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Design and Characterization of Modular Soft Exoskeleton for Hand Rehabilitation

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***Abstract*—In this work, we present the investigation and the results of innovative soft finger modules of an actuated compact glove. The modular finger modules are based on a soft, open-ring structure, to improve the comfort of the user when the hand is relaxed, and at the same time to enhance the glove's structural stability when it is active for grasping assistance. We present a novel modular design of the finger modules, integrated with a working prototype of the actuated glove. Design is then characterized and evaluated with experimental loading tests of the prototype parts and FEM simulation. The simulation helps to understand interface forces between the soft rings and the finger tissue which would be otherwise difficult to evaluate in experiments.**

***Index Terms*—Soft-robotics, Exoskeleton, Rehabilitation, Design, Ergonomics**

I. INTRODUCTION

The role of the hand is crucial in our physical interaction with the environment: most of the Activities of Daily Living (ADL) involve the use of the hand for fine manipulation, grasping, and the use of tools. Restoration of hand motor functions is then fundamental for those patients who have completely or partially lost their motor abilities to gain a better quality of life. Robotic devices supporting the hand can play an important role both for assistance purposes [1] and neurorehabilitation, where haptic feedback, congruent with motor intention, can promote and guide brain plasticity toward a more normal restoration of motor functions [2]. To convey motor assistance at the level of the hand is a challenging objective in the design of robotic devices, due to the complexity of the hand kinematics, variability of hand sizes, limited available workspace, and relatively high forces involved.

The introduction of soft materials in robotics fostered the development of novel hand exoskeleton devices with improved adaptability, comfort in wearing, and lightweight structure [3]. The soft exoskeleton approach exploits the rigid kinematic of the finger itself, by only adding an external actuation system. Tendon actuation is a method widely used in soft gloves presented in literature [4], [5], [6] resulting in slim structures of the device, especially at the finger segment.

In this work, we further developed this open-ring structure, in particular regarding modularity and fabrication methods. In [5] a folded silicone foil was used to obtain the open-ring structure, supporting the finger through three rings in total. We explored how a similar design concept can be implemented by 3D printing in soft materials: the advantage would be a higher number of thinner rings with more distributed support, and a higher level of customization and adaptation to the hand size.

Fig. 1. Preliminary prototype of the compact soft exoskeleton. Actuator and tendon transmission are arranged around the palm and hand dorsum, with no remote mechanical parts.

II. METHODS

A. Finger Modules and Soft Exoskeleton Design

The presented finger modules have been designed and developed for integration in a soft glove prototype, preliminary presented in [7]. The glove consists of a semi-rigid plate structure at the hand palm and dorsum, sewed to an elastic fabric glove. Finger links implement the soft, modular structure investigated in the present work. Tendon routing is folded around the hand palm, to obtain a compact actuating system embedded at the hand dorsum (1-DoF). Still, the presented modular finger approach can be generalized to different glove designs including Bowden cables and remote actuators.

Finger units consist of a series of Thermoplastic Polyurethane (TPU, shore hardness 95A) open rings and a thimble. Polytetrafluoroethylene (PTFE) tubes are embedded at the tips and in the middle part of the open rings where tendons are routed. The number of rings can be varied in number and dimensions to better fit phalanges of different lengths and sizes. Screw terminals on the thimble allow to release of the tendons and to change rings without re-routing the transmission of the whole device.

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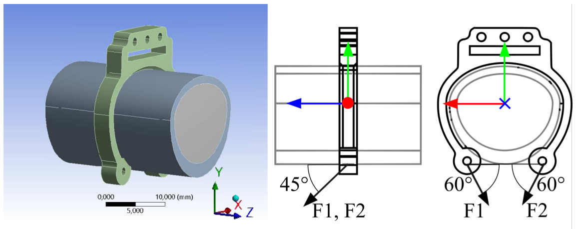
The open ring approach uses two parallel flexion tendons per finger, as presented in [5], [8], and two parallel extension tendons. The design solution has been chosen due to its improved stability and comfort in wearing. The open structure allows to relax clenching forces when the transmission is unloaded. The kinematic model of the soft open ring modules is shown in [5]. Concerning the referenced work, we introduced a redundant number of rings to better adapt to different lengths of the fingers. Also, fabrication in 3D printing, rather than using flat silicone foils, allows for a more precise fit of the rings when tendons are relaxed.

B. *Finite element model*

Two FEMs models were generated to simulate first the behavior of the 3D-printed open ring structure and second the interaction between the ring and the finger during the cable traction. The first model represents the traction and elongation of a TPU ring (internal maximum diameter of 19 mm, radial thickness 1.6 mm, axial thickness 3 mm). The magnitude of the traction force was decided based on the previous characterization of the servomotor. It, powered at $9V$ and with a pulley of radius $10cm$, generates a traction force of 25 N. The force exerted on a single finger is one-third of the total force, so cautiously a force of $10N$ was chosen to test the ring traction. The elastic modulus for TPU was set at $26\,MPa$ from the datasheet. The second model represents a phalanx and the ring, to which the traction force of the cables is applied. The following assumptions were made to simplify the model, while still keeping it reliable. The model considered is the case of the first ring on the proximal phalanx, that is, the ring on which the most force is applied (Fig. 2a). The model was designed following the anatomy of the proximal phalanx and materials were assigned to both tissue and bone [9]. Since the applied forces are low, the materials were considered isotropic with an elastic modulus of 70 kPa for the finger tissue [10] and $11.5\,GPa$ for the bone [11]. Only flexion was considered for this model, as it is the one that stresses the phalanges the most. The sheath, in which the cables run through the rings, was considered to have zero friction. As a consequence, any component parallel to the cable path cancels out as it has no friction. The force applied in space, as shown in Fig. 2b, would have a modulus of $4.16\,N$, but given the assumption of no friction, a 3 N force was applied to the model in the XY plane.

C. *Soft exoskeleton glove preliminary test*

A preliminary test of the whole exoskeleton device was performed, measuring grasping assistance with a healthy participant. The test aims at an overall functionality evaluation of the soft finger modules in the final prototype. We measured the internal pressure of a water-filled sensorized bottle $0.5l$ (Bosch BMP280 pressure sensor in the cap) grasped by the subject's hand. The nominal motor torque was exerted through a step reference signal on ten repetition. Each grasping and release period lasted 10 seconds.



(a) (b)

Fig. 2. Ring-phalanx model: a) CAD model of the ring-phalanx system, including the bone and the tissue; b) model of application of the forces, in evidence the angles on the YZ and XY planes

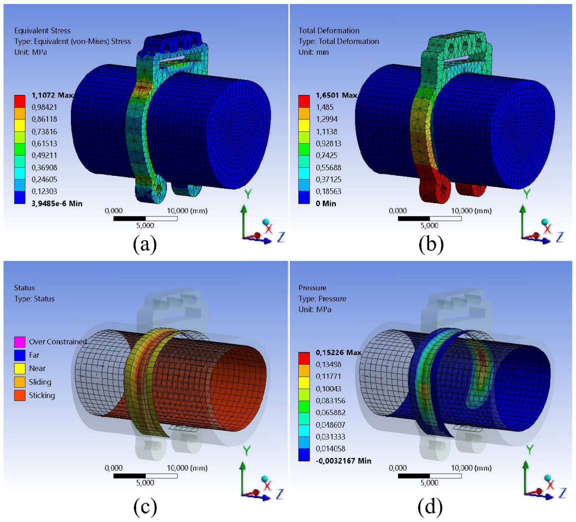
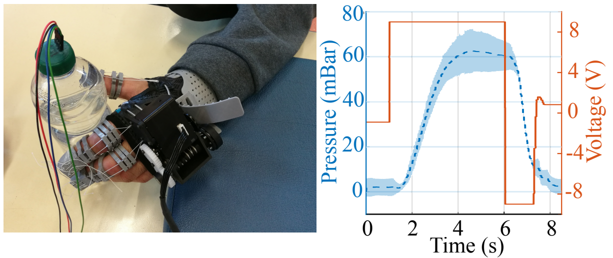


Fig. 3. FEM results: a) Equivalent (von-Mises) Stress; b) Total Deformation; c) Contact Status; d) Contact Pressure.

III. RESULTS

The first FEM simulation showed that the TPU open ring structure does not reach either break or yield under the action of the overestimated load. The second FEM simulation shows the desired ring clenching around the finger. The equivalent stress on the ring remains contained and the patterned tissue flattens against the bone where it discharges all stresses (Fig. 3a and Fig. 3b). Fig. 3c shows how on top of the contact sticking is maintained (red surfaces), a portion slips (orange surfaces) and parts near the contact deform (yellow surfaces). Moreover, Fig. 3d shows the pressure distribution on the skin of the phalanx which has a maximum value below $0.15\,MPa$. Since the human pressure-pain thresholds on fingers can be considered above 0.4 MPa [12], the pressure calculated by the simulation can be considered acceptable and well below the threshold.

Lastly, the preliminary test showed that the device worn by a passive hand, at nominal actuator torque, was capable of generating a pressure of 60 $mBar$, averaged over 10 grasping repetitions (Fig. 4b). In comparison, in [13] we experimented with the same sensorized bottle, filled with water (mass $0.5Kg$), that the minimum pressure required by a human experimenter to lift the bottle is $\pm 8\,mBar$. Although a wider



(a) (b)

Fig. 4. Grasping test: a) subject wearing the device and a pressure-sensorized bottle; b) measured grasping pressure.

characterization and evaluation of the whole prototype will be performed with more subjects and patients, the preliminary test evidenced the overall functionality of the presented soft finger modules.

IV. CONCLUSIONS

In this work, we present the design and the evaluation of the finger modules of a soft actuated glove based on 3D printable soft materials. We adopted an open-ring structure, allowing to exert clenching forces only when the glove is activated, thus improving comfort and wearability. We introduced a redundant number of rings to better distribute forces and adapt to different lengths of the fingers. The experimented 3D printed technology in soft polymer allows also for a higher level of customization. In a final use of the exoskeleton as a rehabilitation or assistive device, size of finger rings can be fabricated matching the patient's hand size. In addition the benefit of soft and open ring structure comes from the clenching forces applied by the tendon transmission, able to tighten and stabilize the soft structure only when activated. To evaluate the feasibility of the novel open-ring design and the envisaged fabrication method, we both conducted experimental characterization of the printed prototypes by applying loading in different directions, and finite element model (FEM) simulation. The simulation allowed for a better understanding of force distribution at the contact interface between the soft rings and the soft tissues of the user's finger. Considering the human pressure-pain thresholds reported in [12], the pressure obtained by the FEM simulation resulted well below the threshold. Together with a final grasping experiment highlighting the overall functionality of the whole actuated prototype, we show the proposed design for the finger modules is a viable solution for further development of soft actuated glove design.

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