GENERAL SYMPOSIA | POLYMER COMPOSITES

Braided Composite System with Haptic Feedback for Teleoperation

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Abstract: A pneumatic-driven soft robotic actuator made from braided nylon coated with silicone elastomer was created using a new fabrication process, with the aim of providing haptic feedback to the fingers in teleoperation applications. The resulting haptic actuator was designed to be flexible, lightweight, and wearable, offering a comfortable user experience. Through the manipulation of the braiding angle, multiple devices were fabricated, focusing on their effectiveness in transmitting haptic sensations to the user's finger.

Keywords: Braided Composites, Haptic Glove, Silicone Matrix, Pneumatic Subsystem

Introduction

Wearable haptic interfaces have been explored for various applications, including teleoperation, virtual reality, healthcare, human-computer interaction, and more [1,2]. When remotely performing teleoperation tasks under unpredictable or non-repetitive conditions, relying solely on visual feedback is not sufficient. Therefore, the presence of haptic feedback becomes crucial, allowing humans to effectively control a robot from a distance and also ensuring operator safety [3].

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Significant efforts have been dedicated to advancing pneumatic-operated systems for haptic feedback, which provides important advantages such as high power-to-weight ratio and increased safety [4,5]. S. Li et al. [3] introduced a haptic glove composed of pneumatic actuators fabricated from heat-sealable plastic. These actuators were rolled into a toroid shape, enabling them to encircle the user's fingers. When inflated, these actuators effectively conveyed the sensation of grasp force. However, the sealed plastic system exhibited wrinkling, suggesting potential for refinement through the adoption of alternative materials. After this work, Rameshwar et al. [6] developed a device constructed from a fabric-silicone composite configured in a toroidal shape. The fabric-silicone composite showed a 35% reduction in applied force during teleoperation compared to the plastic-sealed device, facilitating the manipulation of delicate objects with increased finesse. In addition, the use of a fabric-silicone composite addressed the plastic-like tactile sensation experienced by users with the sealable plastic device. However, the fabric-silicone device developed by Rameshwar et al. showed considerable thickness, had a visible stitch line, and the manufacturing process lacked scalability. The fabric-silicone composite was a promising option for finger-based devices, offering the potential to enhance haptic feedback sensitivity, but further research on alternative fabric types and designs, as well as alternative manufacturing techniques that are less reliant on manual labor, is an exciting opportunity.

Braided composites in the form of elastomer-coated fibers are of particular interest, as they allow for the customization of mechanical properties, as well as flexibility in design [7]. Elastomer braided composites offer impermeability to air and superior foldability, making them remarkably suitable for use in a pneumatic finger-based devices [8].

In this work, an industrially relevant process is presented for the manufacturing of a pneumatic-driven soft robotic actuator from braided nylon coated with a silicone elastomer. The nylon structure was manufactured using a braiding machine that wove the yarns in a circular pattern at different angles and subsequently impregnated them with a silicone elastomer matrix. The resulting pneumatic finger-based haptic device was specifically designed to encase the knuckles of a hand and facilitate the transfer of forces perceived in a robotic hand to the user's own fingers, with the aim of achieving a more sensitive, highly immersive, and realistic teleoperation experience. By investigating a range of braiding angles, this work explored how the braiding structure influences the effectiveness of haptic sensation transmission to the user's finger.

Material, Design, and Fabrication

This study used bonded nylon thread #69 (SGT.KNOTS) for the fiber material. The elastomeric matrix material consisted of a silicone elastomer (DOW DOWSIL 92-009 Dispersion Coating Clear, manufactured by Dow Inc.). According to the supplier specifications, the silicone was diluted with thinner (Varnish Maker and Painter's Naphtha, manufactured by Klean-Strip) in a ratio of 4 parts thinner to 3 parts silicone (v/v). To determine the diameter of the braided tubular structures, rigid

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Teflon rods with diameters of 25.4 mm and 22.2 mm were used. The nylon-silicone pneumatic actuator consisted of two composite tubes of different diameters stacked together and sealed at the ends, forming an inner bladder between them. This bladder was pressurized via a small 3 mm polyurethane tube, which was connected to one end of the actuator to deliver air, as shown in Figure 1.

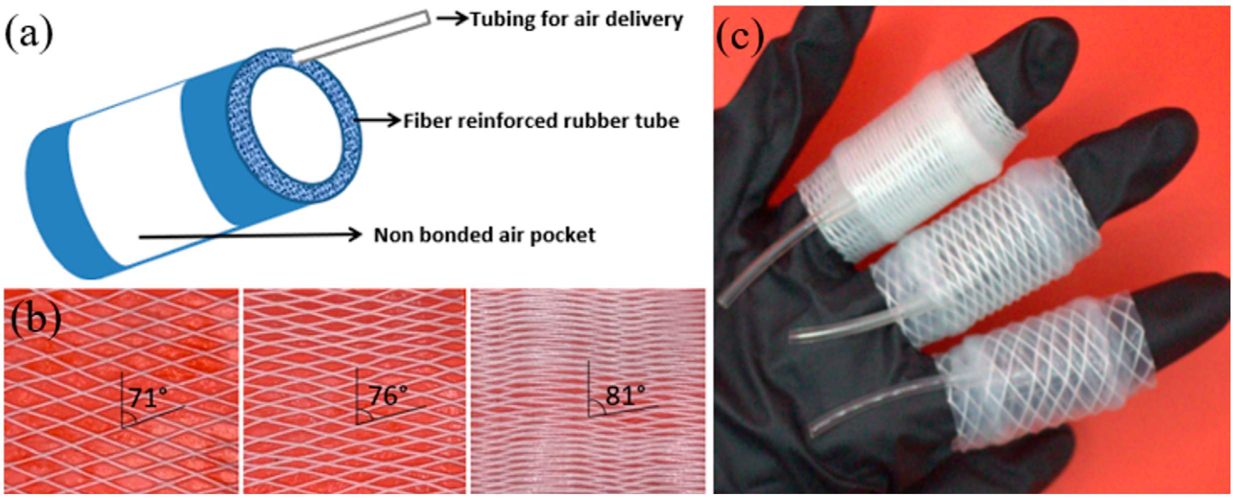

Figure 1. Nylon-silicone pneumatic actuators, (a) conceptual design with an inner pneumatic subsystem, (b) nylon structure coated with silicone elastomer with variations in braiding angles, (c) actuators with different braiding angles.

Fabrication Method

The manufacturing process of the nylon-silicone pneumatic actuator involved four stages, as described below.

Braiding

Nylon tubular structures of two different diameters were braided using a HERZOG braiding machine (model LZ 1/17-80 FZR) equipped with 16 rotating Nylon yarns. The dimensions of each tubular structure were determined using Teflon rods of two different diameters for braiding: 22.2 mm for the inner tubular structure and 25.4 mm for the outer tubular structure. Three braiding angles were systematically evaluated: 71°, 76°, and 81°. The rotational speed of the braider carrier was kept constant at 50 rpm, while the lay length was adjusted to 30 mm, 20 mm, and 10 mm. The resulting braid angles for each condition were measured using the image processing software, ImageJ.

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Coating

The tubular structures mounted on the Teflon rods were impregnated with silicone elastomer solution, while rotating in a custom-built automatic spinner at 30 rpm, forming the elastomeric matrix composite (Figure 1[b]). The coating process was repeated four times. The first three coatings were cured for 30 minutes at room temperature before applying the subsequent coating. The fourth coating was cured for 72 hours at room temperature.

Stacking

The composite with a 25.4 mm diameter was removed from the Teflon tube and trimmed to a length of 3 mm. Similarly, the composite extracted from the Teflon tube with a 22.2 mm diameter was trimmed to a length of 5 mm. Subsequently, the 25.4 mm diameter composite was assembled by sliding it over the 22.2 mm diameter composite. Once precise alignment and stacking of the two tubes were ensured, a polyurethane rubber tube with an internal diameter of 1.8 mm and an outer diameter of 3 mm was inserted between them.

Sealing

The edges of the 3 mm length tubular structure were coated with undiluted silicone while the automatic spinner was in motion, closing the gap between both composites and ensuring the air tube connection. After curing, the assembled structure was extracted from the Teflon tube, resulting in the nylon-silicone pneumatic actuator.

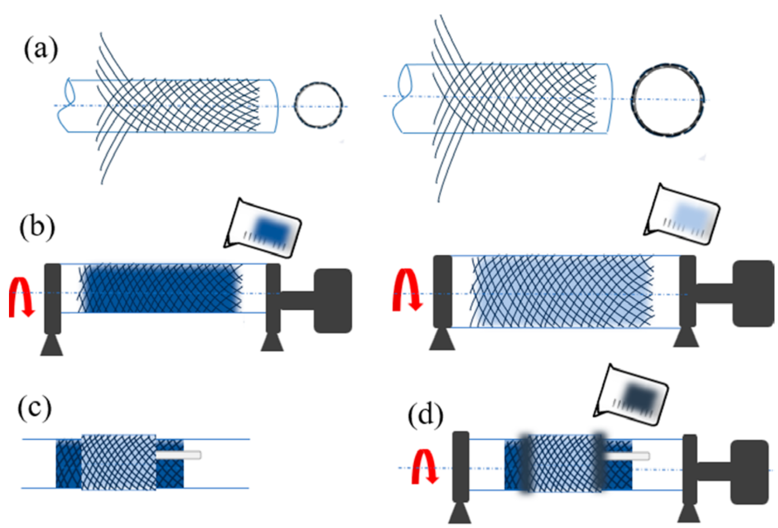

Figure 2. Schematic of the haptic device manufacturing process: (a) braided yarn around Teflon cores of two sizes, (b) braided yarns coated with silicone elastomer solution while placed on automatic spinner, (c) cut and stacked braided composite, and (d) edges coated with non-diluted silicone.

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Experimental

The haptic feedback capability of the nylon-silicone pneumatic actuator was characterized by studying its inflation behavior and force response. During testing, the pressurization of the haptic device was controlled through pneumatic solenoid valves (S070C-VAG-32 manufactured by SMC), actuated by a pulse-width modulation (PWM) signal, which is precisely what regulates the proportion of the source pressure directed through the valve into the haptic device and controls the degree of haptic feedback to the user's finger. Three versions of the nylon-silicone pneumatic actuator with different braiding angles (71°, 76°, and 81°) were tested, as well as one without fiber (only silicone). The experimental procedure was divided into 2 categories: inflation test and force test.

Inflation Test

The inflation test was performed to assess the response of each device to the pressure input and verify control over feedback. The nylon-silicone pneumatic actuators were connected to a pneumatic valve, while placing a digital I^2C interfaced MPRLS pressure sensor into the air pocket to measure the internal pressure. The internal pressure of the devices was monitored under two conditions: first, a stepwise rise in the PWM input and holding each pressure increment for one second and, separately, full inflation input to the pneumatic valve from 0% to 100%.

Force Test

The force response of the nylon-silicone pneumatic actuator was measured using a 3D-printed human-like finger, following a methodology similar to our previous work [6]. The custom-designed device consisted of a tendon-driven finger connected to a load cell and equipped with a flexible sensing resistor (FSR) on the finger. These configurations made it possible to measure the two forces that the user's finger would experience when using the nylon-silicone pneumatic device: compression force and restoration force. The compression force reflects the pressure exerted during contact, detected by the FSR. The restoration force, measured by the load cell, is the resistance keeping the fingers open, while transmitting the grasp of the robotic arm.

Results and Discussion

The nylon-silicone pneumatic actuator created using the braiding manufacturing process weighed less than 5 grams. The device was easy to wear and when pressurized the air pocket inflated to provide haptic feedback to the user's fingers. Direct control over the inflation of the nylon-silicone actuator was verified by observing the linear relationship between the air proportioned by the valve and the pressure registered inside the actuators when subjected to the stepwise rise in the

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PMW input, as depicted in Figure 3(a). These results show it is possible to provide specific haptic feedback to the user through controlled inflation. As shown in Figure 3(a), the actuators did not respond prior to 10% PMW input. After the initial 10%, all actuators showed a linear relationship up to 100% full inflation. The initial 10% is the threshold, where the pressure supplied is sufficient to provide the necessary force for valve opening and to initiate inflation. Within this framework, the nylon-silicone actuators should operate solely within the 10%-100% duty cycle range.

System delays in tactile output under 61 ms are negligible for human users [9]. During the inflation test from 0% to 100%, the nylon-silicone actuators achieved pressures exceeding 10 kPa in less than 61 ms (Figure 1[b]). The minimum detectable pressure, the smallest change a user could perceive with the inflated actuator, is reported to be below 2 kPa [6]. These results indicate that the actuators can provide feedback with virtually no delay.

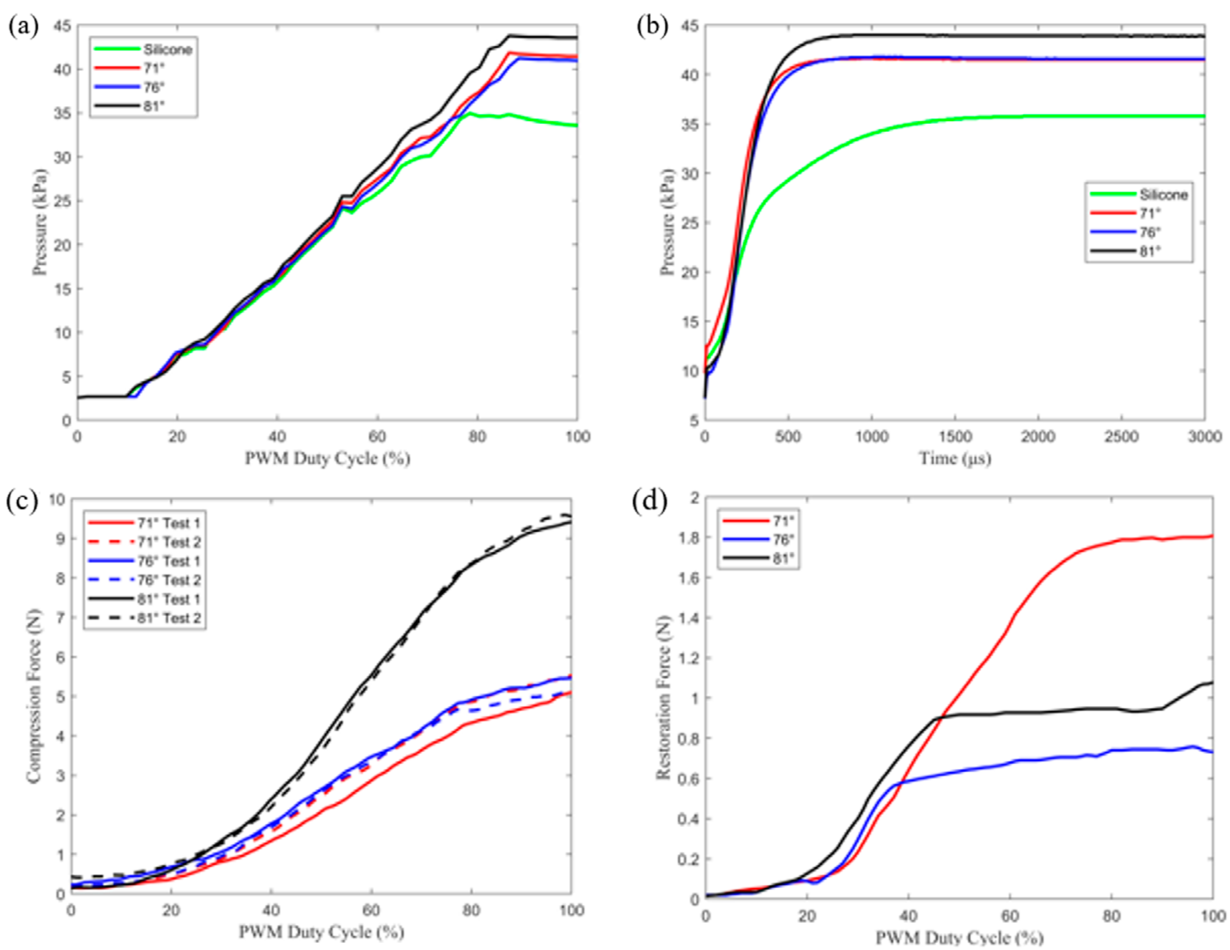

Figure 3. (a) Stepwise pressure rise, (b) Full inflation test results, (c) Compression test, and (d) Restoration test.

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The results for the compression force (Figure 3[c]), or squeezing around the finger, indicated that the maximum pressure registered did not exceed the minimum pressure pain threshold reported by Özcan et al. [10], which is approximately 20 N. The highest compression force, 9.6 ± 0.3 N, was observed with the 81° braiding, followed by the 76° braiding, and lastly the 71° braiding. The results demonstrated that larger braiding angles provided greater applied pressure. This behavior aligns with observations in literature for braided pneumatic systems such as McKibben muscles [11]. Angles closer to 90 degrees mean that the nylon fibers in the composite are more perpendicular to the actuator's length, enhancing force capability in the radial direction. Therefore, greater braiding angles can provide higher haptic feedback forces to the human hand with the designed actuator, allowing the actuators to be tailored for specific applications. It is important to note that the silicone actuators without braiding were not included in the force results, as they were unable to withstand the applied pressure during the tests. This underscores the essential role of fiber reinforcement in ensuring the effective functionality of the designed actuator.

The restoration force results, shown in Figure 3(d), exhibit a linear relationship with air input for the lower braiding angle (71°). However, this relationship was found to be uneven for the samples with higher braiding angles. Throughout this test, the 3D-printed hand undergoes initial flexion, and the inflation of the nylon-silicone actuator facilitates the opening of the hand. Reduced braiding angles, situated nearer to the longitudinal axis, facilitate a higher contraction ratio, empowering the actuator to shorten more noticeably. Moreover, reduced braiding angles and lower fiber density within the composite may promote improved airflow by reducing reinforcement. As a result, smaller braiding angles have demonstrated an increase in restoration force.

Conclusions

A new manufacturing technique has been created for fabricating fiber-reinforced silicone haptic muscles with an integrated pneumatic subsystem that is flexible, lightweight, and wearable. The pneumatic system demonstrates a near-linear correlation between air input and resulting pressure. Moreover, the system's delays in tactile output remain imperceptible to users, remaining below the threshold of human detection. Safety is assured with contact forces kept below 20 N. Evaluation of actuators with varying braiding angles reveals that higher angles yield increased haptic feedback forces, albeit with a less linear relationship to air input compared to lower angles. Thus, braiding angles can be changed to provide optimal performance.

Acknowledgments

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