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# Characterization of a Soft Hand Exoskeleton through a Sensorized Hand Phantom

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***Abstract*—This study focuses on characterization of a soft hand exoskeleton by development of a dedicated, sensorized hand phantom. The hand exoskeleton is developed in the shape of a soft, tendon-driven actuated glove, designed for assisting finger movements, specifically targeting spinal cord injury patients. Due to the flexible and soft kinematic structure, bench-test characterization is challenging without the involvement of a human hand. Rigid hand phantoms do not allow to appreciate compliance of the soft structure of the glove together with the soft tissues of the hand. Moreover, the particular tendon routing of the device is designed to adapt clenching forces around the hand depending on the exerted grasping force. To this purpose we developed a realistic, sensorized hand phantom mimicking human anatomy, in order to obtain repeatable bench-test conditions. In this work we provide an overiview and first characterization of the hand phantom, evaluating its functionality and implementation together with the developed soft hand exoskeleton.**

***Index Terms*—Hand, exoskeleton, actuated glove, phantom, mannequin, sensorized**

Fig. 1. The developed soft hand exoskeleton (left) and the sensorized phantom hand (right) designed for its characterization.

## I. INTRODUCTION

Functionality of the hand is pivotal in performing activities of daily living (ADLs). A broad research effort is performed in developing robotic devices for restoring or assisting at least basic motor functionalities of the hand, such as grasping [1]. Advances in the field are challenging, due to both the complex and fine hand functionalities present in a healthy individual, and the strict constraints in terms of weight and volume that wearable assisting device have to comply with [2]. Several methods have been proposed in the literature [3]–[6], including rigid exoskeletons, under-actuated solutions to better adapt to the user's hand, and soft exoskeletons and gloves with tendon-driven or pneumatic actuation. Belonging to the soft-exoskeleton approach, we recently proposed a novel approach [7] to take advantage of tendon routing to apply clenching forces as well, hence improving stability of the soft device when activated. Due to the soft structure, and to the intrinsic adaptation of the device to the hand kinematics of the user, characterization of similar soft wearable devices is relatively complex, since they require a human hand already at the stage of bench-test characterization. Mechanical phantoms have been successfully used in other exoskeleton domains, to replicate human biomechanics and address challenges associated with soft tissue deformation and assistive force transmission [8]. For that reason, we developed and present in this work a soft and sensorized hand phantom, followed by an implementation of this tool for a first evaluation of an improved version of the soft exoskeleton presented in [7].

## II. METHODS

The design of the soft hand exoskeleton developed in this study focuses on creating a device with one degree of freedom, specifically designed to actuate the flexion and extension of the index, middle, ring, and little fingers, while the thumb is held in opposition. This exoskeleton consists of a semi-rigid glove to which the finger units, routing, and actuation unit are connected.

The finger module is composed of a series of open rings arranged along the length of the finger, following a design inspired by the work of [9] and [10]. When flexion cables are pulled by motors, these rings clench around the finger, helping to maintain stable the structure of the soft glove.

The routing is folded around both sides of the hand, securing PTFE sheaths for the cables to two semi-rigid nylon plates

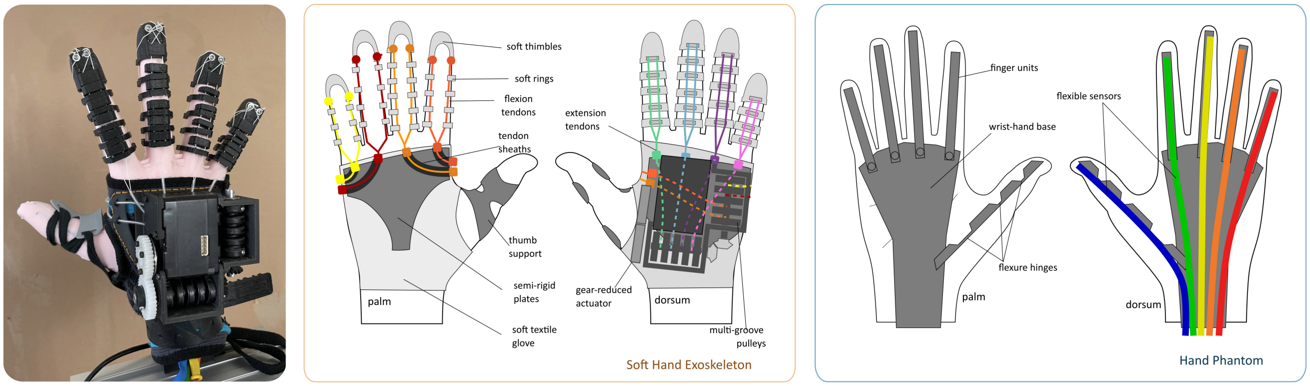

Fig. 2. The soft exoskeleton worn on the silicone phantom hand (left). Scheme of the particular tendon routing of the exoskeleton (middle). Scheme of the rigid skeleton and flexion sensors embedded in the phantom hand (right).

sewn firmly onto the glove. This routing method, as previously demonstrated, increases the stability of the exoskeleton during device actuation. The novel version of the exoskeleton includes all four fingers, excluding the thumb, which is locked in opposition. This design choice was made because of the target population the device is intended for, i.e. patients with spinal cord injuries (SCI), with minimal residual mobility of their fingers, especially the thumb, which is problematic to actuate by a soft kinematic structure due to the multiple degrees of freedom. A significant innovation introduced in this version is the modified actuation unit. The device embeds a single motor unit on the device itself, avoiding the use of remote actuation units with bowden cables. Here, the design implements two orthogonal pulleys connected through two bevel gears specifically designed and developed for this application. One pulley manages all the flexion cables, while the other manages all the extension cables. This design allows for decoupling of the pulleys during the cable length adjustment phase, greatly facilitating the adjustment process and improving the efficiency of the exoskeleton.

### A. *Design of the Hand Phantom*

To evaluate the current hand exoskeleton, and in general other actuated devices for the hand, a realistic and sensorized soft hand phantom was developed to accurately mimic the human anatomy. The hand phantom implements a rigid bone structure, immersed in a soft outern material. In addition, flexible bending sensors, one for each finger, are embedded in the device.

The production process began with the creation of an accurate three-dimensional model by scanning a real hand. Using this model, a PLA negative mold of the hand was made. This procedure was essential to guarantee that the phantom's proportions and shape matched those of an actual human hand. Next, using CAD software, an internal bone structure was designed to match anatomical dimensions and composed of rigid components that mimic human phalanges. Flexure hinges were implemented to replicate the finger joints, enabling a maximum flexion angle of 90°. Stop mechanisms were included to avoid phalange hyperextension. To cut down on production time and costs, this structure was intended to be 3D printed in nylon reinforced with carbon fiber (Markforged Onyx nylon) using a single print bed. Once the bone structure was completed, bending sensors (SpectraSymbol FLS-0095-103) were attached to monitor finger flexion. The bone structure was then centered inside the negative mold, and silicone (Smooth-On Mold Max 20) was poured to create the ”soft tissues” of the phantom. This process allowed the creation of a phantom that replicates not only the bone structure but also the consistency of human soft tissues, ensuring a more realistic testing activity. The hand phantom was tested using this hand phantom. This guaranteed that a comprehensive evaluation of the prototype can be conducted in conditions comparable to real-life scenarios.

### B. *Experimental Characterization*

To characterize the device, the soft hand exoskeleton was worn by the hand phantom, and the finger movements were evaluated during actuation. The exoskeleton was carefully fitted onto the phantom, ensuring proper alignment with the finger joints. An external optical tracking system (Optitrac v120 Trio system) was used as a ground-truth for calibration and validation. Two optical markers were placed on the hand dorsum, and two on the distal phalanx of the finger, in order to measure the relative orientation. The internal bending sensors of the phantom hand were acquired using an ADC IC (Texas Instruments ADS1115) connected to a microcontroller board (Espressif ESP32-S2). The exoskeleton was then activated gradually applying (ramp reference) the nominal output torque of the motor. Data recorded in this first calibration session was used to obtain the characteristic between the embedded sensors output and the flexion angle measured by the external tracking system (Figure IV (a)). A 2nd order polynomial curve was fitted to the measured data. Similarly, a 3rd order polynomial curve was fit between the embedded flexion sensors and the length of the cables driven by the soft exoskeleton actuator (Figure IV (b)).

A second experimental measurement was then performed using a different activation intensity to test vailidity and repeatability of the characterization curves fitted in the first

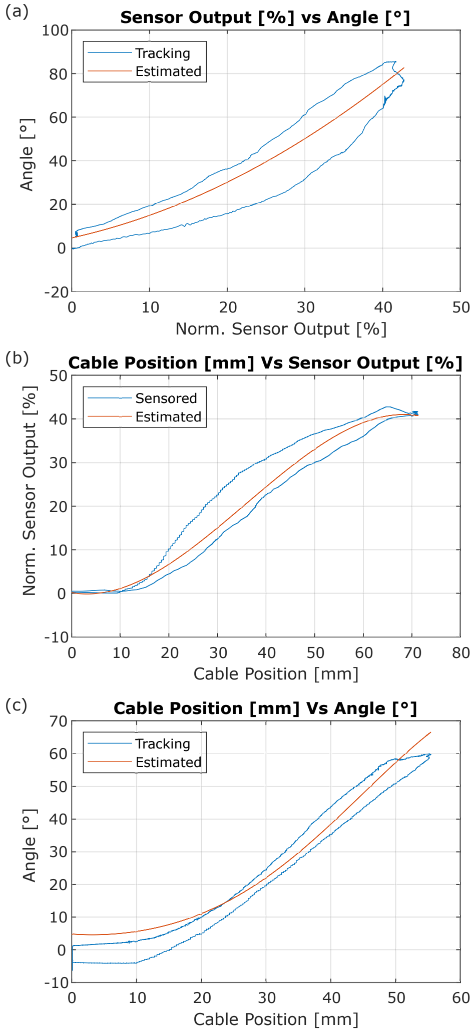

Fig. 3. (a) Angles of the MCP, PIP and PIP finger joints measured from the optical markers (index finger). (b) Comparison of the angle estimated by embedded sensors with angles measured by the external optical tracking in a second experimental session. (c) Comparison of the angle estimated by embedded sensors with angles measured by the external optical tracking in a second experimental session. All graphs are representative of the index finger only.

experiment. In this final experiment, the two curves allowed to estimate the flexion angle from the position of the actuator (Figure IV (c)). Overall, the preliminary experimental characterization shown in this work demonstrate a good matching between the measured and estimated angles using the developed phantom hand compared to the optical tracking ground-thruth. Regarding the hand exoskeleton operation, experiments show the passive fingers could be mobilized across the full grasping range (0-90°).

## III. Conclusions

This work presented the characterization of a novel soft hand exoskeleton with particular focus on the development of a sensorized phantom hand. This tool aims at improve effectiveness and feasibility of bench-test characterization of soft exoskeleton devices, requiring a passive human hand to be operated. Experimental characterization was conducted to calibrate the phantom hand sensors, and to evaluate the overall mobility of the device, eventually adjusting the design of the flexure hinges and of the end-stop mechanisms. Results showed the mobility of the phantom hand resembles the typical open-closing range covered by a human hand during grasping tasks. Moreover, a preliminary test was conducted with the novel exoskeleton prototype, showing that the achieved opening-closing workspace was also adequate to support real grasping tasks.

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