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Development of Soft Pneumatic Actuator Based Wrist Exoskeleton for Assistive Motion

Inderjeet Singh
The UTA Research Institute (UTARI)
The University of Texas at Arlington
Fort Worth, USA
inderjeet.singh@uta.edu

Veysel Erel
The UTA Research Institute (UTARI)
The University of Texas at Arlington
Fort Worth, USA
veysel.erel@uta.edu

Yixin Gu
The UTA Research Institute (UTARI)
The University of Texas at Arlington
Fort Worth, USA
yixin.gu@uta.edu

Alexandra R. Lindsay
The UTA Research Institute (UTARI)
The University of Texas at Arlington
Fort Worth, USA
alexandra.lindsay2@uta.edu

Rita M. Patterson
Family & Osteopath. Manip.Medicine
UNT Health Science Center
Fort Worth, USA
rita.patterson@unthsc.edu

Chad Swank
Baylor Scott & White Research Institute
Dallas, USA
Chad.Swank@BSWHealth.org

Muthu B. J. Wijesundara
The UTA Research Institute (UTARI)
The University of Texas at Arlington
Fort Worth, USA
muthuw@uta.edu

***Abstract*—Exoskeletons are gaining traction for their use as motion assistive devices for human performance augmentation in occupational settings and rehabilitation in clinical settings. When considering upper body exoskeletons, soft robotic systems are more suitable due to their intrinsic compliance, lighter weight, and lower complexity in comparison to conventional rigid robotics. Regardless of many efforts to make soft robotic exoskeletons for the upper body, current marketed exoskeletons are only focused on the hand, and there is a need for development of this type of device for the wrist. This manuscript reports the design and development of a pneumatically driven wearable wrist exoskeleton made with hyperelastic materials. The exoskeleton is comprised of soft actuators using half-bellow architecture which can create bidirectional motion by applying pressure and vacuum. Two exoskeleton configurations are presented: (1) one actuator on either the dorsal or palmar side of the wrist and (2) two actuators with one on each side of the wrist. Simulation and experimental studies were performed to evaluate the range of motion and torque capabilities of the two configurations. The single actuator configuration produced a range of motion of 45 degrees flexion and 7 degrees extension when the actuator was on the dorsal side. Inverse angles were obtained when the actuator was on the palmar side. These ranges of motion and the torque produced by this configuration demonstrated its potential to assist in object manipulation and load bearing. However, it is still limited in bidirectionality, which may reduce its ability to assist in tasks that require both flexion and extension. The two-actuator configuration produced higher bidirectionality with 45 degrees flexion and 45 degrees extension range of motion, as well as sufficient torque for both directions. Therefore, this configuration has higher potential for assisting tasks in occupational, rehabilitation, and activities of daily living scenarios.**

Keywords*—*exoskeletons, soft robotics, wrist exoskeleton, pneumatic soft actuator, assistive motion, rehabilitation

I. Introduction

The assistive robotic exoskeleton field is advancing rapidly and continuing to find new applications in healthcare, industry, military, and consumer markets [1]. Exoskeletons can deliver motion assistance to one or more human joints and reduce the load on joints and muscles. In healthcare settings, robotic-mediated motion therapy is gaining popularity for restoring motor functions in people with neurological and physical impairments. To date, rehabilitation centers are the primary customer for assistive robotic exoskeletons. The use of exoskeletons is also gaining momentum in occupational settings to enhance human performance, reduce fatigue, and minimize stress injuries, as these systems can provide synchronized stable movements with assistive force.

Current exoskeletons come in two forms: portable and stationary/fixed frame. However, the portable form is more attractive as it allows the person to be mobile while still assisting a variety of occupational and daily living tasks. In terms of rehabilitation, portable systems would enable continuation of therapy from clinical settings into the home environment. Current portable exoskeletons are made using either conventional rigid robotic technology or emerging soft robotic methods. For instance, commercially available exoskeletons EksoNR and MyoPro are made using rigid structures, while EsoGLOVE™ is made with soft robotic technology [1]. Rigid exoskeletons can produce high forces/torques and are capable of providing precise movements. To date, almost all lower-body exoskeletons are made with rigid robotic technologies. For upper body portable exoskeletons, however, the use of rigid robotic technology poses challenges due to the complexity, size, and weight of components and mechanisms required for the intricate motions of the upper body. Fitting a rigid exoskeleton to the upper body is also difficult due to its poor compliance with the human body, as well as challenges to accommodate personal size variations and joint alignment requirements [2]. As a better solution, emerging soft robotic approaches have gained widespread attention for upper body exoskeletons because they have the capacity to reduce mechanical complexity and are highly compliant, lightweight, and capable of adapting to human body movement [3], [4]. Although many soft robotic research prototypes have been demonstrated for different joints in the upper body [4]-[6], very few commercial devices are available, and they are only for the hand [1].

Wrist function is essential in performing activities of daily living (ADL) and occupational tasks. Rehabilitation of the wrist joint is also critical in restoring motor functions of the hand and wrist after neurological or physical impairment. Wrist motion is complex, and activities involve flexion/extension and radial/ulnar deviation. In most cases, forearm supination/pronation are also coupled with wrist motion. Developing a portable assistive exoskeleton for the wrist should consider many factors, and there may need to be some variations based on the tasks it would assist in occupational, rehabilitation, and ADL. Apart from the functional requirements, size, weight, compliance with the human body, and safety are key factors to consider [7], [8]. In some cases, the wrist exoskeleton's ability to integrate with other devices, such as hand exoskeletons, may take priority when the assistive motion of fingers is needed.

Significant efforts have been reported in developing soft wearable wrist exoskeletons with various actuation mechanisms. Those include cable-driven, shape memory alloy, and pneumatic actuators (McKibben Pneumatic Artificial Muscles, textile, air bladder), each with their own merits and drawbacks [7],[9]-[12]. From a usability and safety point of view, each of these actuation mechanisms pose some concerns that need attention from developers. For instance, pressure and shear stresses at anchor points are factors of concern in cable-driven systems, while heat dissipation requirements in shape memory alloy actuators need solutions [10]. High operating pressures and bulkiness in McKibben Pneumatic Artificial Muscles pose some challenges in safety and usability. As for other pneumatic actuators made with hyperelastic materials, low torque and nonlinearity in actuators need to be addressed.

Regardless of limitations, pneumatically driven soft actuators are widely investigated for human-centered application due to their inherent compliant nature, ability to accommodate a passive degree of motion, capability to apply variable stiffness, and availability of well-developed production methods [13], [14]. In previous work, our team has investigated a novel half-bellow shaped soft actuator capable of bidirectional actuation to create robotic finger digits for a hand exoskeleton [15], [16]. The kinematics and dynamics of the actuator as well as the exoskeleton have been studied through analytical and experimental methods [17]-[19]. In addition, preliminary usability and safety have been evaluated by applying repeated flexion/extension motion (continuous passive motion therapy) to people with impaired and unimpaired hands [4], [16], [19].

This manuscript details the preliminary development and testing of a wrist exoskeleton that utilizes a similar half-bellow-shaped actuator to our previous work. Simulations and detailed experimental characterization are presented. The exoskeleton is designed to assist in flexion and extension movements, yet its compliance still allows for passive degree of motion. The manuscript discusses how the actuator's geometry, configurations, and materials affect exoskeleton behavior. Data on the range of motion (ROM) and torque will be presented. Results will highlight the appropriateness of the design for assisting motion, as well as its limitations based on envisioned applications.

II. Wrist Exoskeleton Design and Simulations

A. Design

The actuator design shares the common geometrical features of our half-bellow actuator used in a robotic finger digit [15], [16]. Fig. 1 shows the overall geometry of the actuator, and it is designed to fit onto the wrist and allow for integration with our previously developed hand exoskeleton. The top side of the actuator is composed of a corrugated membrane (ridges) that can expand and contract when applying pressure and vacuum respectively. The asymmetric geometry, due to the thick bottom membrane, causes the forward and backward bending motion during pressurization. For practical use, holes are included in the design on the perimeter of the bottom membrane for easily sewing the actuator to a wearable wrist sleeve.

A preliminary Finite Element Modeling (FEM) analysis was conducted on the actuator to determine the initial design parameters (Fig. 1B) for this study. The analysis showed that the number of ridges, ridge gap (g_R), and inner ridge width (w_{IR}) have an effect on the actuator's bending angle. Based on analysis observations, the following geometrical features were chosen for this initial investigation: number of ridges was set to 6, ridge height (h_R) was set to 10 mm, ridge gap (g_R) was set to 4 mm, inner ridge width (w_{IR}) was set to 2 mm, and the bottom membrane thickness (t_B) was set to 8 mm. For the studies described in this manuscript, some parameters were varied to understand their effects on behavior of the actuator. Since the thickness of the corrugated membrane (t_W) is directly linked to the pressure that the structure can withstand, two thicknesses were evaluated in this study, 3 and 3.5 mm. It should be noted that increasing membrane thickness increases the overall length of the actuator, as all the other parameters are constant. Two hyperelastic materials (polyurethane and silicone) with different elastic moduli were also tested to evaluate how actuator performance can be augmented with material selection.

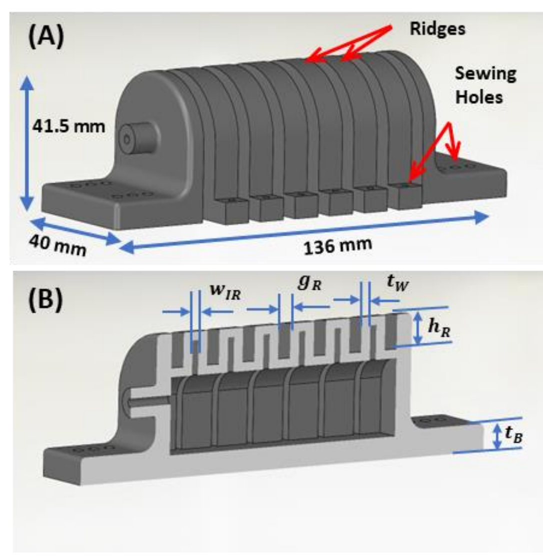

Fig. 1. (A) Actuator dimensions and (B) actuator design parameters.

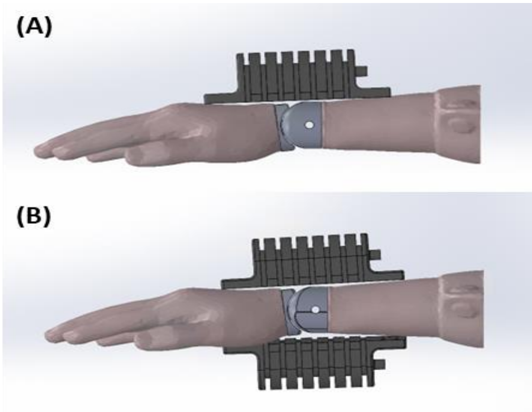

Fig. 2. (A) One-actuator configuration with example shown on dorsal side of hand and (B) two-actuator configuration.

The wrist exoskeleton is designed with two configurations: (1) one actuator on either the dorsal or palmar side of the hand and (2) two actuators, where one is attached on each side. Fig. 2A shows the exoskeleton with the actuator at the dorsal side of the wrist, and Fig. 2B displays the exoskeleton with an actuator attached to both sides of the wrist. Both configurations have distinct advantages and disadvantages in terms of ROM, torque, and capability to assist tasks. These distinctions will be examined in the Results and Discussion Section.

B. Simulation Setup

1) Actuator

A 3D model of the wrist actuator is used to simulate the bending behavior of the actuator under varying pressures. Static structural analyses are performed by using ANSYS simulation software. Uniaxial and planar tension experimental data of polyurethane (PMC™-724, Smooth-on) and silicone rubber (RTV-4234-T4, Xiameter®, Dow Corning) are used to obtain Yeoh's 3rd-order material model (demonstrates best curve fitting) parameters [15]. For the single actuator simulation study, the left-side wall of the actuator is fixed (shown in Fig. 3 as black slanted lines), and 50 kPa pressure is applied to all inner walls of the actuator chamber (shown in Fig. 3 as red region). The right-side wall of the actuator is used to track angular displacement (bending angle) which is collected to examine actuator bending behavior. The angular displacement was measured by comparing the change in the angle of the right-side wall of the actuator before and after inflation.

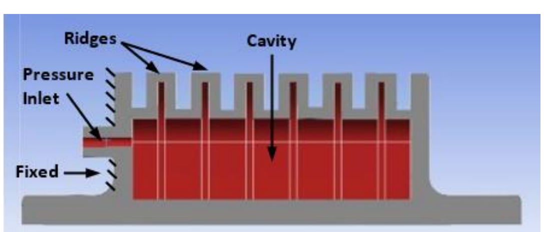

Fig. 3. Single Actuator Simulation Setup.

2) Actuator with Hand and Arm Model

3dMD Flex 4 System 3D Scanner is used to obtain a 3D model of the hand and forearm. Open-source MeshLab software is used to convert scanned geometries to solid models and to reduce the number of faces and vertices, which helps to simplify mesh geometry. Then, SOLIDWORKS® is used to assemble the models with the wrist actuators. Although the actuators are sewed to a wrist sleeve in the experimental test setup, the wrist sleeve and stitches were not included in the simulation setup to reduce the complexity. This variation may lead to some discrepancies when comparing simulation to experimental data.

Two simulations were performed to observe the bending behavior for the two configurations shown in Fig. 2. Polyethylene material is used for the hand and forearm models, while polyurethane is defined for the wrist actuators. All materials are assumed to be isotropic. The right side of the forearm and actuators are fixed, as shown in Fig. 4 (black slanted lines). The wrist joint is defined as the revolute joint between the hand and forearm. Bonded contacts are defined between the front/back-ends of the actuators and the hand/forearm, as shown in Fig. 4 (yellow lines). Pressure/vacuum is applied to all inner cavities of the actuators. For the one-actuator configuration, pressure and vacuum are applied sequentially for forward and backward bending motion. In the two-actuator configuration, one actuator is pressurized while the other actuator is simultaneously subjected to vacuum to create the bending motion. Pressure and vacuum are alternated between the two actuators for creating forward and backward bending. Since the purpose of the simulation is to evaluate the bending capacity of the wrist exoskeleton, gravity was not considered.

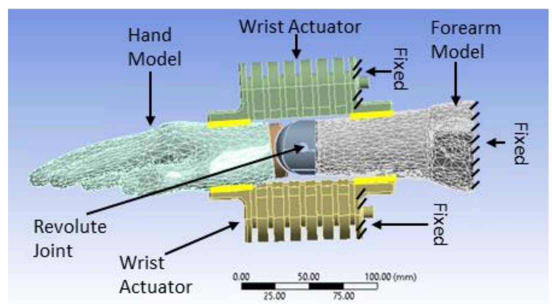

Fig. 4. Two-Actuator Simulation with hand and forearm models.

III. Fabrication and Experimental Setups

A. Fabrication of Actuators and Exoskeleton

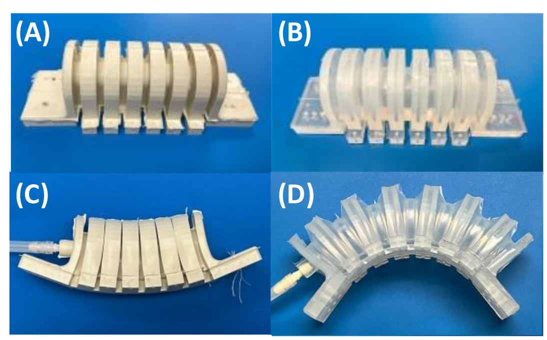

Fig. 5. (A) Polyurethane actuator, (B) silicone actuator, (C) vacuumed polyurethane actuator, (D) pressurized silicone actuator.

The actuators are made with polyurethane rubber (PMC™-724, Smooth-on) and RTV silicone rubber (XIAMETER® RTV-4234-T4, Xiameter®, Dow Corning). Liquid compression molding combined with an over-molding process is used for fabricating actuators. All mold parts are created in the modeling software SOLIDWORKS® and produced using a high-resolution 3D printer (ProJet 6000 HD SLA). The process details were reported earlier [16], [19]. Fig. 5 shows actuators fabricated with the two materials and how they look in different pressurized states.

Exoskeletons are assembled by sewing the actuators to a commercially available wrist sleeve. Actuators are sewed on either the dorsal or palmar side (one-actuator configuration) or one on each side (two-actuator configuration) such that the center of the actuator is approximately aligned with the center of the wrist joint when the sleeve is worn.

B. Experimental Setups

Two experimental setups are designed to study ROM and the torque characterizations of the wrist exoskeleton as follows:

1) Range of Motion Study

To evaluate the capability of the exoskeleton to flex and extend the wrist joint, an experimental setup is assembled as shown in Fig. 6. A forearm model and hand model are connected by a revolute joint (wrist joint) and mounted horizontally on a table, where the forearm is fixed such that the hand rotates freely about the joint. No external loads are included during the ROM study, however, friction from the joint and stiffness of the wrist sleeve fabric are still present. The horizontal positioning of the setup is also meant to reduce the direct loading effect of gravity. An IMU sensor is attached on the hand to measure the angular movement (flexion and extension) of the wrist joint. Both configurations (Fig. 2) of the wrist exoskeleton are tested. In the case of the exoskeleton with a single actuator on dorsal side, applying pressure and vacuum to the actuator creates flexion and extension respectively. The one-actuator configuration is tested with the actuator on each side (dorsal and palmar). For the two-actuator configuration with actuators on the dorsal and palmar sides of the wrist, one actuator is pressurized while the other is simultaneously subjected to vacuum to create bending motion, as described in the simulation section. Flexion and extension angles at varying pressures are measured during both configurations. A simple proportional derivative (PD) controller is used (similar to [19]) to test the capability of the exoskeleton to apply cyclic flexion and extension motion to the wrist joint.

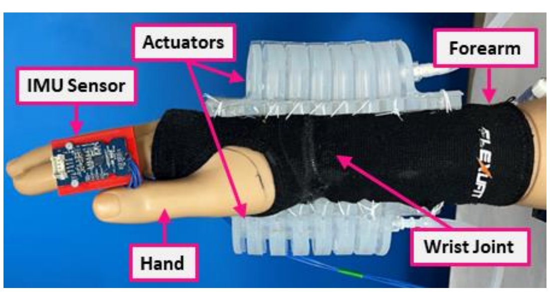

Fig. 6. Experimental setup for Range of Motion (ROM) study.

2) Torque Evaluation

As shown in Fig. 7, an experimental setup is assembled to characterize the torque generation by the proposed wrist exoskeleton. The same forearm and hand model consisting of the wrist joint is used from the previous setup. The forearm is fixed which allows the rotation of the hand about the wrist joint (revolute joint). In this study, torque generation of the exoskeleton is measured for different initial angular positions of the wrist joint. Therefore, the forearm is fixed at different positions depending on the angular position being tested. Pressure and vacuum are applied in both configurations (Fig. 2) to evaluate flexion and extension torques. When actuators are pressurized or vacuumed, the bending motion of the exoskeleton causes the rotation of the hand. As shown in Fig. 7, a load cell is mounted on the rotational path of the hand, where a fixture on the hand applies perpendicular force on the load cell. The horizontal mounting of the wrist joint setup eliminates the gravitational effects on the rotation which would affect the force measurements. The torque generated by the wrist exoskeleton at different angular positions are evaluated with varying internal pressures. Both actuator configurations were tested at 0˚, 15˚, 30˚, and 45˚ angular positions. The applied pressure limits are set based on the material type and membrane wall thickness, such that the actuator will not undergo excessive deformation (ballooning). Torque characterization is performed for the one-actuator configuration with polyurethane and silicone material, while the two-actuator configuration is studied with only silicone. Additionally, different wall thicknesses (t_W = 3mm, 3.5mm) are tested to observe the effect on torque generation.

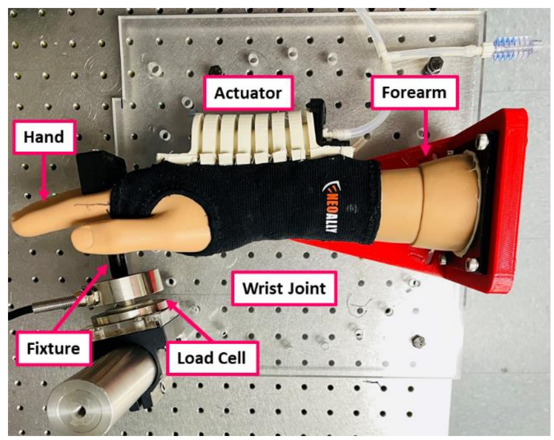

Fig. 7. Experimental setup for torque evaluation.

IV. Results and Discussion

A. Simulation Results

Two simulations were performed: (1) Free expansion of the actuator and (2) actuator(s) with the hand and forearm models in both configurations (Fig. 2). These simulations will give a primary understanding of the wrist actuator's behavior and capability to be used as an assistive motion device.

1) Actuator

The actuator alone was simulated by applying pressure and vacuum to examine its bending behavior. Fig. 8 shows the actuator behavior when it is (A) not pressurized or vacuumed, (B) vacuumed, and (C) pressurized.

As observed in the simulation results, the top side of the actuator expands and contracts more than the bottom side of the actuator. This bending behavior is due to the presence of ridges and a thin membrane on the top side which can expand, while the bottom side is restricted because it is thick and flat. These results demonstrate that the half-bellow ridge design from our previous study [15], [16] can be modified and implemented for a novel wrist actuator that can achieve bidirectional bending behavior.

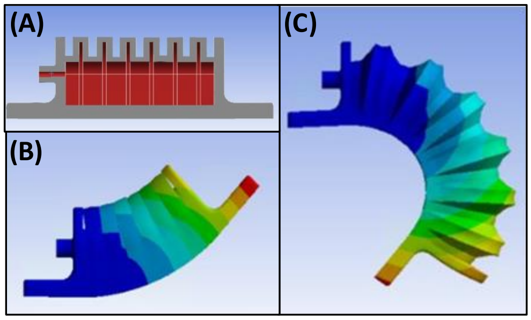

Fig. 8. Actuator bending behavior under (A) no pressure or vacuum, (B) vacuum, and (C) pressure.

2) Actuator with Hand and Forearm Model

A single wrist actuator is attached to hand and forearm models in a 3D assembly to investigate the wrist actuator's assistive flexion and extension capability. By applying pressure and vacuum to the inner cavity of the actuator, forward and backward bending can be achieved. For instance, Fig. 9A shows the simulation results of the single actuator configuration on the dorsal side when applying pressure to achieve flexion. Fig. 9B shows the setup under vacuum condition to achieve extension. As shown in the figure, the angle created by the vacuum is smaller due to folding behavior of the actuator, as well as compression limitations of materials used in the actuator.

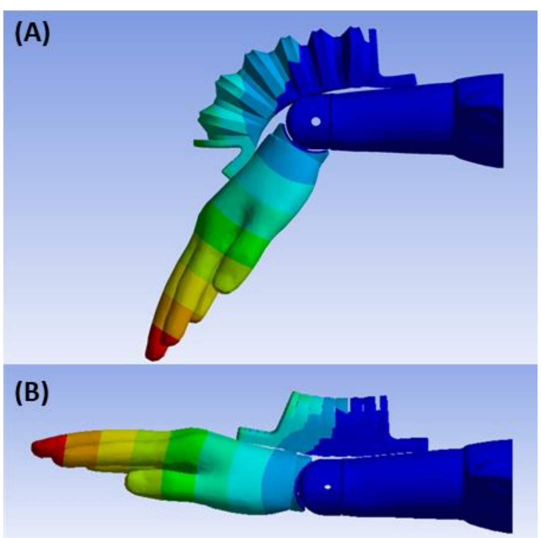

Fig. 9. One-actuator configuration on dorsal side of wrist joint (A) flexion and (B) extension behavior.

Table I shows the flexion and extension data for both configurations of the wrist exoskeleton using polyurethane actuators. For the one-actuator configuration, bending angle data is shown for when the actuator is placed on either the dorsal or palmar side. Of note, the one-actuator configuration can be used for bidirectional motion by applying pressure and vacuum. However, the ROM created by vacuum is small compared to the motion created by pressure. For example, when the actuator is on the dorsal side, flexion due to pressure is 50˚, while extension due to vacuum is only 14˚. Though this single actuator configuration may still be suitable for some assistive applications, there may be limitations where greater flexion and extension are needed for a given task [20]. However, for rehabilitation activities, this configuration may still be applicable as users can alternate between exoskeletons with dorsal or palmar side actuators as needed to assist with selected motion exercises.

TABLE I. FLEXION AND EXTENSION SIMULATION DATA FOR ONE-ACTUATOR AND TWO-ACTUATOR CONFIGURATIONS OF THE EXOSKELETON MADE WITH POLYURETHANE ACTUATORS ON HAND AND FOREARM MODEL

Configuration	Actuator Placement	Flexion Angle	Extension Angle
One-Actuator	Dorsal	50˚ (pressurized)	14˚ (vacuumed)
	Palmar	18˚ (vacuumed)	56˚ (pressurized)
Two-Actuator	Dorsal Palmar	48˚ (pressurized) (vacuumed)	47˚ (vacuumed) (pressurized)

The two-actuator configuration was simulated to investigate how the wrist actuators behave when one is pressurized and the other is vacuumed simultaneously, while attached to a 3D hand and wrist model. Fig. 10 shows flexion and extension behavior of the wrist joint using this configuration. Table I shows that flexion of the wrist joint can achieve 48˚ angular displacement when the dorsal actuator is pressurized and the palmar actuator is vacuumed. Inversely, extension of the wrist joint can achieve 47˚ angular displacement. It should be noted that the actuator on the vacuumed side of the hand restricts attaining higher angular displacement due to the geometry of the actuator, as well as the limiting compression behavior of material. Although the two-actuator configuration slightly compromises the achievable flexion/extension angles compared to the one-actuator configuration, greater bidirectional capabilities are attained with the two-actuator configuration.

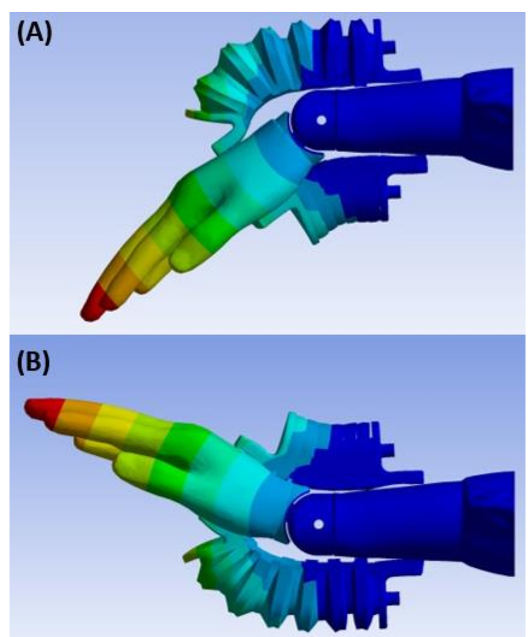

Fig. 10. Two-actuator configuration with wrist joint (A) flexion and (B) extension behavior.

B. Experimental Results

The actuator was integrated with a wearable wrist sleeve to create a wrist exoskeleton. Two configurations (Fig. 2) of the exoskeleton with a physical hand and forearm model connected through a revolute wrist joint were investigated for ROM and torque characterization. Both experimental studies investigate critical aspects to determine the extent to which the exoskeleton can provide assistive wrist motion. Additionally, the results provide insight into suitability of the wrist exoskeleton for given applications.

1) Wrist Exoskeleton with One Actuator

The one-actuator exoskeleton configuration was fabricated and tested for two different materials: polyurethane and silicone.

a) Range of Motion Study

Initially, the one-actuator configuration of the exoskeleton was studied to understand its ROM when the actuator is pressurized or vacuumed. Pressure was applied until the bending angle achieved approximately 45˚. This target angle was selected because the mean flexion angle of the wrist during activities of daily living (ADL) is approximately 38º [20]. Fig. 11 shows pressure versus angular displacement data for both materials when a single actuator is placed on the dorsal side. The pressure required to achieve 45º for polyurethane and silicone were 62 and 76 kPa gauge pressure, respectively (Fig. 11). As the two materials have distinct elastic moduli, actuation pressure required for reaching the same target angle was expected to be different.

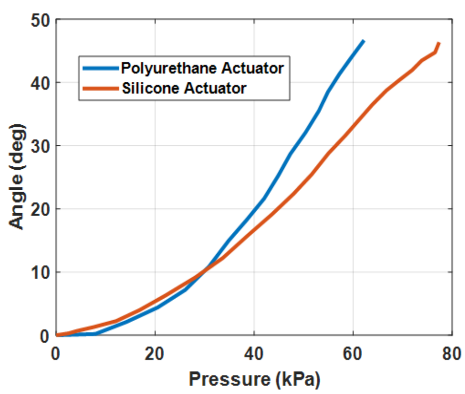

Fig. 11. Angular displacement of wrist joint with varying pressure of a single actuator on dorsal side for polyurethane and silicone.

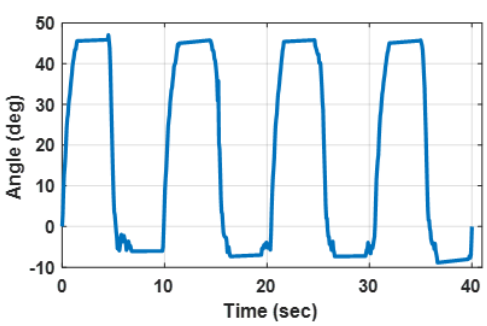

Figure 12. Flexion/Extension using one-actuator configuration on dorsal side with polyurethane actuator.

A PD controller was used to cyclically apply pressure to the actuator to achieve flexion at a set angle and then release the pressure to apply vacuum to achieve extension at a set angle. With the current hardware, an angular velocity of 25˚/s was set in the PD controller. Maximum flexion angle was set to 45˚. Extension angle was set to 7˚, as that was the achievable maximum angle under vacuum at -70 kPa gauge pressure. The low extension angle is due to restrictions imposed by the folded structure of the actuator and vacuum limits. Fig. 12 shows data on four flexion and extension cycles of the exoskeleton with a polyurethane actuator on the dorsal side of the wrist. The PD controller was also able to produce identical results for the silicone actuator. When the actuator was on the opposite (palmar) side, the extension angle was set to 45˚ and the flexion angle 7˚. These data demonstrate the capacity of the exoskeleton to achieve set angles in a cyclic manner while assisting a wrist joint, which is critical for many exoskeleton applications. As angular velocity is dependent on airflow rate, future studies can be performed to optimize the hardware necessary to match the angular velocity demands of the end application.

b) Torque Evaluation

Torque evaluation was performed with one actuator on the dorsal side of the wrist exoskeleton at different angular positions. Fig. 13 shows torque generation as a function of applied pressure for an exoskeleton with a polyurethane actuator. As shown in the graph, generated torque decreases as the angular position of the wrist increases. This is typical behavior for any soft actuator-based exoskeleton joints [6], [22].

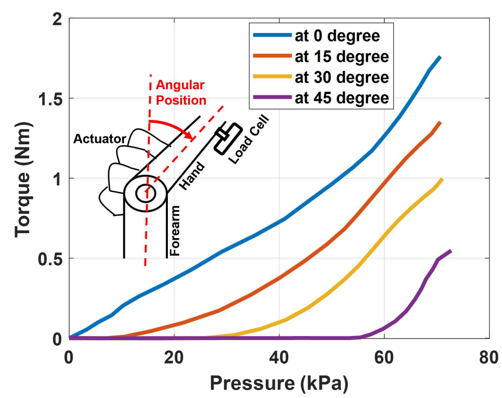

Fig. 13 Torque generation of polyurethane actuator on dorsal side with 3mm wall thickness (at different angular positions).

Table II shows the flexion torque data for the wrist exoskeleton using polyurethane and silicone actuators on the dorsal side and maximum pressure of each actuator type with corresponding membrane wall thicknesses. Maximum pressure was selected so that no ballooning or nonuniform expansion occurs due to pressure. It was observed that the polyurethane and silicone materials withhold different maximum pressures due to differing elastic moduli. From the data seen in Table II, silicone generates greater torque as it is the material with higher elastic modulus. Additionally, greater torque can be generated by increasing the membrane wall thickness (t_W), as the thicker walls of the actuator allow for withstanding higher pressures. At angular position 0˚, the actuator fabricated with silicone and a 3.5 mm membrane wall thickness produced the greatest torque of all tested actuators, which was 5.46 Nm.

TABLE II. FLEXION TORQUE COMPARISON FOR ACTUATORS MADE UP OF DIFFERENT MATERIAL AND THICKNESS FOR ONE-ACTUATOR CONFIGURATION WITH ACTUATOR ON DORSAL SIDE

Angular Position	Polyurethane		Silicone	
	3mm 70 kPa	3.5mm 105 kPa	3mm 140 kPa	3.5mm 175 kPa
0˚	1.80 Nm	2.49 Nm	3.50 Nm	5.46 Nm
15˚	1.42 Nm	2.18 Nm	3.00 Nm	4.55 Nm
30˚	0.90 Nm	1.91 Nm	2.65 Nm	3.34 Nm
45˚	0.48 Nm	1.32 Nm	2.10 Nm	2.36 Nm

It was observed that applying vacuum to the actuator when it is on the dorsal side generates very little extension torque. For actuators with 3 mm membrane wall thickness, torque generated at 0˚ under vacuum was 0.21 Nm and 0.29 Nm for polyurethane and silicone, respectively. By increasing the membrane wall thickness to 3.5 mm, the produced torque was increased to 0.36 Nm and 0.41 Nm for polyurethane and silicone, respectively.

2) Wrist Exoskeleton with Two Actuators

a) Range of Motion Study

The two-actuator configuration of the exoskeleton, made with 3.5 mm membrane wall thickness and silicone, underwent ROM testing. This combination of membrane wall thickness and material was selected based on the single actuator study results, as it produced the highest torque. Flexion is achieved by applying variable pressure in the dorsal side actuator concurrent with vacuum application in the palmar actuator, while extension was achieved by applying pressure to the palmar side actuator with concurrent vacuum applied to the dorsal actuator. This configuration was tested for its capability to achieve 45º for both flexion and extension angles. This range was selected, as the mean flexion and extension angles of the wrist during ADL are approximately 38º and 37º, respectively [20].

b) Torque Evaluation

Table III shows the flexion and extension torques for different angular positions for the two-actuator configuration of the wrist exoskeleton. The torque generated by the two-actuator configuration was slightly lower than the one-actuator configuration, which is likely due to motion restrictions imposed by the opposing actuator under vacuum. The results clearly show that this configuration can generate comparable torques for both flexion and extension. The two-actuator configuration may find applications in both rehabilitation and ADL tasks due to its capability of bidirectional motion and torque.

TABLE III. TORQUE CHARACTERIZATION FOR WRIST EXOSKELETON WITH 3.5 MM WALL THICKNESS SILICONE TWO-ACTUATOR CONFIGURATION AT 175 kPa

Angular Position	Flexion Torque	Extension Torque
0˚	4.69 Nm	4.80 Nm
15˚	3.42 Nm	3.55 Nm
30˚	1.90 Nm	1.86 Nm
45˚	0.64 Nm	0.32 Nm

C. Discussion

By considering the ROM and torque properties of the one-actuator configuration, it has the potential to primarily assist the wrist with one directional movement and load bearing. For example, an actuator on the dorsal side could assist in carrying weight and gravity compensation of the hand. Even though there is no consensus among various studies on the maximum torque produced by the wrist, some studies report 2.5 Nm as the maximum while other comparable studies show up to about 8 Nm [21], [23]. Therefore, this one-actuator configuration which can generate up to 5.46 Nm has the potential to assist in load carrying tasks by supporting a percentage of load. It should be noted that the torque produced by our one-actuator configuration at 0˚ with 175 kPa was much higher in comparison to another pneumatic wrist actuator, which produced about 2.6 Nm at 200 kPa [7]. For ADLs, the actuator on the dorsal side may help people with wrist impairment to handle objects such as a plate of food or holding a pen. The actuator on the palmar side may help activities such as drinking from a cup and getting a can from a shelf [20]. However, some interferences may be present when using a palmar side actuator to handle objects due to its location on the hand. The actuator on the palmar side may also allow for engaging in rehabilitation activities where a person's hand may be contracted and needs to be in an extended position. Additionally, alternating between exoskeletons which have the actuator on either the dorsal or palmar side can aid in reducing wrist/hand muscle tone and related pain and edema.

The results of the two-actuator configuration of wrist exoskeleton with 45º flexion and 45º extension suggests that it has the potential to assist in bidirectional assistive motion. Based on the data reported in previous literature, regarding maximum torques produced by the wrist [21], [23], this two-actuator configuration should also be capable of assisting in object manipulation tasks. Additionally, the flexion and extension exercises are a key part of both orthopedic and neurological rehabilitation, and this wearable form of exoskeleton has significant potential in those areas.

The authors acknowledge that there are some limitations to these configurations, as this initial investigation did not focus on adding capabilities for radial/ulnar deviation. However, the compliant nature of the actuator allows for passive degree of motion in those joint directions during task performance.

V. CONCLUSION AND FUTURE WORK

This work presented the initial development of a wearable pneumatic soft robotic exoskeleton for assisting wrist flexion and extension. Two exoskeleton configurations were created using a bidirectional half-bellow geometry actuator made with polyurethane and silicone. In both configurations, achievable ROM with either material was comparable to each other; however, exoskeletons with silicone actuators produce greater torque. The data also supports that the actuators used in this study can generate significantly greater torque at lower pressure, compared to previously reported literature data. The exoskeleton with one actuator placed on either the dorsal or palmar side has the potential in assistive object manipulation and load bearing; however, limited bidirectionality may reduce the usefulness of this configuration as many ADL require both flexion and extension. The exoskeleton with actuators at both sides of the wrist can produce ROM and torque which are sufficient for most ADL and has the potential to be used as both an assistive and rehabilitation device.

Future work may include geometrical modifications to optimize the form factor of the actuators and adding radial/ulnar deviation capability. Efforts will also be made to develop adaptive control algorithms to assist with the motion and load as needed. Part of the future work will also be dedicated to evaluating the percentage of assistance provided by the exoskeleton by using electromyography signals from muscles. The usability of these exoskeletons will need to be studied for their capabilities to assist in selected real-world scenarios. The work will also explore the integration of these exoskeleton configurations with our previously developed pneumatic hand exoskeleton.

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