, in which its position or velocity control methods are well known, the motion of an FRA is derived both from the input pressure and the load. As such, a feedback controller to determine the angle of the individual chambers of the 3CA is needed. One approach could be soft stretch sensors embedded into the actuator itself, with the ratio of their outputs being used to determine angle given a predetermined conversion formula. Alternatively, sensors such as inertial measurement units could be employed. Finally, we aim to evaluate the system having impaired users wear and control it to handle objects encountered in activities of daily living and thus prove the feasibility of this novel concept.

References