A Hybrid, Soft Exoskeleton Glove Equipped with a Telescopic Extra Thumb and Abduction Capabilities

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Abstract— **Over the last years, hand exoskeletons have become a popular and efficient technical solution for assisting people that suffer from neurological and musculoskeletal diseases and enhance the capabilities of healthy individuals. These devices can vary from rigid and complex structures to soft, lightweight, wearable gloves. Despite the significant progress in the field, most existing solutions do not provide the same dexterity as the healthy human hand. In this paper, we focus on the development of a hybrid (tendon-driven and pneumatic), lightweight, affordable, wearable exoskeleton glove equipped with abduction/adduction capabilities and a pneumatic telescopic extra thumb that increases grasp stability. The efficiency of the proposed device is experimentally validated through three different types of experiments: i) abduction/adduction tests, ii) force exertion experiments that capture the maximum forces that can be applied by the proposed device, and iii) grasp quality assessment experiments that focus on the effect of the inflatable thumb on enhancing grasp stability. The hybrid assistive glove considerably improves the grasping capabilities of the user, being able to exert the forces required to assist people in the execution of activities of daily living.**

I. Introduction

The human hand plays a vital role in the way humans interact with the environment surrounding them. Many neurological and musculoskeletal diseases can reduce the mobility of the human hand, such as multiple sclerosis, arthritis, spinal cord injury, and stroke. The rehabilitation process of impaired people depends on the repetition of movements performing activities of daily living (ADLs) [1], [2]. Multiple hand exoskeletons have been proposed over the last years to assist patients with hand impairment during physical therapy or to augment the capabilities of healthy users [3], [4]. Although the robotic exoskeleton gloves currently found in the literature can assist impaired people, they still have limited dexterity. Most of the devices cannot replicate all the hand motions performed during ADLs. In [5], the authors describe the variety of grasps that the human hand can execute and classify them based on the position of fingers and palm relatively to the object.

Finger abduction is one of the most important motions that the majority of soft robotic gloves cannot execute. More than 50% of the types of grasps require thumb abduction [5], and the abduction of the other fingers are necessary to grasp objects of different sizes and shapes [6]. Also, exercises involving abduction/adduction of the fingers and thumb opposition are vital for the rehabilitation programme of impaired hands [7]–[12].

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Fig. 1. The hybrid robotic glove is equipped with a cable-driven system for finger flexion, pneumatic actuators for finger abduction, and an inflatable, telescopic extra thumb for grasp quality enhancement. The soft glove is connected to the control box that houses the actuators that control the motions of the robotic device.

The quality and stability of grasps are directly related to the hand's ability to constrain efficiently the object motion. An effective grasp is characterized by the ability of the hand to withstand external disturbances while maintaining stable object contact. In general, a hand can grasp a given object in multiple ways. According to [13], the number of contact points and their distribution while grasping an object give a good measure of the grasp quality. The Grasp Wrench Space can be described as the largest perturbation wrench the grasp can resist in any direction [13]. The higher the volume of this grasp wrench space, the better the grasp. Geometrically, the quality of the grasp is equivalent to the radius of the largest ball centered at the origin of the wrench space and fully contained inside the grasping area [14]. Thus, methods that better distribute or increase the number of contact points between the hand and the object, improve also grasp quality.

The actuation types of robotic exoskeletons range from rigid structures that use linkage systems to transmit forces [15], to soft gloves equipped with cable-driven systems [16], [17], and soft inflatable structures that bend the fingers employing pneumatic systems [18]–[20]. In [4], the authors provide a detailed review of soft robotic devices for hand rehabilitation and every day life assistance. Soft pneumatic gloves benefit from their inherent compliance that allows them to actuate the fingers in a graceful manner and grasp

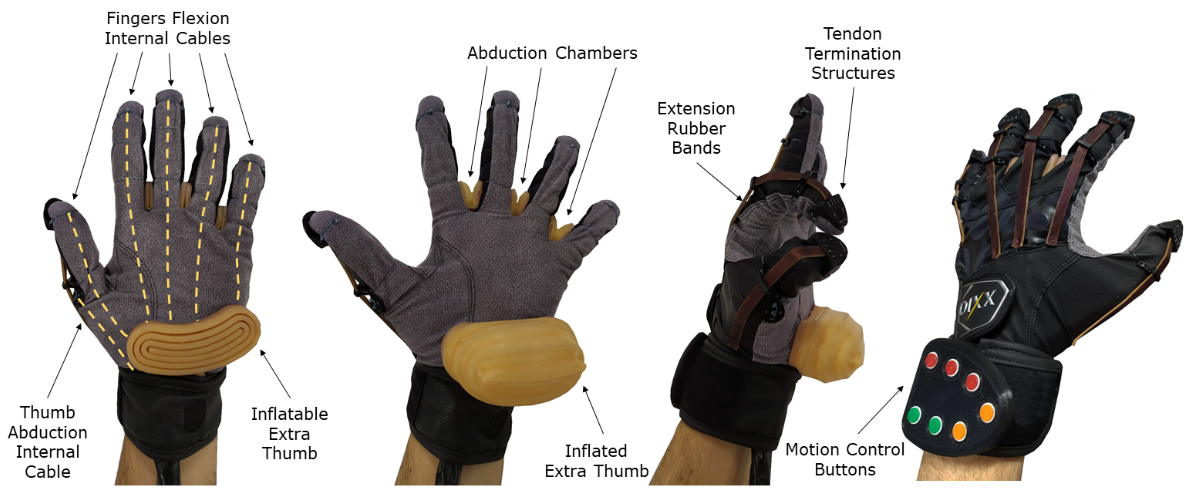

Fig. 2. The soft glove is tendon-driven and it employs six artificial tendons and a pneumatic system that consists of four soft actuators. Artificial tendons connect the actuators with the tendon termination structures at the tips of the fingers and an extra tendon is terminated at the thumb's interphalangeal joint region. Three of the pneumatic chambers are designed for the execution of the abduction/adduction motion of the fingers. The fourth soft actuator was designed to act as a telescopic extra thumb that participates in grasping tasks, increasing the area of the contact patches between the hand and the object and increasing both grasp efficiency and stability. At the back of each digit, an elastic band was added to implement a passive extension of each finger. The control buttons at the back of the hand palm allow the user to control which motions she/he wants to execute with the exoskeleton glove. An Electromyography (EMG) sensor is used to trigger the execution of the selected grasping motion when significantly high muscular activity is detected.

objects both stably and delicately. Also, inflatable structures can easily control multiple degrees of freedom (DOFs) with a single control input. However, soft pneumatic gloves suffer from several disadvantages, such as bulkiness of the soft actuators, leakages, and difficulty in controlling the amount of force being exerted by the device [16]. Meanwhile, cable-driven systems allow for reduced weight and increased compactness of the glove system [21]. The actuation and control units of such devices are more portable, and higher contact forces can be more easily achieved compared to the pneumatic solutions. Also, tendon-driven robotic gloves are generally lighter than soft pneumatic gloves, according to the comparison of devices performed in [4]. Tendon-driven robotic gloves also have several disadvantages. For example, they exhibit limited dexterity since they employ a limited number of actuators (e.g., a single actuator) to control independently multiple DOFs. Both types of assistive gloves have been shown to assist people who suffer from hand paralysis to execute ADLs [22], [23]. For this reason, in this work, a hybrid, robotic exoskeleton glove is proposed that combines the best characteristics of each actuation type: the compactness and high forces of tendon-driven systems and the compliance and conformability of soft actuators.

In this paper, we focus on the development of a hybrid, soft, robotic exoskeleton glove (Fig. 1) that is equipped with abduction capabilities and a telescopic extra thumb that increases grasp stability. The hybrid device is experimentally evaluated using three types of experiments: i) abduction/adduction experiments that evaluate the efficiency of the pneumatic actuators and the proposed abduction structures, ii) force exertion experiments that assess the maximum forces that can be exerted by the proposed exoskeleton glove, and iii) object stability tests that assess the effect that the inflatable extra thumb structure has on the grasp quality.

The rest of the paper is organized as follows: Section II presents the design of the soft exoskeleton glove and the modelling and design of the soft actuators, Section III details the experimental setup used and presents the results, while Section IV concludes the paper and discusses some possible future directions.

II. Designs and Modelling

In this section, we present the design and modelling of the hybrid, soft robotic exoskeleton glove, discussing also its functionalities and operation.

A. Hybrid Robotic Exoskeleton Glove

The hybrid, robotic exoskeleton glove that is presented in this paper has been designed to assist an impaired human hand during the rehabilitation process and increase the manipulation capabilities of all hands, facilitating object grasping for both impaired and able-bodied people.

The device is composed of two main systems: the soft exoskeleton glove and the control box. The control box is composed of five Dynamixel XM430-W350-T motors, two mini 12V air pumps, two solenoid valves, a microcontroller (Robotis OpenCM9.04), a Li-Po battery, and a small circuit to control the air pumps. All six tendons are connected to the pulleys of the motors and run though polyurethane tubes that are used for tendon routing from the control box to the soft glove. The ring and pinky fingers are connected to the same motor since these fingers have a supplementary role during object grasping [24]. Another two tubes connect the air pumps to the abduction motion and the inflatable, telescopic thumb. The soft glove system of the device is composed of a thin, high sensibility glove, a tendon-driven system that consists of six artificial tendons, a pneumatic system that consists of four soft actuators, five elastic bands

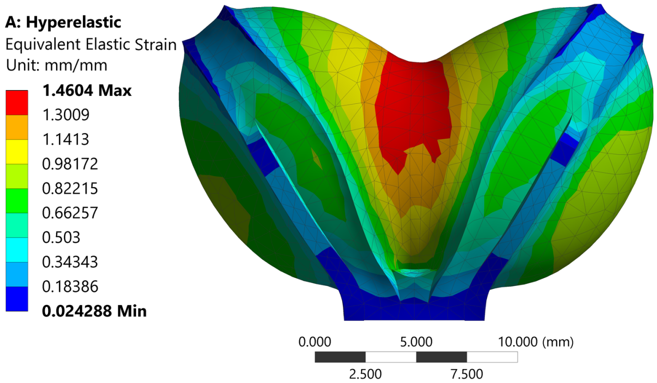

Fig. 3. FEM analysis of the soft actuator that is employed for the execution of the abduction motion of the fingers at a pressure of 70 kPa. The maximum strain takes place in the interface between the two lateral walls of the actuator.

that facilitate passive extension of the fingers, and control buttons at the back of the hand. Five plastic tendon termination structures are stitched onto the fingertips of the glove. Soft anchor points have been added in the glove structure for rerouting the tendon (that is connected to the tendon termination structure), as shown in Fig. 2. Soft anchors offer better sensibility of the grasped objects than the rigid anchor points. The soft anchors have been positioned according to the findings reported in [21]. A tendon-driven solution for the thumb abduction was chosen over a soft actuator based solution in order to avoid the obstruction of the region between the index and the thumb, as many different grasps types require the object to be positioned in-between the thumb and the index metacarpophalangeal joints (in the human hand purlicue area). The artificial tendons used in the tendon-driven system of the proposed exoskeleton glove, are made out of a low friction braided fiber of high-performance UHMWPE (Ultra-High Molecular Weight Polyethylene) and can withstand a pulling force of 500 N.

The soft actuators are used for two different purposes, to allow for the execution of abduction / adduction motions of the fingers and to increase grasp stability by activating a telescopic extra thumb that provides grasp support. Three pneumatic chambers have been developed with a "V" shape, and they have been fixed in the region in between the fingers to facilitate the execution of the abduction motion of the fingers, as shown in Fig. 2. The human hand is naturally adducted, for that reason, the actuator was designed to provide active assistance on finger abduction and passive on finger adduction. The soft actuators that have been designed are described in the following subsections. At the back of each digit, an elastic band has been added to keep the hand in its natural pose (zero-effort pose), extending the fingers when the tendons return to the initial position and the tendon is slack. The control buttons attached at the back of the hand allow the user to control which motions she/he wants to execute (e.g., flexion of specific fingers, opposition of the thumb or inflation of the extra thumb). The particular motion is triggered by the myoelectric activation of the human forearm flexor muscles (*Flexor Digitorum Superficialis* area) that is detected and decoded using an appropriate surface Electromyography (EMG) sensor.

The operation of the device is straightforward. Initially, the user selects which motions will be executed by pressing the control buttons located at the back of the hand. Then, after approaching the object, the user tries to execute the grasp. The EMG sensor board: i) detects appropriate muscle activities that are related to grasping, ii) filters, rectifies, and computes the envelope of the signals by integrating them, and iii) sends them to the microcontroller, triggering the system's actuation via simple thresholding. The EMG sensor (MyoWare muscle sensor) is only used for triggering the system. If the muscle activity sensed is below the threshold, the motors remain still. However, when the muscle activity sensed is above the set threshold, the motors start moving, tensioning the tendons, and inflating the soft actuators, facilitating the execution of stable grasps. The amount of force applied by each finger is determined through a current control of each motor and can be adjusted according to the user's needs (the motor control details can be found in [25]).

B. Soft Actuator Model for Abduction / Adduction

The proposed robotic exoskeleton glove contains three soft pneumatic actuators that execute the abduction and adduction motions of the fingers. These actuators are made out of urethane rubber (Smooth-On Vytaflex 40), and they are inspired by the open-source designs found in the Soft Robotics Toolkit [26]. The correct estimation of the limits of the soft actuator in terms of force and motion capabilities is highly important in order to design the best actuator that fits the selected grasping requirements. For this reason, a finite element method (FEM) model was developed to estimate the performance of the actuator according to the available air pressure of the system. Similar structures, like soft reinforced actuators for finger flexion, have been previously modeled [27], [28]. The proposed abduction / adduction actuator can be modeled using the Mooney-Rivlin model for hyperelastic structures [29]. The strain energy density W of the model can be written as:

$$W = C_1(I_1 - 3) + C_2(I_2 - 3) + \frac{1}{D_1}(J_{el} - 1)^2, \qquad (1)$$

where C_1 and C_2 are the materials constants, I_1 and I_2 are the strain invariants, J_{el} is the elastic volume ratio, and D_1 is the material constant that controls bulk compressibility. Assuming the incompressibility of the urethane rubber for this model, the third term of Eq. 1 is discarded. In this simulation, the following values were adopted: $C_1 = 0.076$ MPa and $C_2 = 0.022$ MPa. The FEM analysis was performed using ANSYS Workbench 18.2 computer-aided engineering (CAE) software. In this simulation, all the internal walls were pressurized while the base nodes were constrained. Fig. 3 demonstrates the results for free motion and maximum strain at a pressure of 70 kPa. When the lateral walls are constrained, the maximum pressure that the system can withstand is much higher (as described in Section III-A).

In order to validate the FEM model, the abduction angles of the actuator obtained during the FEM analysis for multiple pressures were compared to the abduction angles of the physical prototype that we collected during actual experiments. The results are shown in Fig. 4. The behaviour of the FEM model is similar to the soft actuator, however, the experimental angle values are slightly smaller than the FEM model. This is probably due to inaccuracies during the fabrication process, which can change the material properties (e.g., varying mix ratios of liquid parts, contamination, stiffness variations due to sub-optimal curing conditions). After experimental validation (see Fig. 4), the FEM model can be used to improve the design of the actuator, testing multiple materials and geometries (for future design iterations), without requiring the manufacturing of physical prototypes.

C. Soft Telescopic Actuator

The soft telescopic, extra thumb actuator is based on a urethane rubber (Smooth-On Vytaflex 40) structure designed for grasping assistance during the execution of ADLs. The foldable structure was designed in such a way that it does not influence grasps that do not require an extra thumb due to its small thickness and telescopic behaviour. The rounded shape of the actuator was chosen so as to maximize the size of the objects that could be grasped by employing the actuator. The actuator operates at a pressure of 20 kPa, weighs 18 g, is 10 mm thick, and 80 mm long. The manufacturing process of the telescopic actuator involves three different molding steps. Fig. 5 illustrates the steps required to manufacture the actuator. Initially, the foldable part and the base layer of the actuator are fabricated. The base layer is 2 mm smaller than the upper part in all directions so that they can be molded together. After both parts are cured, a third mold is used to combine the upper part and the base layer part, filling the remaining gaps between the two parts and bonding them together. This technique avoids leakages and deformations in the actuator. Although having a thick elastomer base, a fabric layer can be added to the base to restrict the extension of the actuator along the base axis.

The soft telescopic extra thumb has been designed to increase the stability and quality of the grasps being executed with the proposed soft exoskeleton glove. Extra robotic fingers that are connected to the human hand have been proved to be an efficient solution for increasing the grasping capabilities and dexterity of impaired people [30], [31]. The assessment of the role of this mechanism on the robotic glove can be performed through a grasp quality analysis. A popular grasp quality measure discussed in [13], is based on the area of the grasp polygon generated by the contact points between the object and the hand. In order to achieve a robust grasp that can resist large external torques, the grasp should maximize the area of the grasp polygon. Thus, the grasp quality Q_{AGP} can be expressed as:

$$Q_{AGP} = Area(Polygon(p_1, p_2, p_3, \ldots, p_n)) \tag{2}$$

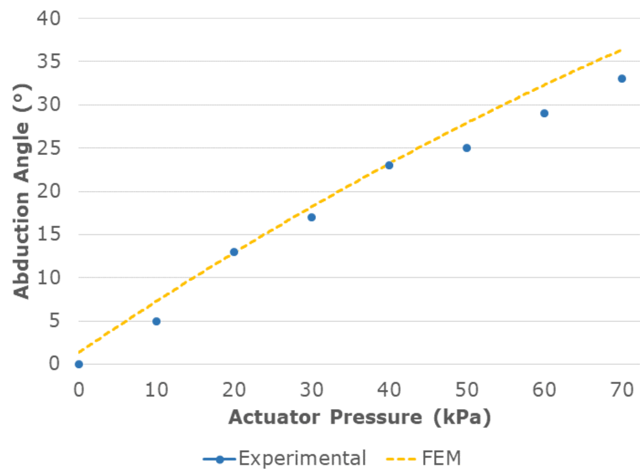

Fig. 4. Abduction angles of the actuator obtained during the FEM analysis for multiple pressures compared to the experimentally measured abduction angles of the physical prototype. The results demonstrate a similar abducting behaviour for the model actuator and the actual soft actuator.

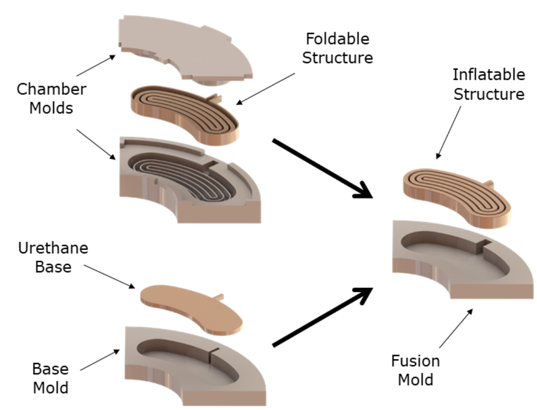

Fig. 5. The manufacturing process of the inflatable thumb (made out of Smooth-On Vytaflex 40 silicone rubber) involves the following three molding steps: i) the foldable part of the actuator is fabricated using two molds, ii) the base layer is fabricated using a third mold, with the base layer being 1.5 mm thick and 2 mm smaller than the foldable part in all directions (so that they can be molded together), iii) after both parts are cured, a fourth mold is used to combine the upper and the base layer parts.

III. Experiments and Results

The experiments that were conducted to assess the performance of the robotic glove were divided into three parts. The first part focused on evaluating the use of the soft actuators for executing the abduction / adduction motion of the fingers. The second experiment assessed the forces that the device is capable of exerting. The third experiment focused on verifying the benefits of the telescopic, extra thumb structure in enhancing grasping quality and stability. The characteristics of the developed soft exoskeleton glove are reported in Table I.

A. Abduction/Adduction Experiment

The first experiment was conducted to evaluate the mechanisms that execute the abduction / adduction motion of the fingers. This experiment focuses on the amount of abduction force that each mechanism can exert and on the values of the

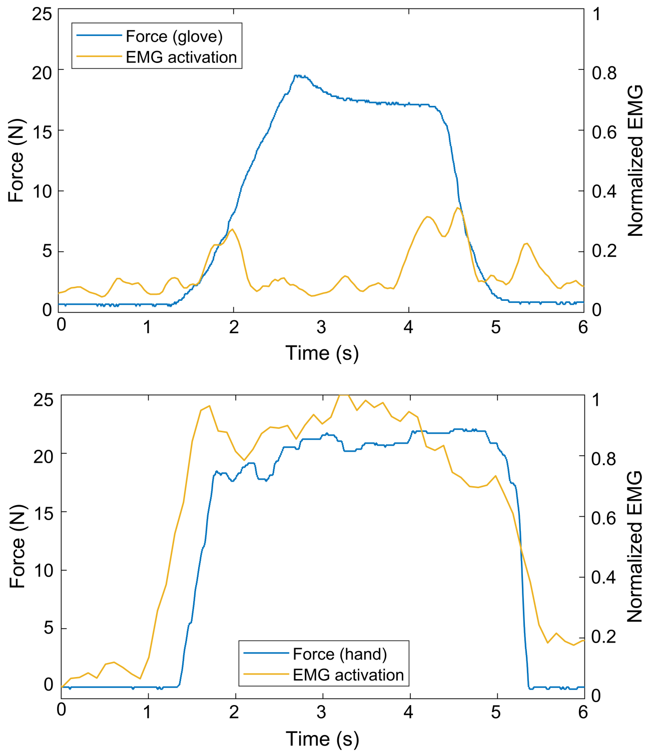

Fig. 6. EMG sensors were attached to the forearm of the subject to monitor the muscle activity and guarantee that no involuntary forces were exerted while grasping the dynamometer. The first experiment (top) assessed the force that the robotic glove could exert without a voluntary human participation. It can be noticed that while increasing and decreasing the force exerted, the subject's hand exerted involuntarily resistive forces that act against the motion of the glove. This does not significantly affect the maximum forces exerted because when the forces are constantly high, the muscle activation is minimal. The second experiment (bottom) assessed the muscle activity of the subject while exerting similar forces without the assistance of the robotic glove. It can be noticed that while exerting high forces of similar magnitude (about 20 N), significant muscular effort can be observed. Thus, the forces measured during the first experiment (top plot) were a result of the exoskeleton glove's force exertion capabilities.

TABLE I
SUMMARY OF THE CHARACTERISTICS OF THE HYBRID, SOFT, ROBOTIC EXOSKELETON GLOVE.

Description	Value
Power grasp maximum force	19.5 N
Pinch grasp maximum force	12.4 N
Maximum abduction force	15.8 N
Abduction actuators width	8 mm
Extra thumb thickness	10 mm
Glove weight	90 g
Total robotic glove weight (including glove)	1120 g

achievable abduction angles. The abduction force experiment involved the application of pressure to the soft actuator while employing rigid lateral walls to constrain its lateral motion. A calibrated force-sensing resistor (402-Round sensor, Interlink Electronics, USA) was placed between the actuator and one of the walls to measure the abduction force that the actuator can exert. The maximum force obtained was 15.8 N at a pressure of 130 kPa, which is within the range of abduction forces that the human finger can exert [32].

Fig. 7. Grasping experiments executed with five different everyday life objects while the subject was wearing the proposed soft exoskeleton glove. The soft telescopic extra thumb module is employed in most cases with the exception of the golf ball that is very small and requires a tripod grasp.

TABLE II
MAXIMUM ABDUCTION ANGLES ACHIEVED FOR EACH FINGER BY THE SOFT ACTUATOR THAT IS RESPONSIBLE FOR THE EXECUTION OF THE ABDUCTION MOTION.

Abduction Region	Angle
Thumb/Index	73°
Index/Middle	34°
Middle/Ring	31°
Ring/Pinky	30°

The abduction angle experiment measured the finger abduction angles wearing the proposed hybrid robotic glove. For the fingers, the experiments consisted of placing the hand flat on the table surface and inflating the abduction actuators separately until a steady condition was reached (at which an increase in pressure does not generate any motion) and the angles between consecutive fingers were measured using a specialized joint goniometer. For the thumb, the tendon was pulled until the steady condition was reached, and the abduction angle was measured. The results obtained for this experiment are reported in Table II. The results demonstrate that the abduction system can assist the user in abducting the fingers in an efficient manner. The abduction angles are similar to the values found in the literature for safe abduction of the human fingers, approximately 25° for other fingers and 70° for the thumb [6]. Thus, the proposed device can assist finger abduction with a similar range of motion to the human hand. The limitation of this type of solution is that the soft actuator that has been employed for executing the fingers abduction is significantly thick, not allowing consecutive fingers to touch each other. More precisely, the soft actuator structure constraints the fingers to be separated by at least 8 mm (the width of the actuator unit when it is not inflated).

B. Grasp Force Experiment

The second experiment focused on measuring the maximum forces that the device can apply to grasp objects. In this experiment, a Biopac MP36 data acquisition unit (Biopac Systems, Inc., USA) was used with the SS25LA dynamometer to measure the forces exerted during pinch and power grasps. EMG sensors were connected to the forearm of

TABLE III

RATIO BETWEEN THE GRASP QUALITY MEASURE VALUES FOR 13 EVERYDAY LIFE OBJECTS IN TWO DIFFERENT SCENARIOS: GRASP ASSISTED BY THE EXTRA THUMB (Q_{glove}) AND GRASPING WITHOUT ASSISTANCE (Q_{hand}). THE RATIO VALUE DENOTES HOW MANY TIMES THE GRASP QUALITY GETS IMPROVED WHILE WEARING THE GLOVE.

Object	Q_{glove}/Q_{hand}	Object	Q_{glove}/Q_{hand}
Banana	2.08	Mustard Bottle	2.16
Bleach Bottle	1.96	Plate	1.85
Softball Ball	1.88	Drill	1.72
Golf Ball	1.00	Hammer	1.90
Cracker Box	2.07	Jelly Box	1.61
Can	1.88	Pear	2.11
Cup	1.00	**Mean**	**1.78**

the subject (*Flexor Digitorum Superficialis* area) to monitor the muscle activity and guarantee that the subject was not exerting any kind of involuntary forces while grasping the dynamometer. The forces exerted and the corresponding myoelectric activations during task execution with and without the soft exoskeleton glove can be found in Fig. 6. During the experiment, the forearm was placed on the table surface to keep the hand still, and the system was actuated until the torque limit of the motors was reached (3.8 N.m). Six trials were recorded and the maximum force obtained in each scenario is found in Table I. According to [33], the required force to grasp objects during ADLs does not exceed 15 N, and the pinch forces required to execute most of the daily life tasks are lower than 10.5 N [34]. Thus, the proposed soft robotic glove can exert enough force to stably grasp everyday life objects (see Fig. 7), and these forces are similar to most of the devices found in the literature [4].

C. Grasp Quality Experiment

The third experiment focused on evaluating the effect of the soft telescopic extra thumb on grasping objects. In total, 13 different objects were grasped. All daily life objects used in this experiment were selected from the Yale-CMU-Berkeley (YCB) object set [35], an object set designed for facilitating benchmarking in robotic manipulation and grasping. After grasping each object, the area of the polygon generated by the geometric center of the contact regions (approximate contact point) was calculated to be used as input to the grasp quality measure. Pictures were taken after each grasp perpendicularly to the hand palm to determine the area of the polygon generated by the contact points between the objects and the robotic glove, in two different scenarios: i) considering the contact point at the extra thumb and ii) considering only the contact points generated by the five digits (index, middle, ring, pinky, and thumb). Fig. 8 illustrates the grasp quality measure calculation for four objects. The ratios between the areas of the polygons in both scenarios for all objects are reported in Table III. The results demonstrate that the inflatable extra thumb increases considerably the grasp quality. The average improvement of 78% in the grasp quality can validate that the use of the soft structure in the exoskeleton glove improves its overall

Fig. 8. Grasp quality measure calculation for four objects: a softball ball, a mustard bottle, a drill, and a jelly box. The yellow polygon represents the area generated by the center of the contact regions of the five fingers. The blue polygon represents the area generated by the center of the contact regions considering also the point of contact generated by the inflatable extra thumb.

performance. However, the high percentages presented could be an overestimation, as for some objects, the real grasp quality improvement could be lower due to different grasp types and strategies involved. This improvement may be more significant for impaired people with limited mobility of the hand, since the extra thumb will increase their ability to execute stable grasps. The limitation of the inflatable extra thumb is that it does not improve the grasping capabilities of the device for small objects, like the golf ball and the cup, since the geometry of these objects does not reach the area where the extra thumb is located. On the other hand, small objects can be stably grasped, covering most of the object's area using the thumb, the index, and the middle fingers. When not inflated, the telescopic actuator does not affect the grasping of objects since the structure is totally soft and relatively thin (10 mm thick), and the available hand aperture remains unaffected.

IV. CONCLUSIONS AND FUTURE DIRECTIONS

In this paper, we presented a hybrid, soft exoskeleton glove that combines a tendon-driven actuation system and soft pneumatic actuators. The device facilitates the execution of the abduction/adduction motion of the fingers and the thumb, and it improves grasp stability by increasing the area of the contact patches between the grasped object and the glove. A series of experiments demonstrate that this hybrid solution can enhance the grasping capabilities of the users, offering robust grasping with a lightweight and soft design.

Regarding future directions, we plan to reduce the number of motors in order to make the exoskeleton glove more portable, affordable, and lightweight. Also, we plan to implement a closed-loop pneumatic system to control the abduction actuators in a more accurate manner.

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