Fabric-Silicone Composite Haptic Muscles for Sensitive Wearable Force Feedback

Raagini Rameshwar
rrameshwar@wpi.edu
Worcester Polytechnic Institute
Worcester, Massachusetts, USA

Erik Howard Skorina
ehskorina@wpi.edu
Worcester Polytechnic Institute
Worcester, Massachusetts, USA

Cagdas D. Onal
cdonal@wpi.edu
Worcester Polytechnic Institute
Worcester, Massachusetts, USA

ABSTRACT

Robot teleoperation is an emerging field of study with wide applications in exploration, manufacturing, and healthcare, because it allows users to perform complex remote tasks while remaining distanced and safe. Haptic feedback offers an immersive user experience and expands the range of tasks that can be accomplished through teleoperation. In this paper, we present a novel wearable haptic feedback device for a teleoperation system that applies kinesthetic force feedback to the fingers of a user. The proposed device, called a 'haptic muscle', is a soft pneumatic actuator constructed from a fabric-silicone composite in a toroidal structure. We explore the requirements of the ideal haptic feedback mechanism, construct several haptic muscles using different materials, and experimentally determine their dynamic pressure response as well as sensitivity (their ability to communicate small changes in haptic feedback). Finally, we integrate the haptic muscles into a data glove and a teleoperation system and perform several user tests. Our results show that most users could detect detect force changes as low as 3% of the working range of the haptic muscles. We also find that the haptic feedback causes users to apply up to 52% less force on an object while handling soft and fragile objects with a teleoperation system.

ACM Reference Format:
Raagini Rameshwar, Erik Howard Skorina, and Cagdas D. Onal. 2023. Fabric-Silicone Composite Haptic Muscles for Sensitive Wearable Force Feedback. In Proceedings of the 16th International Conference on PErvasive Technologies Related to Assistive Environments (PETRA '23), July 05–07, 2023, Corfu, Greece. ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3594806.3594853

1 INTRODUCTION

Robot arm teleoperation is an emerging field of study that enables users to safely perform remote or dangerous tasks [24][6][19]. Telerobotics has major applications in healthcare and assisted living. The COVID-19 pandemic clearly showed the challenges of performing normal nursing tasks when dealing with a severely contagious disease [11]. There is a need for teleoperated nursing robots that allow experienced nurses to provide patients with personal care while staying distanced [15][16]. Because tasks involving hospital patients are generally varied and delicate, visual feedback alone is insuficient and haptic feedback is necessary for a smooth teleoperation experience [1][2][14]. Haptic feedback, that is, the simulation of the sense of touch, closes the loop between the human user and teleoperated robot, offering a "telepresence" experience that makes the robot an extension of the user's body. There are several modes of haptic feedback, such as contact, cutaneous, and force feedback. In this paper we focus on force feedback, and in particular kinesthetic feedback that applies real forces to the user's fingers during teleoperation.

Kinesthetic feedback has been shown to communicate stability in grasp forces during teleoperation, which is vital when performing delicate or hazardous tasks [10]. However, an ongoing challenge, especially when applying real forces to a user's fingers, is to make the feedback as realistic and intuitive as possible while keeping the safety and comfort of the user in mind. We addressed this in our previous work by presenting a novel mode of wearable haptic feedback dubbed the "haptic muscle" [22]. We proved the eficacy of the haptic muscle within a teleoperation context, and also collected user data concerning the comfort and quality of the haptic feedback [12]. In this paper, we apply what we learned to a more in-depth study of the haptic muscles, as well as to development of a novel version using a fabric-silicone composite.

1.1 Related Works

We explore existing work in finger-based haptic feedback devices as well as the use of silicone and fabric in various soft robotic applications.

1.1.1 Haptic Feedback Devices.

There are several ways to apply kinesthetic haptic feedback to a user's fingers. In [26], for example, the authors present a data glove where the user's fingers are attached to mechanical linkages, driven by motors on the glove. The users use the glove to drive a remote-controlled car around a maze, curling their fingers to control the car's speed. If the car is about to crash, the linkages pull the user's fingers straight, applying both kinesthetic feedback and preventing the user from crashing the car. In a similar vein, the authors in [8] use shape-memory alloy brakes to stop a user's fingers from closing past a certain threshold. These examples would impede a user performing a teleoperated task with a robotic hand and gripper, because it would be impossible to continue working or manipulating an object while receiving haptic feedback. Additionally, ideal teleoperation systems provide both contact and kinesthetic feedback [10]. When the two feedback modes require different equipment, this can lead to a bulky and

This material is based upon work partially supported by the National Science Foundation (NSF) under Grant Nos. DGE-1922761 and IIS-2024802. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

PETRA '23, July 05–07, 2023, Corfu, Greece

ACM ISBN 979-8-4007-0069-9/23/07...$15.00
https://doi.org/10.1145/3594806.3594853

uncomfortable wearable. In [7] for example, the authors present a device that provides both kinesthetic and cutaneous feedback, providing a holistic telepresence experience. However, the device is extremely bulky and does not allow the user to comfortably move during teleoperation. More recently, in [9], the authors present a fabric-based haptic armband made TPU-coated nylon, an inextensible material that is appropriate for surface-level haptics but less so for delicate grasping tasks.

Our goal with our haptic device is to offer both contact and kinesthetic feedback in one lightweight and portable device. Additionally, because it is pneumatically-driven, we can apply higher forces with a greater degree of safety than cable-driven mechanisms.

1.1.2 Fabric-Silicone Composites. Though the exploration of soft materials for haptic feedback is relatively new, the combination of silicone and fabric has applications in a variety of fields. Caldwell et. al. applied for a patent in 1985 with a fabric-silicone material for use in architecture [3]. Shi et. al investigated a fabric-silicone for use in clothing, investigating the tradeoff between water resistance and the wearer's comfort [21]. Silicone itself has been shown to be particularly suitable for skin-related and wearable applications because of its material properties [18]. It is also one of the major standard materials for manufacturing soft actuators [17].

Fabric has historically been used to add inextensiblity to soft pneumatic manipulators. Layers of fabric within a manipulator can prevent extension when pressurized, increasing the bending range and simplifying the kinematics of the soft robot [23]. Additionally, pneumatic actuators made from inextensible fabrics with elastomer coatings are thin, light, and have high force outputs [13]. More recently, Wang et. al. investigated combing stretchable fabric with silicone to improve the mechanical properties of soft structures [25]. It is clear that fabric-silicone materials have several advantages that lend themselves to haptic feedback applications.

1.2 Contributions

Our contributions in this paper are as follows:

- An improved design for a novel, wearable, pneumatically-driven kinesthetic haptic feedback mechanism
- Experiments to show the responsiveness of the haptic feedback actuator in a stand-alone context and in a teleoperation context

2 HAPTIC MUSCLE DESIGN AND FABRICATION

2.1 Haptic Muscle Design and Control

The haptic muscle, presented in our previous work [22], is a toroidal structure with two layers and an air pocket for inflation. The structure fits around the user's finger, and when uninflated is easy to bend. When pressurized, as shown in Fig 1, the structure inflates around the user's finger and applies a moment force to the knuckle, gently opening the finger. This simulates how a real object in the user's hand would prevent their fingers from closing, thus providing a realistic feeling of grasping something. Because the actuator surrounds the finger, this also provides a contact force on the finger's palmar side.

The haptic muscles are controlled through pneumatic solenoid valves that are driven by a pulse-width modulation (PWM) signal. The duty cycle of the PWM signal determines what percentage of the source pressure flows through the valve into the haptic muscle. Thus we can directly control the degree of haptic feedback to the user.

We integrated initial prototypes of the haptic muscles constructed from a heat-sealable plastic into a data glove. We used the data glove to run tests where several users performed pick-and-place tasks by teleoperating a robotic arm and hand. During teleoperation, we sensed forces at the fingertips of the robotic hand, and directly mapped these forces to the haptic muscle inflation. The users felt a level of feedback proportional to the grasp forces, and were thus able to distinguish good grasps from poor grasps. These tests provided some results towards proving the eficacy of this kind of feedback.

During these teleoperation tests we found several areas of improvement. We received feedback during user interviews that the haptic muscles were uncomfortable to bend and more uncomfortable when inflated because of the "plasticky" feeling. Users also reported that the haptic feedback was rather binary, instead of proportionally following the force sensors' output. In the remainder of this paper, we discuss what we learned about the requirements for an ideal haptic muscle, our novel design and manufacturing process, and two phases of testing that show the capabilities of the new haptic muscles. We wanted to create haptic muscles that could communicate not only grasp quality as in [12], but also force applied during a grasp. This would ideally allow a user to handle fragile objects without deforming or dropping them.

2.2 Design Requirements

There are several aspects of haptic feedback that are essential to a good teleoperation experience. Haptic feedback should ideally feel natural and intuitive to the user. This means that when there is no feedback, the haptic structure should be unnoticeable. Additionally, the user should easily detect changes in the haptic feedback, and the smaller the detectable change, the more natural the haptics feel. Finally, there should be very little delay between force detection on the robot side and haptic feedback detection on the human side. That is, the human and robot should "feel" forces at the same time.

To address these requirements, we chose to construct new haptic muscles using a fabric-silicone composite. The fabric is a ribbed cotton-spandex hybrid that is lightweight, comfortable, and asymmetrically flexible, that is, more elastic perpendicular to the ribs than along them, as shown in Supplementary Video [20]. When inflated, the haptic muscle will inflate around the user's finger more than along it, allowing us to apply greater kinesthetic forces with lower pressures.

Adding silicone makes the fabric air-tight for pneumatic actuation, and also allows us to add stiffness to the material. The added stiffness allows us to tune the haptic muscle to be elastic enough for comfort, but stiff enough to react to very small changes in input pressure. This ensures the end user will be able to detect minute changes in force during teleoperation. In the next sections, we choose a suitable silicone for this purpose.

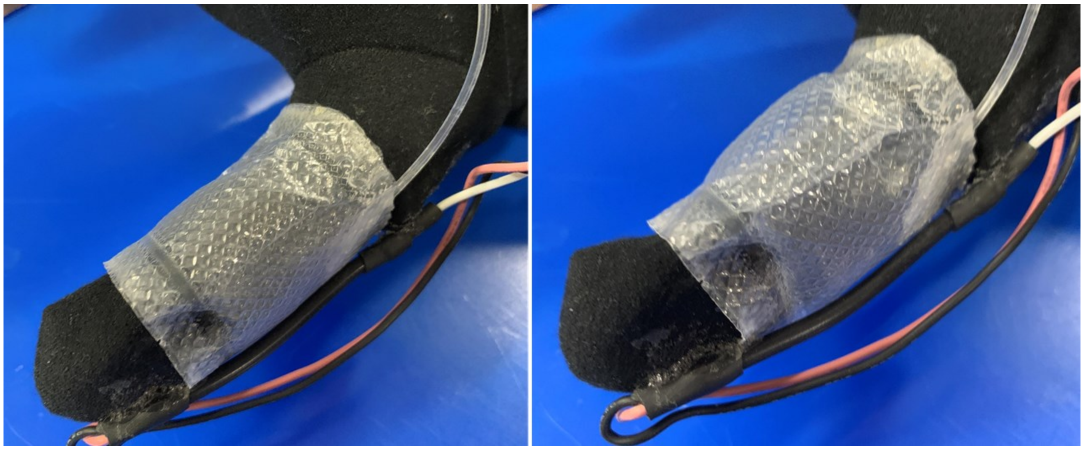

Figure 1: Initial prototypes of haptic muscles fabricated using heat-sealable plastic deflated (left) and inflated (right).

2.3 Fabrication Process

Constructing haptic muscles from a fabric-silicone composite is a multi-step process that involves applying silicone to the fabric, layering it into a pouch, then rolling the pouch into a toroid that fits around the finger. The specific steps are as follows, and are shown in Fig 2.

(1) Laser-cut the fabric into two isosceles trapezoids. When rolled into a toroid, the taper allows the haptic muscle to fit snugly around the users' finger rather than fitting loosely at the fingertip. We measured the length and circumference of a diverse range of peoples' fingers and averaged them to get our final measurements. (Fig 2A)
(2) Coat both sides of each fabric trapezoid with silicone (either Ecoflex 0030 or Dragonskin 10). We placed the fabric in 3D-printed molds before pouring the silicone to minimize leakage. (Fig 2B-C) When using Ecoflex 0030, we placed the fabric-silicone pieces in a vacuum chamber to de-gas the silicone.
(3) After curing the silicone, place a 3D-printed mask (black) to cover the edges of each trapezoid and apply mold release (Ease Release 200 from Mann). The mask ensures that when the two halves are attached together in the next steps, only the edges are sealed, forming an air-tight pouch. (Fig 2D)
(4) Remove the mask, and pour silicone around the perimeter of one fabric-silicone trapezoid. Lay the second trapezoid on the first. (Fig 2E)
(5) After curing, remove the pouch from the mold and pierce a tube through the perimeter to allow for air intake. Apply silicone sealer as required to ensure that the pouch remains air-tight. (Fig 2F)
(6) Roll the pouch into a toroid and sew the two edges together. (Fig 2G)

The finished haptic muscle is shown in Fig 3, both deflated and inflated. A full inflation cycle is shown in Supplementary Video [20].

3 MATERIAL SELECTION EXPERIMENTS

We chose a suitable silicone for the haptic muscles by constructing two versions using two standard silicone types of different stiffnesses (Ecoflex 0030 and DragonSkin 10) and conducting isolated user and pressure response tests. We also included the older haptic muscle design, constructed from heat-sealable plastic, as a control. We performed these tests on all three haptic muscles to gauge their sensitivity, transient pressure response, and controllability.

3.1 User Sensitivity Tests

We designed user tests to quantify the sensitivity and accuracy of each haptic muscle. We define "sensitivity" as the smallest change in pressure a user can accurately detect while wearing a haptic muscle. We define "accuracy" as the user's ability to distinguish between different set pressures. These tests show how well each haptic muscle communicates pressure levels and pressure changes to users, thus proving their ability to communicate grasp quality and force in a teleoperation context.

We performed two user tests on 16 users to determine haptic muscle sensitivity. We chose users who had no prior experience with haptic devices. In each test, we had users wear one haptic muscle on one finger, close their eyes, and wear headphones to block the sound of the pneumatic valves. In each of the tests, we inflated and deflated the haptic muscle in a particular pattern by varying the PWM duty cycle input of the pneumatic valve controlling the muscle. The tests were respectively dubbed the "Minimal Detectable Change (MDC) Test", and "Presure Identification (PI) Test". Because we were testing haptic muscles of varying materials, and each haptic muscle could withstand a different maximum pressure, we designed the tests around PWM input rather than total pressure input. However, we report the results based on absolute pressure input in kPa.

We created the "Minimal Detectable Change (MDC) Test" to quantify the smallest change in haptic feedback a user could feel when the muscle was already inflated. We began the test at a 40% PWM duty cycle (the haptic muscle partially inflated), then increased the input by 5% for one second before dropping back to 40% for one second. We then increased the pressure by an additional

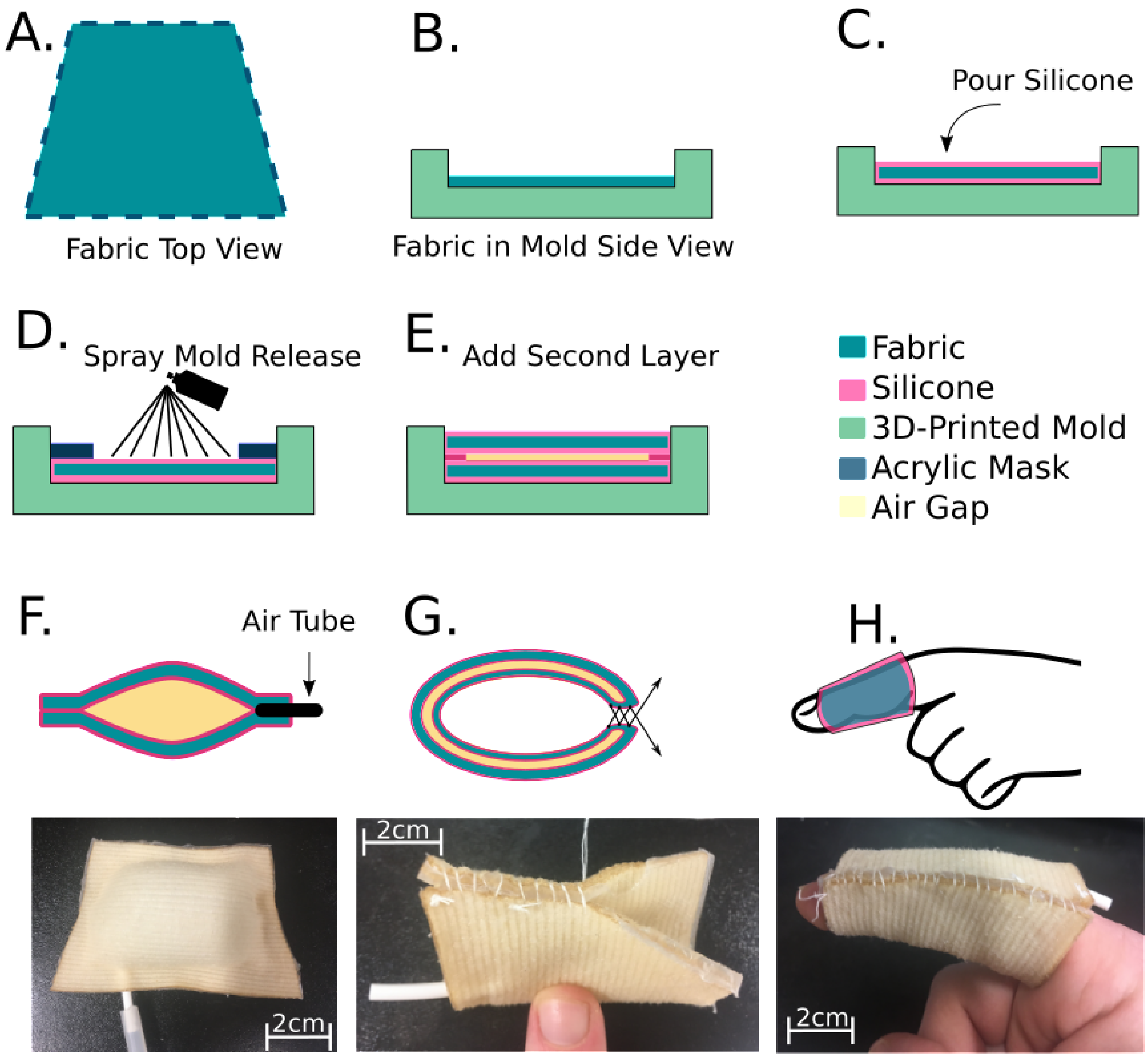

Figure 2: The manufacturing process to construct one haptic muscle. We coat a trapezoid-shaped piece of fabric with silicone (A-C), spray mold release in the center (D), and add another fabric-silicone piece to create a pouch (E). After inserting an air tube (F), we sew the pouch into a toroid (G).

5%, then repeated the process, dropping back to 40% each time. The input was thus 40%, 45%, 40%, 50%, and so on. We continued this pattern until a user verbally indicated that they noticed the increase in pressure. We repeated this process three times per haptic muscle for a total of 9 tests, and recorded the minimum detected pressure change as a percent duty cycle. Users were allowed to take as many breaks as required for them to stay sensitized to the haptics.

The "Pressure Identification (PI) Test" was a general accuracy test where users had to identify different inflation levels with very little training. We chose 4 evenly spaced inflation levels within the working range of the actuator, between 20% and 100% duty cycle. After allowing the users 2 minutes to get a feel for the different inflation levels, we began the test. We randomly switched between the 4 inflation levels and had the users identify which level they were feeling. We repeated this 12 times for each haptic muscle, for a total of 36 tests, and recorded each user's accuracy for each haptic muscle. Again, each user was allowed rest time when required.

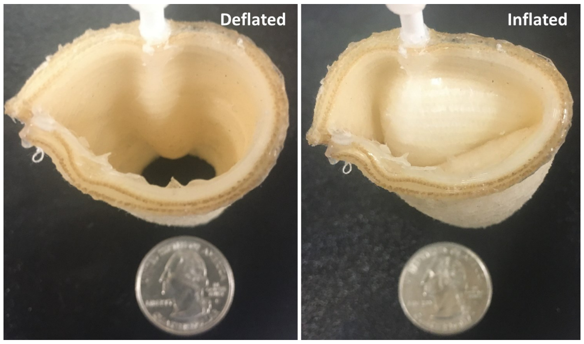

Figure 3: A complete fabric-silicone haptic muscle deflated (left) and inflated (right).

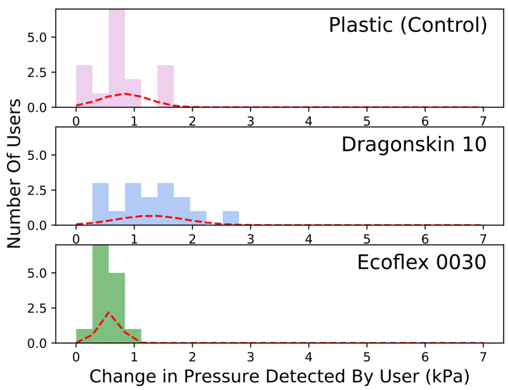

Figure 4: User results for the "MDC Test", indicated the change in pressure detected for all three haptic muscles. The haptic muscle made with Ecoflex has the highest sensitivity with the lowest variance.

After performing these tests, we also asked each user to rank the three haptic muscles from most to least comfortable overall.

The results of the tests described above are shown in Table 1. The MDC Test results are shown as the minimum change in pressure the users could detect in kPa. The PI Test results are user accuracy, and the User Comfort results are an average ranking across all users. Because the MDC Test results were the most conclusive, we also show a histogram of the user results with fitted normal curves in Fig 4. The heat-sealable plastic muscles scored fairly low, quantifying the previous feedback we received that they were uncomfortable and provided very binary haptics, where one pressure was indistinguishable from another. The Dragonskin-based muscles scored similarly, potentially because Dragonskin10 is a very stiff silicone. Though relatively comfortable, Dragonskin10 was too stiff to apply accurate and detectable pressures to users' fingers. In contrast, the Ecoflex0030 haptic muscles scored highly on comfort, accuracy, and sensitivity.

Table 1: Haptic Muscle Sensitivity Test Results

Test		Heat Sealed Plastic	Ecoflex 0030	Dragonskin 10
MDC Test (kPa)	Mean	0.83	0.56	1.29
	Std Dev	0.41	0.18	0.59
PI Test (accuracy)	Mean	54%	68%	51%
	Std Dev	23%	6%	22%
User Comfort (rank)		3	1	2

3.2 Transient Pressure Characterization

In order to characterize haptic muscle actuation, and to calculate the time lag in haptic feedback, we characterized each haptic muscles' pressure response. We attached each muscle to a pneumatic valve, then changed the PWM input to the pneumatic valve from 0% to 100% duty cycle. We recorded the internal pressure of the muscle using a pressure sensor inserted into the air pouch (Adafruit MPRLS Ported Pressure Sensor) as shown in Fig 5. Note that the initial pressure response is different for all three materials, because of the difference in stiffness and how much input pressure is required to begin inflating each structure.

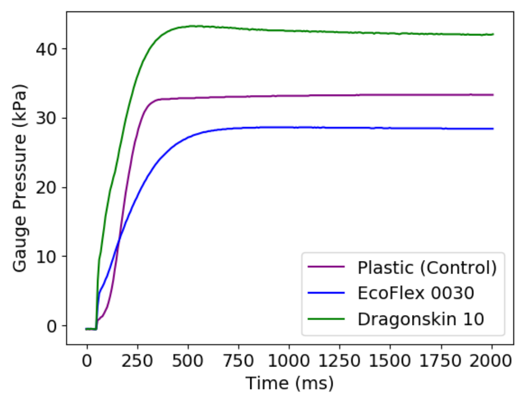

Figure 5: The transient pressure response of three haptic muscles to immediate (step) full inflation input.

To calculate the latency, we find the time it takes for each haptic muscle to reach a detectable pressure. That is, we use the results from the previous user tests to find the lowest detectable inflation point, and find the time to reach that point. The Ecoflex and Dragonskin haptic muscles both reach a detectable pressure in 63ms, while the plastic haptic muscle reaches its detectable pressure in 133ms. It has been shown that humans can only sense a haptic feed-back delay over 61ms [4]. Therefore, the Ecoflex and Dragonskin actuators will provide haptic feedback with no perceptible delay. The plastic ones, however, have a perceptible delay that our users noticed during testing.

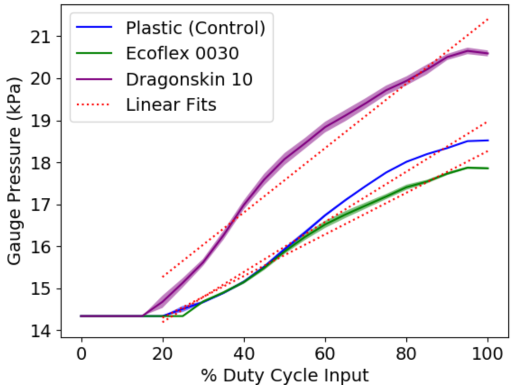

Figure 6: The duty cycle vs pressure plot for all three haptic muscles, as well as one standard deviation and linear fits. This confirms that the relationship between our input and resulting pressure are approximately linear after an initial duty cycle offset.

3.3 Duty Cycle and Pressure Relationship

In order to verify that we have direct control over the feedback output by the haptic muscles, we must confirm that the PWM duty cycle input is linearly related to the internal pressure of the haptic muscles. For this test, we incrementally increase the PWM input to the haptic muscles and read the internal pressure as in the previous experiments. We hold each pressure increment for one second. After five cycles of testing, we show the average pressure reading from each increment, as well as standard deviations (Fig 6). Note that the x-axis is "% Duty Cycle Input", that is, percent inflated, because each haptic muscle can withstand a different maximum pressure.

Each haptic muscle has a small dead-zone from 0%-20% duty cycle where there is not enough airflow to begin inflation. In teleoperation contexts we would work solely in the 20%-100% duty cycle range.

3.4 Material Selection Results

In the user tests, we found that the fabric-silicone haptic muscle made with Ecoflex0030 was the most effective. Not only did it allow users to detect the smallest changes in pressure (3.3% duty cycle), it also allowed for the most accuracy in the Identification Test and was the most comfortable. We believe that this is because the Ecoflex0030 provides a good balance of extensibility and stiffness. The Ecoflex0030 haptic muscle also behaved fairly linearly and had a fast enough pressure response for teleoperation. Therefore, from the perspective of sensitivity, accuracy, and comfort, we can say that the Ecoflex0030 is a clear improvement on the heat-sealable plastic haptic muscles.

4 PERFORMANCE TESTS

To further quantify the difference between the plastic haptic muscle and Ecoflex0030 haptic muscle, we run several performance tests to gauge their force outputs and usability in a teleoperation context.

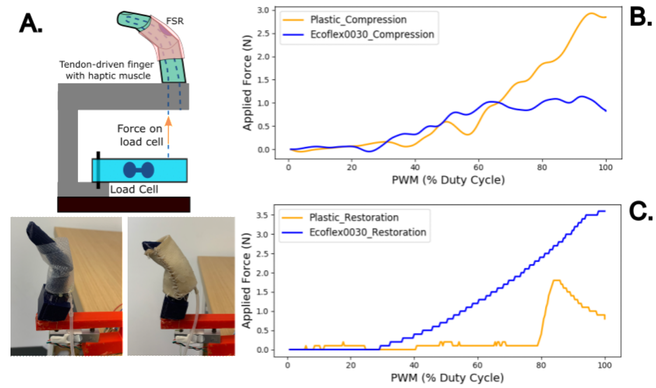

Figure 7: (a) The setup to track compression forces and restoration forces while inflating the plastic (bottom left) and Ecoflex0030 (bottom right) haptic muscle. It consists of a tendon-driven 3D-printed finger, a force-sensitive resistor (FSR) to track compression, and a load cell to track restoration force. (b) The results of the compression tests for both haptic muscles. (c) The results of the restoration tests for both haptic muscles.

4.1 Force Output Experiment

The two forces a user experiences with the haptic muscles are a compression force and a restoration force. The compression force squeezes the user's fingers and conveys a contact force, and the restoration force is what keeps the user's fingers open, conveying a grasp force. Ideally, the compression force should plateau fairly quickly, ensuring that the force is observable but not uncomfortable. The restoration force should be larger than the compression force because the user's fingers should be noticeably straightened for the grasp force sensation to feel realistic. Additionally the restoration force should be linear so we can control the amount of grasp force the user feels.

To track both compression and restoration force, we placed a haptic muscle on a 3D-printed 3-jointed tendon-driven finger, as shown in Fig 7a. The finger closes when we pull on the palmar tendon and opens with the dorsal tendon. We mounted a force-sensitive resistor (FSR) on the finger, fixed the dorsal tendon to a mount, then attached the palmar tendon to a load cell. During inflation, the haptic muscle compresses the FSR and attempts to open the finger, pulling on the palmar tendon and, in turn, the load cell. This gives us simultaneous compression and restoration forces as we slowly inflate the haptic muscle.

The results for the compression test are shown in Fig 7b. We observe that all forces are well within the pain tolerance threshold of 17N for human fingers [5]. The EcoFlex0030 haptic muscle saturates fairly quickly, providing the ideal binary feedback to communicate contact forces. The plastic muscle has a consistently increasing compression response which is higher than its restoration force.

The results for the restoration test are shown in Fig 7c. The Ecoflex0030 haptic muscle provides a restoration force that is linearly related to the PWM input, except for a dead zone which we do not operate in. Additionally, the restoration force is reasonably high, which means the user will actually experience this force during teleoperation. The plastic haptic muscle, however, shows uneven restoration forces during inflation. This uneven force application is because the plastic haptic muscle buckles at the finger joint. The buckle prevents air from reaching beyond the joint for 80% of the inflation, and only the bottom half of the haptic muscle is inflated, which does not apply any restoration force to the finger. At the 80% mark, the air breaks through the buckling and fills the rest of the haptic muscle. We observe a sudden increase in restoration force, and then a decrease as the available air fills a larger pocket. Additionally, the maximum restoration force applied is only 1.5N as compared to the 3.5N applied by the Ecoflex0030 haptic muscle.

These results quantify our previous users' observations that the plastic haptic muscles feel binary and uncomfortable during teleoperation tasks. Because the Ecoflex0030 haptic muscles have a more linear restoration response and a lower compression response, they are more controllable and comfortable. We verify this in the next section with a comparative teleoperation-related user study.

4.2 Teleoperation-Related User Tests

To test the new haptic muscles in a full teleoperation context, we integrated them into a teleoperation system consisting of a commercial robotic arm (Kinova Gen3), a commercial 2-fingered gripper (Robotiq 2F-85) with force sensors on the fingers, and the motion capture system presented in [12], with a data glove and inertial measurement units (IMUs). We placed the haptic muscles on the user's hand over the data glove. Users wore noise cancelling headphones to block the sound of the solenoid valves.

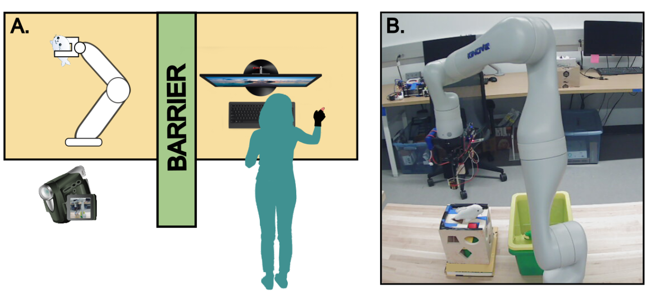

Figure 8: User test setup simulating remote teleoperation with a robotic arm and gripper. (a) The setup includes a camera pointing at the robot with the video fed to the monitor, and a barrier to prevent the user from seeing the physical robot. The user wears a data glove with haptic muscles and controls the arm with the glove and a keyboard. (b) The user watches a monitor which streams live video of the robot arm.

We ran one user test with 10 novice users, and one pilot study with an expert user.

4.3 Novice Teleoperation Study

Robot arm teleoperation is a complex problem with many variables. To focus on the interaction between the force sensors and haptic feedback mechanism, we designed a simpler pick and place test for novice users. Users wore the data glove and were able to open and close their hand to control the robotic gripper. Rather than controlling the robotic arm with IMUs, they were also given a computer keyboard which sent the robotic arm to pre-programmed positions for a pick-and-place task. To remove variables related to visual feedback, we blocked the users' view of the physical robot and instead showed them a monitor with a live feed from a camera facing the robot. The user test setup and the users' view are shown in Fig 8. Their task was to pick and place a small soft toy, and we instructed users to be as gentle as possible with the toy.

The sequence was as follows: 1) the user pressed a button to move the arm from its "home" position to hover over the soft toy, 2) the user closed their hand (thus closing the gripper) until they were confident that they had grasped the toy 3) the user pressed the button to send the arm to a position over a bin and 4) the user opened their hand, causing the gripper to drop the toy into the bin. They completed this task with no haptic feedback, while wearing the plastic haptic muscles presented in the previous paper, and while wearing the Ecoflex0030 haptic muscles presented in this paper.

After practicing twice in each scenario, users performed the pick and place task 5 times with each type of feedback, for a total of 15 tests. During the tests we kept track of how many times they dropped the soft toy. After each set of 5 tests, we asked users to rate how challenging it was to handle the soft toy delicately, from 0 (not at all challenging) to 10 (extremely challenging).

We synthesized the pick and place results by calculating the maximum force applied during each attempt by averaging the highest 10 force readings. We then took an average of maximum force readings across all users for each scenario. We also averaged their ratings from the user experience questions. The results of these user tests are shown in Table 2.

Without haptic feedback, a user only has visual cues about whether the object they are handling is deforming or not, which are not suficient. With haptic feedback, users are able to first detect contact, then gauge whether the grasp strength is suficient to transport the object without dropping or damaging it. One novice user stated that the silicone-based haptic muscles allowed them to more accurately gauge how hard they were grasping the soft toy because "the sensation was more linearly related to the amount I was squishing it". These user tests demonstrate that that the new sensitivity gained from the re-design of the haptic muscles greatly improves the teleoperation experience as well as the capabilities of the teleoperation system. They also emphasize the results of the previous force output experiments that showed the plastic haptics to be too binary to allow for fragile object handling during teleoperation.

4.4 Expert Teleoperation Study

As a final study to show the potential of the new haptic muscles in a full teleoperation setting, we ran a pilot test with an expert user who has trained on the teleoperation system for several hours. They used the system, including full control of the robotic arm and gripper, to pick and place soft baked fruit bars (Kellogg's Nutrigrain). The fruit bars were particularly fragile and brittle, prone to cracking and deforming during even normal handling. The expert performed this task with no haptic feedback and while wearing the Ecoflex0030 haptic muscles. They completed 3 tests in each scenario, for a total

Table 2: Novice Teleoperation Test Results

	Avg Max Force	Number of Drops (Total)	Avg Challenge Rating
Without Haptics	0.947 N	6	6.2
Plastic Haptic Muscles	0.698 N	3	5.1
Ecoflex0030 Haptic Muscles	0.457 N	0	4.7

of 6 tests. A subset of test runs is shown in Supplementary Video [20].

As above, we calculated the average maximum force applied across all attempts, and the results are shown in Table X. Two representative plots of the expert test are shown in Fig 9. The expert user applied on average 58% less force given haptic feedback, and this was reflected in the state of the fruit bars after testing. The attempts with haptic feedback resulted in intact fruit bars with little to no damage, while all attempts without feedback and with plastic haptic muscles resulted in deformed or entirely broken bars. The more sensitive haptic muscles allowed the user to adjust their grasp to keep hold of the fruit bar (Fig 9b). These preliminary results are very promising, and we will continue to explore the capabilities of the Ecoflex0030 haptic muscles with more expert users in future work.

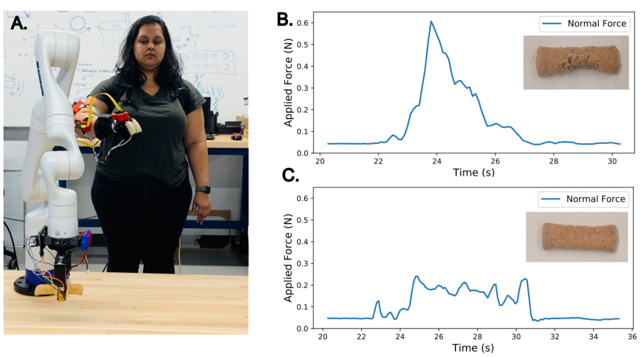

Figure 9: Teleoperation experiment to pick and place a soft fruit bar by an experienced user: (a) without haptic feedback and (b) with haptic feedback. The plots show normal force applied during the task, as well as the state of the fruit bar at the end of the attempt.

5 CONCLUSION AND FUTURE WORK

In this paper, we discussed the development and testing of an improved soft haptic feedback actuator. We constructed the actuators from a fabric-silicone composite with anisotropic stiffness, allowing us to apply a large range of haptic feedback levels while maintaining safety and comfort. We demonstrated the transient pressure response of three haptic muscles made of different materials, tracked their force output when inflated, and performed user tests with novice users to choose the best material. Our choice, fabric combined with Ecoflex 0030, was based on haptic muscle sensitivity and comfort. We found that the added sensitivity provided by these haptic muscles enabled users to handle fragile objects more delicately during simple teleoperation tasks. Novice users applied on average 35% less force during teleoperation using the fabric-silicone haptic muscles than with the plastic haptic muscles, and 52% less force compared to having no haptic feedback. Our pilot study shows that, with practice, the haptic muscles allow users to perform very delicate pick-and-place tasks using our full teleoperation system.

There are several avenues for the future of this research. Exploring various fabrics was out of the scope of this paper, but a more elastic fabric with greater anisotropic properties could increase the range and sensitivity of haptic feedback. Finally, we leave more detailed analysis of the teleoperation system itself, including further user tests with several objects and a larger expert user group, for future work.

The data glove using our new fabric-silicone actuators allowed users to detect minute changes in the state of grasped objects. We would like to utilize this intuitive connection between the user and a teleoperated robotic arm to collect detailed data on grasping and object manipulation, creating an effective data set to train robotic systems to autonomously perform complicated tasks.

ACKNOWLEDGMENTS

Our user studies were approved by our institution's review board, under protocol IRB-19-0122. Please find accompanying video here.

REFERENCES

[1] R Boboc, H Moga, and D Talaba. 2012. A REVIEW OF CURRENT APPLICATIONS IN TELEOPERATION OF MOBILE ROBOTS. Bulletin of the Transilvania University of Brasov 5, 2 (2012), 9,9. http://search.proquest.com/docview/1506343930/

[2] A. Bolopion and S. Régnier. 2013. A Review of Haptic Feedback Teleoperation Systems for Micromanipulation and Microassembly. IEEE Transactions on Automation Science and Engineering 10, 3 (July 2013), 496–502. https://doi.org/10.1109/TASE.2013.2245122

[3] James M. Caldwell, Michael R. Lubitz, and Eric J. Ruston. 1985. Silicone coated fabric. https://patents.google.com/patent/US4666765A/en US Patent 4,666,765 A.

[4] Andrew J. Doxon, David E. Johnson, Hong Z. Tan, and William R. Provancher. 2013. Human Detection and Discrimination of Tactile Repeatability, Mechanical Backlash, and Temporal Delay in a Combined Tactile-Kinesthetic Haptic Display System. IEEE Transactions on Haptics 6, 4 (2013), 453–463. https://doi.org/10.1109/TOH.2013.50

[5] Ayse Edeer, Zeliha Tulum, Lamia Pinar, and Ferdi Başkurt. 2005. Comparison of Pressure Pain Threshold, Grip Strength, Dexterity and Touch Pressure of Dominant and Non-Dominant Hands within and Between Right- and Left-Handed Subjects. Journal of Korean medical science 19 (01 2005), 874–8. https://doi.org/10.3346/jkms.2004.19.6.874

[6] Alex Ellery. 2000. An introduction to space robotics. Springer, London ;.

[7] A. Frisoli, M. Solazzi, F. Salsedo, and M. Bergamasco. 2008. A Fingertip Haptic Display for Improving Curvature Discrimination. PRESENCE: Teleoperators and Virtual Environments 17 (2008), 550–561.

[8] Kouhei Fujimoto, Futoshi Kobayashi, Hiroyuki Nakamoto, and Fumio Kojima. 2013. Development of haptic device for five-fingered robot hand teleoperation. System Integration (SII), 2013 IEEE/SICE International Symposium on, 820,825.

[9] Barclay Jumet, Zane A. Zook, Doris Xu, Nathaniel Fino, Anoop Rajappan, Mark W. Schara, Jeffrey Berning, Nicolas Escobar, Marcia K. O'Malley, and Daniel J. Preston. 2022. A Textile-Based Approach to Wearable Haptic Devices. In 2022 IEEE 5th

International Conference on Soft Robotics (RoboSoft). 741–746. https://doi.org/10.1109/RoboSoft54090.2022.9762149

[10] R. P. Khurshid, N. T. Fitter, E. A. Fedalei, and K. J. Kuchenbecker. 2017. Effects of Grip-Force, Contact, and Acceleration Feedback on a Teleoperated Pick-and-Place Task. IEEE Transactions on Haptics 10, 1 (Jan 2017), 40–53. https://doi.org/10.1109/TOH.2016.2573301

[11] The Lancet. 2020. Covid-19: Protecting health-care workers. The Lancet 395, 10228 (Mar 2020), 922. https://doi.org/10.1016/s0140-6736(20)30644-9

[12] S. Li, R. Rameshwar, A. M. Votta, and C. D. Onal. 2019. Intuitive Control of a Robotic Arm and Hand System With Pneumatic Haptic Feedback. IEEE Robotics and Automation Letters 4, 4 (Oct 2019), 4424–4430. https://doi.org/10.1109/LRA.2019.2937483

[13] X. Liang, H. K. Yap, J. Guo, R. C. H. Yeow, Y. Sun, and C. K. Chui. 2017. Design and characterization of a novel fabric-based robotic arm for future wearable robot application. In 2017 IEEE International Conference on Robotics and Biomimetics (ROBIO). 367–372. https://doi.org/10.1109/ROBIO.2017.8324445

[14] Wei Sheng Liu and Yuanyuan Li. 2012. The research for control strategies and methods of teleoperation system. World Automation Congress (WAC), 2012, 1,4.

[15] Honghao Lv, Depeng Kong, Gaoyang Pang, Baicun Wang, Zhangwei Yu, Zhibo Pang, and Geng Yang. 2022. GuLiM: A Hybrid Motion Mapping Technique for Teleoperation of Medical Assistive Robot in Combating the COVID-19 Pandemic. IEEE Transactions on Medical Robotics and Bionics 4, 1 (2022), 106–117. https://doi.org/10.1109/TMRB.2022.3146621

[16] Abdeldjallil Naceri, Jean Elsner, Mario Tröbinger, Hamid Sadeghian, Lars Johannsmeier, Florian Voigt, Xiao Chen, Daniela Macari, Christoph Jähne, Maximilian Berlet, Jonas Fuchtmann, Luis Figueredo, Hubertus Feußner, Dirk Wilhelm, and Sami Haddadin. 2022. Tactile Robotic Telemedicine for Safe Remote Diagnostics in Times of Corona: System Design, Feasibility and Usability Study. IEEE Robotics and Automation Letters 7, 4 (2022), 10296–10303. https://doi.org/10.1109/LRA.2022.3191563

[17] Elango Natarajan and Ahmad Athif Mohd Faudzi. 2015. A review article: Investigations on soft materials for soft robot manipulations. The International Journal of Advanced Manufacturing Technology 80 (04 2015). https://doi.org/10.1007/s00170-015-7085-3

[18] Elango Natarajan, Ahmad Athif Mohd Faudzi, Azman Hassan, and Muhammad Razif. 2014. Experimental investigations of skin-like material and computation of its material properties. International Journal of Precision Engineering and Manufacturing 15 (09 2014), 1909–1914. https://doi.org/10.1007/s12541-014-0545-0

[19] Janko Petereit, Jürgen Beyerer, Tamim Asfour, Sascha Gentes, Björn Hein, Uwe D. Hanebeck, Frank Kirchner, Rüdiger Dillmann, Hans Heinrich Götting, Martin Weiser, Michael Gustmann, and Thomas Egloffstein. 2019. ROBDEKON: Robotic Systems for Decontamination in Hazardous Environments. In 2019 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR). 249–255. https://doi.org/10.1109/SSRR.2019.8848969

[20] Raagini Rameshwar. 2023. Fabric-Silicone Composite Haptic Muscles for Sensitive Wearable Force Feedback - Accompanying Video. https://raw.githubusercontent.com/RRameshwar/TeleoperationVideos/main/PETRA_Teleop_AccompanyingVideo.mp4.

[21] Yunlong Shi, Liang Wang, Wenhuan Zhang, and Xiaoming Qian. 2018. Thermal and Wet Comfort of Fabrics Based on Fractal Dimension of Silicone Coating. Journal of Engineered Fibers and Fabrics 13, 1 (2018), 155892501801300102. https://doi.org/10.1177/155892501801300102 arXiv:https://doi.org/10.1177/155892501801300102

[22] Erik Skorina, Raagini Rameshwar, Saraj Pirasmepulkul, Tri K Khuu, Alexander Caracappa, Peerapat Luxsuwong, Ming Luo, William R Michalson, and Cagdas Onal. 2018. Soft Robotic Glove System for Wearable Haptic Teleoperation. In Wastewater Management Symposium. Phoenix, Arizona.

[23] Y. Sun, Y. S. Song, and J. Paik. 2013. Characterization of silicone rubber based soft pneumatic actuators. In 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems. 4446–4453. https://doi.org/10.1109/IROS.2013.6696995

[24] Sebastiaan Swart, Hannes J. Zietsman, Niel D. Goslett, and Pedro M.S. Monteiro. 2015. Ocean robotics for sustainable, long-range marine resource and ecosystem management in the 21st century : natural environment. 8, 2 (2015), 102,103. http://reference.sabinet.co.za/webx/access/electronic_journals/csir_sci/csir_sci_v8_n2_a50.pdf

[25] Yue Wang, Cherry Gregory, and Mark A. Minor. 2018. Improving Mechanical Properties of Molded Silicone Rubber for Soft Robotics Through Fabric Compositing. Soft Robotics 5, 3 (2018), 272–290. https://doi.org/10.1089/soro.2017.0035 arXiv:https://doi.org/10.1089/soro.2017.0035 PMID: 29649416.

[26] Pinhas Zhou Ma and Pinhas Ben-Tzvi. 2015. RML Glove; An Exoskeleton Glove Mechanism With Haptics Feedback. Mechatronics, IEEE/ASME Transactions on 20, 2 (2015), 641,652.