Advancing Shoulder Rehabilitation: A Wearable Soft Robot Utilizing Pneumatic Actuation

MAE 586 – Project Work in Mechanical Engineering Fall 2023

NC STATE UNIVERSITY | Mechanical and Aerospace Engineering

Jaykumar Girdhar Deshani
Graduate Student
Department of Mechanical and Aerospace Engineering
North Carolina State University
jdeshan@ncsu.edu

Faculty Advisor:
Dr. Hao Su
Associate Professor
Department of Mechanical and Aerospace Engineering
hsu4@ncsu.edu

Course Instructor:
Dr. Hsiao-Ying Shadow Huang
Associate Professor and Director of MS Non-Thesis Program
Department of Mechanical and Aerospace Engineering
North Carolina State University
hshuang@ncsu.edu

Table of Contents

List of Figures:

Advancing Shoulder Rehabilitation: A Wearable Soft Robot Utilizing Pneumatic Actuation

Jaykumar Girdhar Deshani

Abstract:

This study presents a novel design of a soft wearable actuator for aiding humeral elevation in people with arm weakness. The actuator aims at enhancing comfort and functionality compared to existing state-of-the-art solutions. The actuator, featuring a double-layer inflatable design, is anchored to the body through a custom harness with velcro-based straps, allowing flexibility in mounting on either shoulder. To address issues such as discomfort and reduced torque production, a built-in bending angle was imposed on the actuator design. Fabrication involves heat sealing TPU-coated Nylon layers, with a preliminary heat press step to create the bending crease and subsequent sealing of the actuator edges. Challenges encountered include difficulty in sealing the bending crease due to its non-planar nature, requiring manual sealing to cover leaking areas. Control and sensing utilize a pump, microcontroller, and pressure sensor. Future work will focus on refining fabrication techniques and enhancing control mechanisms to optimize actuator performance and usability.

Introduction:

Textile-based pneumatic actuators have garnered considerable attention in recent years due to their remarkable strength-to-weight ratio and diverse range of actuation capabilities, making them particularly appealing for wearable applications. These actuators, crafted from textile materials, offer a unique blend of flexibility, lightweight construction, and compatibility with various wearable technologies. However, harnessing their potential requires navigating the intricate nuances of textile behavior, presenting engineers and researchers with an iterative design process to optimize performance while ensuring durability and reliability in real-world applications.

In the realm of wearable robotics, significant strides have been made in developing assistive devices to address a myriad of health and medical needs [6]. Among these applications, stroke rehabilitation has emerged as a primary focus, given the widespread prevalence of stroke-induced upper limb disability. It's estimated that approximately 77.4% of stroke survivors experience upper limb motor deficits, highlighting the critical importance of effective rehabilitation strategies. Of particular interest to clinicians and therapists is the rehabilitation of the shoulder joint, as it serves as the primary joint in the upper limb's kinematic chain, significantly influencing overall limb functionality.

Central to successful rehabilitation outcomes is the delivery of intensive therapy sessions. However, challenges such as therapist fatigue often limit the number of repetitions per session, underscoring the need for innovative solutions. In rehabilitation robotics, an emerging field aimed at augmenting caregiver efforts during therapy sessions, thereby maximizing therapeutic benefits for patients.

Neuromuscular conditions such as stroke, spinal cord injury, muscular dystrophy, and ALS profoundly impact an individual's ability to perform activities of daily living (ADLs), leading to a loss of independence and diminished quality of life [1]. Specifically, impairments in upper limb function pose significant barriers to ADLs, highlighting the pivotal role of shoulder rehabilitation in sustaining independence and enhancing overall well-being.

Despite advancements in robotic rehabilitation technologies, several challenges persist. Most notably, the dominance of rigid exoskeletons in the market has limited natural movement and comfort for users. Additionally, there is a glaring lack of comprehensive clinical evaluation, with less than 30% of prototypes tested on stroke patients. Furthermore, existing technologies are primarily tailored to large-scale clinical settings, constraining their applicability for at-home or outpatient assistance [3].

The portability and accessibility of robotic rehabilitation solutions are critical considerations in expanding their reach beyond clinical environments. Portable devices have the potential to revolutionize rehabilitation by providing therapy in outpatient clinics and home settings, thereby maximizing therapy dosage and improving patient outcomes. Soft wearable robots, characterized by their lightweight, compliant nature, and cost-effectiveness, offer a promising avenue for at-home rehabilitation, facilitating greater patient engagement and adherence to therapy protocols.

In conclusion, textile-based pneumatic actuators hold significant promise for wearable applications, particularly in the realm of rehabilitation robotics. Addressing the challenges of design complexity and optimizing performance will be crucial in realizing their full potential to enhance rehabilitation outcomes and improve the quality of life for individuals with neuromuscular conditions. With continued innovation and interdisciplinary collaboration, soft wearable robots have the potential to transform the landscape of rehabilitation therapy, providing accessible, personalized, and effective solutions for patients worldwide.

Background:

This section delves into the design considerations and prior research that have shaped the development of soft robots.

The emergence of pneumatically actuated soft robots presents significant potential for aiding various tasks, notably supporting shoulder movement. The aim of this background section is to explore the design considerations and provide an overview of previous research influencing the development of such soft robots.

One study highlighted the prioritization of discrete wearability in the design of a pneumatically actuated soft robot for shoulder assistance. This involved minimizing the actuator profile and relocating it beneath the arm to enhance user acceptance [1]. Balancing actuator volume with necessary output forces and moments was essential, resulting in a wearable robot with textile-based actuators attached to a neoprene vest. A flexible plate was incorporated for stability, along with adjustable arm wraps for individual user accommodation

The actuator itself comprises a segmented chamber (as seen in the **Figure 1**) crafted from non-stretchable textile material, connected to a spine consisting of two flexible plates linked via a flexible hinge [1]. This design ensures resistance to misalignment between segments, with the stitching serving as a hinge. An oversized bladder made of heat-sealed TPU is inserted into the textile component to create an inflatable, airtight volume, facilitating air retention while the fabric structure absorbs and disperses stresses from pressurization.

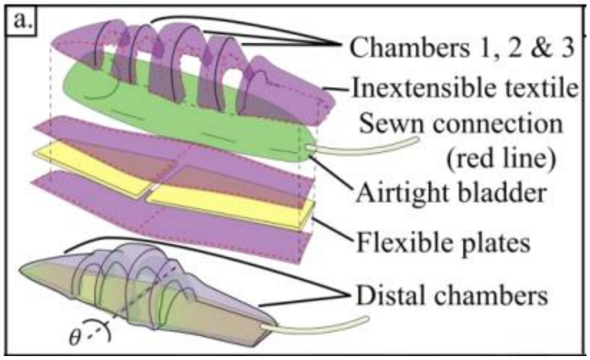


Figure 1

Exploded View of the Abduction Actuator

Adapted from 'A Soft Wearable Robot for the Shoulder: Design, Characterization, and Preliminary Testing' by Ciarán T. O'Neill, Nathan S. Phipps, Leonardo Cappello, Sabrina Paganoni, and Conor J. Walsh.

Another noteworthy research endeavor involved integrating an inflatable actuator into functional apparel, ensuring optimal comfort and adaptability using inextensible elements and zippers [3]. Engineered to distribute forces evenly around the shoulders, this actuator effectively supports the weakened limb while allowing for ease of donning and personalized fit adjustments. The bifurcated end of the inflatable actuator enhances stability and comfort, providing significant gravity compensation for rehabilitation. (as seen in the **Figure 2**)

Figure 2

Soft wearable robot worn by a person. The bifurcated actuator cradles the anterior and posterior of the arm, distributing the forces and stably locating the arm between both chambers.

Adapted from 'Inflatable Soft Wearable Robot for Reducing Therapist Fatigue During Upper Extremity Rehabilitation in Severe Stroke' by Ciarán O'Neill, Tommaso Proietti, Kristin Nuckols, Megan E. Clarke, Cameron J. Hohimer, Alison Cloutier, and David J. Lin.

Powered and controlled externally through a manual pneumatic supply, this device offers versatility and ease of operation during therapy sessions. Through meticulous design and iterative refinement, textile-based wearable robots signify a significant leap forward in soft robotics, offering tailored assistance for stroke survivors' recovery journey.

Methodology:

In both the examples given above, they utilized a combination of different layers of textiles and an inflating element to provide the required bending direction and angle. To ease up the fabrication process we are using TPU (Thermoplastic Poly-Urethane) coated Nylon which is most commonly used in inflatables. There is research that suggests using TPU-coated Nylon for the fabrication of heat-sealing inflatable design which changes shape.

Initially, we experimented with an alternative actuator model that employed a pneumatic heat-sealing hinge mechanism, enabling shape alterations or bending in the actuator when inflated. This hinge is formed by heat-sealing two layers of TPU together. The extent of shape change can be adjusted by modifying the shape of the heat-sealed hinges. However, this method had its shortcomings, leading us to discontinue further development of this design. The subsequent section delves into our previous design in detail and highlights the lessons learned during the process. The new design is thoroughly explored later in the report.

Overview of previous design:

In our previous actuator design, we utilized the pneumatic hinge mechanism that allowed changes in shape or bending in the actuator when inflated. The hinge is created by heat-sealing two layers of the TPU. The shape change can be varied by varying the shape of heat-sealed hinges. **Figure 3 shows how different hinge shapes can lead to varying bending angles in an actuator.** The bending angle can also be calculated by using the formula:

$$\theta = acos(\frac{a^2 + b^2 - w^2}{2ab})$$

Equation (1)

For prototyping, we used TPU sheets to fabricate the inflatable. We heat-sealed the TPU layers manually with a heating iron at a temperature of 280F for 10 seconds. After achieving a successful seal and testing the prototype, we wanted the fabrication process to be accurate and less complex. Hence, we are currently testing a heat press and custom-designed aluminum frame to provide uniform sealing. **Figure 4a shows the design for the aluminum frame and Figure 4b shows the schematic for the sealing operation.**

Figure 3

The width/height aspect ratio of the diamond hinge

Adapted from aeroMorph - Heat-sealing Inflatable Shape-change Materials for Interaction Design by Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii.

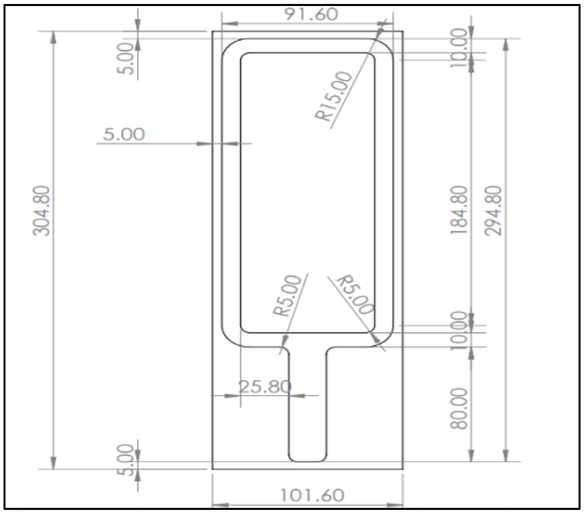


Figure 4a

Aluminum frame used to create the straight actuator.

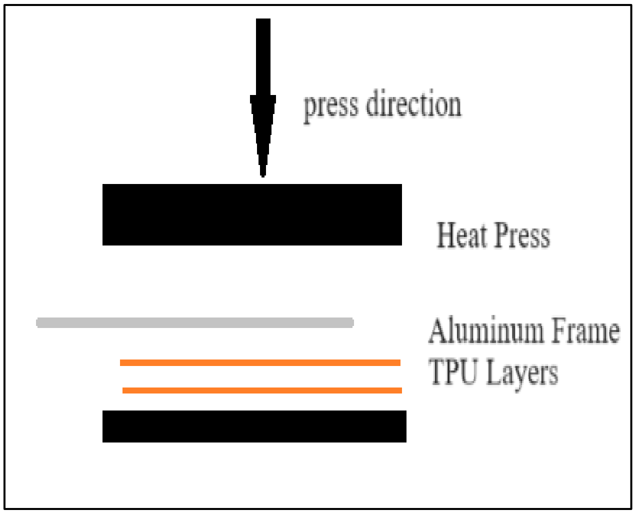


Figure 4b

Schematics for the heat-sealing process.

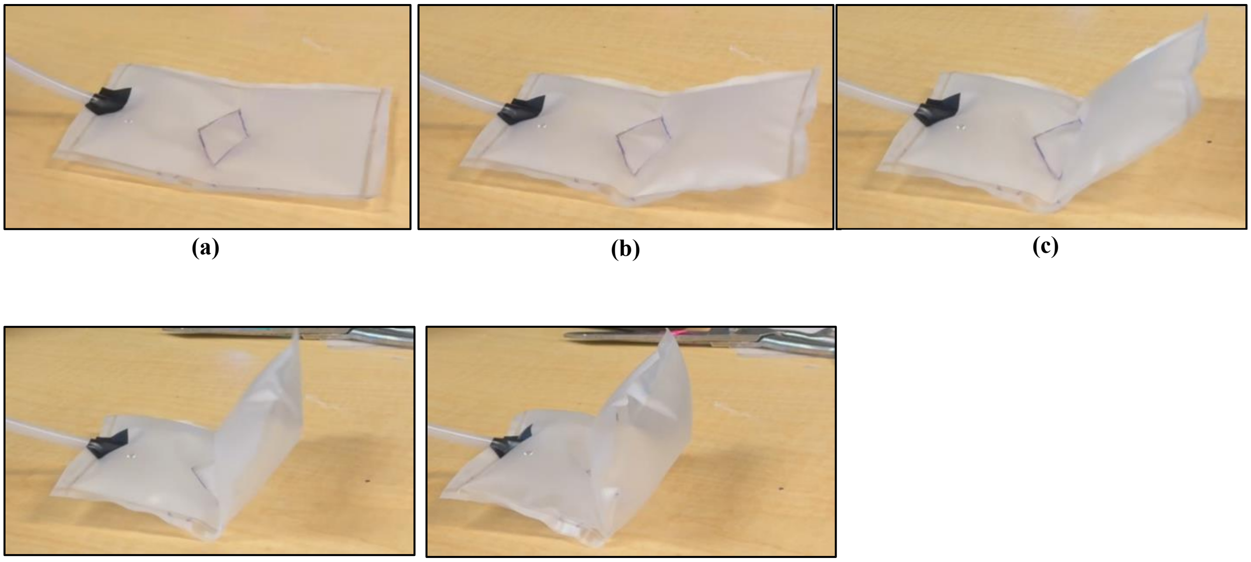
We employed two fabrication methods for producing heat-sealed hinges. Manual sealing is straightforward, does not necessitate costly equipment, and is ideal for rapid experimentation and prototyping. Heat press sealing provides a means for producing consistent hinges in large quantities.

Challenges:

Besides choosing the hinge size to achieve the desired bending angle, a significant challenge we faced was heat sealing. It was crucial for the hinge to be precisely positioned on the actuator because even minor adjustments in its placement could lead to unfavorable bending of the actuator. Consequently, we devised a bracket that could be affixed to the heat press to aid in aligning the aluminum frame and hinge patterns accurately. We created two brackets: one for the hinge pattern and another for the aluminum frame. The procedure involved initially positioning the hinge pattern with the assistance of the bracket, followed by aligning the aluminum frame.

Previous Results:

We achieved a maximum bending of more than 90^{O} after experimental trial and error. Many different hinge shapes were tested and validated through equation (1). The hinge mechanism proved to be successful in creating reliable bending angles and eases up the fabrication process. **Figure 5(a-b-c-d-e) shows our actuator bending as it is inflated through an opening using a hose.**



(a) (b) (c)

(d) (e)

Figure 5

From (a) to (e) the actuator bends as it is inflated. The bending occurs at the hinge and depends on the shape and size of the hinge.

Previous Design Flaws:

We integrated the hinge sealing method into the Y-shaped actuator to enhance comfort and support, and conducted successful testing on various sizes of hinge patterns. By adjusting the width and height of the hinges, we achieved different bending angles as calculated using Equation (1). Despite the actuator's ability to achieve favorable bending angles, it lacked the necessary torque to lift the arm or exert force against gravity, even for smaller objects. The narrow gap between the actuator border and hinge resulted in the actuator bending near the hinge, restricting airflow when subjected to external pressure.

In conclusion, while hinge patterns can induce bending suitable for applications like programmable shape-changing materials for interaction design, they fall short in generating high torque required for performing movements such as lifting objects.

New Design:

Transitioning to the exploration of our innovative design, we depart from conventional approaches characterized by a TPU bladder encased in a textile-based shell. Instead, our novel approach integrates a single material, streamlining manufacturing while potentially enhancing actuator durability. Additionally, our design features a built-in bending angle, optimizing contact with the armpit for heightened comfort compared to traditional straight structures. Moreover, to bolster sustainability and comfort, we have unified the extremities of the Y-shaped actuator using a nylon hammock.

Material:

Our material of choice is TPU-coated Nylon, commonly employed in inflatables. Research suggests that TPU-coated Nylon is suitable for creating heat-sealing inflatable designs capable of changing shape. The thermoplastic polyurethane (TPU) coating enhances the nylon fabric's resistance to abrasion, tearing, and punctures, making it highly durable for inflatable applications. Additionally, TPU-coated nylon maintains flexibility even in low temperatures, ensuring the inflatable remains pliable and functional across various environmental conditions. Moreover, the airtight nature of TPU-coated nylon prevents air leakage, facilitating efficient inflation and retention of desired shapes in inflatable structures. Overall, these qualities make TPU-coated nylon a reliable choice for manufacturing inflatables, particularly in applications where durability and airtightness are crucial.

Actuation Unit:

Our innovative design incorporates a double-layer inflatable actuator crafted from a TPU-coated nylon sheet, as illustrated in Figure 4 depicting the actuator manufacturing process. Drawing from previous works, we opted for a Y-shaped configuration to optimize arm accommodation in terms of both comfort and support. However, in a departure from conventional designs, we utilized a nylon hammock to secure the extremities of the Y-shaped actuator, enhancing both sustainability and comfort.

Addressing the tendency of straight actuators to displace from the armpit upon inflation, potentially leading to a reduced on-body torque production and discomfort, we introduced a built-in bending angle to our design. To achieve this, we employed a simplified model (Equation (2)), which facilitated the estimation of the required length of a single crease in one of the layers forming the actuator's inflation chamber. While multiple shorter creases could theoretically be modeled, for the sake of manufacturing simplicity, we opted for a single crease design.

The simplified model equation is as follows:

$$\Delta l = d \cdot \alpha \cdot c \qquad \textbf{(Equation (2))}$$

Here, Δl represents the additional material length (i.e., the length of the crease), d denotes the actuator diameter, α signifies the desired bending angle, and c represents an empirical coefficient accounting for material elasticity and the effect of self-folding of the actuator on the opposite side of the bending. Specifically, we designed a bending angle of $\alpha = 45$ degrees, which was consistently applied throughout our work (with $d = 6.4$ cm, $c = 0.7$, and $\Delta l = 3.9$ cm).

To ensure secure anchoring to the body, we implemented a custom harness equipped with two velcro-based straps on the torso and one on the arm, facilitating adjustable and personalized fitment of the wearable. Additionally, our design allows for versatile mounting options on either the left or right shoulder. To prevent actuator rupture, we capped the maximum pressure for experimentation at 70 kPa.

Fabrication:

In **Figure 6**, the placement of the soft actuator before the heat press operation is demonstrated. To prevent sealing of the inner part of the actuator, a heat-resistant layer is applied to the hollow side of the aluminum frame. The crease is formed during a preliminary local heat press step by folding the first layer and pressing the crease pattern. The anchoring harness refers to the surplus material on the sides of the actuator, which is subsequently trimmed to shape after the heat pressing process. A hole is created at the bottom of the actuator to accommodate the hose insertion. Currently, a hot glue gun is utilized to seal the hose, with plans to adopt a more robust technique in the future.

In contrast to the TPU sheets utilized in our prior design iteration, we opted for TPU-coated nylon, a material commonly employed in inflatables. With this change in material, we conducted heat sealing of the two layers at a temperature of 325°F for 25 seconds. Additionally, we employed a bracket compatible with the heat press to ensure precise positioning of the aluminum frame.

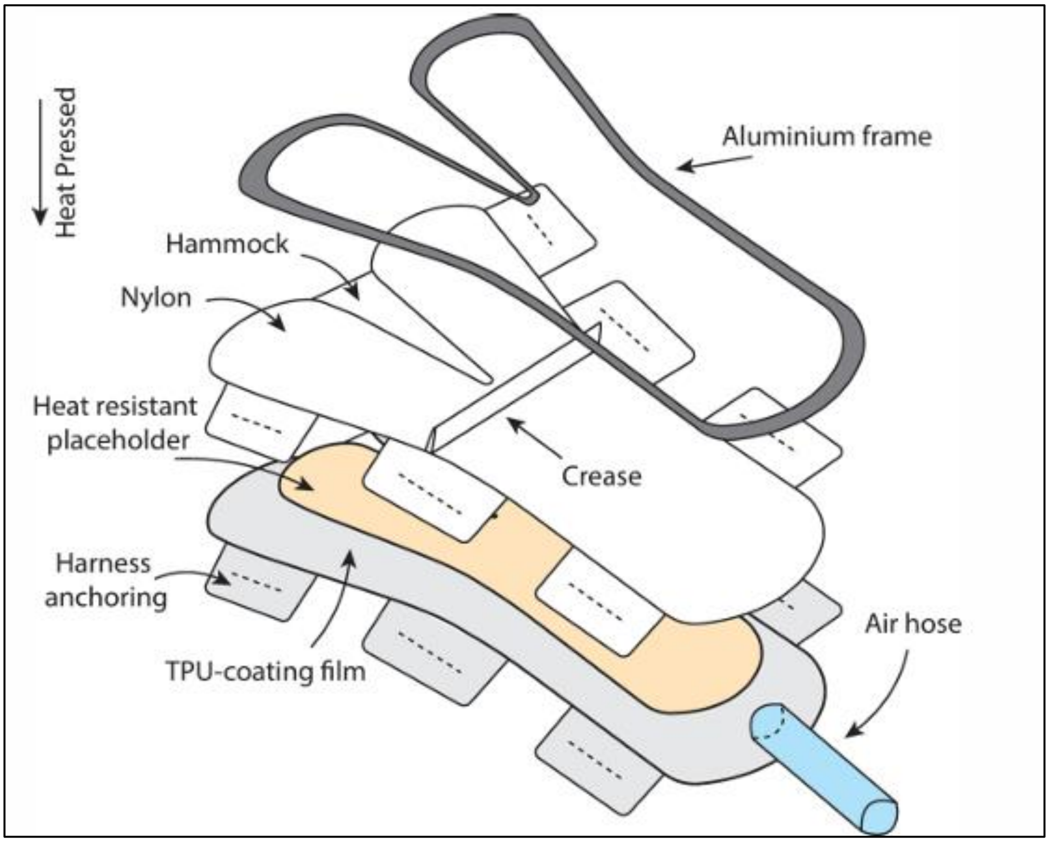


Figure 6

(Preparation of the soft actuator prior to the heat press involves the use of an aluminum frame, which assists in directing heat primarily to the edges of the actuator. This frame is subsequently removed upon completion of the process. The crease necessary for bending the actuator is formed through a local preliminary heat press step. Once cooled, the air hose is inserted into the chamber and sealed using a hot glue gun. Flaps are then cut along the dashed line to facilitate insertion of the harness, enabling anchoring of the actuator to the body.)

Control and Sensing:

Our current setup includes a pump (SP 622 EC-BL-DUp-DV, Schwarzer Precision) capable of reaching a maximum pressure of 1.8 bar, a microcontroller (Arduino Uno R3), and a pressure sensor (Honeywell 100PGAA5). We are actively developing improved control mechanisms for the actuator, which involves integrating a feedback-controlled loop to regulate the power supplied to the pump based on pressure feedback from the sensor. Presently, the actuator features a deliberately loose seal near the hose to prevent rupture. Our ongoing efforts are focused on enhancing control over the actuator.

Challenges:

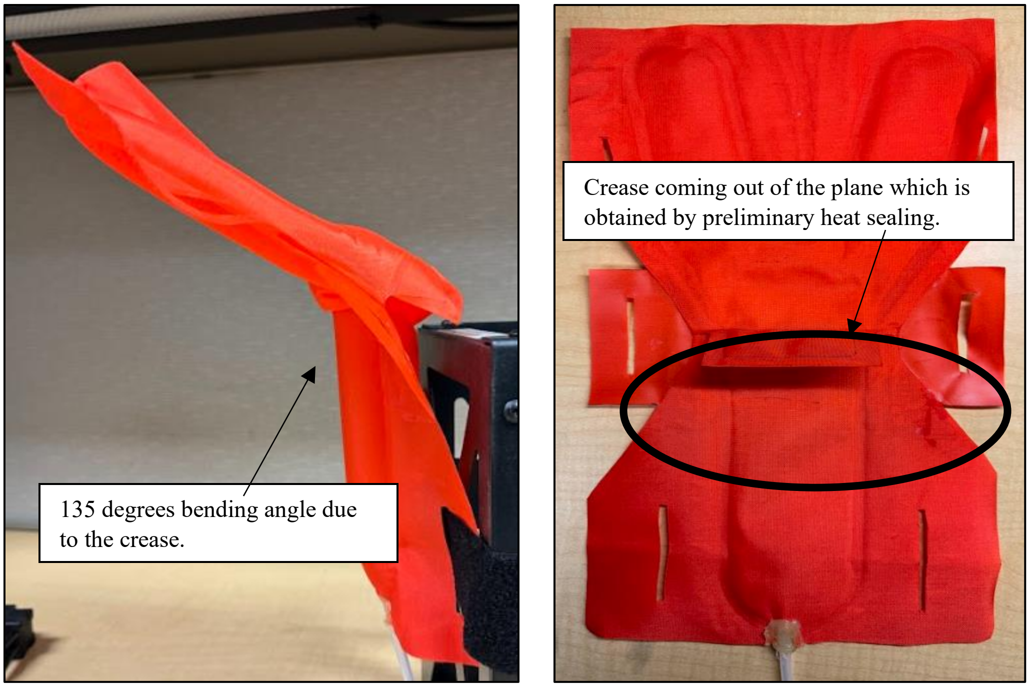
One notable challenge we encountered pertained to heat sealing for the new actuator. Specifically, fabricating the crease proved to be particularly challenging. Due to the crease not lying in the same plane as the rest of the actuator, achieving a complete seal at the intersection of the crease and the actuator was difficult. As a result, air escaped at this intersection, necessitating additional heat sealing to address leaks. To mitigate this issue, manual sealing was employed to cover the unsealed areas. This process relied heavily on trial and error, underscoring the need for a more effective technique to seal at the intersection.

Results:

The Y-shaped actuator functions similarly to a McKibben muscle, contracting near the inflation chamber when air is supplied, owing to the presence of a crease that induces a built-in angle of 135 degrees, as depicted in **Figure 7**. Contact between the inflation chamber and the armpits enhances torque generation. The straps provide support to the actuator, increasing comfort and restricting undesired movement, thereby reducing degrees of freedom to desired planes.

Testing the actuator at 70 kPa pressure resulted in arm elevation just below shoulder height. Future torque calculations will ascertain the actuator's actual lifting capacity. Varying the actuator size and sealing width allows for elevation of different loads by adjusting internal pressure. At this stage of prototyping, a valve was not employed to control inlet and outlet pressure, causing air to escape when the pump is disconnected due to the wearer's arm weight.

The variation in the actuator angles is evident in **Figure 8**, illustrating how the removal of the crease causes the actuator to not stop at a specific angle. This angle is deliberately implemented to ensure safe use of the actuator in the rehabilitation process, where permitting the arm to elevate beyond a certain height may pose more harm than aid to rehabilitation efforts.



135 degrees bending angle due to the crease.

Crease coming out of the plane which is obtained by preliminary heat sealing.

Figure 7

The picture on the left shows how the presence of a crease that induces a built-in angle of 135 degrees. The picture on the right shows the actuator deflated and the crease can be seen coming out of the plane.

Figure 8

The picture on the left shows how the actuator has no bending due to the absence of the crease as shown in the picture on the right.

The y-shaped design effectively supports the arm, and the addition of a nylon hammock enhances wearer comfort. Actuator movement is regulated by air flow, which can be optimized with improved control and sensing. Testing utilized a mannequin with movable joints, as shown in **Figure 9a and 9b**, illustrating arm positions before and after actuator inflation respectively. Tests were conducted at pressures lower than 70 kPa to prevent actuator rupture during ongoing sealing improvements.

Figure 9a

Arm position before actuator inflation

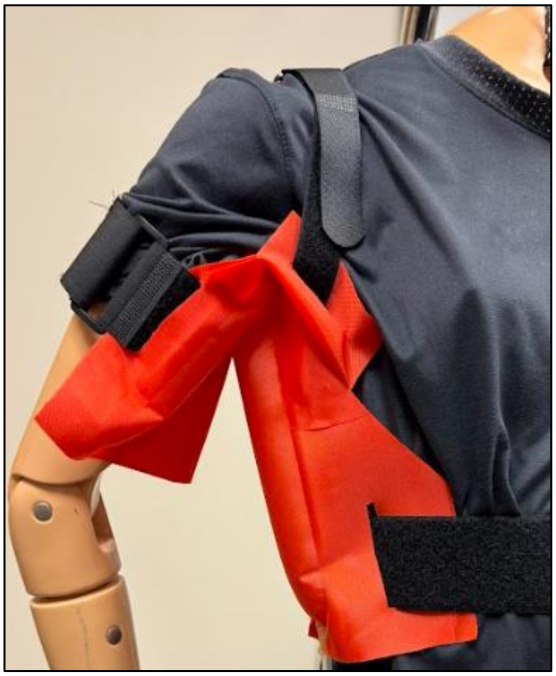


Figure 9b

Arm position after actuator inflation

Discussion:

The development of the soft wearable actuator presented in this study marks a significant advancement in the field of rehabilitation robotics, offering a novel approach to assist individuals with arm weakness in humeral elevation. Through a comprehensive design process and iterative refinement, our innovative actuator aims to address key challenges faced by existing state-of-the-art solutions, particularly in terms of comfort, functionality, and usability.

Advantages of the Novel Design:

Our novel design departure from conventional solutions by employing a single material, TPU-coated Nylon, simplifies the manufacturing process while potentially enhancing actuator robustness. By integrating a built-in bending angle into the actuator design, we optimize contact with the armpit, thus improving comfort compared to traditional straight structures. Furthermore, the incorporation of a nylon hammock at the extremities of the Y-shaped actuator enhances sustain and wearer comfort, addressing key concerns related to long-term usage and user experience.

Functionality and Performance:

The Y-shaped actuator functions akin to a McKibben muscle, contracting near the inflation chamber upon air supply due to the presence of a crease inducing a built-in angle of 135 degrees. This design feature enhances torque generation, facilitating effective humeral elevation. Testing conducted at 70 kPa pressure demonstrated the actuator's capability to elevate the arm just below shoulder height, showcasing promising functionality. However, future torque calculations are warranted to precisely determine the actuator's lifting capacity and performance metrics.

Challenges and Areas for Improvement:

Despite the significant advancements achieved in the development of our soft wearable actuator, several challenges were encountered throughout the design and fabrication process. Heat sealing, particularly in fabricating the crease, proved to be a notable challenge due to the crease's non-planar nature, necessitating manual sealing to address leakage issues. Future efforts will focus on refining heat sealing techniques and exploring more effective sealing methods to optimize actuator performance and reliability.

Future Directions:

Moving forward, our research endeavors will prioritize refining fabrication techniques and enhancing control mechanisms to optimize actuator performance and usability. The integration of a feedback-controlled loop to regulate power supplied to the pump based on pressure feedback from the sensor holds promise for achieving finer control over the actuator's operation. Additionally, ongoing efforts will focus on improving sealing techniques to mitigate leakage issues and enhance actuator durability.

In conclusion, the development of our soft wearable actuator represents a significant step forward in rehabilitation robotics, offering a promising solution for individuals with arm weakness. Through continued innovation and interdisciplinary collaboration, we aim to further enhance the functionality, comfort, and usability of our actuator, ultimately contributing to improved rehabilitation outcomes and enhanced quality of life for individuals with neuromuscular conditions.

References:

1. *A Soft Wearable Robot for the Shoulder: Design, Characterization, and Preliminary Testing by Ciarán T. O'Neill, Nathan S. Phipps, Leonardo Cappello, Sabrina Paganoni, and Conor J. Walsh.*
2. *aeroMorph - Heat-sealing Inflatable Shape-change Materials for Interaction Design by Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii.*
3. *Inflatable Soft Wearable Robot for Reducing Therapist Fatigue During Upper Extremity Rehabilitation in Severe Stroke by Ciarán O'Neill, Tommaso Proietti, Kristin Nuckols, Megan E. Clarke, Cameron J. Hohimer, Alison Cloutier, and David J. Lin.*

4. *Unfolding Textile-Based Pneumatic Actuators for Wearable Applications by Ciara´ n T. O'Neill, Connor M. McCann, Cameron J. Hohimer, Katia Bertoldi, and Conor J. Walsh.*
5. *Restoring arm function with a soft robotic wearable for individuals with amyotrophic lateral sclerosis by Tommaso Proietti, Ciaran O'Neill, Lucas Gerez, Tazzy Cole, Sarah Mendelowitz, Kristin Nuckols, Cameron Hohimer, David Lin, Sabrina Paganoni, and Conor Walsh.*
6. *Di Lallo A, Yu S, Huang TH, Bulea TC, Su H. High-performance soft wearable robots for human augmentation and gait rehabilitation. InSoft Robotics in Rehabilitation 2021 Jan 1 (pp. 1-38). Academic Press.*