Delicate Fabric Handling Using a Soft Robotic Gripper With Embedded Microneedles

Subyeong Ku, Jihye Myeong, Ho-Young Kim, and Yong-Lae Park

***Abstract*—We propose a soft robotic gripper that can handle various types of fabrics with delicacy for applications in the field of garment manufacturing. The design was inspired by the adhesion mechanism of a parasitic fish called 'lamprey'. The proposed gripper not only is able to pick up and hold a single sheet of fabric from a stack but also does not make any damages on it. In this work, we first modeled the holding force of the gripper and then experimentally evaluated its performance with different types of fabrics, in terms of the holding force and the response time. The experimental data showed a reasonable agreement with the predicted values by the model. The actuation time and the maximum holding force measured in the experiments were 0.32 seconds and 1.12 N, respectively. The gripper showed high success rates in picking up a single sheet of air permeable fabric, which was not possible by a commercial vacuum pad. It also showed durability in repeated motions of gripping test over 20,000 cycles. We believe the proposed gripper has a high potential in realizing smart manufacturing in garment industry.**

***Index Terms*—Soft robot applications, soft robot materials and design, grippers and other end-effectors.**

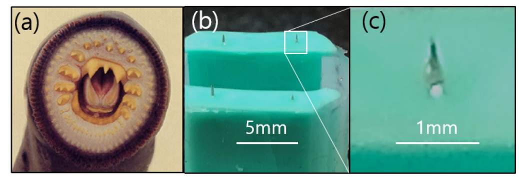

Fig. 1. (a) Oral disc with sharp teeth of Pacific lamprey (Lampetratridentata). (b) Top view of microneedle-embedded soft gripper. (c) Enlarged image of embedded microneedle.

I. Introduction

INDUSTRY 4.0 refers to a technological trend in which the advancement of robotics, artificial intelligence (AI), and the internet of things (IoT) enable automation and data exchanges in manufacturing to realize a "smart factory" (i.e., smart manufacturing) [1]. As conventional manufacturing factories are transformed into smart factories, we can expect high levels of productivity and efficiency when human laborers are replaced by robots and machines through automation [2]. Garment industry, among others, will be one of the main beneficiaries of the advances in smart manufacturing [3], since it is highly labor-intensive and overly relies on a human workforce. There exists no automated robotic systems that can handle different types of fabrics with a high level of delicacy yet. Even a simple manipulation task, such as "pick and place" requires relatively high dexterity when handling fabrics, since they are thin and flexible and do not return to their original shapes when deformed.

For increased dexterity and adaptability, robotic grippers made of soft materials and structures have been developed. The mechanical compliance of these soft grippers provides the ability of deforming and adapting their shapes to the objects with different shapes to be gripped. Examples of actuation mechanisms for soft grippers include tendon-driven [4]–[6] and fluidic [7]–[10] actuators for flexion or extension motions, stiffness control by particle jamming [11], and simple air suction [12], [13]. They have successfully demonstrated the ability of picking up and manipulating objects with different shapes. However, fabrics are known for their complex morphological and mechanical properties and also for nonlinear static and dynamic behaviors [14]–[16]. These characteristics make it extremely difficult to conduct even one of the most basic manipulation tasks in the field of garment manufacturing, such as separation of a single sheet of fabric from a stack, using the above soft gripper mechanisms. Therefore, we propose a soft robotic gripper that can handle various types of fabrics with delicacy, as shown in Fig. 1.

Grippers specifically designed to handle fabrics were initially proposed in the early 1980's [17]. Since then, different gripping mechanisms, such as pinching, vacuum suction, needles, and electroadhesion, have been investigated [18].

A pinch gripper with two jaws buckles fabric by bringing the jaws that are pressing down the fabric and secures it between the jaws [19], [20]. In spite of the simplicity in its mechanism and cost efficiency, if multiple sheets of fabric with rough surfaces are stacked, it is difficult to separate the top layer from the rest only by sliding it with pressure due to the high friction between the sheets.

A suction gripper employs a simple mechanism of negative air pressure [21], but most fabrics have porous structures by which

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the negative pressure either cannot hold the fabric or holds more than one sheet of the fabric at a time.

To address this issue, grippers with needles have been proposed. They can easily hold porous objects, which are difficult to grip using vacuum, by penetration and interlocking [17]–[23]. However, previously developed needle grippers are not suitable for soft fabrics, since they were designed for objects made from specific materials, such as sponge and rubber. Furthermore, thick needles (over 700 μm in diameter) sometimes leave permanent penetration marks on the objects.

Electroadhesion is an alternative gripping method that does not damage the surface of the object. It employs the electrostatic effect between the gripper surface and the fabric subjected to an electrical field [24]. However, it takes longer than one second to charge nonmetallic fabrics (5 ms for metallic fabrics), which may significantly slow down the production process involved with textile handling [25].

To overcome these limitations, we propose a hybrid method that integrates a couple of the advantages of the above fabric grippers. The proposed gripper employs a soft structure made of elastomer materials that can be easily and quickly actuated by a pneumatic power. Another important design feature is embedded microneedles at the soft tip of the gripper, which do not damage the fabric. The design was inspired by parasitic fish called lamprey [26] that can attach itself to the skin of the host body with a strong holding force (Fig. 1(a)). Its characteristic oral structure and adhesion mechanism are the key ideas behind our gripping system.

In this letter, we first describe the mechanism and the important design features of the soft gripper and develop an analytical model to predict the holding force. We then evaluate the performance of the gripper experimentally by measuring the holding forces of different fabrics. Finally, we conclude the paper with discussion of ongoing and future work.

II. Design

A. Gripper Design

It is not too difficult to find gripping mechanisms in nature that show better performances in certain tasks than human hands. Among those, we focused on a particular type of parasitic fish called *lamprey* that is known for its strong adhesion force to the surface which it clings to. Lampreys make mechanical adhesion to the body of their host enabled by an oral disc equipped with intrusive teeth. We designed our gripper that consists of two different silicone elastomers and embedded microneedles by mimicking the lamprey's buccal flesh and a unique dentition (Figs. 1(b) and 1(c)). The actuation mechanism was then developed following the two attachment phases of lampreys: an intrusive phase of tooth penetration and a suctorial phase of adhesion enhancement and retention. Our gripper first engages the porous structure of fabric with the microneedles, similar to the intrusive phase of lampreys. Vacuum is then responsible for operating the rest gripping mechanism for stable grasping, similar to the suctorial phase.

There exist two main forces used to hold fabric: friction and suction. The microneedles on the tip of the gripper are used only for pinching the fabric but not for holding. The friction is proportional to the coefficient of friction between and the normal force applied to two surfaces, and the normal force in our case is determined by the contact area between the gripper wall and the fabric and also by the pressure difference between the inside and the outside of the gripper. Therefore, we can maximize the friction of the gripper by maximizing the grip area and minimizing air leakage during operation. However, there is a constraint in the practical size of the gripper to be applied to actual garment manufacturing, in which sewing is one of the most critical processes. In general, sewing connects two fabric pieces, requiring a margin of 7 mm from the edge of each piece. Therefore, no contact should be made beyond the 7 mm margin to prevent any contamination or damage on the fabric, which decides the distance of 6 mm between the two pinching walls of the end-effector (Fig. 2(a)-left).

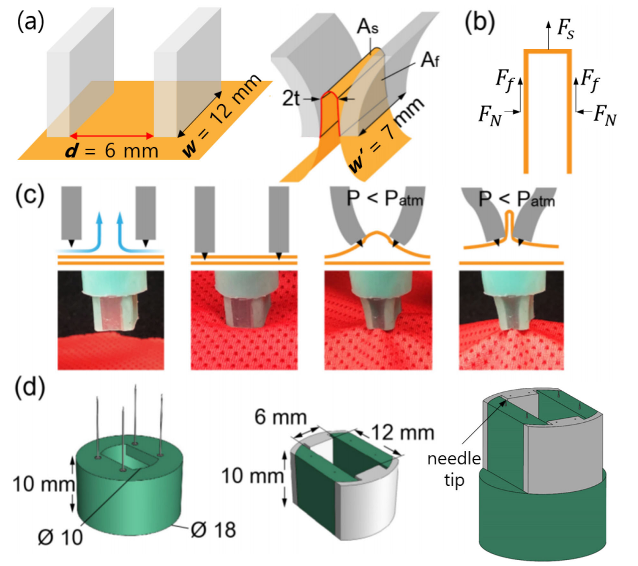

Fig. 2. (a) Schematic of the proposed gripping mechanism. A_s and A_f are the areas of suction $(2t \times w')$ and pinching $((6 - 2t)/2 \times w')$, respectively, where t is the thickness of the fabric. (b) Simple free-body diagram with forces applied to the fabric. (c) Schematics (top) and actual photos (bottom) of gripper operation. The pressure inside the gripper, P, is lower than the atmospheric pressure. (d) Gripper base with embedded needles (left), deformable end-effector (middle), and assembled gripper (right).

B. Analysis

It is necessary to determine the shape of the fabric to be gripped first for modeling the holding force of the gripper. The gripper covers a rectangular area of 6 $\times$ 12 mm^2 on the fabric at the time of the engagement of the needles with the fabric. As soon as a negative air pressure is applied, the gripper deforms and closes the tip of the end-effector and folds the fabric in half (Fig. 2(a)-right). During this process, the needles contribute only to buckling of the fabric during the initial sliding and folding stage. However, as soon as the end-effector holds the fabric with the maximum vacuum pressure, the needles lose their engagement with the fabric. This means the holding force is determined by the friction and the suction forces only.

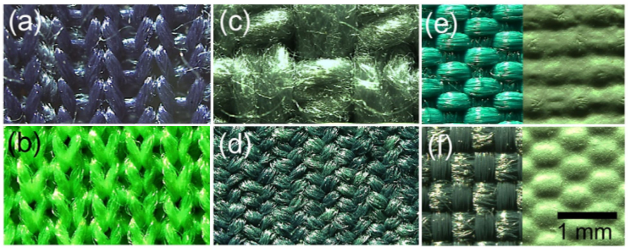

Fig. 3. Magnified photos of the tested fabrics: (a) Type 1-1: Double-mesh French terry, (b) Type 1-2: Coolmax, (c) Type 2-1: Canvas, (d) Type 2-2: Soft-shell, (e) Type 3-1: PU-coated nylon, and (f) Type 3-2: PU-coated polyester. (e) and (f) show one side of woven yarn (left) and the other side with polyurethane coating (right).

TABLE I
INFORMATION ON THE FABRICS USED IN MODEL CALCULATION

Fabric type	1-1	1-2
Number per unit area [1/mm^2]	4	6
Average radius [mm]	0.15	0.11
Coefficient of friction	1.06	0.92

The width of the pinching wall decreases from $w = 12$ mm to $w' = 7$ mm when the gripper holds the fabric due to the negative pressure inside the end-effector. The forces acting on the gripper during this process are schematically shown in Fig. 2(b), and F_s, F_f, and F_N are the suction force, the friction between the pinching wall and the fabric, and the normal force of the pinching wall to the fabric, respectively. The pinching area under vacuum, A_s, is then $2t \times w'$. Considering the porous structure of the fabric, the areal ratio of the yarn to the entire fabric including the pores, covered by the end-effector, is $a = 1 - N \times \pi \times r^2$, where r is the average radius of the pores, and N is the number of pores in a unit area (1 mm^2). These values were measured from the microscopic images (Fig. 3) for the two fabric types to be tested for the holding force (Table I). The suction force acting on the porous fabric is then

$$F_s = a \times A_s \times \Delta P = 14(1 - N\pi r^2)t\Delta P \tag{1}$$

where ΔP is the pressure difference between the inside and the outside the gripper.

We now need to find the friction force F_f. Since the contact area between the pinching wall and the fabric A_f is $(d - 2t)/2 \times w'$, the friction is

$$F_f = \mu \times A_f \times \Delta P = 7\mu(3 - t)\Delta P \tag{2}$$

where μ is the friction coefficient between the pinching wall and the fabric, which can be measured by an inclined friction test. The measured coefficients are also shown in Table I.

Finally, the total holding force of the combined suction and friction forces can be calculated as

$$F_h = F_s + 2 \times F_f = 14[(1 - N\pi r^2)t + \mu(3 - t)]\Delta P. \tag{3}$$

This equation shows that the holding force is a linear function of ΔP with a slope of $14[(1 - N\pi r^2)t + \mu(3 - t)]$ that consists of the structural and geometric characteristics of the fabric. This means that different forces will be generated depending on the types of fabric under the same ΔP.

TABLE II
INFORMATION ON THE FABRICS USED IN THE EXPERIMENTS

	Type 1		Type 2		Type 3	
Fabric type	1-1	1-2	2-1	2-2	3-1	3-2
Thickness [mm]	0.75	0.62	1.02	1.43	0.33	0.36
Weight [N/m^2]	2.28	1.47	3.26	3.13	1.35	1.91
Air permeability [cm^3/cm^2/s]	82	160	7.14	0.15	0	0

C. Operation Procedure

The operation sequence of the gripper is shown in Fig. 2(c). It starts with approaching of the gripper to the fabric stack. When the gripper makes a contact with the fabric, the needles engage the top sheet. Vacuum is then applied to the gripper, and the pressure difference between the inside and the outside of the gripper is generated, causing the two pinching walls to collapse toward each other. While bending, the end-effector buckles and holds the fabric between the two pinching walls.

D. Fabrication

The base (Fig. 2(d)-left) of the gripper was made from relatively stiff elastomer (Smooth-Sil 960, Smooth-On) to support the structure and also for connecting a pneumatic line.

The shape of the base is a thick-walled cylinder to which the needles are fixed. We used thin acupuncture needles (diameter: 200 μm) that are commercially available not to damage the fabric.

The end-effector part (Fig. 2(d)-middle) was made from two different materials to generate the pinching motion by deformation. While the pinching walls were made from the same stiff material of the base, the side walls shorter than the pinching walls are made from much softer elastomer (Ecoflex 0030, Smooth-On). When the end-effector was assembled with the base, the needles protruded the top surface by approximately 0.5 mm.

III. EXPERIMENTS

Since fabrics used in the garment industry have a wide variety of structural features and the gripper behaves differently depending on these characteristics, different types of fabrics were tested to evaluate the performance of the gripper. The test fabrics are classified into three types: Type 1 - porous, slouchy, lightweight, and thin, Type 2 - densely woven, stiff, and thick, and Type 3 - coated fabrics (Fig. 3 and Table II).

The experimental setup to measure the holding force is shown in Fig. 4. In all experiments, the gripper was mounted on a six-axis industrial robot arm (UR3, Universal Robots). We placed a test piece of fabric (60×70 mm^2) on a precision balance (Pioneer PAG4102, OHAUS) and fixed its one end on the balance. For testing, the gripper first moves down to the other end of the fabric. When the gripper makes a contact with the

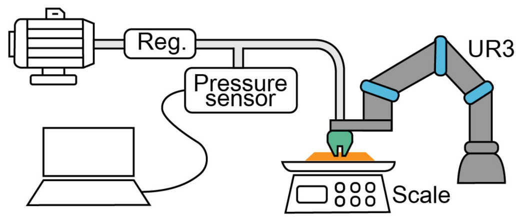

Fig. 4. Schematic of the experimental setup.

fabric, vacuum is applied and the gripper pinches and hold the fabric. Then, the gripper moves up along a pre-determined path, and the weight data measured by the balance are recorded. At the same time, a vacuum pressure sensor measures the pressure inside the gripper. We also conducted an experiment to measure the response time of the gripper actuated by a vacuum pump and the vacuum pressure sensor.

A. Model Evaluation

The power of the vacuum pump was set with six levels. For a comparison with the model in Section II-A, ΔP and the holding force were measured for the six power levels. Experiments were conducted on Type 1-1 and 1-2 porous fabrics 10 times for each power level. The assumptions of the model were also validated by calculating the effective contact area of the gripper to the fabric.

B. Comparison Test

To check the effect of the needles, the holding force was measured using a gripper without needles as well. We tested all three types of fabrics shown in Fig. 3.

The performance of the proposed gripper was also compared with that of a commercial ϕ10 vacuum pad (VPC10R6J, Pisco) with all three fabric samples.

In addition to the gripper tests, we compared the damage levels to fabrics by the needles with different diameters, as even a small damage to fabrics can be critical to the quality of the final product in business. Since the needles used in conventional needle grippers are over 700 μm in diameter 22, 23, we visually checked the penetration marks made by needles with three different diameters: 200, 500 and 900 μm.

C. Durability Test

The durability of the gripper was also tested by gripping and releasing a single fabric sheet on a flat surface for 20,000 cycles. During the 20,000 cycles, we measured the changes in ΔP to evaluate the mechanical reliability of the gripper. This experiment was conducted with Type 1-2 fabric.

D. Single-Sheet Handling

It is important for the gripper to pick up only a single sheet of fabric from a stack. Considering that 60 to 100 sheets in a batch are typically used in an actual garment production process, 80 sheets of fabric were set up on the precision balance. When the test starts, the gripper moves down to the stack, picks up and removes the top fabric and places it out of the balance. The precision balance was used to measure the weight reduction that indicates the number of sheets removed at a time. Success is defined when the gripper holds only the top single sheet in the stack and failure otherwise. The success rate is determined by the number of successful grips divided by the number of trials for each fabric. This experiment was conducted with all three types of fabrics.

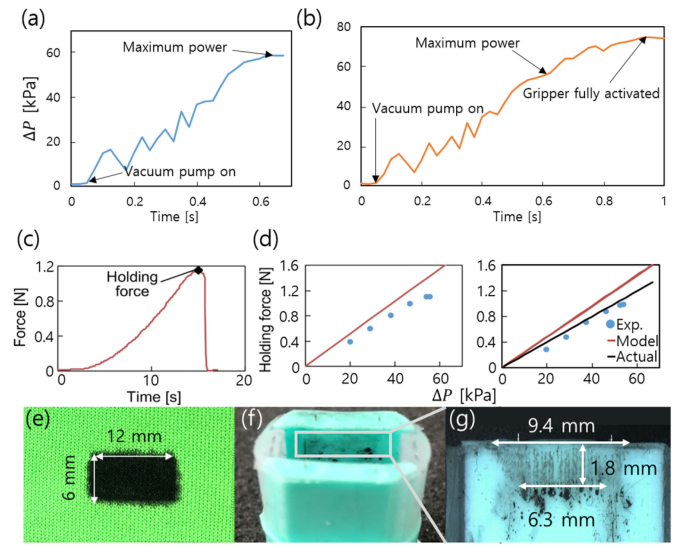

Fig. 5. (a) Pressure response of the vacuum pump. (b) Pressure response of the gripper. (c) Vertical force measured when the gripper picks up fabric. The maximum force, 1.12 N, is the holding force. Type 1-1 fabric was tested with the maximum vacuum power (– 60 kPa, sampling frequency: 12 Hz). (d) Holding force as a function of ΔP showing a comparison between the experimental data (blue dots) and the model prediction (red lines) for Type 1-1 (left) and Type 1-2 (right) fabrics. (e) Mark of black ink on Type 1-2 fabric with the size of the area covered by the gripper before pinching. (f) Mark of the black ink from the fabric on the inside of the pinching wall after one-time gripping. (g) Enlarged image of the inside of the pinching wall showing the size of the black mark.

IV. Results

In order to check the response time of the gripper, we first analyzed the pressure response of the vacuum pump. The response time for the pump to reach the maximum vacuum power was approximately 0.61 (Fig. 5(a)), and the time for the gripper to reach the maximum pressure was approximately 0.93 (Fig. 5(b)). Therefore, the actual actuation time of the gripper itself is 0.32 that is much shorter than that of electrostatic grippers (up to 1).

The holding force was measured using the precision balance. When the robot arm slowly moves up vertically while the gripper is holding the fabric, the pulling force is measured until the gripper loses its grip even the vacuum pressure is maintained the same, as shown in Fig. 5(c). The maximum force measured during this process is defined as the holding force of the gripper, and it was 1.12 N.

A. Model Evaluation

The holding force is a linear function of ΔP, and its slope is determined by the structural characteristics of the fabric, as discussed in Section II. Therefore, the model predictions have

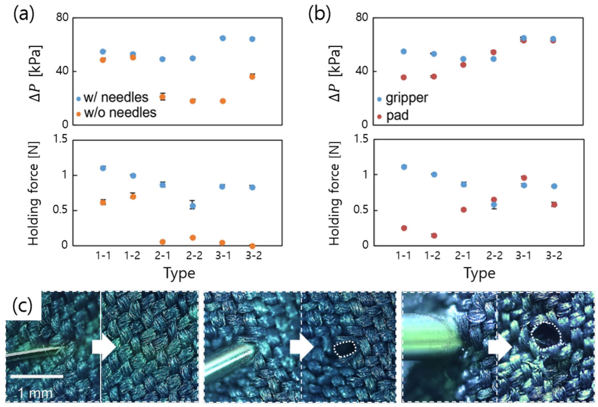

Fig. 6. (a) Performance comparison between grippers with and without needles: pressure difference between the inside and the outside of the gripper (top) and holding force (bottom). (b) Performance comparison between the soft gripper and the vacuum pad. (c) Microscopic images of Type 2-2 fabric after being punctured by microneedles with different diameters (200 μm, 500 μm and 900 μm from left to right).

different slopes depending on the types of fabric, as shown in Fig. 5(d). The model slightly overestimated the experimental data, since the actual grip area on the fabric was smaller than that calculated in the model. To check the actual grip area, we tested the gripper with a sheet of fabric that has a mark of black ink (Fig. 5(e)). As shown in Fig. 5(f), the fabric leaves stains on the inside of the pinching wall when gripped (Fig. 5(f)). We can now calculate the actual contact area of the gripper to the fabric from the trapezoidal area of the stains (Fig. 5(g)). The predicted force response based on the actual contact area is shown with a black line in Fig. 5(d)-right, which matched the experimental data better than the original prediction.

B. Comparison Test

The needle tips on the gripper surface are extremely useful in holding the fabric during the initial buckling and pinching motion of the end-effector as they mechanically engage the porous structure of the fabric. We tested the performance of the gripper with and without needles for different types of fabrics. The gripper with needles was able to effectively buckle and pinch all the fabrics. However, the gripper without needles was not able to hold Types 2 and 3 fabrics. The fabrics only puckered on the floor surface and did not adhere to the gripper in this case.

Fig. 6(a)-top compares ΔP for the grippers with and without needles tested with different fabrics. It was already shown that ΔP has a linear relationship with the holding force in Fig. 5(d) and can be used as a measure of the performance of the gripper. There was no significant difference in the performance whether the gripper had needles or not for Type 1. However, ΔP was much smaller for Types 2 and 3 when the gripper had no needles. The differences in ΔP for the two types were between 2 kPa and 47 kPa.

The holding force was also measured for the gripper with and without needles, and it was higher for all fabric types when needles were used (Fig. 6(a)-bottom). The difference was larger when the thick, stiff, and coated fabrics were used because they

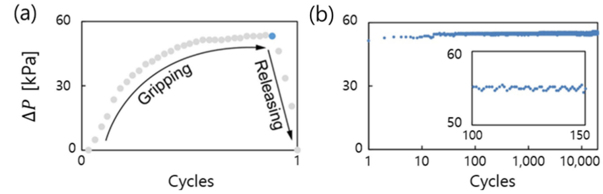

Fig. 7. Results of durability test: (a) change in the pressure difference during a single cycle of gripping and releasing with ΔP defined by blue dot and (b) ΔP for the same tests over 10,000 cycles with enlarged view between 100 and 150 cycles (right).

required a higher critical buckling load due to the high bending stiffnesses. The gripper without needles showed much lower holding forces for Type 1, since it was not able to hold as large area of the fabric as that of the gripper with needles. For Types 2 and 3, the forces were almost zero without needles, indicating that the gripper did not hold the fabric at all.

The proposed gripper was also compared with a commercial vacuum pad, which is currently used for automation of many processes in garment manufacturing. The vacuum gripper tested in this study had a cross-sectional area of 72 mm^2 and an area of the suction pad of 78.5 mm^2 that is similar to the contact area to the fabric of the proposed soft gripper.

Fig. 6(b)-top compares the performances of the soft gripper and the vacuum pad in terms of ΔP. The differences were significant only for Type 1 that were porous. Due to the extremely low permeability, both grippers were able to generate high vacuum pressure for Types 2 and 3. The performance difference between the proposed gripper and the vacuum pad became more obvious when the holding force was measured (Fig. 6(b)-bottom). The soft gripper was able to generate holding forces that were 4.4 and 7.1 times larger than the suction pad, for Types 1-1 and 1-2, respectively. In contrast, there was no significant difference in holding forces for Types 2 and 3. The suction pad even showed a slightly better performance for Types 2-2 and 3-1. This indicates that the proposed soft gripper is most effective for porous fabrics.

We also conducted an experiment to compare the damage levels to the fabric by the proposed gripper and conventional needle grippers. The needle with a diameter of 200 μm in our gripper did not damage the fabric at all since the hole created by the needle was self-healed by the weave structure. In contrast, needles of 500 μm and 900 μm in diameter left unrecoverable holes (Fig. 6(c)). The threads in the structure were also destroyed by the needle in this case. Therefore, needles with a diameter exceeding 500 μm are not suitable for practical applications due to the permanent damages.

C. Durability Test

Since ΔP has a direct relationship with the holding force we measured ΔP during cyclic gripping tests evaluate the durability of the gripper under repeated work.

Fig. 7-left shows the changes ΔP during a single cycle of gripping and releasing. We are interested in the maximum ΔP (blue dot in Fig. 7(a)), and it was plotted from over 10,000 cycles (Fig. 7(b)). ΔP was maintained even after tens of thousands cycles without any noticeable changes. The average value of

TABLE III
RESULTS OF SINGLE-SHEET HANDLING TEST WITH THE NUMBERS OF SUCCESSFUL TRIALS (SUCCESS RATE)

Fabric type	1-1	1-2	2-1	2-2	3-1	3-2
Soft gripper	58 (72.5%)	69 (86.3%)	65 (81.3%)	71 (88.8%)	80 (100%)	80 (100%)
Vacuum pad	0 (0%)	0 (0%)	0 (0%)	0 (0%)	80 (100%)	80 (100%)

the maximum ΔP was 55 kPa, with a standard deviation of 0.2 kPa. The slope of the experimental trend line was 1×10^{-8}, confirming that there is almost no decrease in ΔP over 20,000 cycles.

D. Single-Sheet Handling

As can be seen in the results summarized in Table III, the soft gripper achieved the success rates over 70% for Types 1 and 2 fabrics and 100% for Type 3. In the first two fabric types, Types 1-2 and 2-2 showed higher success rates than Types 1-1 and 2-1, respectively. This is due to the higher permeability in Types 1-1 and 2-1, which sometimes caused a failure of picking up two or more sheets at a time.

The vacuum pad was not able to pick up a single sheet at all for Types 1 and 2 while it showed a success rate of 100% for Type 3, due to the permeability of the fabrics. The vacuum pad always picked up about 10 sheets at a time for Types 1 and 2, but the coating of Type 3 fabrics prevented the vacuum from being applied to the sheets below the top one.

V. DISCUSSION

The main contribution of this work is the bio-inspired design of a soft gripper particularly focused on delicate handling of fabrics. The gripper is made of soft materials that can easily deform by a pneumatic power for actuation of the pinching motion. In addition, the gripper has embedded microneedles at the tip that facilitate gripping of the fabric at the time of a contact. Moreover, the small diameter (200 μm) of the needles does not damage the fabric even though the needles penetrate the fabric while holding. The proposed design showed a potential to be a critical element in automating many processes in current labor-intensive garment manufacturing involved with multiple manual steps.

One limitation we observed in our design during testing is that the performance of the gripper is dependent on the type of fabrics. If a fabric has a high air permeability with a loosely woven structure (Fig. 8(a)), the gripper had a hard time in closing the tip due to the air leakage, causing only buckling of the pinching walls rather than generating the gripping motion. To address this issue, we are currently working on improving the gripper design specialized for fabrics with a high air permeability. One possible design modification is the closed tip, as shown in our preliminary prototype (Figs. 8(b) and 8(c)). This design completely divides the gripping task into two subtasks, locking and pinching. The microneedles first lock the fabric by engaging themselves into

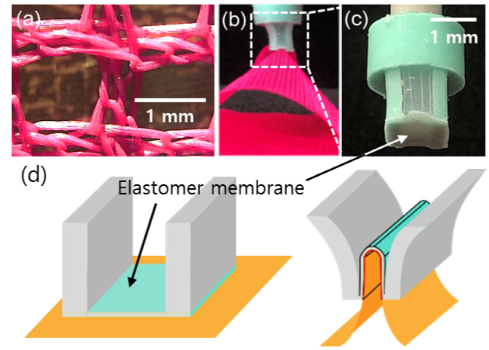

Fig. 8. (a) Fabric with high air permeability. (b) New gripper prototype holding the fabric shown in (a). (c) Magnified photo of the new gripper showing the closed end-effector with an elastomer membrane. (d) Gripping mechanism of the new gripper design.

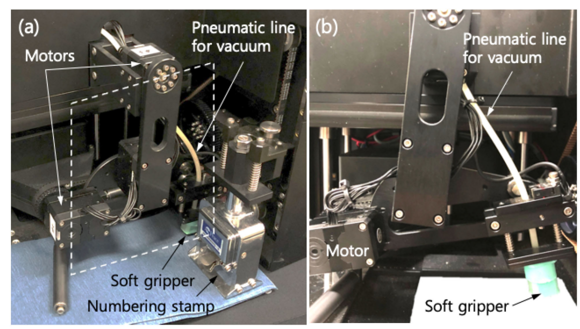

Fig. 9. (a) Prototype of pattern-numbering machine composed of soft gripper, three degrees-of-freedom robot arm, and numbering stamp. (b) Magnified photo of dotted box in (a).

the pours and then the vacuum deforms the gripper to pinch the fabric without pulling it up with a negative pressure. The gripping performance is not dependent on the air permeability of the fabric any more in this design but only on the locking mechanism (Fig. 8(d)). Further investigations are underway to analyze and optimize the locking mechanism.

We are also greatly interested in implementing the our soft gripper with microneedles to a practical system. Numbering each sheet from a stack of identical sewing patterns is one of the most common processes fully operated by human workers in garment manufacturing, which requires repeated motions of picking up a single sheet of fabric from the stack. As shown in Fig. 9, we installed our gripper in a preliminary prototype of a pattern-numbering machine (developed by the authors and Hojeon Ltd.) to check the applicability of our design. The soft gripper showed a reliable performance on the numbering task, composed of repeated motions of separation of a fabric sheet from a stack and stamping a serial number on each sheet, in relatively high speed (approximately 1 Hz). Further research on characterization and control of the numbering machine is currently ongoing. Supplementary video demonstrates the numbering task with the prototype.

One immediate area of future work is addition of a sensor for detecting the number of fabric sheets engaged to the gripper. Although the current design showed relatively high success rates of separating a single sheet from a stack, it tended to have less successes for fabrics with high air permeability. The failure happened when either the fabric slipped out of the gripper during the lifting motion or more than one sheet of fabric were engaged to the gripper. Therefore, it would be highly useful to detect the failure modes to adjust the control settings in real-time. Possible solutions include embedding soft pressure sensors at the tip of the gripper that can detect changes in electrical resistance [27], [28], capacitance [29], [30], or optical properties [31]–[33] caused by deformation.

Another area of future work will be investigation on the effect of the substrates on the gripper performance. In garment manufacturing, one of the immediate target application areas of the soft gripper, a fabric sheet to be handled is always on top of a stack of the same fabric. Therefore, we tested the single-sheet handling test with a stack of the same fabric with different types. However, it will be useful to know how the gripper performance changes depending on the surface roughness of the substrate for a wide range of applications.

VI. Conclusion

We developed a soft gripper for handling delicate fabrics. The design was inspired by the adhesion mechanism of a parasitic fish called 'lamprey.' The proposed gripper not only was able to pick up and hold a single sheet of fabric from a stack but also did not make any damages on it. In this work, we first modeled the holding force and then experimentally evaluated the performance of the gripper with different types of fabrics. The maximum holding force measured in the experiments was 1.12 N. The gripper showed high success rates in picking up a single sheet of air permeable fabric, which was not possible by a commercial vacuum pad. It also showed durability in repeated motions of gripping test over 20,000 cycles. We believe the proposed gripper has a high potential in realizing smart manufacturing in garment industry.

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