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A Hybrid, Wearable Exoskeleton Glove Equipped With Variable Stiffness Joints, Abduction Capabilities, and a Telescopic Thumb

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ABSTRACT Robotic hand exoskeletons have become a popular and efficient technological solution for assisting people that suffer from neurological conditions and for enhancing the capabilities of healthy individuals. This class of devices ranges from rigid and complex structures to soft, lightweight, wearable gloves. In this work, we propose a hybrid (tendon-driven and pneumatic), lightweight, affordable, easy-to-operate exoskeleton glove equipped with variable stiffness, laminar jamming structures, abduction/adduction capabilities, and a pneumatic telescopic extra thumb that increases grasp stability. The efficiency of the proposed device is experimentally validated through five different types of experiments: i) abduction/adduction tests, ii) force exertion experiments that capture the forces that can be exerted by the proposed device under different conditions, iii) bending profile experiments that evaluate the effect of the laminar jamming structures on the way the fingers bend, iv) grasp quality assessment experiments that focus on the effect of the inflatable thumb on enhancing grasp stability, and v) grasping experiments involving everyday objects and seven subjects. The hybrid assistive, exoskeleton glove considerably improves the grasping capabilities of the user, being able to exert the forces required to execute a plethora of activities of daily living. All files that allow the replication of the device are distributed in an open-source manner.

INDEX TERMS Exoskeletons, assistive devices, robotic rehabilitation, human augmentation, soft robotics.

I. INTRODUCTION

The human hand allows us to execute a wide range of complex tasks that require increased dexterity as well as to interact with our surroundings in a skillful manner. A plethora of neurological and musculoskeletal diseases can reduce the mobility of the human hand, such as multiple sclerosis, arthritis, spinal cord injury, and stroke, leaving humans impaired. In such cases, the rehabilitation process depends on the repetition of motions involving activities of daily living (ADLs) [1], [2]. According to [3], the exercises of finger flexion/extension and finger abduction/ adduction are two of the most important exercises that improve the hand function allowing it to better perform daily activities in the case of Multiple Sclerosis (MS) patients. In [4], the author describes the effectiveness of different types of hand exercises for persons with rheumatoid arthritis, including combined and individual flexion of the fingers, as well as thumb opposition and bending. Spinal Cord Injury (SCI) can cause changes in strength, sensation, and other body functions. According to [5], approximately 40% of SCI patients suffer from contracture of both the hand and the wrist. By performing daily life exercises, which include opening and closing the hand as well as grasping various objects, spinal cord injury patients can improve their hand function [6]. Another medical condition that can affect the hand function is a stroke.

According to the World Stroke Organization, stroke is the leading cause of death and disability worldwide, and one in six people will suffer a stroke in their lifetime [7]. Flexion/ extension and abduction/adduction of the fingers, as well as opposition of the thumb are common and useful exercises for restoring the strength and dexterity of patients that suffer from medical conditions such as a stroke [8]. Robotic exoskeletons for the human hand have been proposed over the years to

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facilitate the physical therapy of people with hand impairment or to augment the capabilities of healthy individuals [9], [10]. Although the soft, robotic exoskeleton gloves currently found in the literature can assist impaired people, they still offer limited dexterity to the user. Most of the devices cannot replicate all the hand motions performed during ADLs. In [11], the authors describe various complex grasps the human hand can perform and classify them based on the position of fingers and palm relative to the object. Finger abduction is one such important motion that the majority of soft robotic gloves cannot execute. The previously proposed designs employ passive finger abduction mechanisms [12] or actively abduct only the thumb [13]. More than 50% of the different types of grasps require thumb abduction [11], and the abduction of the other four fingers is necessary to grasp objects of different sizes and shapes efficiently [14]. Also, as previously described, exercises involving abduction/adduction of the fingers and thumb opposition are a vital part of a rehabilitation programme for impaired hands [3]–[8].

The hand's ability to efficiently constrain the object motion is directly related to the quality and stability of the grasps executed. The ability of the hand to withstand external disturbances while maintaining stable object contact characterizes an efficient grasp. According to [15], a good measure of the quality of the grasp can be obtained from the number of grasping points and their distribution on the object surface, while grasping an object. The Grasp Wrench Space can be described as the largest perturbation wrench the grasp can resist in any direction. 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 [16]. Thus, the quality of the grasp can be improved by employing methods that better distribute or increase the number of contact points on the object surface.

Various methods of actuation have also been employed. Robotic exoskeletons range from rigid structures that use linkage systems to transmit forces [17], to soft gloves that are equipped with tendon-driven systems [18], [19], and soft inflatable structures that employ pneumatic systems to bend the fingers [20]–[22]. In [10], the authors provide a detailed review of soft robotic devices for hand rehabilitation and every day life assistance.

The inherent compliance of the soft pneumatic gloves allows them to execute grasps in a graceful manner while maintaining stability. Also, inflatable structures can easily control multiple degrees of freedom (DOFs) with a single control input. However, disadvantages of such systems are their bulkiness, the leakages that occur during operation, and the difficulty to control the amount of force being exerted by the device [18]. In comparison, tendon-driven systems have reduced weight and increased compactness of the glove system [23], [24]. Such devices offer more portable actuation and control units, and higher grasping forces as compared to the pneumatic solutions. Also, according to the review of soft robotic rehabilitation devices [10], tendon-driven gloves

FIGURE 1. The hybrid exoskeleton glove is equipped with a tendon-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.

are generally lighter than soft pneumatic gloves. A disadvantage of the tendon-driven systems is that they offer limited dexterity since they employ a limited number of actuators to control multiple DOFs. Conclusively, both types of devices have advantages and disadvantages and both facilitate the execution of ADLs by people who suffer from paralysis or other impairments [25], [26]. For this reason, in this work, a hybrid robotic exoskeleton glove is proposed that combines the best characteristics of the two actuation types: i) the compactness and high forces of tendon-driven systems and ii) the compliance and conformability of soft actuators [27].

In particular, in this article, we focus on the development of a hybrid, soft, robotic exoskeleton glove (Fig. 1) that is equipped with abduction capabilities for all the fingers, a telescopic extra thumb that increases grasp stability, and variable stiffness soft structures at the back of the glove that can adjust the bending profiles of the fingers, facilitating also the stabilization of a desired grasping pose. The efficiency of the proposed hybrid device is experimentally validated using five different types of experiments: i) abduction tests, ii) force exertion experiments that assess the force exertion capabilities of the device under different conditions, iii) bending profile experiments that evaluate how the fingers of the user bend in different operation modes, iv) grasping quality assessment experiments that focus on the effect of the inflatable thumb on enhancing grasp stability, and v) grasping experiments that involve a plethora of everyday life objects and seven subjects. All the files that are required for the replication of the exoskeleton glove device are disseminated and distributed in an open-source manner.

The rest of the paper is organized as follows: Section II discusses the design considerations, Section III presents the design of the glove, Section IV presents the modelling and analysis of the inflatable soft actuators for abduction and the telescopic extra thumb, Section V details the experimental setup used and presents the results, Section VI provides the open-source dissemination details, while Section VII concludes the paper and discusses future directions.

II. DESIGN CONSIDERATIONS

The current success and popularity of soft robotics are attributed to the inherent mechanical properties (e.g., structural compliance) of the soft and elastic materials that are used to create these structures. This enables high adaptability to unstructured environments, allowing the devices to conform to complex shapes, while being robust enough to withstand crushing loads. Hence, appropriate material selection has an important role in imposing a desired behaviour and guaranteeing the success of soft robotic devices. Although soft materials show promise and can assist robots in conforming to fragile objects during grasping, they suffer from a number of drawbacks such as: low control accuracy, limited force exertion capabilities, and low resistance to deformation [28].

In order to mitigate these disadvantages, researchers have developed several controllable, variable stiffness actuation methods for soft robotic structures. Devices using such structures have been applied to various fields such as the medical industry, structural engineering, automotive, and aerospace engineering [29]. Depending on the selected materials and their working principles, the approach to controlling the stiffness of each system can differ. Stiffness can be controlled by changing the temperature, the electrical current, the pressure, and the magnetic field of the system. The use of such an approach can be observed in a soft gripper utilising shape memory alloys (SMA) [30] to get a significant increase of the grasping force (ten times). The low response speed and the significant time required to change the material temperature and stiffness in SMA and shape memory polymer (SMP) structures, limit them to non-time critical and slow tasks [31], [32]. An alternative approach is to use magnetorheological (MR) fluid the viscosity of which is affected by the presence of a magnetic field. In [33], the authors propose a gripper employing MR fluids to enable improved finger pad conformation to object geometries. However, the reliance on large and heavy electromagnets to achieve a sufficient magnetic flux density to solidify the MR fluid limits the applicability of such a structure [34]. Moreover, the presence of a magnetic field may affect the interaction of the device with certain objects (e.g., metallic objects and sensitive electronics), potentially damaging them. In [35], the authors propose a voltage-driven dielectric elastomer actuator (DEA) that is capable of grasping a plethora of objects. However, DEA's have limited force output (a few grams) [36], [37].

Another approach for controlling the stiffness of a soft structure is through jamming, where a vacuum pressure is applied to a granular or laminar set of materials compressing them together, causing the materials to stiffen due to geometric constraints or friction. In [38], the authors present a joint assistance device composed of granular jamming elements

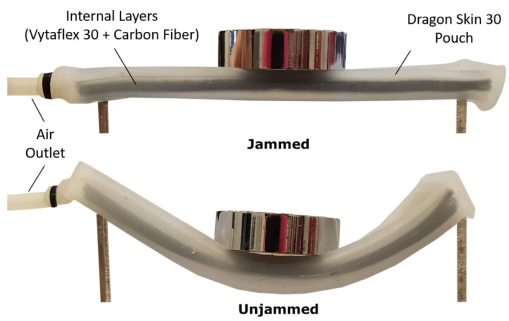

FIGURE 2. The soft laminar jamming structure can achieve multiple stiffnesses by applying a pressure gradient into the system. The structure is composed of a soft pouch made out of silicone rubber (Smooth-On Dragon Skin 30), an air outlet, and several thin layers made out of a combination of carbon fiber and silicon rubber (Smooth-On Vytaflex 30). When the vacuum is applied inside the pouch, the high friction between layers stiffens the entire structure.

(a silicone sleeve encasing rubber granules), aiding in variable joint support. Further, granular jamming can be used to increase the efficiency of soft actuators, enabling them to exhibit more than ten times the load resistance when a vacuum is applied [39]. However, granular jamming structures are unable to withstand high tensile and bending loads, limiting their applicability. Alternatively, laminar jamming structures utilize layers of flexible sheets/fibres that are stacked together inside a pouch in which a vacuum is applied and they are able to resist higher tensile and bending loads [40]. In [41], the authors present a variety of laminar jamming applications ranging from variable stiffness furniture for multipurpose use cases to variable softness shoes for walking assistance. Moreover, such elements can be used to control the dynamic responses of robots by increasing the stiffness of structural elements by more than 20 times once a vacuum is applied. Thus, in this article, we chose to apply the concept of laminar jamming to a robotic exoskeleton. We use the soft laminar jamming structures to control the forces required to bend the fingers and to keep them in desired configurations.

The soft, laminar jamming structure proposed was designed to achieve multiple stiffnesses by applying a pressure gradient to the system. A 100 g weight was used to demonstrate the structure's ability to resist deflecting loads when jammed (high stiffness) and to freely deform when unjammed (low stiffness), as shown in Fig. 2. The structure consists of a soft pouch with several thin layers inside it. When the vacuum is applied inside the pouch, the high friction between layers stiffens the entire structure. The pouches tested in this study are made out of silicone rubber (Smooth-On Dragon Skin 30), and their walls are 1 mm thick. The jamming structures used pouches 160 mm long, 11 mm high, and 22 mm wide. Each jamming structure contains seven thin layers encased in the silicone vacuum pouch. Each layer is made out of a urethane rubber matrix (Smooth-On Vytaflex 30) and carbon fiber sheets. The composite layers retain the high flexibility of the rubber (promoting passive extension of the fingers) and low deformation in the axial

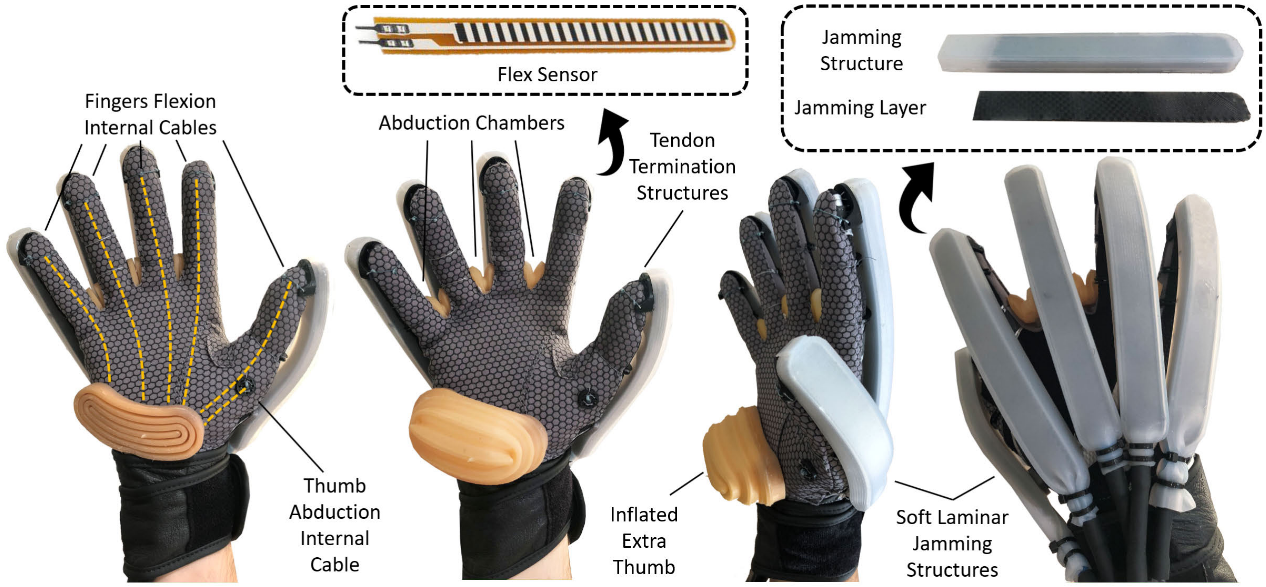

FIGURE 3. The soft glove system of the device consists of a glove, a tendon-driven system, and a pneumatic system that is composed of four soft actuators and five laminar jamming structures. Five plastic tendon termination structures are stitched onto the fingertip regions of the glove. The tendon-driven system has a tendon connected to each of the tendon termination structures and an extra tendon that is connected to the thumb's interphalangeal joint region, facilitating the execution of the opposition motion. The soft structures are used for three different purposes: to perform abduction/adduction of the fingers, to increase grasp stability by implementing an extra thumb structure, and to change the bending profile of the fingers. Three of the pneumatic chambers are connected to the region in between the fingers allowing for the execution of the abduction/adduction motion of the fingers. Another 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 the glove, five laminar jamming structures were added to adjust the stiffness of the joints and to perform a passive extension of each finger and keep the hand in its natural, zero effort position. A flex sensor is located at the index finger and can be used to control the motion of the exoskeleton glove.

direction of the carbon fiber (increasing the bending resistance when the structure is under vacuum). Further details regarding the modelling and characterization of laminar jamming structures can be found in our previous work on variable stiffness joints [42]. The elastic properties of the jamming layers and the soft pouch promote the passive extension of the fingers, keeping the human hand in a natural, zero-effort pose.

III. DESIGN OF THE ROBOTIC EXOSKELETON GLOVE

In this section, we present the design and operation of the components of the proposed robotic exoskeleton glove.

The soft, robotic exoskeleton glove was designed to assist human hands with limited mobility during the motion rehabilitation process and to improve the grasping and dexterous manipulation capabilities of the hands of both impaired and able-bodied individuals. The proposed device consists of two main systems: the soft exoskeleton glove and the control unit. The control unit is composed of five Dynamixel XM430-W350-T motors, two mini 12V air pumps, one 12V vacuum pump, three solenoid valves, a microcontroller (Robotis OpenCM9.04), and a small circuit to control the air pumps. The index, middle, and thumb tendons are connected to dedicated pulleys of individual motors, while the ring and the pinky finger tendons are coupled together and connected to a single pulley and motor. The tendons run though polyurethane tubes that are used for tendon routing from the control unit to the soft glove (Fig. 3). When the motors are actuated, the tendons get wrapped around the pulleys, bending the fingers. The ring and pinky fingers have a supplementary role during object grasping [43], therefore, they are connected to the same motor. The motors operate at a maximum torque of 1.4 N.m., maximum current of 0.9 A, and speed of 30 RPM. A vacuum tube connects the vacuum pump to the jamming structures located at the back of the hand, and another two tubes connect the air pumps to the abduction soft actuators and the inflatable, telescopic thumb.

The soft glove system of the proposed 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, and five laminar jamming structures. 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, offering better sensibility of the grasped objects than the rigid anchor points. The soft anchors have been positioned according to the optimized positions reported in [23]. The tendon-driven system has a tendon connected to each of the fingertip structures and an extra tendon that is connected to the thumb's interphalangeal joint region so as to allow for the execution of the thumb's opposition motion.

A tendon-driven solution for the thumb abduction/opposition 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 tendons used in the exoskeleton glove are made out of a low friction braided fiber of high-performance Ultra-High Molecular Weight Polyethylene (UHMWPE) and can withstand forces up to 500 N. The particular tendon type is very common in related studies that focus on the development of exoskeleton gloves [10] and robotic hands [44] and it provides higher resistance against wear and fatigue. The tendon is affordable and readily available in hardware stores around the world. The soft actuators are used for two different purposes, to allow for the execution of the abduction/adduction motion 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. 3. The soft actuator was designed to provide active assistance on finger abduction and passive on finger adduction, once the human hand is naturally adducted. The soft actuators that have been designed are described in the following subsections. At the back of each digit, laminar jamming structures are attached to control the force required to close the digits, to maintain the fingers steady in a desired configuration, and to perform passive extension of the fingers keeping the hand in its natural, zero effort position. The laminar jamming structures can achieve multiple stiffnesses by applying a pressure gradient to the system, relying on the friction between the layers. A single vacuum pump is used to jam the layers of all fingers, enabling variable joint stiffness.

A hybrid design, containing a tendon-driven system, four different soft actuators, and laminar jamming structures, was chosen over a purely soft or tendon-driven solution in order to combine the advantages of both types of designs and overcome their individual limitations. For instance, by employing soft actuators for grasping assistance, the hybrid glove takes advantage of the high adaptability and conformability to the object shape of soft structures. Also, the variable stiffness laminar jamming flexures not only assist passive extension, but they also improve the performance of the tendon-drive system by allowing the exertion of higher fingertip forces during pinch grasps, reducing reconfiguration (as further demonstrated in Section V-B).

The operation of the device is straightforward (see Fig 4). Using the smartphone app, the user selects the mode desired to control the exoskeleton glove. The user can combine the motions (e.g., full grasp with abducted fingers or tripod grasp with the extra thumb inflated and the jamming structures activated). The flex sensor can be used in order to trigger the desired function when a set bending angle is reached. The desired function is selected from a predefined set stored within the smartphone app, like tripod grasp, full grasp, or jamming structures triggering, as shown in Fig 5. The information is transmitted to a microcontroller through

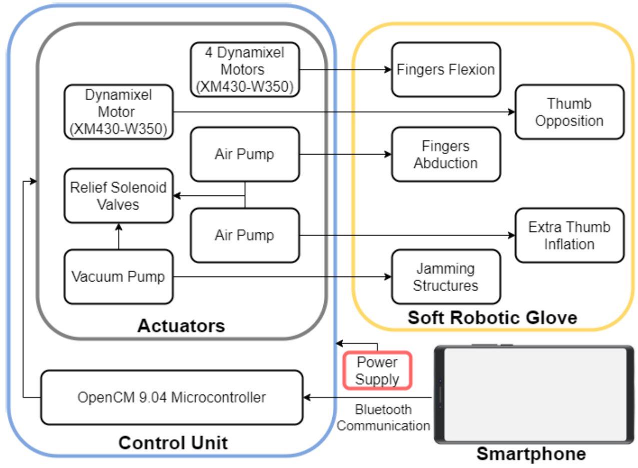

FIGURE 4. **The operation of the soft exoskeleton glove is simple and intuitive. Using the smartphone app, the user selects the action desired and the information is transmitted to a microcontroller through Bluetooth communication. The microcontroller activates the chosen actuators that are connected to the glove. Each air supply is connected to a solenoid valve that is used to release the air pressure of the system, returning the glove to its original position. The system is powered by a 12V power supply.**

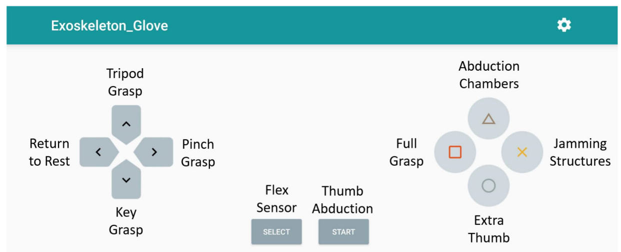

FIGURE 5. **The smartphone app interface is used to control the exoskeleton glove operation. The user can combine the motions desired (e.g., full grasp with abducted fingers or tripod grasp with the extra thumb inflated and the jamming structures activated). The flex sensor can be selected to trigger the desired motion when a set bending angle is reached.**

Bluetooth communication. Then, the microcontroller activates the chosen actuators that are connected to the glove. Each air supply is connected to a solenoid valve that is used to release the air pressure of the system when the glove returns to its original position. The entire system is powered by a 12V power supply. A battery can be added to the control unit to make the device portable and wearable. 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 [45].

IV. SOFT ACTUATORS

In this section, we discuss the modelling of the soft pneumatic actuators used for abduction, and we perform an analysis of the proposed inflatable extra thumb, describing its manufacturing process.

A. SOFT ACTUATOR MODEL FOR ABDUCTION/ADDUCTION

The abduction and adduction motions of the fingers in the hybrid robotic exoskeleton glove are executed by three

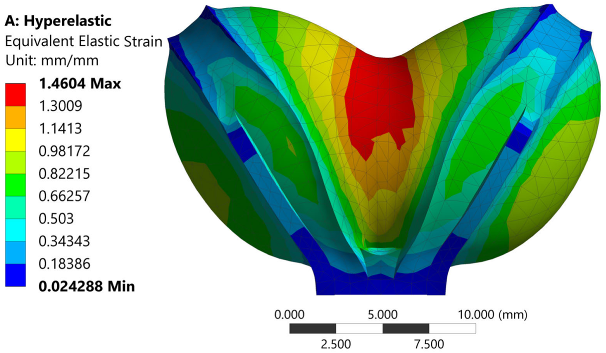

FIGURE 6. FEM analysis of the soft actuator employed for the execution of the abduction motion of the fingers at a pressure of 70 kPa. The maximum strain takes place in the interface between the two lateral walls of the actuator.

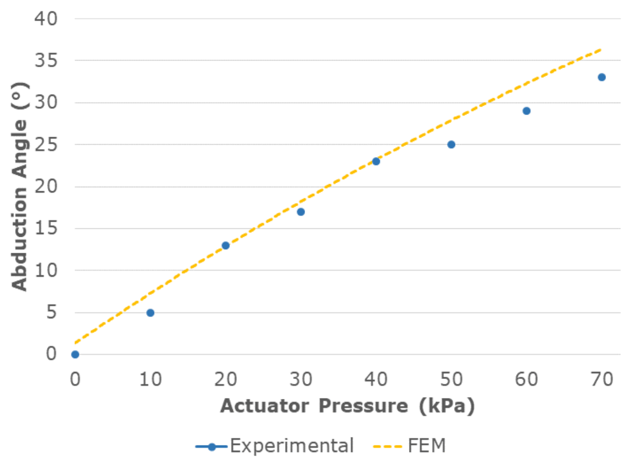

FIGURE 7. Abduction angles of the actuator obtained during the FEM analysis for multiple pressures compared to the experimentally measured abduction angles of the physical prototype. The results demonstrate a similar abducting behaviour for the model actuator and the actual soft actuator.

identical soft pneumatic chambers. These actuators are made out of urethane rubber (Smooth-On Vytaflex 40), and they are inspired by the open-source designs of the Soft Robotics Toolkit [46]. The accurate estimation of the limits of the soft actuator in terms of force and motion capabilities is highly important to design the best actuator that fits the selected grasping strategies. For this reason, a finite element method (FEM) model was developed to estimate the performance of the actuator according to the available air pressure.

Similar structures, such as soft reinforced actuators for finger flexion, have been previously modeled [47], [48]. The proposed soft abduction/adduction actuator can be modeled employing the Mooney-Rivlin hyperelastic model [49]. The strain energy density W of the model is 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. The third term of Eq. 1 is discarded for this model, assuming that the urethane rubber is incompressible. The simulation used the following values: $C_1 = 0.076$ 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. 6 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 further described in Section V-A).

The validation of the FEM model consisted of comparing the abduction angles of the actuator obtained during the FEM analysis for different pressures (similarly to Fig. 6) to the abduction angles of the physical prototype that were recorded during actual experiments (varying from 0 kPa to 70 kPa). The results are shown in Fig. 7. The trend of the FEM model is similar to the results of the soft actuator, however, the experimental angle values are slightly smaller than the results obtained from the FEM model. This is possibly due to discrepancies 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, etc.). Since the experimental results satisfactory match the simulation, the FEM model can be used to improve the design of the soft actuator, comparing different materials and configurations without manufacturing physical prototypes. Such a design optimization process can reduce the cost and time required to develop the soft actuator.

B. SOFT TELESCOPIC ACTUATOR

The soft, telescopic, extra thumb actuator is based on a urethane rubber (Smooth-On Vytaflex 40) structure developed for grasping assistance during the execution of ADLs. The small thickness and telescopic behaviour of the foldable structure were design choices that guarantee that the structure does not compromise the ability of the device to execute grasps that do not require an extra thumb. Also, the rounded shape of the actuator maximizes the size of the objects that can be grasped. 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 distinct molding steps. Fig. 8 shows the steps to manufacture the actuator. Initially, the foldable part and the base layer of the actuator are manufactured. The base layer is 2 mm smaller than the upper part in all directions so that they can be bonded (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 fabrication technique avoids leakages and unwanted deformations in the actuator. Although having a thick elastomer base, a fabric layer can be added to its base to restrict extension along the base axis.

As previously mentioned, the soft telescopic extra thumb has been designed to increase stability and quality of the

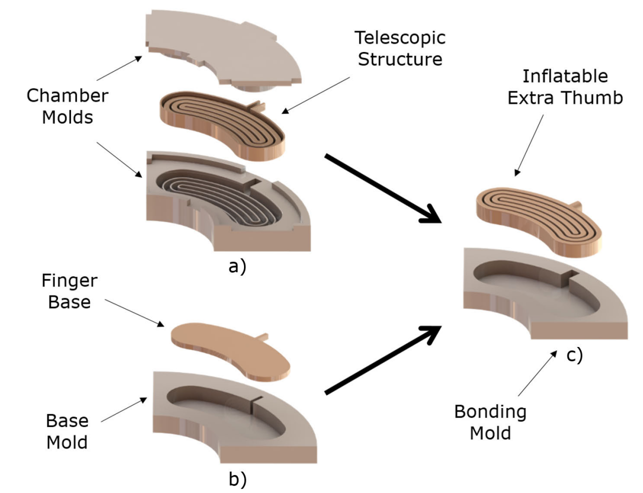

FIGURE 8. **The manufacturing process of the inflatable thumb, which is made out of silicon rubber (Smooth-On Vytaflex 40), involves the following three molding steps: a) the foldable part of the actuator is fabricated using two molds, b) the base layer is fabricated using a third mold, with the base layer being 1.5 mm thick and 2 mm smaller than the foldable part in all directions so that they can be molded together, c) after both parts are cured, a fourth 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. The final structure is 10 mm thick and 80 mm long.**

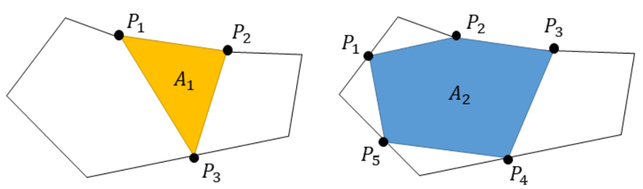

FIGURE 9. **Illustration of the physical interpretation of the grasp quality measure based on the geometric relation between the object and the contact points for three contact points (left) and five contact points (right).** $P_1, P_2, P_3, \ldots, P_n$ **denote the contact points, and** A_1 **and** A_2 **denote the area generated by the contact points. The larger the area generated by the contact points the better the grasp.**

grasps executed. In past studies, authors have proved that extra robotic fingers connected to the human hand are an efficient solution for increasing the grasping capabilities of impaired people [50], [51]. The assessment of the extra thumb on the robotic glove can be performed through a grasp quality analysis. A popular grasp quality measure discussed in [15] 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, as illustrated in Fig. 9. The grasp quality Q_{AGP} can be expressed as:

$$Q_{AGP} = Area(Polygon(P_1, P_2, P_3, \ldots, P_n)) \tag{2}$$

V. EXPERIMENTS AND RESULTS

Five different experiments assessed the performance of the soft exoskeleton glove and each of its features. The first part focused on evaluating the use of the soft actuators during the abduction motion of the fingers using a subject's hand. The second experiment assessed the fingertip forces that the device could exert under different conditions using an anthropomorphic dummy hand. The third experiment analyzed the bending profile of the finger with the robotic glove and the effect of the jamming structure in the human finger bending. The fourth experiment verified the benefits of the telescopic, extra thumb structure in enhancing grasping quality and stability of the human hand. The last part focused on grasping experiments executed with seven subjects and everyday life objects. The characteristics of the developed soft exoskeleton glove are reported in Table 1.

TABLE 1. **Summary of the characteristics of the hybrid, robotic exoskeleton glove.**

Description	Value
Maximum fingertip force	13.8 N
Maximum abduction force	15.8 N
Grasp speed (full grasp)	< 3 s
Abduction actuators width	8 mm
Extra thumb thickness	10 mm
Grasp Improvement (by the extra thumb)	75%
Glove weight	300 g
Total robotic device weight (including control unit)	1700 g

A. ABDUCTION EXPERIMENT

The first experiment evaluated the efficiency of the pneumatic chambers that perform the abduction motion of the fingers and verified that the soft actuators can facilitate finger abduction with a similar range of motion to the human hand. The experiment focuses on the amount of abduction force that each abduction chamber can exert and on the values of the achievable abduction angles. During the abduction force experiment, pressure was applied 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 during the experiment was 15.8 N at a pressure of 130 kPa, which is the maximum force that the soft actuator can exert to perform the abduction motion between any two fingers. The abduction force of 15.8 N is within the range of abduction forces that the human finger can exert [52].

Another experiment measured the finger abduction angles wearing the proposed soft robotic glove. 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 abduction angles between two

TABLE 2. Maximum abduction angles achieved for each finger by the soft actuator that executes the abduction motion.

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

consecutive fingers were measured using a hand goniometer for anthropometry measurements. For the thumb, the tendon was pulled until a steady condition was reached, and then the abduction angle was measured. The results obtained for this experiment are reported in Table 2. The results demonstrate that the abduction system can efficiently assist the user in abducting the fingers. The abduction angles are similar to the values found in the literature for safe abduction of the human fingers, approximately 25° for the fingers and 70° for the thumb [14] (thumb opposition). 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 abduction chambers are 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).

B. FINGER FORCE EXPERIMENT

The second experiment assessed the fingertip force exertion capabilities of the proposed soft robotic glove and how the tendon-driven system's performance (e.g., force exertion capabilities) is improved by employing the jamming structures. The fingertip forces were recorded using a setup containing a hand mount and an indexing plate with different angle positions, as shown in the setup in Fig. 10. The fingertip forces were acquired for angles from 0° to 120°. A dummy hand [53] wearing the soft assistive exo-glove was used to conduct the experiments. The 3D printed hand used has humanlike dimensions, three joints in each finger, and similar kinematics to the human hand. The use of a dummy hand prevents involuntary forces from being executed and guarantees that the device is steady during the execution of the tests, facilitating the replication of the experiments by other research groups. The maximum force exerted at each angular position was obtained before the fingertip slipped away from the force sensor connected to the indexing plate (S8-100N, SingleTact, USA), due to the finger reconfiguration. Fig. 10 presents the results of the experiment for the jammed and unjammed conditions. The force exerted was 13.8 N at 90° when the robotic glove was unjammed and reached a maximum value of 12 N at 45° when the jamming structures were activated (at a pressure of 50 kPa). Five trials were recorded for each condition (jammed and unjammed), and the maximum force obtained is found in Table 1.

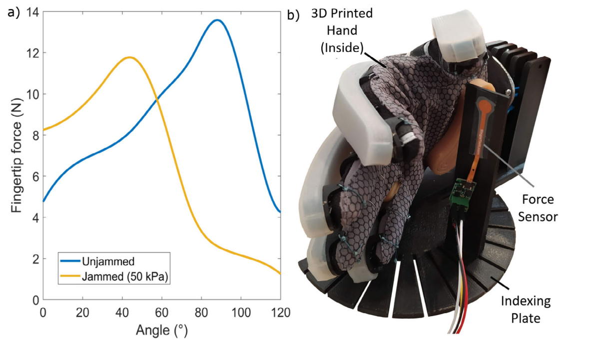

FIGURE 10. Results (subfigure a)) and experimental setup (subfigure b) used for the fingertip force experiments conducted with the proposed exoskeleton glove under the jammed and unjammed control modes. The setup consists of a 3D printed hand (model hand) wearing the robotic glove, a force sensor, and an indexing plate with an increment value of 15°. The force profiles were acquired for a total of eight different positions (from 0° to 120°).

According to [54], the required force to grasp objects during ADLs does not exceed 10 N to 15 N, and the pinch forces required to execute most of the daily life tasks are lower than 10.5 N [55]. Thus, the proposed soft robotic glove can exert enough force to stably grasp everyday life objects (see Fig. 13), and these forces are similar to most of the devices found in the literature [10]. If desired, higher grasping forces can be achieved by reducing the stiffness of the jamming structures and, therefore, reducing the passive extension forces. To do so, less stiff materials can be used to manufacture the vacuum pouch and the composite layers. The results also demonstrate that the jamming structure is capable of increasing the maximum fingertip force at small bending angles if compared to the unjammed structure. By exerting higher forces at small bending angles, it is possible to improve grasps with the fingertips (e.g., pinch grasp, key grasp) and efficiently execute the desired task resulting in less finger reconfiguration.

C. FINGER BENDING PROFILE ANALYSIS

The third experiment analyzed the bending profile of the index finger in three different modes: natural motion (robotic glove turned off) shown in Fig. 11a, assisted by the robotic glove without the jamming structure (Fig. 11b), and assisted by the robotic glove employing also the jamming structures (depicted in Fig. 11c). The experiment's goal was to verify the effect of the jamming structures on the finger configuration during grasping. A camera was placed perpendicularly to the hand, and a MATLAB implementation of a point tracking algorithm (Iterative Image Registration Technique [56]) based on visual features (colored dots) was used to track the position of the joints while bending the finger. Fig. 11 shows the paths of the proximal interphalangeal joint (PIP), distal interphalangeal joint (DIP), and the fingertip for the three different scenarios. The muscle activation was also measured in all conditions to guarantee that the user does not participate during finger flexion and that the motion is imposed only by

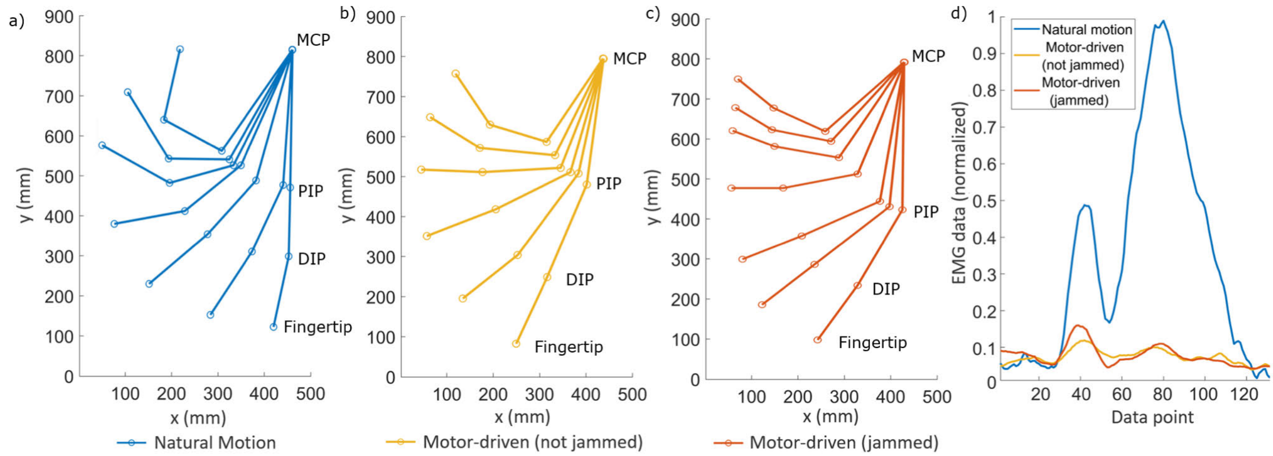

FIGURE 11. **Bending profile analysis for the index finger under three different control modes of the robotic glove: a) natural motion (device turned off), b) motor-driven with the jamming structure deactivated, and c) motor-driven with the jamming structure activated. The myoelectric activation was also measured in all conditions to guarantee that no voluntary force was being exerted while bending the finger (depicted in subfigure d)).**

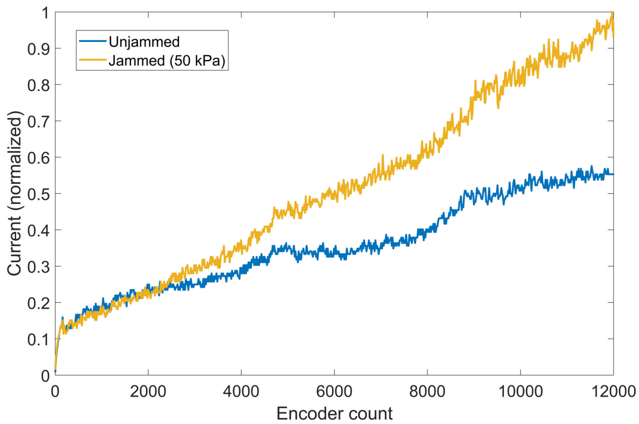

FIGURE 12. **Motor current values while bending the finger. Two different conditions were used: index finger bending with the jamming structures activated (50 kPa) and deactivated (unjammed). The results show that when the structure is jammed, higher motor current is required to bend the finger.**

the glove. An electromyography sensor (EMG) was placed at the Flexor Digitorum Superficialis region (FDS) [57].

The results demonstrate that when the robotic glove is unjammed but motor-driven, the device can impose a bending profile similar to the natural motion. When the jamming structure is activated, the motions of the DIP and PIP joints are reduced, and the motion at the Metacarpophalangeal Joint (MCP) is increased. Thus, the jamming structures can be used for handling objects that require fingertip/pinch grasps since natural pinch grasps require small bending angles at the PIP and DIP joints to be executed efficiently (as discussed in [58]). The motor current was also measured for the jammed and unjammed conditions. The motor current values are reported in Fig. 12 for a set number of encoder counts. Two different conditions were tested: index finger bending with the jamming structures activated (50 kPa) and deactivated (unjammed). The results demonstrate that when the jamming structure is activated, a higher motor current is required to bend the finger. Therefore, the jamming structures can be used as a tool in the rehabilitation process of impaired people by adjusting the force required to bend the fingers or to maintain a desired grasp shape by increasing the resistance to hand opening (e.g., hook grip).

D. GRASP QUALITY EXPERIMENT

The fourth experiment evaluated the effect of the soft telescopic extra thumb on efficiently grasping objects as well as on improving grasp quality and stability. A total of 14 different objects were grasped. The daily life objects used in this experiment were based on the Yale-CMU-Berkeley (YCB) object set, an object set designed for facilitating benchmarking in robotic manipulation and grasping (the dimensions and weight of each object can be found in [59]). The average grasping time for each object was less than 3 seconds (time from rest state until the fingers are fully closed). The actuation time of the hybrid exoskeleton glove is within the range for devices found in the literature (from about 2 seconds to 4 seconds) [20], [60]–[62]. 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 perpendicularly to the hand palm were taken after each grasp to determine the area of the polygon generated by the contact points between the objects and the robotic glove. Two different scenarios were used: i) considering the contact point at the extra thumb and ii) considering only the contact points generated by the five digits. Fig. 13 (first picture) illustrates the grasp quality measure calculation. The ratios between the areas of the polygons in both scenarios for all objects are reported in Table 3.

The results demonstrate that the inflatable extra thumb increases the grasp quality considerably. The average

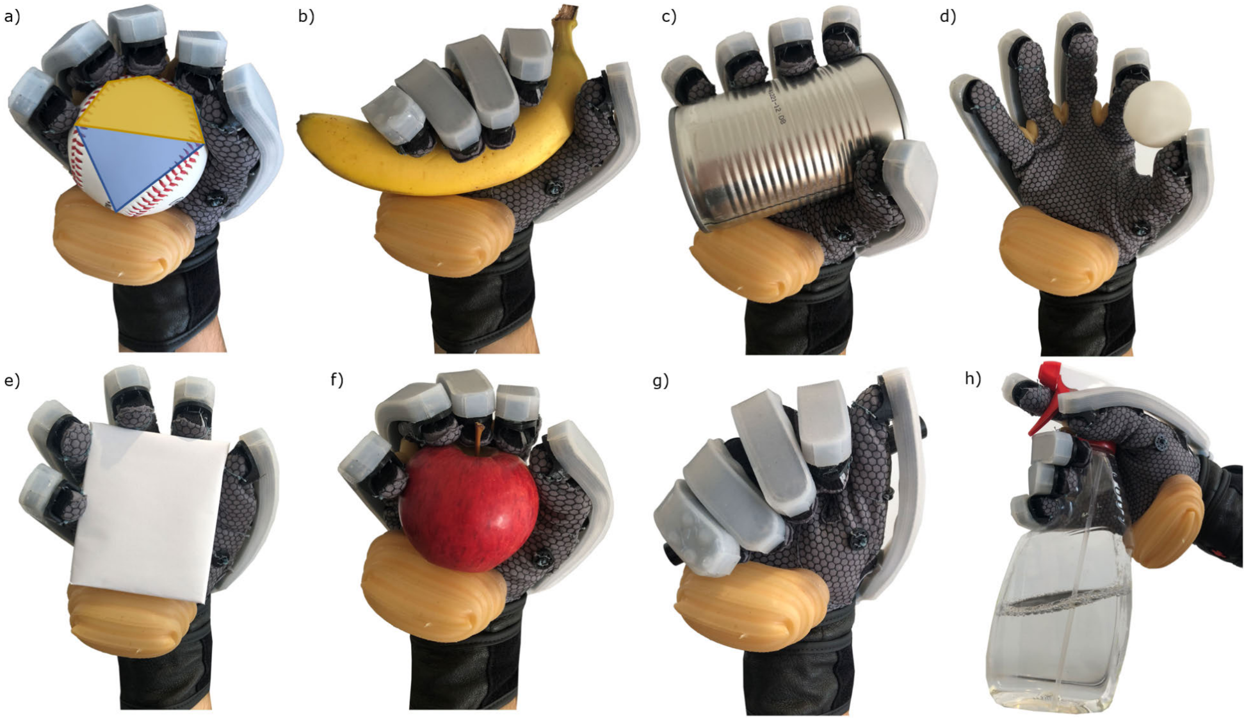

FIGURE 13. Grasping experiments executed with eight different everyday life objects: a) baseball ball, b) banana, c) can, d) table tennis ball, e) jelly box, f) apple, g) marker, and h) bottle, while the subject was wearing the proposed soft exoskeleton glove. The soft telescopic extra thumb module is employed in most cases, with the exception of the table tennis ball that is very small and requires a pinch grasp. The polygons in the baseball ball illustrate the grasp quality measure calculation for the objects: 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 also considering the point of contact generated by the inflatable extra thumb.

TABLE 3. Ratio between the grasp quality measure values for 14 everyday life objects in two different scenarios: grasp assisted by the extra thumb (Q_{thumb}) and grasping without the extra thumb (Q_{glove}). The ratio value denotes how many times the grasp quality gets improved while using the extra thumb module. The third column shows if the telescopic extra thumb was employed in the grasp.

Object	$\mathbf{Q_{thumb}/Q_{glove}}$	Extra Thumb?
Apple	2.11	Yes
Banana	2.08	Yes
Bottle	1.74	Yes
Baseball Ball	1.68	Yes
Cracker Box	2.07	Yes
Can	1.88	Yes
Cup	1.00	No
Drill	1.72	Yes
Hammer	1.90	Yes
Jelly Box	1.61	Yes
Marker	1.74	Yes
Mustard Bottle	2.16	Yes
Plate	1.85	Yes
Table Tennis Ball	1.00	No

improvement of 75% in the grasp quality demonstrates that the use of the extra thumb structure in the exoskeleton glove improves its overall performance. However, the high percentages presented could be an overestimation, as for some objects the real grasp quality improvement could be lower due to significantly 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 facilitates the execution of stable grasps. In general, the extra thumb and the abduction chambers are more effective when grasping bigger and longer objects due to the better distribution of the contact points over the object's surface, resulting in more 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 table tennis ball and the cup, since the geometry of these objects does not reach the area where the extra thumb is located. 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). Overall the soft, telescopic extra thumb is an efficient solution for improving the grasp quality and stability in exoskeleton gloves.

E. OBJECT GRASPING EXPERIMENT

The last experiment was executed to assess the efficiency of the hybrid robotic glove in grasping everyday life objects and to receive user feedback for future designs. A total of seven healthy subjects participated in this experiment. All the participants were male of ages between 23 and 30 years old, and with similar hand dimensions. The same glove structure could be worn by all subjects (medium size glove). For much bigger or much smaller hands, new glove structures should be used due to significantly different finger dimensions. These different glove sizes can be easily accommodated in the design. The study has received the approval of the University of Auckland Human Participants Ethics Committee (UAHPEC) with the reference number #019043. Prior to the study, the participating subjects provided written and informed consent to the experimental procedures.

Initially, the subjects were given a set of objects to grasp so as to learn how to use the device and familiarize themselves with the features of the glove. To evaluate the muscle effort required for performing the Activities of Daily Living (ADLs) with and without the glove, isometric grasping experiments were conducted. To do this, one bipolar EMG channel was placed at the FDS region (similarly to the placement described in Section V-C). The Flexors Digitorum muscle group has high correlations with the high grip forces [63], [64], and FDS has been employed in predicting the exerted grip forces using myoelectric activations [65]. The EMG signals were acquired by a g.Tec g.USBamp bioamplifier. A sampling rate of 1200 Hz was used, and the signal was bandpass filtered using a Butterworth filter (20 Hz - 500 Hz). A notch filter of 50 Hz was applied to reduce the electric noise. The Maximum Voluntary Contraction (MVC) while flexing the fingers was recorded for each subject as a baseline measure. Next, the subjects were asked to grasp, hold, and release a drill without using the glove and then repeat the same experiment using the glove, executing a full grasp (activating all four motors for finger flexion and thumb abduction) with the assistance of the abduction soft actuators and the telescopic extra thumb. Five trials for each scenario were recorded and the hybrid exoskeleton glove was triggered by the researcher conducting the experiment to avoid any involuntary motions by the subjects. The EMG activation while using the jamming structures was not assessed in this experiment since it was already described in Section V-C. The myoelectric activations were recorded in both cases. During the post-processing that is required for the analysis, the recorded activations were full-wave rectified and normalised against the MVC, following the guidelines of the International Society of Electrophysiology and Kinesiology (ISEK) [66]. Fig. 14 shows the myoelectric activations for MVC, as well as during the grasping of a drill with and without the glove. The activation percentages of the muscles with and without the glove are reported in Table 4. The reported percentage values are percentages of the MVC. The results demonstrate that there was minimal muscle effort involved during the execution of the drill grasping task when the user was wearing the glove.

After performing the experiments, each subject was asked to fill a questionnaire that focuses on her/his opinion regarding the system's usefulness, satisfaction, ease of learning, and ease of use [67]. The questionnaire uses a seven-point scale to assess the quality of the device. The mean and the respective standard deviation values are presented in Table 5. In general, the subjects were satisfied with the device and reported that the device is easy to control. Most of the subjects were positively surprised by the assistance provided by the extra thumb, especially for big objects, which require better distribution of the contact points to achieve a successful grasp. They also reported that the device could be improved by adding more grip to the glove and more comfort where the plastic parts are sewed (tendon termination structures).

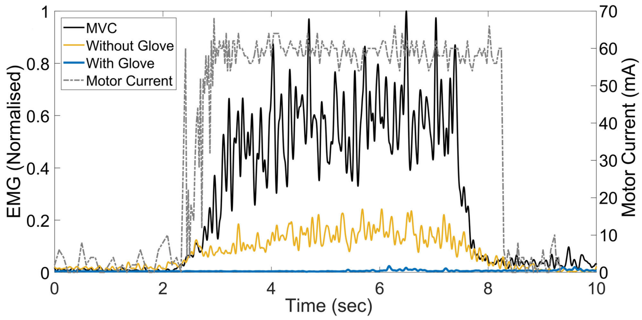

FIGURE 14. The fifth experiment focused on assessing the levels of the myoelectric activation of the user while grasping everyday life objects with the glove. To do that, the Maximum Voluntary Contraction (MVC) electromyography signal was recorded for each subject as a baseline measure. Next, the subjects were asked to grasp, hold, and release a drill without using the glove and then repeat the same experiment using the glove. It is evident that the amplitude of the myoelectric activation without the glove is much higher than the amplitude of the myoelectric activation using the glove.

TABLE 4. Comparison of Muscular Effort in performing Grasping Tasks with and without Glove (with respect to % MVC). All subjects were male, aged from 23 and 30 years old.

Subject	1 M26	2 M26	3 M24	4 M30	5 M23	6 M26	7 M26
Without Glove	30.3 ± 5.0	23.7 ± 5.9	6.7 ± 1.9	3.9 ± 1.8	27.7 ± 5.6	21.5 ± 11.0	12.1 ± 5.9
With Glove	2.9 ± 1.7	3.2 ± 0.7	3.5 ± 2.1	0.8 ± 0.4	3.6 ± 2.2	1.1 ± 1.0	3.0 ± 0.9

TABLE 5. Questionnaire results for seven subjects analysed. Each questionnaire contained 30 questions and the marks ranged from 1 (strongly disagree) to 7 (strongly agree). Mean and standard deviation (SD) are reported for each section.

Questionnaire Sections	Mean	SD
Usefulness	5.7	0.5
Ease of use	5.6	0.9
Ease of learning	6.5	0.1
Satisfaction	6.0	0.8

VI. OPEN-SOURCE DISSEMINATION

All the exoskeleton glove designs, electronics, and code are disseminated in an open-source manner to allow replication by others. More information and the links to the files can be found at the following URL:

http://www.newdexterity.org/exogloves/

VII. CONCLUSION AND FUTURE DIRECTIONS

In this article, we presented a hybrid, soft exoskeleton glove, which combines soft pneumatic actuators and a tendon-driven actuation system. The device is equipped with actuators that facilitate the execution of the abduction/adduction motion of the fingers and the thumb, a soft telescopic structure that improves grasp stability by increasing the area of the contact patches between the grasped object and the glove, and variable stiffness structures that adjust the bending profile of the fingers and stably keep a desired grasping pose. A series of experiments have demonstrated that the hybrid design combines the individual advantages of tendon-driven systems and pneumatic actuators, allowing the execution of multiple grasping postures and gestures with adequate contact forces (more than 13 N) for the execution of ADLs. The device has a lightweight structure (300 g) and an intuitive interface.

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

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