A Wearable Robotic Glove based on Optical FMG Driven Controller

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Abstract— **This work presents the development of an underactuated glove-like orthosis to be used by people with disability in hand and difficulty to perform firm grasps. The wearable glove uses a tendon-driven system to perform fingers flexion/extension, triggered by optical fiber force myography sensors placed on an opposites muscle pairs with the aim to activate the glove actuators. The steps involving the physical construction of the sensor and the underactuated glove-like orthosis are explained, as well as the architecture and the control strategy of the system. Experiments conducted using the glove indicated satisfactory results related to the type of grasp and confirm that the optical FMG sensor can be used as a control input for trigger the tendon-driven system.**

I. INTRODUCTION

In 2011, the World Health Organization estimated that more than one billion people in the world lived with some form of disability [1]. Amongst the several disabilities, those that affect the upper limb movements, as stroke and spinal cord injury (SCI), can generated great frustrations because these people need the assistance of other people to perform their activities of daily living (ADLs). Moreover, most of them are residents of low- and middle-income countries, whom cannot afford health care.

As a means of helping people with these disabilities, several hand exoskeletons have been developed in the last two decades, aimed to be used as orthoses [2]–[6]. In the work proposed by [2], a pneumatic system is used to perform the opening and closing actions of the hand, whereas in other works such as described in [3]–[6], a tendon-driven system is employed in order to perform the same actions. Both of these devices, regards the user intent detection as the main control input. Usually, the user intent detection applied in orthoses chiefly encompasses control input from surface electromyography (sEMG) [2,4,6], key/button press mechanisms [5] and detecting the flexion of the wrist [3,7].

The most common way used to trigger orthoses and prostheses, is by detecting signals registered from muscles activity through the traditional approach based on sEMG. Despite this technique it is based on a noninvasive procedure to detect the muscle activity, the sEMG signals must be filtered and rectified to compute its power envelope what makes them more difficult to treat [8]. Moreover, sEMG can be affected by electromagnetic noise, sweat, among other drawbacks [9].

Another way to detect muscles activity and overcome the leading drawbacks presented by the use of sEMG is using force myography (FMG). In the FMG approach the muscle activities are assessed in terms of mechanical stimuli generated by the volumetric changes of the muscles, producing results comparable to the electrical approach using sEMG [10]. Some relevant works considering FMG applied on the forearm, highlighted that the FMG technique provides a high classification accuracy when regarding cases as estimation of grip force, grasp detection, hand gestures classification, and prediction of finger movements [10]–[14], encouraging the use of FMG as an alternative technique to supersede the conventional sEMG. However, the aforementioned researches made use of a flexible forearm bracelet containing force-sensitive resistors (FSRs) for collecting pressure signature from muscles. Envisioning new applications for FMG, differently from the previous achievements, in this work, we report the development of a glove-like orthosis, using a tendon-driven actuator, and we make use of optical fiber force myography (FMG) for assessing the muscle activities and trigger the tendon-driven system. We will use a device consisting of a noninvasive optical fiber FMG sensor similar to that proposed in [15,16]. However, there is not enough evidence in the literature of projects using this type of control input.

In order to present this work, this paper is divided into four sections. This first section presented a brief introduction to the problem of hand disability and exposed our contribution to solve this problem. Information concerned with the glove design, system architecture, the optical fiber force sensor and integration of sensors in the control strategy are described in Section II. Experimental results using the FMG sensor and the designed soft glove are reported in Section III, followed by Section IV related to conclusions and future works.

II. METHODS AND MATERIALS

In this work, we propose an assistive device for patients who have any degenerative illness that prevent them from provide force in upper limbs for accomplishing of activities of daily life (ADLs), e.g. weak grasp. This device makes use of two channels of a FMG transducer that is based on optical

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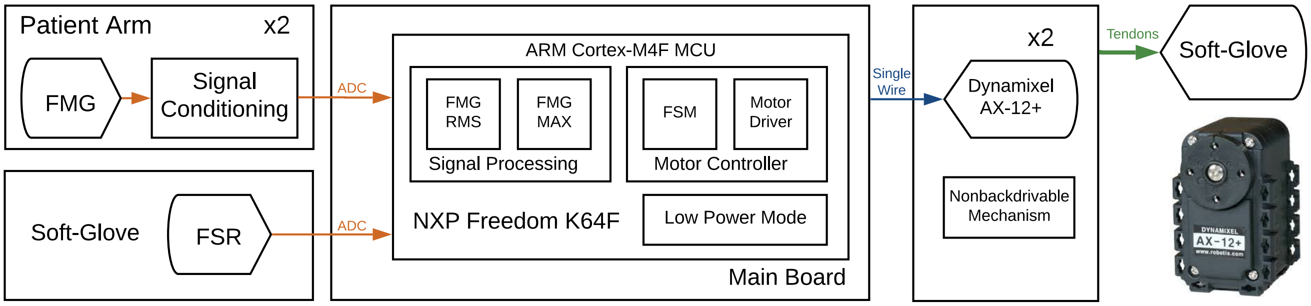

Fig. 1. Block diagram showing the system architecture of the optical fiber FMG driven controller and the wearable robotic glove.

fiber to interpret the user intent in a easier and more robust way. These signals are processed by a microcontroller unit (MCU) that implements a logic of control in order to open or close an underactuated soft robotic glove with two degrees of actuation (DOA) . The MCU sends angular velocity commands to two Dynamixel AX-12A+ Smart Servos using a Daisy Chain topology and through a single wire Half-Duplex asynchronous serial communication. Each motor is linked with a 3D printed nonbackdrivable mechanism. Finally, a force-sensing resistor (FSR) is used as grip strength feedback performed by the device. The block diagram proposed in Fig. 1 shows an overview of the full system.

A. Glove Design

In order to develop the glove-like orthosis, a bike glove made out polyester and neoprene (see Fig. 2) was chosen. It was selected based upon criteria as comfort, lightweight, softness and fabrics strong enough to withstand the tensile forces generated by the tendons used to actuate the fingers.

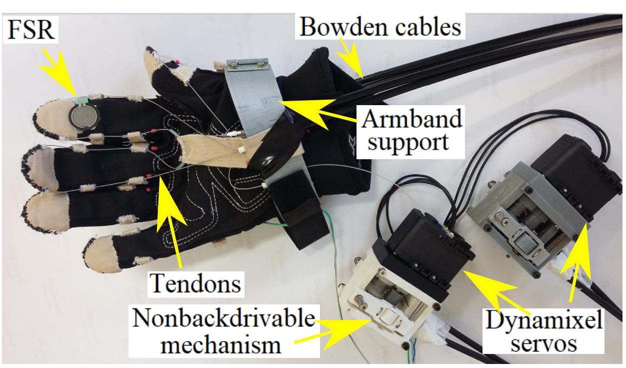

Fig. 2. Wearable robotic glove and its components.

A group of three fingers was chosen to be actuated by two motors, the thumb, index finger and middle finger, since with this set is possible to perform most ADLs [17]. Thumb is actuated by one motor whereas index finger and middle finger share the same driving motor. Since the glove uses an underactuated systems to perform the grasps, a differential mechanism is applied to achieve stable grasping and reduce the number of actuators used in the project.

In order to execute the flexion/extension movements, a tendon-driven system is used, acting similar to the human hand tendons. On the volar side, the tendons (implemented with cables) pass through small tubes of Teflon stitched in pairs in the phalanges dorsal sides of the fingers. On the dorsal side, the tendons are routed via a tube stitched between intermediate and proximal phalanges, and other on the back of the hand. U-shaped tubes were fixed on both actuated fingertips by a thimble-like cap, made from inextensible fabric. This arrangement allows the cables turn around the fingertips and provides the support to the tendons, transmitting the force generated by the tendon-driven system.

The tendon-driven system is comprised of Bowden cables, the tendon actuator mechanism and motor, and the tendons. The sheaths chosen for the Bowden cables were bicycle brake outer housing with helical wire structure.

The tendon actuator mechanism used in this project was based in [18]. The main advantages of using this type of mechanism can be summarized in: (1) this mechanism can manage in a plain manner the problems of cables derailment in similar projects involving tendon actuation; (2) making use of one-way clutches to turn it into a nonbackdrivable device, it provides passive brake and thereby energy saving; (3) since it is nonbackdrivable, it applies unidirectional friction to maintain the tendon strained inside of the device while enabling slack to the tendon part out of it, which is important to avoid injuries in the users' hands by pre-tension; (4) furthermore, it is a mechanism which can wind flexor tendon of each fingers set when rotating in one direction and, at the same time, unwind the extensor tendon, and vice versa. The Dynamixel servomotors employed to drive the mechanisms were chosen due to hardware specifications, such as torque, angular velocity, controllability as well as its easy programming and price. The cables selected to act as tendons were a bead string wire (flex-rite bead stringing wire, (21 strand nylon-coated stainless steel micro-wire, from Bead Smith), owing to its flexibility and capacity of adjusting to the spool body surfaces used in the actuator mechanism. Finally, a FSR (with a round, 0.5-inch diameter, sensing area) was attached to the digital pulp of the index finger. This device is used to control the opening and closing the glove, as explained on Section II-D.

B. System Architecture

A simple controller using optical-fiber FMG was implemented with a high performance microcontroller unit (MCU) based on the ARM Cortex-M4F architecture.

This MCU has Digital Signal Processing (DSP) capabilities due its SIMD instruction set and two separate stack pointers ideal for real-time applications through the use of Real-Time Operating Systems (RTOS) [19]. The system takes advantage of the CMSIS-RTOS RTX 5 which is designed for Cortex-M processor-based devices in order to implement two different threads (sampler and control threads) that run in a concurrent way [20]. On the Sampler thread, two channels of FMG signals are collected using the on-chip ADC with a 1000 kHz of sample rate, and then are processed through a single-threshold method in order to detect the *On* and *Off* timing of the muscles, by comparing the RMS value with predefined thresholds whose values depends on the desired sensibility required to detect the user intent with least possible effort [21]. Moreover, a single channel of FSR is sampled in the same thread with the aim of controlling the pressure with which the user grabs the objects. Details about the control strategy adopted on the control thread are described on the Section II-D and Fig. 4.

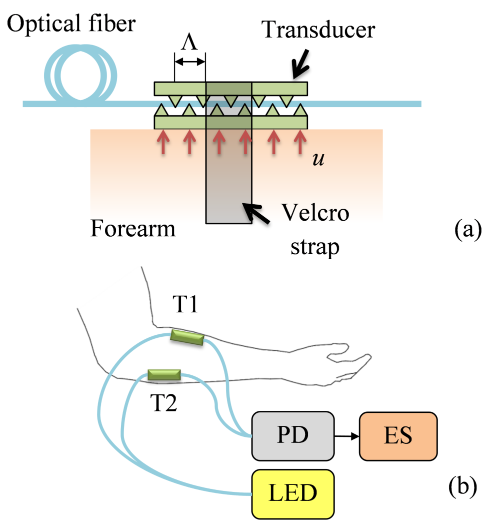

Fig. 3. FMG sensor system: (a) microbending transducer representation; (b) measurement setup. Note: u: displacement caused by muscles activity; PD: photodiode; ES: embedded systems. T1 and T2: transducers.

C. *Optical Fiber Force Myography*

Optical fiber sensors (OFS) are being considered as promising alternatives for bio-mechanical measurements, specially due to its immunity to electromagnetic interference. Therefore, this transducer is ideal to capture the user's intention as a mechanical counterpart of the sEMG that does not demands expensive hardware for its implementation [16]. This transducer takes advantage of the microbending effect, which consists of using two corrugated transducers (plates) attached to a waveguide segment, which by means of external contact forces induce deformation to the fiber, causing light attenuation that can be modulated by the magnitude of the applied forces and displacements [22]. Each microbending device showed in Fig. 3 (a) is comprised of two 3D printed Nylon polymer.

The dimension plates are $65 \times 14 \times 5\ mm^3$. The upper plate is a rigid plate providing support to the Velcro straps used to attached the device to the user's forearm, whereas the lower is a flexible one, responsible to cause deformation to the fiber when radial forces exerted by the forearm muscles displace it. Both the plates are corrugated with pyramidal form, with 0.5 mm high, equally spaced with Λ = 1 cm periodicity.

With the aim of assess the muscular activities, two transducers, T1 and T2, were attached to specific locations of the user's forearm. One of them, T1, is placed on the Flexor Digitorum Superficialis (FDS) set of muscles; the other one, T2, is placed on the Extensor Digitorum Communis (EDC), as represented in Fig. 3 (b). The transducers are attached to 2 m length of silica multimode fiber. One endings of the fiber is connected to a 850 nm light-emitting diode (LED), and the other is coupled to a photodiode (PD), (as measurement setup in Fig. 3 (b)), where the modulated light is conditioned to be measured by an embedded system (ES), which in turn executes the control as depicted on the Section II-D.

D. *Control Strategy*

The state of the muscles activity is continuously measured and used to close, open, or hold the position of the glove by monitoring the signals coming from the two optical fiber FMG transducers. These devices detect the muscle activity related to the intention of closing or opening the hand, and the state of holding position is deduced from the signals acquired. After the signal conditioning stage, the voltage output span in the range of 0 to 3.3 V. The MCU processes both signals to calculate the RMS value of a 10 ms time window in order to be compared with predefined thresholds of FMG values to actuate the glove through the driving motors. The strategy of control was designed using a state machine of four states as shown in Fig. 4. In the initial state *("State 0")*, when the hand is fully open and the user tries to perform a grasp, the FMG transducer placed on the flexor set of muscles, captures a signal that is proportional to the deformation performed by the group of muscles and that is also related with the they force performed. If the FMG flexor RMS value (F) is greater than the predefined FMG flexor threshold (FT), the state machine switches to the *"State 1"* and turns on the motors responsible for closing the hand.

The hand closes until the RMS value calculated from the FSR signal is greater than a threshold settled in a force set-point leading the system to switch to the *"State 2"*. This set-point is defined as $SP = \alpha F_{max}$, where F_{max} is the maximum value taken from a time window of 100 ms of FSR RMS values and α is a proportional gain used to calibrate the desired relationship between the force performed by the flexor group of muscles and the grip strength measured by the FSR sensor. The FSR sensor is attached to the index finger and provides signal when the finger presses the object's surface intended to be grasped. The motors remains in this state until the user performs a contraction that captures the intention to opening the hand and release the object. In this way, the FMG transducer placed on EDC group of muscles detects a deformation in the same way as the flexors.

Hence, whether the FMG extensor RMS value (E) is greater than the FMG extensor threshold (ET), the system switches to the *"State 3"* and the glove starts to open by changing the direction of the motors. For the sake of simplicity and taking advantage of the capabilities of a RTOS, the elapsed time T in ms which the glove remains closing until stopping is stored in the variable Timer from the transition of the *"States 0 to 1"*, and then it is used to open the glove by the same amount of time, returning the glove to the opened hand position and to the *"State 0"*. This procedure guarantees that the glove is kept always in the initial position, that is, in the neutral position for the wrist with the hand opened. The glove remains in this state until a new intention of the user for closing the hand be detected by the FMG transducer on the FDS.

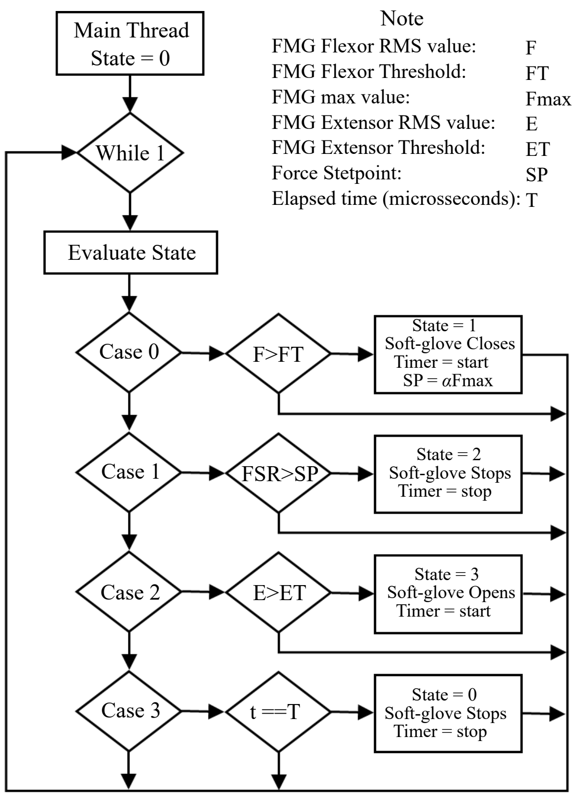

Fig. 4. Main thread flowchart showing the control strategy of the system.

III. RESULTS

In order to evaluate the system response, some experiments were conducted, as procedure describe on Section II-C. For the experiments, a healthy user donned the glove on the right hand. The first experiment consisted in a set of movements executing the closing and opening the hand using the glove, in order the user adapt to the glove. For this first trial, instead using FMG signal to trigger the motors, the system operation was evaluated using the sEMG bio-potential collected from the FDS (the MyoWare muscle sensor with pre-gelled disposable electrodes Kendall, shape/size round/24 mm, thickness 1 mm, were used). One of the signals was recorded with a sample rate of 1 kHz to its posterior comparison with the FMG sensor. For the second experiment, the sEMG sensor was replaced with the FMG sensor, repeated the same contraction many times to record the muscular activity with the same sample rate used with the sEMG. For the purpose to contrast the signals, both of them are showed in Fig 5.

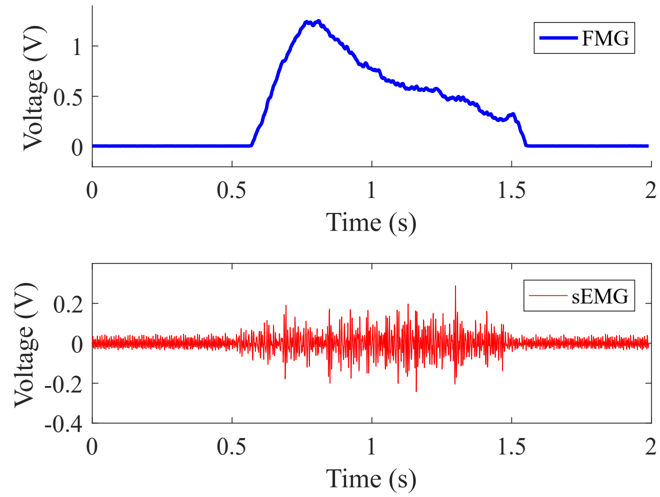

Fig. 5. Comparison of FMG vs sEMG.

The sEMG signal was filtered using an IIR Elliptic Band-Pass filter of order 20 with a pass-band from 100 to 480 Hz and quantized for single precision. The filter was implemented using the Biquad Cascade IIR Filters Using a Direct Form II Transposed Structure from the CMSIS-DSP API for ARM Cortex-M4 microcontrollers [20].

To validate the control strategy depicted in Fig 4, all the sensor signals, FMG flexor RMS value, FMG Extensor RMS value, and FSR signal, were recorded during the execution of a task and plotted in Fig 6, with the signal conditioned. The tasks executed were (a) a stick glue grasping and (b) an insulating tape grasping.

As can be noted in Fig. 6 (a), until approximately 2.3 s the systems is in *State 0*, which indicates the motors are stopped and the hand is opened. When the flexion movement intention is detected by the FMG sensor placed on the FDS muscle, the state changes to *State 1* and glove starts closing. The dashed line represents the *On* and *Off* state of the motor. The hand is kept closing until the FSR signal surpasses a threshold and them switches to *State 2*. It implies the FSR touched the surface object and the motors are stopped. When the extension movement intention is detected by the FMG placed on the EDC muscle, the state changes to *State 3* and glove starts opening. Finally, *State 3* remains until the specified time is met, i. e. by the same time that *State 1* remains in high level, and thus switches again to *State 0*. It means that glove is fully opened again and motors are stopped. The system continues in this state until a new flexion movement intention is detected, restarting the loop. The Fig 6 (b), shows the same signals evaluated, but related to the task of grasping an insulating tape. Since the task makes use of the differential mechanism, signal shapes vary greatly.

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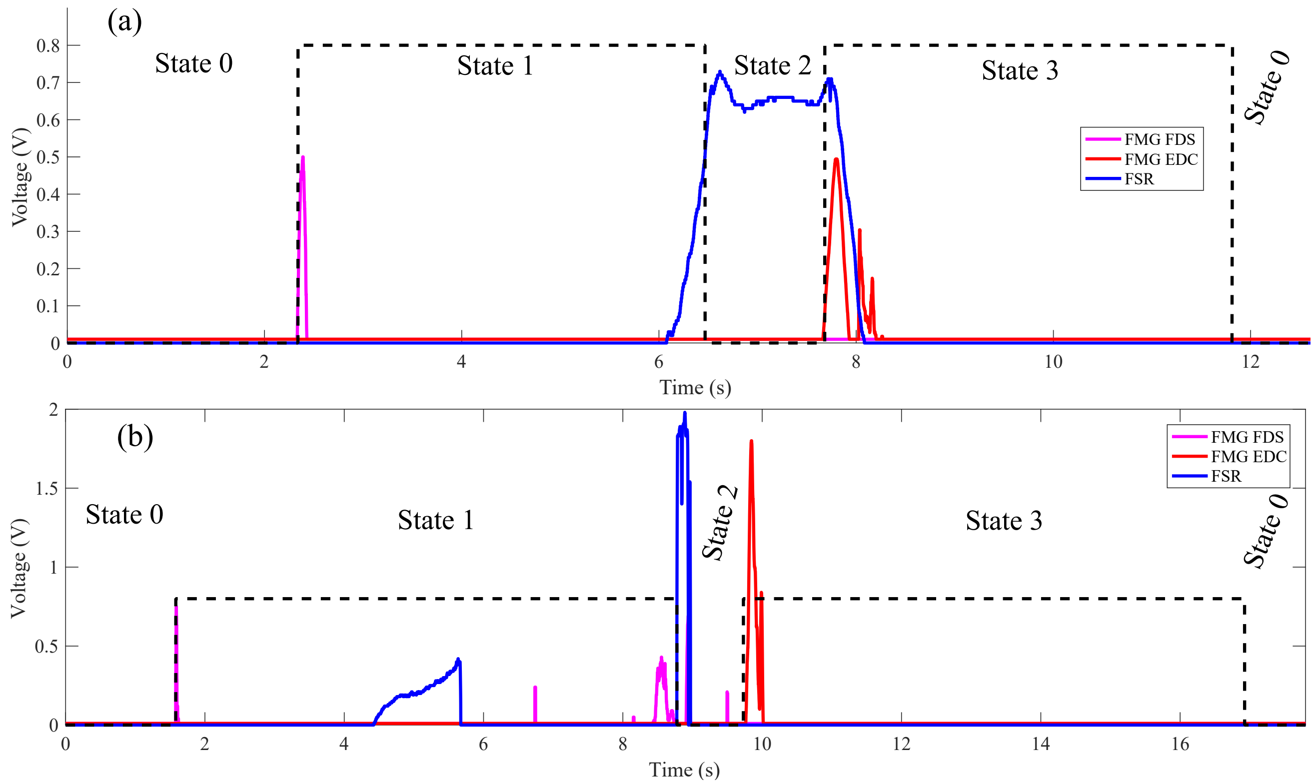

Fig. 6. Signals from grasping (a) a stick glue and (b) an insulating tape. Note: FMG FDS = FMG flexor RMS value; FMG EDC = FMG Extensor RMS value; FSR = FSR signal.

Between period of time 4 and 6 s, the FSR signal starts increasing, because the index finger touched the object's surface. However, the glove remains closing because middle finger is bending. When the middle finger closes totally, approximately in 9 s, the force is distributed between the two fingers and FSR signal starts increasing again, up to the motors stop *State 2*.

Compare the difference between the amplitude and the shape of the signals in Figs. 6 (a) and (b). For each task developed, as for those represented in Fig. 7, we will have several different times for switching the states, but the procedures are the same.

Finally, to qualitatively appraise the glove grasps and testing the control strategy, some objects were used, was showed in Fig. 7. As can be seen, the differential mechanism applied allows the actuated fingers to adapt to the objects surface, as was expected. For security reasons, a test was conduct to preclude the glove from closing or opening the hand beyond natural positions that can cause injury, as a wrist hyperextension or an over-curled fingers position towards the palm or wrist. The experiment consisted in keeping the hand in the neutral position, and afterwards it was started the fingers flexion movement until the fingers were fully closed (clenched fist) in a comfortable way. This time of course was saved and used as a standard time limitation for closing and opening the hand. This simple procedure can avoid awkward hand positions and insures that the glove's motors will stop in cause of signal failure coming from the FSR.

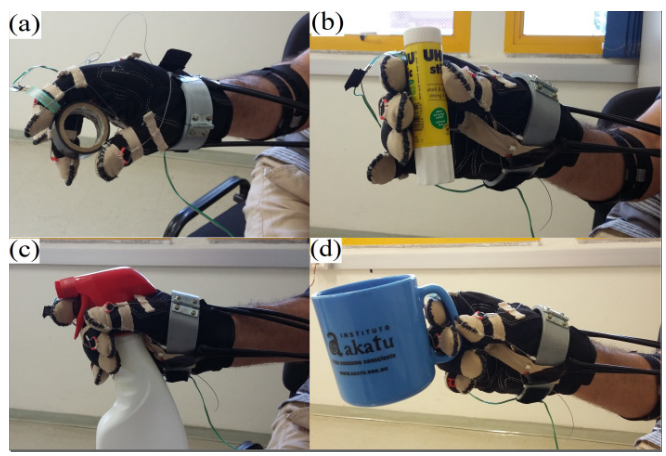

Fig. 7. Objects used in the test: (a) insulating tape, (b) stick glue; (c) trigger pump bottle; (d) mug.

IV. CONCLUSION AND FUTURE WORKS

A simpler control method to activate the glove actuators by using optical fiber FMG transducers was successfully tested and validated. Furthermore, a glove-like orthosis system was presented in order to be used by people with upper limb disabilities (i.e. limited upper limb movements), which assists them to perform the ADLs in a satisfactory way. The experiments confirm that the performance of the optical fiber FMG transducers are very satisfactory and can be considered a good substitute for sEMG sensors.

In order to modify the time it takes to grab an object, a proportional speed controller can be implemented to vary the timing of the grip in the control loop. In addition, a robotic glove with more actuators will be implemented to add finger synchronization in order to improve its grasping abilities by using more user-friendly human machine interfaces, such as computer vision based object recognition for grasping selection applied to prosthetic hands [23]. Another future work is to quantify the force contribution of the glove while grasping an object, which can be made monitoring the electromyographic activity of FDS and EDC muscles, either using sEMG or FMG. Differently from the sEMG method which is susceptible to the electromagnetic noise, the FMG method does not have this limitation. This allows its application into other novel investigations, as the use of functional electrical stimulation (FES) for rehabilitation.

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