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Development of a Polymer-Based Tendon-Driven Wearable Robotic Hand

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Abstract— **This paper presents the development of a polymer-based tendon-driven wearable robotic hand, Exo-Glove Poly. Unlike the previously developed Exo-Glove, a fabric-based tendon-driven wearable robotic hand, Exo-Glove Poly was developed using silicone to allow for sanitization between users in multiple-user environments such as hospitals. Exo-Glove Poly was developed to use two motors, one for the thumb and the other for the index/middle finger, and an under-actuation mechanism to grasp various objects. In order to realize Exo-Glove Poly, design features and fabrication processes were developed to permit adjustment to different hand sizes, to protect users from injury, to enable ventilation, and to embed Teflon tubes for the wire paths. The mechanical properties of Exo-Glove Poly were verified with a healthy subject through a wrap grasp experiment using a mat-type pressure sensor and an under-actuation performance experiment with a specialized test set-up. Finally, performance of the Exo-Glove Poly for grasping various shapes of object was verified, including objects needing under-actuation.**

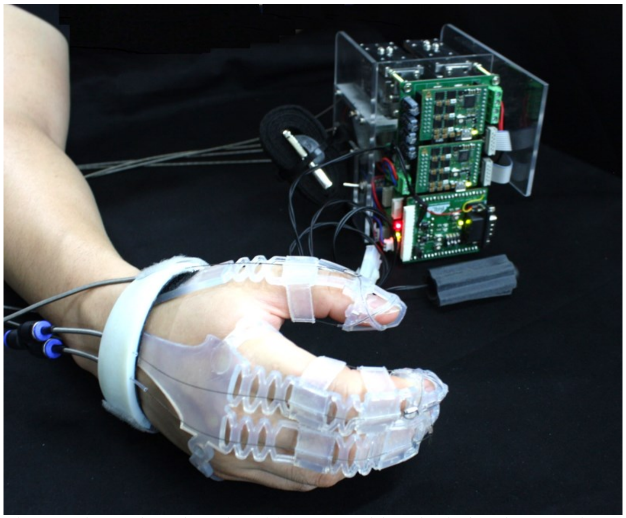

Fig 1. Polymer-based tendon-driven wearable robotic hand (Exo-Glove Poly).

I. INTRODUCTION

Recently, owing to the rapidly increasing number of spinal cord injury [1] and stroke [2] patients, many wearable devices have been developed to assist with activities of daily living (ADLs) or to help rehabilitation. Since the hand is the most important body part with respect to ADLs, many researchers have been developing wearable hand robots for patients with hand motor function impairment. Conventionally, these robots were designed in three ways: a link-based rigid exoskeleton [2-6], a polymer-based soft exoskeleton using pneumatic actuation [7-8], and a fabric-based soft exoskeleton using a tendon drive [9-11].

A link-based rigid exoskeleton has the advantages of easy force transmission and easy control, but the wearable part is bulky because of the need to align robotic joints to the human finger joints. To improve the compactness of the hand-wearable part of the robot, soft exoskeletons made of polymer and fabric have been proposed. The compliant and soft characteristics of soft robots make them easy to customize, to adjust to the user's hand, and to don and doff. On the other hand, the robot's compliance increases the nonlinearity of the system, making such robots complicated and difficult to control.

The soft exoskeleton hand robot also has its pros and cons, according to the actuation method that it uses. A pneumatic-actuated soft exoskeleton is basically manufactured with polymers. The key design issue is how to design and fabricate the air chamber in the pneumatic actuator. Pneumatic actuators are usually placed on the dorsal side of the hand to transmit evenly distributed force on the finger. However, problems remain to be solved for pneumatic-actuated soft exoskeleton robots: They can only perform flexion, and they are not portable owing to the requirement for an air compressor system. A tendon-driven soft exoskeleton based on fabric is portable, but force transmission to the finger is weak. The wearable part is more compact than for pneumatic soft exoskeleton, and portability is ensured because small linear actuators and rotary actuators are adequate for the robot. However, unlike the pneumatic actuator, it is difficult to provide the right amount of force on each finger joint, high wire tension on the tendon is not evenly distributed on the hand. Additionally, the extreme compliance of the fabric used raises extra barriers to overcome in manufacturing, force distribution, and control.

In a previous study, we developed a fabric-based tendon-driven wearable hand robot, Exo-Glove, to assist people with loss of hand mobility to perform ADLs, especially those with spinal cord injury (SCI) at C5 to C7 [11]. Exo-Glove enables the wearer to grasp using only the thumb and the index and middle fingers. The system uses under-actuation to permit the wearer to grasp various objects adaptively and to reduce the number of actuators needed. The robot uses two actuators, one for thumb flexion/extension and the other for index/middle finger flexion/extension. However,

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Exo-Glove has limitations when used in a multiple-user environment such as a hospital because of the difficulty of sanitizing it between uses. The fabric portion of the robot absorbs sweat, but the fabric is not suitable for frequent cleaning. Sanitization is not a problem for solo users, who are using Exo-Glove in daily living as an assistive device.

In this paper, we present a version of the Exo-Glove that uses polymer instead of fabric. This new polymer-based tendon-driven wearable robotic hand, Exo-Glove Poly (Fig. 1), has new design features and a new fabrication process owing to the change of materials. We verified the mechanical performance of Exo-Glove Poly via pressure sensors and a distinctive test set-up using load cells. Successful grasping performance was verified through experiments in which volunteers wearing the robot grasped various objects.

II. EXO-GLOVE POLY

A. *Design Criteria*

As mentioned above, owing to the sanitation problem hospitals prefer wearable robots to be made of polymers rather than fabric. Impurities such as sweat on a polymer-based wearable robot can be cleaned easily by wiping it with an alcohol swab. Thus, Exo-Glove Poly was developed to be a fabric-free soft wearable robotic hand.

Exo-Glove and Exo-Glove Poly differ not only in their base materials but also in terms of design perspective and fabrication process. In Exo-Glove, the compliant fabric is comfortable to wear and adapts easily to different hand sizes. Even though fabric is so compliant that it cannot maintain its structural shape by itself, nevertheless the fabric glove can support all parts of the wire path. Polymer is also compliant, but it has very different material properties.

By choosing the proper compliant polymer as the base material, the hand wearable part of the robot can match the performance of a fabric glove in terms of comfort and ability to support its structural shape. Adaptability to different hand sizes will be obtained through novel design features.

When using fabrics, other components can be easily added by sewing or adhesives. In contrast, because polymer is manufactured by a molding process, adding additional components is not possible. Therefore, all necessary components must be seriously planned for in the design stage.

Moreover, considering the fact that silicon is not capable of ventilation, Exo-Glove Poly should aspire to cover the least amount of area on the hand, consistent with maintaining functionality.

B. *Parts and Materials*

As shown in Fig. 2, the Exo-Glove Poly wearable part consists of a main body, a thumb body, three thimbles, and five straps. These parts are fabricated with silicone (KE-1300 or KE-1300T, Shinetsu). Silicone was also used to build RAPAEL [12], a rehabilitation system with a wearable hand robot that has an embedded bending sensor, from Neofect. The material properties of the silicone are shown in Table 1.

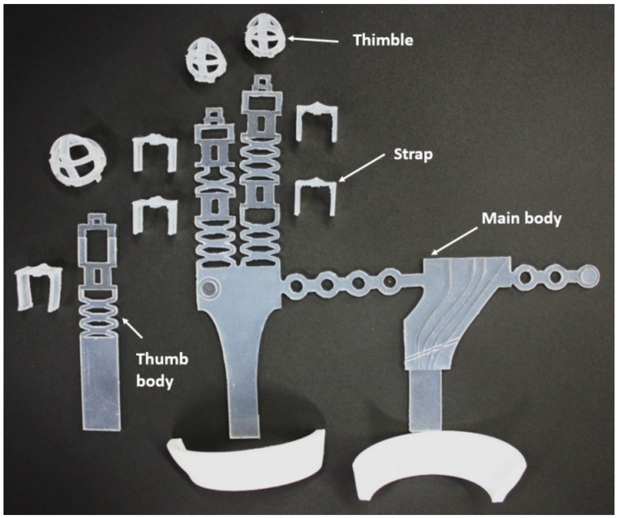

Fig. 2. Components of the wearable portion of Exo-Glove Poly.

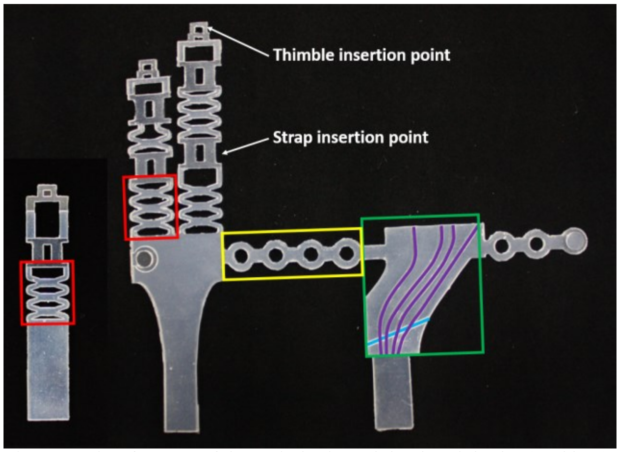

Fig. 3. Design features of the main body and the thumb body. (Red box) Diamond shapes for actuation adjustment and skin protection. (Yellow box) "∞" design conferring stretchability. (Green box) Palmar part with flexion wire paths. (Blue line) Thumb flexion. (Purple lines) Index/middle finger flexion.

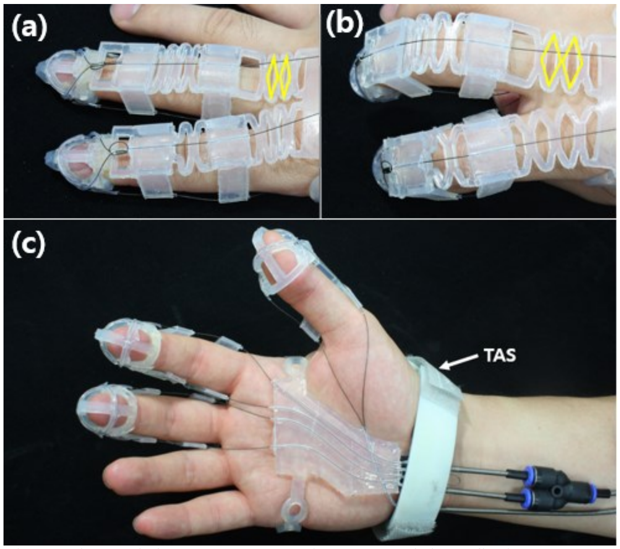

Fig. 4. Diamond shapes (a) at extension state and (b) at flexion state. (c) Flexion wiring of Exo-Glove Poly. TAS, Tendon anchoring support

TABLE I. MATERIAL PROPERTIES OF SILICONE

Property	Typical Value
Shore A hardness	40
Tensile strength (psi)	850
Tear strength (ppi)	125
Density @ 23°C (g/cm3)	1.07
Young's Modulus (MPa)	1.76
Cure conditions	24 hours at 23°C
Colors	Translucent

The wearable part is connected to the actuator unit through a tendon anchoring support (TAS) and sheath. Velcro is used to attach the wearable part to the TAS. The TAS was fabricated with a three-dimensional (3D) printer (Objet Connex 260, Stratasys) using VeroWhite. The TAS was designed to fit the distal part of the wrist joint to enable force transmission of the wire, determine the wire path, and anchor one end of the sheath [13]. The other end of the sheath is anchored to the actuator.

To reduce friction in the wire path, a Teflon tube is embedded into the silicone. A tension spring with a diameter of 2.6mm was used for the sheath. The Teflon tube is also inserted in the sheath to decrease the friction of the wire along the sheath.

C. Main Body and Thumb Body

The wearable part was manufactured as two separate bodies, a thumb body for thumb actuation and a main body for index/middle finger actuation. When designing the body design, three features were considered.

The first design feature is the diamond shapes between the straps and the thimble (Fig. 3, red box), which have two functions. One is to create an extendable design that permits adjustment of the distance between the straps and the thimble during actuation and that accommodates different finger lengths. The other function is to prevent skin abrasion during actuation caused by contact between the wire and skin. These functions can be seen in Fig. 4 (a, b).

The second design feature is embedded Teflon tubes that determine the wire path on the palm of the hand (Fig 3, green box). The wire paths were designed in two layers, one for thumb flexion (Fig. 3,blue line) and the other for index/middle finger flexion with under-actuation (Fig. 3, purple lines). Also, to avoid disturbing thumb movement, the index/middle finger flexion wire paths were curved. Owing to the curved two-layer wire paths, the Teflon tubes could not be embedded during the molding process. As a counterplan, the tubes were embedded in concave paths on the main body. Four concave paths for under-actuation of index/middle finger flexion was designed on the top side and another single concave path was designed for thumb flexion on the bottom side of the main body. After the main body was molded-in, Teflon tubes were placed on the concave paths and additional silicone was plastered on.

The third design feature is the "∞" shape design (Fig. 3, yellow box). This shape was chosen because it is stretchable, which enables Exo-Glove Poly to adjust to different palm girths.

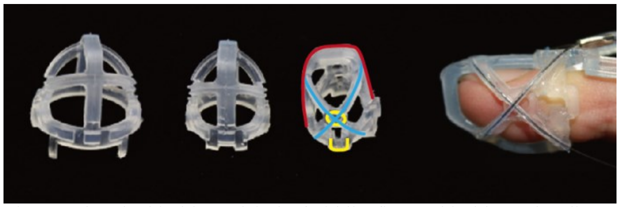

Fig. 5. Thumb thimble and index/middle finger thimble. (Blue lines) Cross-shaped end where teflon tubes are embedded. (Red line) Reinforcing silicon bar. (Yellow lines) Design for adjusting to different sizes of fingertip.

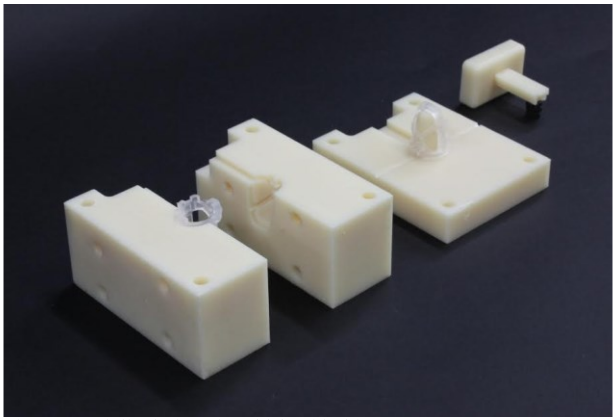

Fig. 6. Specially designed mold for thimble.

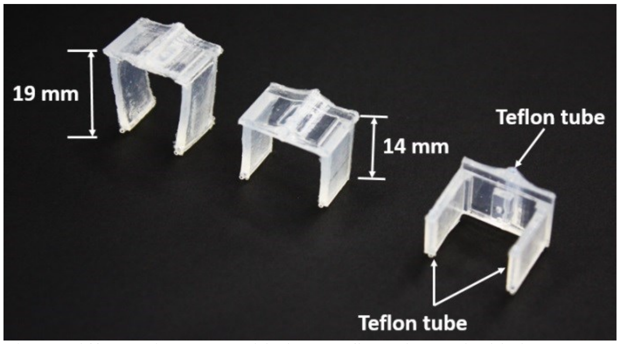

Fig. 7. Different size straps with three Teflon tubes embedded.

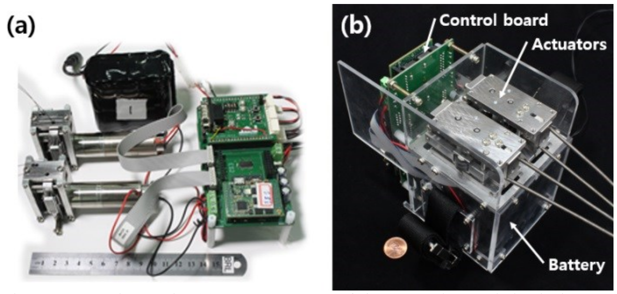

Fig. 8. Actuation unit. (a) Components of the actuation unit include two actuators, a control board, and a battery. (b) Assembled actuation unit.

D. Thimble

Using silicone instead of fabric imposed three design constraints on the thimble. First, for ventilation of the finger, the thimble should have minimum coverage area on the fingertip. Second, two Teflon tubes must be embedded into the thimble. One tube is the wire path for the under-actuation flexion wire, which requires low-friction wire movement through the thimble. The other tube is for extension wire fixation. The thimble's Teflon tubes reduce wire friction and protect the silicone from being ground by wire during actuation. Third, because silicone is not capable of ventilation, Exo-Glove Poly must have minimum coverage area on the hand, which means that it cannot be shaped like a glove. To fix one end of the wire to a fingertip, the thimble has to fit tightly to the finger or else the wire path will change during actuation.

To fulfill all these design criteria, the thimble includes three special features (Fig. 5). The first feature is a cross-shaped silicone part that determines the wire paths. Two concave paths were designed on this cross-shaped silicone (Fig. 5, blue lines) to allow easy embedding of Teflon tubes. After the thimble is molded-in, Teflon tubes were placed along the concave paths and additional silicon was plastered along the tubes to fix them to the thimble. Second feature is a reinforcing silicone bar along the sagittal plane of the finger (Fig. 5, red line). The main function of this bar is to maintain the thimble shape and the wire paths during actuation. The third feature is a circular shape and a "U" shape on the side of the thimble (Fig. 5, yellow lines). These shapes enable the thimble to adjust to various sizes and shapes of fingertips.

Owing to the complicated design of the thimble, especially the undercut design, the mold was specially designed to have four pieces, just like in 3D puzzles (Fig. 6).

E. Straps

Main function of the strap is to determine the flexion wire path and the extension wire path. Determining the flexion wire path defines the size of the moment arm between the wire and the finger joint, which affects grasping performance. The robot has straps of two different lengths, 14mm and 19mm (Fig. 7).

Since the Teflon tubes in the straps have a straight path and need to bear wire tension, the tubes were inserted into the mold and embedded during the molding process. The straps also need to be as thin as possible to avoid colliding with the adjoining fingers.

F. Actuator Unit

The actuator unit consists of two actuators (DCX22, 24V, 20W, Maxon), a control board, and a battery (Fig. 8). One actuator is for thumb flexion/extension, and the other is for index/middle finger flexion/extension. Each actuator is designed to push and pull a flexion wire and an extension wire antagonistically using an upgraded version of a slack prevention actuator [14-15]. For the control board, TMS320F2808 (Texas Instruments) was used for the processor, and an embedded coder with Simulink (Mathworks) was used as software. A lithium-ion battery with 28.8V, 2200mAh was used. The actuator unit size is 86mm x 145mm x 130mm, and the total weight of the actuator unit is 1.63kg.

G. Control Input

Considering the fact that the user of Exo-Glove Poly is a patient with impaired hand motor function, it is important to keep control input simple. In a previous study, a bending sensor on the wrist was used as control input [11]. This design was inspired by the tenodesis effect, which is the occurrence of finger flexion with wrist extension. However, after performing usability evaluations of different control inputs, including an analog switch, electromyography (EMG), and a bending sensor on the wrist with SCI patients, patients and the researchers felt that the analog switch was the easiest way to control the robot. EMG signals were not easy to detect owing to the degraded arm muscle of SCI patients. The bending sensor using the tenodesis effect was uncomfortable because the wrist had to be kept extended to actuate the robot. Therefore, Exo-Glove Poly decided to use a simple button as control input.

III. PERFORMANCE

A. Wrap Grasp Force

Wrap grasp is the most commonly used motion for grasping large and heavy objects. The experiment was conducted with a healthy subject wearing Exo-Glove Poly. The subject was assigned to grasp three different cylindrical objects with different diameters (Fig. 9). To verify the performance of the wrap grasp, a mat-type pressure sensor (160 x 160mm^2 sensor; Pliance Hand Mat Sensor, Novel Inc., Germany) was used. Fig. 10 shows the test set-up using the pressure sensor and different cylindrical objects.

Experimental results are shown in Fig. 11. In each case, the white dots on the thumb indicate the areas of highest pressure during grasping. The sum of all the normal forces during grasping was 20.4N, 29.5N, and 18.8N for the 50mm, 75mm, and 100mm objects, respectively. Even though the largest object is associated with the highest maximum pressure, the sum of all the normal forces was smaller than the sums for the other objects, because the largest object was too big to allow the palm to be used during grasping. Considering the fact that the forces applied to the objects were all normal and assuming the friction coefficient between Exo-Glove Poly and the objects is 0.5, we expect that a cylindrical object of about 1kg can be held, regardless of its size.

B. Under-Actuation Performance

To evaluate under-actuation performance during grasping, an individual test set-up was built as shown in Fig. 12. Two load cells (333FB Cell, Ktoyo Co., Ltd., Korea) were mounted on specially designed cylindrical rods made by a 3D rapid prototyping machine (3Dison, Rokit Co., Ltd., Korea) to have different gaps. These rods were mounted with load cell gaps of 0mm, 10mm, and 20mm (Fig. 13). The experiment was designed to have maintain the same index finger position while the middle finger flexes as the load cell gap increases. The expected results of this under-actuation performance test were to see increasingly delayed response times of the load cells as the gap increases and to have an evenly distributed force output. For each case, the under-actuation performance test was conducted three times with a healthy subject. The results are shown in Figure 14.

In Fig. 14, first three curves show the data for the 0mm gap, the middle three curves show the data for the 10mm gap, and the last three curves show the data for the 20mm gap. In the graph, as the gap increases, we can see that the middle finger response is gradually delayed, which shows the performance of under-actuation. However, the force outputs for each case show that force is not equally distributed. The main cause of this phenomenon is friction along the actuation wire. Despite

Fig. 9. Objects used for the wrap grasp force experiment.

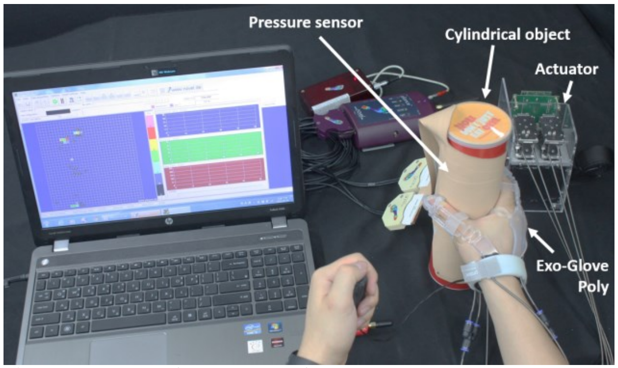

Fig. 10. Test set-up for wrap grasp force.

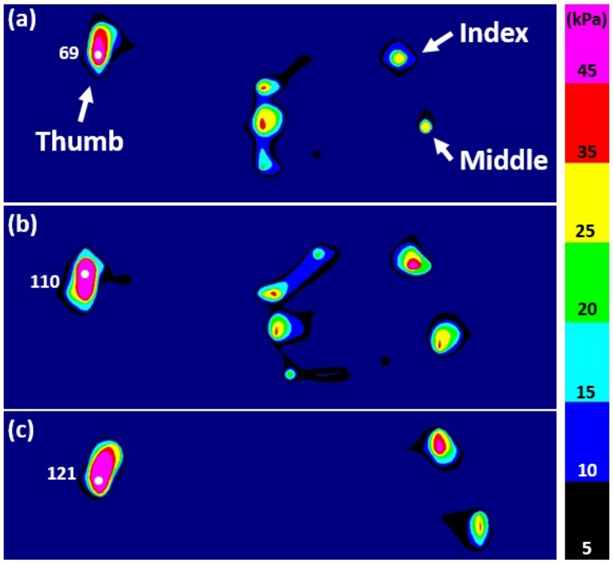

Fig. 11. Results of the pressure distribution experiment for objects with diameters of (a) 50mm, (b) 75mm, and (c) 100mm.

the care taken to embed Teflon tubes in all the wire paths, friction by curvature of the under-actuation wire path still hinders smooth under-actuation performance.

C. Grasping Various Objects

The last experiment was conducted with a healthy subject who grasped a variety of objects: a) wine glass, b) tennis ball, c) clamp, d) golf ball, e) banana, f) cylindrical object, g) small box, and h) spray bottle (Fig. 15). Objects were selected to include different shapes of object and different sizes of objects with the same shape, and two objects that require under-actuation in order to be grasped (clamp, spray bottle). The subject was asked to voluntarily change the orientation of the hand and arm path according to the state of the objects.

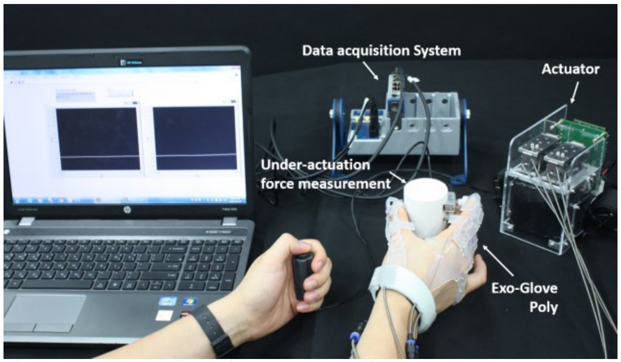

Fig. 12. Test set-up for under-actuation performance.

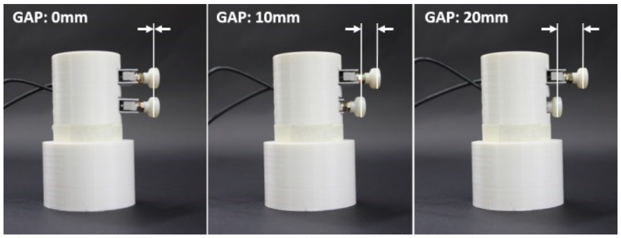

Fig. 13. Load cell settings on 3D-printed cylindrical rods.

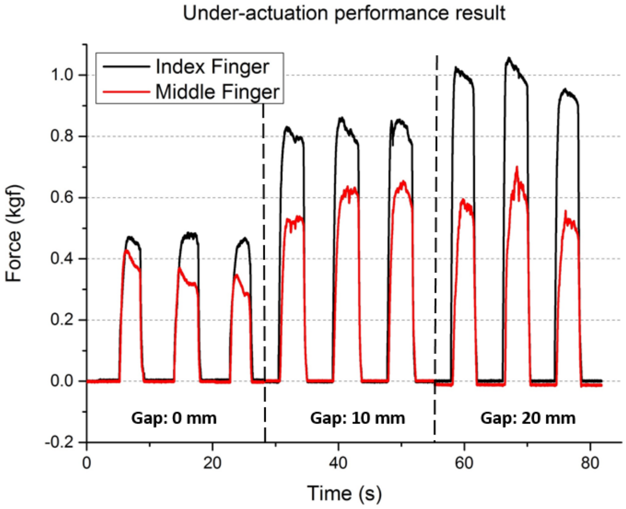

Fig. 14. Results of the under-actuation performance experiment.

Simple actuation control and under-actuation allowed the subject to grasp all the objects in a first trial without any practice. Fig. 15 shows the grasp of various objects with Exo-Glove Poly.

IV. DISCUSSION & CONCLUSION

A polymer-based tendon-driven soft wearable robotic hand, Exo-Glove Poly, was proposed and detailed design features of the components were described. Exo-Glove Poly uses silicone as its base material to fulfill the sanitation requirements of hospitals and other multiple users. Since Exo-Glove Poly does not use any fabric, it can be easily cleaned by wiping with an alcohol swab.

Unlike the fabric-based tendon-driven wearable robotic hand, Exo-Glove, adaptability to different hand sizes and actuation were accomplished through detailed design features and fabrication processes, not with material compliance. Moreover, Exo-Glove Poly includes design features that protect users from injury from exposed wires during actuation.

Fig. 15. The grasping posture with various objects: (a) wine glass, (b) tennis ball, (c) clamp, (d) golf ball, (e) banana, (f) cylindrical object, (g) small box, (h) spray bottle. (See attached video)

Mechanical performance of Exo-Glove Poly was verified through a wrap grasp experiment and an under-actuation experiment. The wrap grasp experiment results showed that Exo-Glove Poly is capable of holding objects weighing 1 to 1.5kg. The under-actuation experiment showed great performance in adaptability and good force distribution. Even though the Teflon tubes were embedded in all wire paths, friction along the actuation wire was not avoidable due to the curved path.

Following successful verification of the mechanical performance of Exo-Glove Poly, performance of Exo-Glove Poly was tested with various kinds of real-life objects. Exo-Glove Poly was successful in grasping objects with ball, box, and cylindrical shape and objects that need under-actuation while grasping, such as spray bottle and clamp.

The main goal of Exo-Glove Poly is to provide a soft and safe wearable robotic hand with a compact, lightweight, ergonomic design. To satisfy these goals, the wearable part needs to be as thin as possible so that users feel as if they are not wearing a robot while grasping. Additionally, designing the silicone wearable part to withstand larger wire tension may potentially increase the ability of Exo-Glove Poly to grasp even more varied objects.

Future goals for Exo-Glove Poly include experiments to find optimal design parameters based on the material properties of each component. Another challenge is to fully cover the flexion wire to protect users from injury during actuation. Also, additional research is needed in fabrication processes, such as embedding curved Teflon tubes in silicone during the molding process or applying other mechanical components to the silicone. But in particular, trials with patients who have lost their hand motor function involving use of Exo-Glove Poly will be pursued.

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