Soft Robotic Fabric Actuator With Elastic Bands for High Force and Bending Performance in Hand Exoskeletons

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***Abstract*—In current designs soft robotic bending actuators, the need for high force capabilities is not adequately addressed. In this article, we present a new inflatable actuator that exploits textile manufacturing techniques, using an elastic band to improve both bend and force performance. At a pressure of 102 kPa, the index finger sized actuator exerts 24.8 N of force on the environment. It is also capable of a full 360° bending angle for pressures between 30 kPa and 102 kPa with a maximum bending stiffness of 288.4 N/m. We further demonstrate feasibility of this new actuator in a case study of an entirely fabric based soft robotic hand exoskeleton that increases robustness and user comfort. Our results suggest that textile robotics could provide an attractive solution in terms of the development of user-friendly hand exoskeletons.**

***Index Terms*—Prosthetics and exoskeletons, soft robot applications, soft sensors and actuators.**

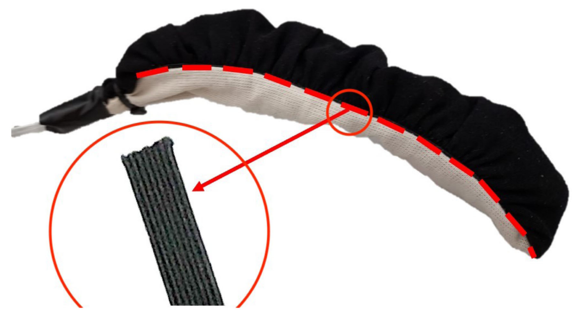

Fig. 1. The here presented novel fabric actuator design with one-way ruffled stretch (black) and integrated elastic band (circled and enlarged).

I. Introduction

In THE rapidly growing field of soft robotics, we have seen novel elastic materials replace heavy metallic links, and soft inflatable actuators being used instead of electromechanical rotational motors [1]. In human-robot interaction, too, using flexible materials has been shown to provide attractive design alternatives due to their safe nature [2]. Despite these obvious advantages, however, the performance of soft inflatable bending actuators (about 10–15 N) cannot keep up with torque output of traditional rotational motors (about 80 N for a medium size DC motor). This reduces their application areas for high force/torque required fields, but provokes new developments and designs for soft robotics, to which we contribute with this letter.

Two of the most common materials used for making soft inflatable bending actuators are silicones and fabrics. Thanks to their soft and flexible, yet sturdy nature, fabric based bending actuators have proven to be a more reliable option, partly due to their ability to exert higher forces than their silicone counterparts [3]. Moreover, these textile structures present a familiar and comfortable interface, that is useful for applications involving humans, including wearables [4]. In regard to manufacturing technologies, fabrics provide a well established, easily accessible wide range of designs and tools, cost-efficient, robust and user-friendly.

Textile qualities are important when designing bending actuators for applications like hand exoskeletons that are used in different areas. For example, they serve as assistive devices for people with motor disabilities, and in rehabilitation for stroke patients, where they need to be capable of repeating flexion and extension movements [5]. In general, soft inflatable bending actuators are commonly used for achieving bending motions for these applications [6]–[8]. But also in the gaming industry, hand exoskeletons have become an increasingly popular product of interest, even more so since the recent announcement of *Meta*'s new haptic virtual reality soft glove prototype [9].

To create bending of an inflatable textile actuator, an imbalance between two layers of fabric must be achieved. Usually this imbalance is created by using pleating techniques [10]. With this method, excess material of one layer is folded and stitched onto the other, and unfolds when inflated. This approach, however, has potential drawbacks, e.g., when the space between the layers is too small for the pleats to unfold (which, for finger sized designs, can become imminent). Another technique to create such imbalance is the use of different types of fabric with varying elasticity [11]. This way, one layer stretches more when actuated and the structure will bend towards the less elastic one. Combining these two methods is possible to enhance bending ability [12], too. Lastly, industrially manufactured bending

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actuators can create excess fabric on one layer only without seams through knitting [13]. When advancing in design engineering aspects, however, compromises are often made in performance.

In this work, we introduce a novel soft actuator design to address existing challenges and propose a technique that originates in the apparel industry (Fig. 1). We present the integration of a braided elastic band to significantly increase bending capability of an already stretchy fabric. With a case study of embedding this actuator in a soft hand exoskeleton, we show that this textile based design yields promising results for both high force required and high bending angle required applications. Achieving realistic kinesthetic feedback and grasping heavy objects can be given for example to these applications. This letter documents the engineering and evaluation of this design and contributes to advancements in the evolving domain of textile robotics.

II. Actuator Design

In soft robotics, textile materials play an increasingly important role. The most common textile surfaces are woven and knitted fabrics. Traditionally, woven fabrics are not elastic, while knitted fabrics show high elasticity in multiple directions, which appears useful when designing bending actuators. On the other hand, wovens are usually more robust and maintain their shape better. A research question that guides the design of a fabric based bending actuator therefore is: how can we achieve a maximally stretchy surface while providing enough robustness for high force applications? Furthermore, another goal was to find a technique to create excess material without putting the fabric into folds, avoiding potential drawbacks of this commonly used technique.

This section outlines the design process, starting with a selection of materials for the engineering of actuators using different methods to achieve bending. Three actuators are made and evaluated against each other, before we present the final, novel actuator design.

A. Materials

For the two layers of the actuator, different textile properties are required:

- The bottom should be non-stretchy and able to compress,
- while the top should be able to expand and guide the bending direction of the actuator, so should be able to stretch maximally—but only in the desired direction.

Taking the intrusive nature of existing exoskeleton actuators into consideration, our design additionally aims to provide wear comfort through soft and not unduly heavy materials.

1) Textile Structures: Under these premises, two woven fabrics are chosen:

- a plain cotton weave for the bottom base of the actuator (light fabric in Figs. 2 and 3), and
- a cotton mix with elastane yarn integrated to the weft of the fabric (dark fabric in Figs. 2 and 3) for the top layer.

Both fabrics are woven in the canvas structure, which by default is non-stretchy, robust, yet maintains a soft touch. With

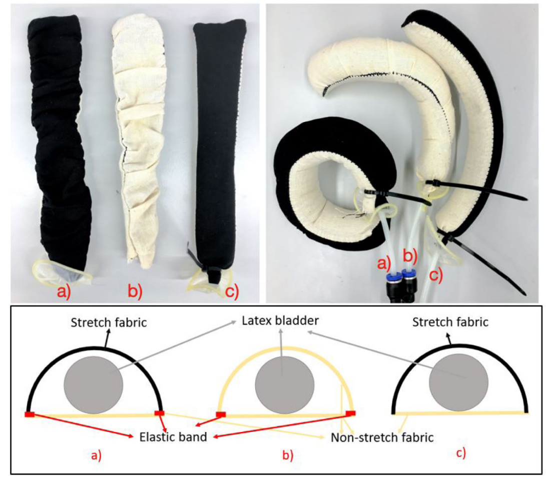

Fig. 2. Actuator designs with different top layers: (a) elastic band and ruffled one-way stretch; (b) elastic band and ruffled non-stretch; (c) one-way stretch only. Unactuated (left), actuated (right), and cross-sectioned (bottom).

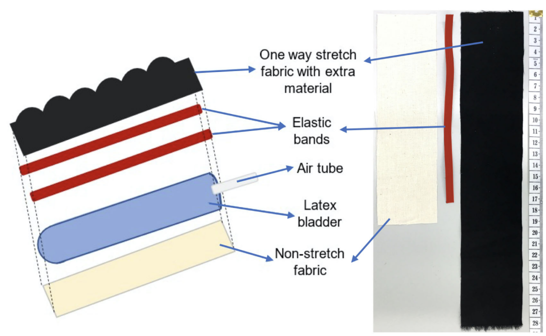

Fig. 3. Assembly specification of the elastic band integrated actuator. Left: order of fabric layering with elastic band attached to stretch fabric, then sewn onto non-stretch cotton, before latex bladder inserted. Right: measurement proportions of cut fabrics with stretch fabric excess length of 1.8.

the added elastane, however, additional stretch in weft direction is produced, enabling mono-directional bending.

2) Elastic Band: To enhance a fabric's stretch behavior and create the desired material imbalance between layers, an additional support material can be used that is integrated when assembling the actuators: an elastic band, also called *elastics*, see Figs. 1 and 3, commonly used in clothing to create ruffles or elastic waistbands. Being a standard method in the textile industry, it has not been employed for the development of textile robotics. It consists of braided polyester and a small part of thin rubber, making it durable and extremely stretchy.

3) Airtightness: To be able to pneumatically inflate the actuator, it must also be airtight, which is hard to achieve in textile structures—especially in stretch ones. Although there are airtight fabrics coated with microfibre films available on the market, when sewing them together with a needle punctures the fabric and it loses its airtightness. In this letter, airtightness is achieved by inserting a commercially available latex bladder between the fabric layers, a simple and popular solution for textile designs (e.g. [13]). Other approaches use *TPU* coated

TABLE I
SPECIFICATIONS OF THE ACTUATORS REFERRING TO FIG. 2

	Bottom layer	Top layer	Excess material
a)	Cotton	One way woven stretch	Elastic band ruffles
b)	Cotton	Cotton	Elastic band ruffles
c)	Cotton	One way woven stretch	No excess material

fabrics that can be welded together, or covering the stitch holes with latex tapes [14].

B. Fabrication of the Actuators

With the two selected fabrics and the haberdashery accessory elastic band, a combination of actuator designs could be produced with the purpose of evaluating the performance of the use of each of the methods and materials mentioned above against each other. To imitate the aimed for application of a hand exoskeleton, finger sized actuators were designed. Rectangular shaped patterns, as shown in Fig. 3(b), are cut in 3×16 cm for the bottom and different lengths for the top layer. When inflated cross-section shape of the actuators change to 2–2.5 cm diameter circles. Cross-section of actuators with extra material on top layer tend to be bigger. The bottom layer is made from the same plain cotton weave across all prototypes. The three different designs are distinguished from each other through their top layers.

1) Top Layer Differences: First, the mono-directional stretch black fabric was cut to the same length as the cotton bottom layer fabric. Both fabrics were sewn together without stretching one or holding together the other, shown in Fig. 2(c). For the second prototype, both layers consisted of the non-elastic cotton weave (Fig. 2(b)). Here, the top layer was cut 80% longer than the bottom one and combined with the elastic band to tame the excess material and create ruffles. Lastly, a combination of the previous two approaches was manufactured, applying the elastic band. This actuator is shown in Fig. 2(a). The top layer is cut to the same length as the second actuator, stretching into the desired bending direction both through the fabric's stretch and the supporting elastic band.

A summary of the different combinations of design parameters is listed in Table I. Comparing these three, we expect to see how elastic bands and stretch fabrics enhance (or worsen) the abilities of textile actuators.

2) Elastics Integration: The elastic band was integrated on the side seam between the top and bottom layer, first stitched onto the excess fabric of the top layer (marked red in Fig. 1) while being stretched, and then sewn onto the bottom layer in a relaxed state. This enabled the top layer to reach an excess length of 180% of the bottom layer (see measurements in Fig. 3), that could be equally distributed across the bottom layer—an endeavour more challenging in pleated fabrics. Additionally, since none of the fabrics are naturally airtight, all actuators are equipped with a latex bladder, illustrated in Fig. 3.

3) Assembly: The fabric layers were joined with a domestic *overlocker* machine, a type of sewing machine often used for stretch fabrics with the function of edge finishing and double seam for greater seam stability. Most importantly, however, an overlocker seam remains elastic in comparison to a conventional sewing stitch—a useful characteristic for our actuator.

For the two actuators featuring the elastic band, the assembling was done in two steps: first, the elastic band was stretched while sewn onto the top layer fabric. When relaxed again, the band held the fabric together, creating equally distributed ruffles. This layer was then stitched onto the cotton weave and turned inside out - the overlocker seam and the elastic band on the inside of the actuator.

III. EVALUATION

To identify the best actuator of the three designs, we ran tests to measure their flexion angle and force capabilities. We discounted weight as a distinctive parameter on account of the samples all being within the same ballpark (5–10 g). In this section, we present the procedure and results of these experiments. Each test was run five times and with three different prototypes for each different actuator designs. The results are given along with mean values and standard deviations.

A. Tests

For an inflatable bending actuator to grasp objects or apply forces on the environment flexion angle is a crucial parameter. Work-space of the robot that actuator is mounted on also depends on this parameter. In example, for rehabilitation or assistive hand exoskeletons it is imperative that each finger is unrestricted in relation to its maximum angle [5]. Inflatable actuators therefore often need significant bending capabilities.

To test flexion angle, video recordings of mounted actuators are made during inflation. The air pressure steadily increased using 15 different pressure values. The recordings are then decomposed into frames, each one providing readings of bend angle and pressure.

Another important parameter for an inflatable bending actuator is its force exertion capability to the environment. For grasping objects, the actuator should be able to apply forces to hold them, and for exoskeletons the actuators should be able to bend the limbs. An acceptable force capability for achieving activities of daily living with hand is around 10–15 N [5]. The force requirements of haptic feedback also put a high demand on exoskeleton outputs. While soft inflatable actuators are yet to satisfy these requirements there is little doubt that the potential is there.

In this test we focused on exoskeleton application and built a test rig that represents exoskeleton environment the best. The test rig is shown in Fig. 4. The actuators were sewn into the glove, unable to separate themselves. To simulate this constraint a "limiting layer" is added which barely touches the actuator when inflated, exerting no extra force. Similar test setups have been built before in the exoskeleton related researches including this "limiting layer" idea [7], [8], [15].

The pressure of the actuator was steadily increased using a SMC ITV2050 pressure regulator. For each of 15 data points (pressure values), the corresponding force data measurement was taken by a ROBOTOUS RFT40-SA01 force sensor, which

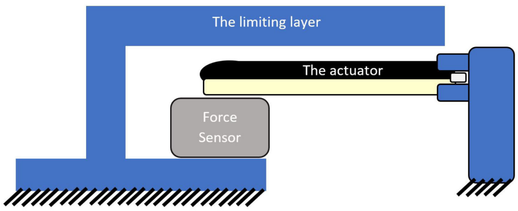

Fig. 4. Illustration of the test rig for measuring actuator's tip force output.

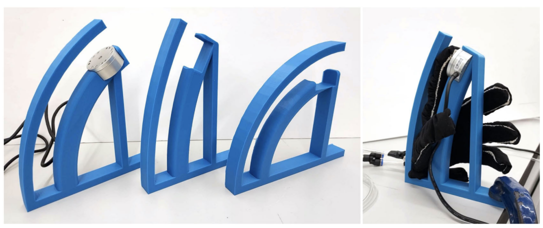

Fig. 5. Test rig for measuring the force output for different bending angles. **Left:** Three angled setups with embedded force sensor. **Right:** Set up when performing tests with actuator.

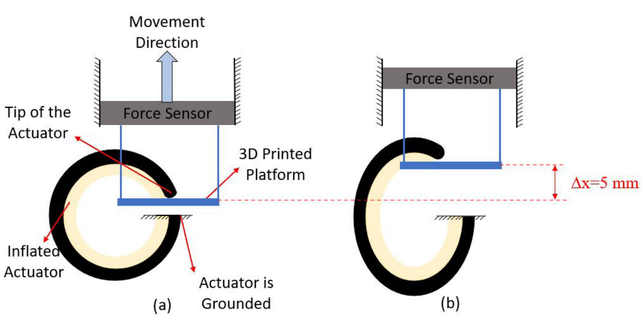

Fig. 6. Side view of the test rig set up to measure bending stiffness of the actuators. (a) At start of the test, the actuator is fully inflated and exerts a negligible amount of force on the 3D printed platform. (b) At the end of the test, having displaced the 3D printed platform by 5 mm, the force exerted by the tip of the actuator is measured by the force sensor.

can measure force/torque along six axes with a resolution of 0.2 N.

Among the other key features of inflatable bending actuators for soft hand exoskeletons, change of force capability with respect to its bending angle is worth mentioning. The previously mentioned test setup only measures force output for zero degree bending angle, for measuring force output for 30, 60, and 90 degrees, following the same force measurement principle, three different setups were 3D printed. The principle of the test setup is presented in Fig. 5. This particular test is run with the actuator mounted on an exoskeleton, but without a hand in it and the same force sensor that is used for measuring force output for zero degree bending angle is used for these measurements.

Lastly, the bending stiffness test was conducted. This test is commonly run to determine the grasping capability of soft actuators. Although this actuator is designed for use in hand exoskeletons, analysing its gripper application potential is useful. The bending stiffness test rig is illustrated in Fig. 6, and is similar to those in [16], [17]. The lower end of the bending

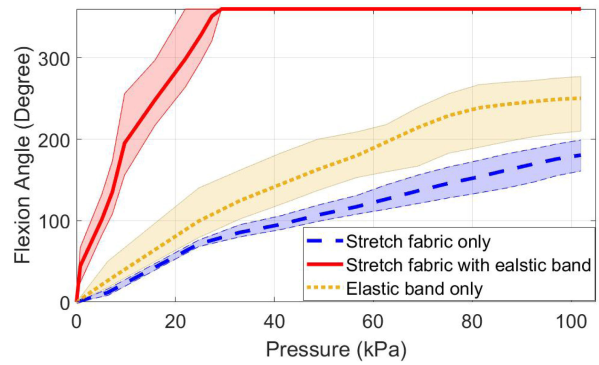

Fig. 7. Flexion angle versus pressure for three actuator designs. For each design three different prototypes are tested. The thick lines indicate the mean values of the data, the area between the minimum and maximum values are colored.

actuator is fixed using a clamp, whereupon inflated with pressurised air. The actuator bends to its maximum capacity (360 degrees for the stretch fabric with elastic band actuator), barely touching the 3D printed platform which is connected to a force sensor (Fig. 6(a)). In this starting position there is still a very small force registered by the sensor due to the thickness of the 3D printed platform, and this initial value is subtracted from the readings. When the test starts the force sensor and the 3D printed platform are lifted at a speed of 0.1 mm/s, and the actuator tip begins to exert some force on the platform thanks to its flexural rigidity. The sensor reads the force value, and after 50 seconds the platform has reached its maximum displacement of 5 mm (Fig. 6(b)). An alternative to this test methodology is to keep the force fixed and to measure the change in displacement, as in [18], [19].

To measure force in the bending stiffness test, INSTRON 5967 test machine with 2525-800 Series 100 N load cell is used.

For these tests the maximum available pneumatic pressure is determined by running a failure test to the latex bladders. The bladders are put inside the actuators and inflated with steadily increasing pressured air 10 times and the failure of the bladder happened only between 110 and 140 kPa pressures. The bladder failure points are similar for all three actuator designs. Then running repeated inflating tests at 90, 100, and 110 kPa pressures, we decided to use 100 kPa as the optimal maximum pressure value for the following evaluations.

B. Results

The bending angles of three actuator designs with changing input pressure are plotted against each other in Fig. 7.

Fig. 7 shows that flexion angle capacity of the stretch fabric with elastic band actuator is superior to the others. It can turn a full cycle (360 degrees) at 30 kPa pressure. It maintains the position after this point, because it is geometrically impossible for actuator to bend further. The stretch fabric only and the elastic band only actuators can bend approximately 180.5 degrees with 12.8 degrees standard deviation and 250.4 degrees with 23.9 degrees standard deviation respectively under about 100 kPa pressure. While these values are also acceptable for most soft

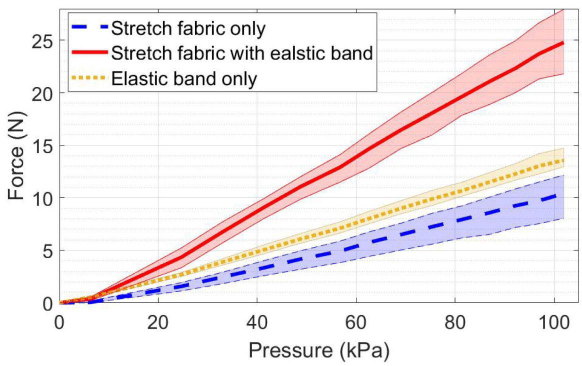

Fig. 8. Force versus pressure for three selected actuator designs. For each design three different prototypes are tested. The thick lines indicate the mean values of the data, the area between the minimum and maximum values are colored.

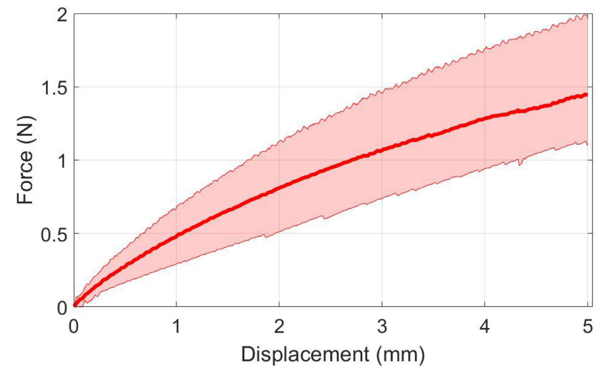

Fig. 9. Force versus displacement graph for bending stiffness of the stretch fabric with elastic band actuator. The thick red line indicates the mean value for three different prototypes, while the thin lines above and below it indicate the maximum and minimum data values.

TABLE II
COMPARISON OF FORCE OUTPUTS OF DIFFERENT INFLATABLE SOFT HAND EXOSKELETON ACTUATORS

Reference	Actuation	Force Capability
This paper	Fabric Pneumatic	24.8 N at 102 kPa
[6]	Silicone Pneumatic	1.3 N at 43 kPa
[7]	Silicone Hydraulic	10 N at 375 kPa
[20]	Fabric Pneumatic	9.3 N at 172 kPa
[15]	Silicone Pneumatic	13.6 N at 153 kPa
[8]	Fabric Pneumatic	14.3 N at 70 kPa
[11]	Fabric Pneumatic	9.1 N at 30 kPa
[21]	Fabric Pneumatic	19 N at 200 kPa
[13]	Fabric Pneumatic	5.3 N at 180 kPa

robotic applications, the stretch fabric with elastic band actuator is clearly a better option.

From Fig. 8 it is seen that the stretch fabric with elastic band actuator can apply 24.8 N with force with 2.1 N standard deviation at approximately 100 kPa pressure. This result is spectacular for a fabric or silicone based soft inflatable bending actuator so we run additional test to check how the applied force reduces for different bending angles for this particular actuator. The tests run for 100 kPa and they show that, for 30 degrees bending angle the applied force reduces to 11.5 N with 0.75 N standard deviation, for 60 degrees bending angle to 10.4 N with 0.81 N standard deviation, and for 90 degrees to 9.5 N with 0.76 N standard deviation. These tests show that even after bending 90 degrees the actuator can still exert a good amount of force.

The stretch fabric only actuator produces force up to 10.4 N with 1.7 N standard deviation, and the elastic band only actuator can go up to 13.6 N with 0.7 N standard deviation. These results show that, the use of elastic bands makes a significant difference in terms of force capability of the actuators.

Table II shows a comparison of force capabilities between actuators that are used on soft hand exoskeleton prototypes. When compared these silicone and fabric based soft hand exoskeleton bending actuators, our stretch fabric with elastic band actuator proves to be the best in terms of force capability. Although [21] can also apply 19 N force, the actuator requires 200 kPa air pressure to achieve that. The stretch fabric with elastic band actuator can exert 24.8 N force at just 102 kPa pressure.

The bending stiffness test was only run with the stretch fabric with elastic band actuator, as this was the best performing actuator on the bending angle and force output tests. The result from this test is given in Fig. 9.

The flexural stiffness of the actuator k is determined using the formula:

$$k = \frac{\Delta F}{\Delta x} \tag{1}$$

where ΔF is change in force exerted by the actuator between 0 and 5 mm displacement, and Δx is the extent of platform displacement. At 5 mm displacement the actuators produce a mean of 1.44 N force with 0.38 N standard deviation. The bending stiffness of the actuator is therefore about 288.4 N/m. This value shows that the novel actuator does also have some gripper potential. However, due to its high bending angle capability, instead of grasping an object this actuator can furl around the object and gently squeeze it.

These tests confirm that in comparison to the alternatives, the actuator using stretch fabric with additional elastic bands shows excellent performance both in relation to bending and force capability. The findings of these tests can now be used in a case study of a hand exoskeleton.

IV. CASE STUDY: A SOFT ROBOTIC HAND EXOSKELETON

To show that our actuator can be implemented in a soft robotic application, we present a case study for a hand exoskeleton. Encouraged by the findings reported above, we embedded the best performing actuator to bend the fingers of the robotic glove.

A. Glove Design

The basic glove on which the actuators are mounted is fabricated from a soft, four-way stretch fabric: a black viscose jersey knit, see Fig. 10(a). The flexible nature of this knit fabric allows it to easily mould around differently sized hands and fingers with a simple pattern construction (Fig. 10(a)), while its material composition guarantees a soft feel on the skin, making it comfortable to wear.

Fig. 10. (a) Making of the exoskeleton prototype: pattern cutting (top) and attachment of actuators onto glove with latex bladders inserted; (b) The final assembled prototype with attached air tubes.

The fabric based soft hand exoskeleton is manufactured using our "stretch fabric with elastic band" actuator (Fig. 10(b)) which we established as the best candidate based on the above tests. The five inflatable actuators were assembled as described above with an overlocking machine in two steps, and later hand-stitched onto the glove, reaching from the fingertip down to the centre of the back of the palm. For this prototype, all five bending actuators were fabricated identically. The actuator caps were closed with slightly rounded edges, while the other end was kept open to insert the latex bladder as in Fig. 10(a). Lastly, the exoskeleton actuator of the thumb is fabricated differently to the others. To mimic the natural movement of the thumb, it makes a sideways motion when actuated. This is achieved by distributing the excess length of the top layer fabric unevenly, so that when inflated, it can bend more at one side than on another, following the natural twist of a thumb.

For the glove to be able to assist with the extension motion of the hand as well, another fabric actuator is needed that is hand-stitched onto the base glove and concealed by the bending actuator, as documented in Fig. 10(a). This actuator was constructed with two equally long layers (since it didn't have to bend) of airtight, extremely lightweight woven fabric that are sewn together and additionally sealed with heat bonding tape. When actuated, they prevent flexion motion and support the hand extension motion—a principle that is also used by [22]. In unactuated state they have almost no effect to flexion motion thanks to their very light and flexible nature. The final exoskeleton prototype can be seen in Fig. 10(b).

With this final design taking into account all previous findings, rather than using the test rig, we examined performance and design in conjunction with their deployment onto human hands.

B. Flexion and Extension Performance

The manufactured design of the exoskeleton glove has been used to carry out a simple series of flexion and extension tasks by grasping, holding onto, and releasing objects. With these tasks, we can assess the performance of the two layers of actuators, drawing special attention to the top layer of the elastic band actuators, inspecting whether they achieve a similarly large bending angle and force capability integrated as fingers in a wearable system than as individual actuators.

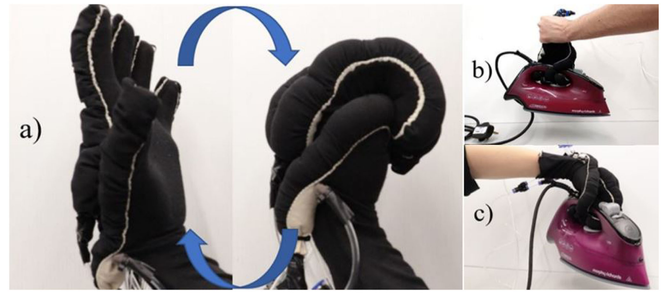

Fig. 11. (a) The final hand exoskeleton glove can achieve flexion and extension motions, (b) The exoskeleton grasping an iron without a hand inside, (c) The prototype is "in action," worn by a human subject, grasping and holding a heavy objects like an iron.

The different objects used for this evaluation were of different shapes and weights: a small ball, a tea mug, a smart phone, and—the heaviest of the objects—an iron. In Fig. 11(b), the exoskeleton glove can be seen lifting the iron without a hand in it—the most challenging of the tasks in terms of the force required, and in Fig. 11(c) doing so again, supporting the hand within. In informally inspected user tests, our glove was able to pick up and hold all objects with ease, which provides enough indication for this developed actuator to be a promising design for further investigations towards hand exoskeleton applications. Most obviously, the performed tasks suggest suitable use cases in rehabilitation and assisting activities of daily living [5]. The force and bending results support this, too, when comparing our design to specifications of other adequate and successful prototypes.

V. Conclusion

In summary, this letter presents a new soft inflatable fabric actuator design exploiting manufacturing techniques taken from the textile industry. A braided elastic band integrated one-way stretch fabric actuator offers high force exertion to the environment and a full cycle bend even in low pressure values. With these results, we overcome a common force related challenge in soft robotics. Overall, with the use of this textile elastic band in combination of the stretchy woven fabric, our design outperforms existing similar approaches, as compared in Table II. The implementation of such elastic band is a novelty for inflatable, fabric based bending actuation and contributes to the field of emerging textile robotics.

Additionally, considering prominent applications of soft bending actuators like hand exoskeletons, we find further material advantages in our design. We are accustomed to being aware of the "touch" of textile on our skin, and wearing plastic, silicone or a 3D printed material would obviously feel rather awkward. Manufacturing a wearable robot using fabric and textile materials would therefore potentially eliminate that discomfort. The proposed exoskeleton prototype being fully fabric based, it will make the robot considerably more usable and acceptable to the user, and pushes research towards ubiquitous assistive robotics.

When producing textile actuators, a sewing machine is used to join fabric layers together. Such needle stitches create tiny holes even into airtight fabrics. For this reason, solutions like our integrated latex bladder are proposed. However, this compromises the idea of a solely textile based robotic system and poses a limitation to the design process. We believe, however, that this issue can be overcome in future iterations. With precise textile manufacturing techniques, also other remaining challenges can be tackled. This concerns the importance of accurate stitching to create symmetrical seams for consistent bending.

To demonstrate the advantages of our novel fabric bending actuator in the proposed context of soft hand exoskeletons, a case study is conducted for the actuator. Because textile actuators preferable in human robot interaction, the novel actuator is studied taking into account the hand exoskeleton requirements. The custom-made prototype can be envisioned to be used in rehabilitation of post stroke patients. Furthermore, because it is lightweight, safe, and easy to actuate independently of a technician, it can be deployed in non-clinical settings, too, in example, at home, providing support for everyday tasks. With the employed techniques, it is easy to create personalised gloves of different sizes. To perform more complex tasks, one could also consider controlling each finger separately, though this would require a pressure regulator for each actuator—a costly addition. The potential use cases of the actuator, however, is not limited to exoskeletons. It is safe to assume that, integration of an elastic band to textile actuators will be valuable for many different soft robotic applications.

Planned future research will be directed towards haptic related aspects of the design. Having shown that this innovative actuator can exert considerable forces, it may be possible to use the manufacturing method of our elastic band integrated actuator to fabricate a soft hand exoskeleton for haptic feedback, too. Further iterative design engineering using expert textile technologies would allow the yet limited and underinvestigated area of wearable haptics to be advanced.

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