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Modeling and Prototyping of a Soft Prosthetic Hand Exploiting Joint Compliance and Modularity

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***Abstract*— Losing an hand seizes nearly all principal activities of amputees life. However, with the development in the field of prosthesis, amputees can get back to normal life with use of simple yet functional prosthetic devices. In this study, we presents the design, model and 3D printed prototype of a tendon driven underactuated modular soft prosthetic hand. The proposed robotic hand is actuated using only one motor and a differential mechanism. The flexible fingers of the hand are built with stiff link connected with soft joints. Different stiffness of the soft joints can be set to follow the desired bending trajectory of the fingers. A mathematical representation to calculate the desired stiffness needed to follow the predefined trajectory of the finger is detailed. We also present a method to realize the computed stiffness through FDM 3D printer. The presented methodology is used to characterize the soft joints deformation and to realize prototype of the prosthetic hand. Finally, we presented electromyography (EMG) based control interface of hand prosthesis and experiments with activity daily objects consisting of grasping objects of various shapes, sizes and textures. The results showed the good grasping performance of the hand and its ability to adapt different shapes.**

I. Introduction

The development of prosthetic devices is necessary and need because of debilitating diseases, accidents and congenital defects. According to a survey in worldwide, each year, the number of new amputees is increased by 150,000 to 200,000 [1], [2]. Although, substantial progress have been made towards anthropomorphic prosthetic hand in the past years using emerging technologies. However, the trade-off between functionality, reliability, affordability, appearance have not been fully settled. Soft hands are an interesting and promising direction of research in robotic hands leading toward solutions that are characterized by a simplified hardware structure, with a limited number of actuators, where the needed adaptability is guaranteed by the presence of passive compliant elements [3], [4], [5], [6] or by the compliant structure of the hand [7] or regulating the compliance of robotic joints [8], [9], [10]. Exploiting compliance and underactuation in robotic hands enable to improve the adaptability of the devices to unstructured environments and the capability of manipulating fragile objects with uncertain shapes. Apart from prosthetic applications,

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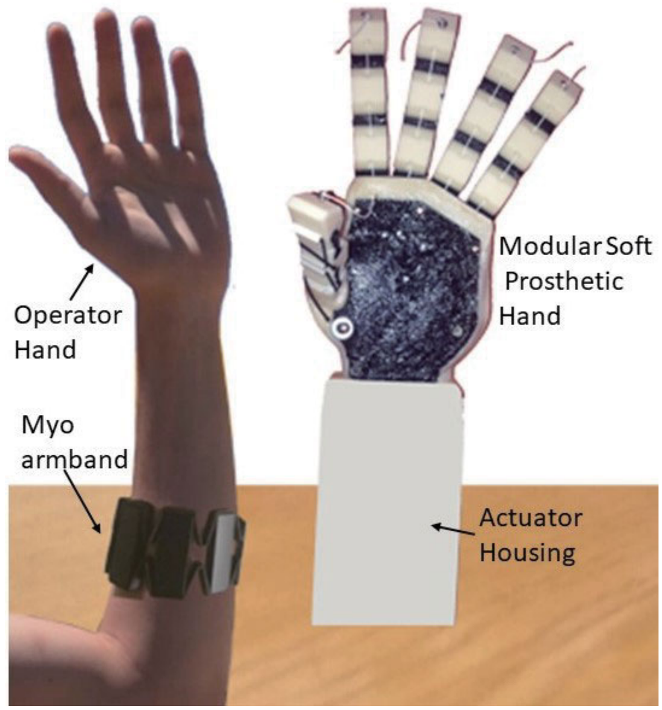

Fig. 1. The modular tendon driven soft prosthetic hand and its Myo armband based interface. The motion of robotic hand has been associated with the gesture of operator hand.

the other interesting applications could be, for instance food industry [11] or other assistive devices [12], [13]. In such devices, a proper design of passive elements is paramount to guarantee the suitable contact force distribution [14]. In principle, the prosthesis and other assistive devices must meet ergonomics and functional requirements related to ease of use, lightweight, robustness, and cosmetically pleasing [15]. Most of these objectives can be achieved by good mechanical design, actuation and selecting suitable materials [16].

The design process of soft hands differs from that of traditional robotic structures. Rigid robots are composed of rigid links connected to actuators and, in such systems, the problems of structural behavior and device control are basically decoupled. On the other hand, in the emerging field of soft robotics, these boundaries are blurred and there is a need to define new paradigms in engineering that challenged us to re-examine the relationships between materials and mechanisms behavior and device performance and control [17], [18]. In particular, the advent of the so–called 3D–printing

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technology changed modern manufacturing [19].3D–printed parts based on the fused deposition method (FDM) are widely used in many different applications including robot design and fabrication [20], [21].

New materials introduced by additive manufacturing techniques opens a set of possibilities for designers. Beside geometric shape, additional parameters such as chemical composition, surface treatments, infill density percentage, printing pattern, etc. can be used to get the desired mechanical properties [22]. In underactuated compliant robots, the lack of actuation can be partially compensated by regulating, during the design phase, the stiffness and deformation of compliant elements.

In [23], [24], [25], we presented our preliminary studies on modular underactuated robotic fingers, where we presented an approach of obtaining different joint stiffness to obtain a predefined fingertip trajectory. The proposed prosthetic hand consists of a soft modular structure actuated through a cable as shown in Figure 1. The soft joints improve the shape adaptation to the grasped object and safety during the interaction with the environment. The cable driven actuation system of the hand consists of only one motor and a differential mechanism. A mathematical framework to calculate the stiffness of soft joints is reported. Furthermore, the realization of the desired stiffness is achieved by using simple 3D printer. The results of mathematical formulation are used for the kinematic and deformation analysis of soft joint to achieve desired flexion trajectory of the robotic fingers. In order to control the motion of the prosthetic hand, we presented electromyography (EMG) based control interface. We performed experiments consisting of grasping various activity daily objects with different shapes and sizes to confirm the grasping ability and shape adaptation of the soft hand.

The rest of the paper is organized as follows. Sec.II presents the main structure of the modular soft prosthetic hand and its realization through 3D printing. In Sec.III, the proposed mathematical framework and numerical simulations are detailed. In Sec.IV, we report the experiments with the soft prosthetic hand and myoarm band. Finally, in Sec. V conclusion and future work are outlined.

II. Mechanical Structure of Soft Prosthetic Hand

A. Mechanical structure

The prosthetic hand consists of two main parts, the flexible fingers and a palm. The complete CAD design of the soft hand and its prototype are shown in Figure 2. The soft fingers are built with soft-rigid modules. The modules are built with stiff links and soft joints. The rigid and flexible parts are 3D printed with ABS (Acrylonitrile Butadiene Styrene, ABSPlus, Stratasys, USA) and thermoplastic polyurethane (Lulzbot, USA) respectively. The main material parameters of both flexible and stiff material are shown in table II. The passive elements have many benefits in robotic structure e.g. storing elastic energy and shape adaptation. The soft-rigid parts of the modules are assembled without using any screws i.e. just sliding the soft part in stiff part. A single motor drives all the fingers of the robotic hand through a cable mechanism.

TABLE I
Characteristics of the Soft Prosthetic Hand.

Characteristics	Prosthetic Hand
Length of Palm	93 mm
Width of Palm	65 mm.
Stiff Modules dimensions	23 mm x 15 mm x 12 mm.
Flexible Modules dimension	13 mm x 15 mm x 5 mm
Max. actuator torque	3.1 Nm @ 12 V.
Max. non-loaded Velocity	684 deg/sec

B. Differential Mechanism

The palm of the hand contains a two layered differential mechanism connecting all the fingers of the hand to form a single structure hence enabling the finger/hand to adapt to the specific shape and dimensions of the grasped object. Multi-fingered robotic hands consist of multiple fingers. Incase these fingers are actuated through actuators less than the number of fingers, a particular mechanism is needed which is called differential mechanism. This mechanism allows the motion of fingers decoupled from each other. Thus incase one or more fingers come in contact with the object, the other continue to move until all the fingers grasped fully the object. considering our prosthetic hand case where only one motor is use to move five fingers: during the closing motion of the fingers while grasping an object. If one or more fingers are blocked or come in contact with the object first, the other fingers should continue their motion. This is achieved through the differential mechanism and using the tendon driven approach. This also enables the robotic hand to apply uniform force distribution on the grasped object.

The differential mechanism is realized through a mobile link and cable driven as shown in figure 2. The driving cable is attached to the pulley of motor at one end while the other is connected to the center of first sliding element of the differential mechanism, The two outputs of the first sliding elements are attached to the center of next two sliding elements. As a result their output cables are attached to the distal phalange of each finger. The motor used for the prosthetic hand is the servo motor (MX-28T, Robotis, South Korea). The principle characteristics of the motor are outlined in table I.

C. Material and printer settings

The soft filament considered in this work is a commercially available thermoplastic polyurethance (TPU) named NinjaFlex (Lulzbot, USA). NinjaFlex is one of the most widely used material thanks to its high flexibility and longevity compared to non-polyurethane materialsIts consistency in diameter and roundness is competitive with respect to other polyurethane materials. It is made of a specially

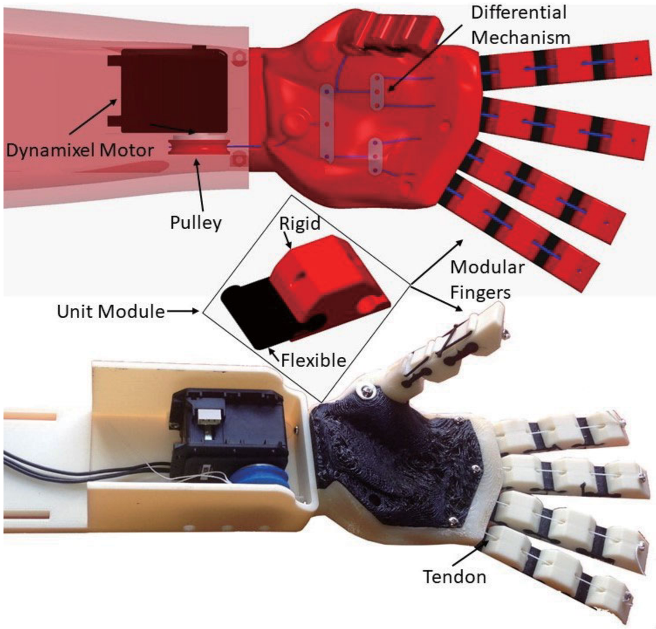

Fig. 2. On top: the CAD design of the tendon driven modular soft prosthetic hand is shown. The hand consists of single motor, differential mechanism and modular fingers. Each module is composed of soft joint and rigid link. On bottom: 3D printed prototype of the soft prosthetic hand. The soft joints are realized in Ninjaflex material while the rigid parts are printed with ABS material.

TABLE II
MAIN MATERIAL PARAMETERS AND 3D PRINTING INFILL DENSITY PERCENTAGE FOR EACH PHALANGE OF THE ROBOTIC HAND.

Material Parameters	Flexible Part	Stiff Part
Material type	Thermoplastic polyurethane (TPU)s.	Acrylonitrile Butadiene Styrene (ABS)
Modulus of elasticity (E)	15.2 MPa.	40 MPa.
Shore Hardness	85 A.	70D
3D printing infill density percentage		
Proximal Phalange	70 %	100 %
Medial Phalange	60 %	100 %
Distal Phalange	50 %	100 %

formulated TPU material which possesses a low-tack, easy-to-feed texture. The result are very flexible and resistant prints ideal for direct-drive extruders. The mechanical and thermal properties of the NinjaFlex material are summarized in Table II.

One of the important setting to be taken into account while 3D printing, is the infill density, that can be defined as the amount of material deposited by the printer. The higher the infill density is, the stiffer the printed part is expected to be. Infill density is typically expressed as a percentage and can be varied from 10% to 100%, where 10% is the lowest infill density resulting in a very flexible/soft output part, while 100% infill density will produce a stiffer and very tightly packed model, which needs more material. We chose the printing infill density through our mathematical model presented in section III to obtain different stiffness of flexible joints. The resultant percentage of infill density for each phalanx of the prototype is reported in table I.

III. MATHEMATICAL MODEL OF MODULAR SOFT-RIGID FINGER

In this study, we focus on modularity in building under-actuated complaint robotic hands. The main idea lies in the realization of modules built with soft (joint) and rigid (link) parts. The modules can easily be assembled to realize soft fingers of the hand.

In such kinds of structure, it's important to important a mathematical model to better understand their bending behaviour. Considering a simple design of a module composed of a flexible joint and stiff link as shown in figure Figure 3

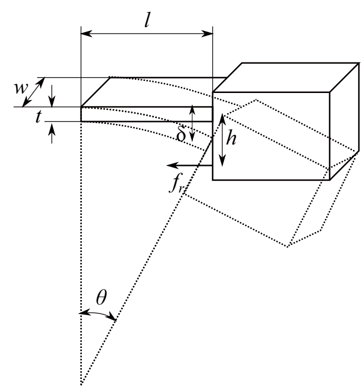

Fig. 3. Main geometrical parameters of the modular passive joint.

A torque $\tau_i = f_{rj}h$ is produced when the motor applies the force f_{rj} through the j-th wire. If we present the resultant deflection δ_i of the flexible joint, which can be computed as

$$\delta_i = \frac{-f_{rj}hl_i^2}{2E_iI_i}, \tag{1}$$

where E_i is the modulus of elasticity of 3D printed material,l_i is the length of flexible part and I_i is the second moment of area. The resultant joint rotational angle can be determined as

$$\theta_i = \frac{-f_{rj}hl_i}{E_iI_i}. \tag{2}$$

To keep it simple, we have ignored the deflection in other two unactuated directions (torsional and lateral) The joint's bending stiffness can be determined as

$$k_i = \frac{E_iI_i}{l_i}, \tag{3}$$

The second moment area can be computed as (assumption: rectangular shape with centroid at origin)

$$I_i = \frac{w_it_i^3}{12}. \tag{4}$$

One can see from Eq. (3), the bending stiffness relies on the geometric and material properties of the element. If we further consider a linear elastic case of modulus of elasticity E, i.e. $k = k(\mathbf{d}, E)$, where $\mathbf{d}$ is a vector containing all the parameters defining joint geometry (e.g., for a parallelepiped joint, its length l, width w and thickness t, see Fig. 3). Young's modulus E depends on material parameters and fabrication methods, i.e. $E = E(p_1, p_2, \cdots, p_n)$, where each value p_i indicates one specific material property. In this paper, we investigate the dependency of E with respect to a specific parameter p_1, indicating the percentage infill density. Thus we can write

$$k = f(p_1). \tag{5}$$

A. Actuator force evaluation

The mathematical representation is further extended to find the relationship between the force of fingertip to motor applied force. The motor exerted force by the wire causes a moment along the soft part of the finger. In this case, beam theory can be applied by considering it a simplified model of cantilever beam. There are two force that are acting on the finger. One is the motor force and other is the resultant reaction force (same as fingertip force F_{tip}). We can calculate the resultant bending by each separately.

Let δ_a be the bending caused by the force by motor and δ_r be the bending caused by the reaction force

$$\delta_a = \frac{f_r h l^2}{2EI}, \delta_r = \frac{F_{tip} l^3}{3EI}. \tag{6}$$

The combination of both bending can be equal to zero and the F_{tip} can be calculated as

$$F_{tip} = \frac{3 f_r h}{2l}. \tag{7}$$

This mathematical representation can be applied to any number of soft-rigid parts, as reported followings

$$F_{tip} = \frac{3 f_r h}{2 \sum_{i=1}^{2N} l_i}. \tag{8}$$

Moreover, we can also include the cable friction in the model as following

$$F_{tip} = \frac{3 f_r h}{2 \sum_{i=1}^{2N} l_i} \prod_{i=2,even}^{2n-2} e^{\mu(\theta_{i-1} - \theta_i)},$$

where μ is the coefficient of friction .

B. Numerical Simulations

In this subsection, we show the simulation results of the soft finger using methematical formulation previously reported. In order to see the finger trajectory variation in response to variation of density percentage variation, we performed the model simulations. Finally we selected the density percentage of each soft joint for the suitable finger trajectory. The selected percentage for each joint of finger is presented in II and the corresponding finger trajectory is shown in figure 4. The resultant bending of each soft part with respect to the base of the finger is presented in figure 5. Furthermore, figure 6 reports the plot of the force applied by the motor to fingertip force. This relationship gives us the idea of how much actuator force is required to bend the finger completely (in other words, the force required to overcome the passive stiffness of the compliant elements).

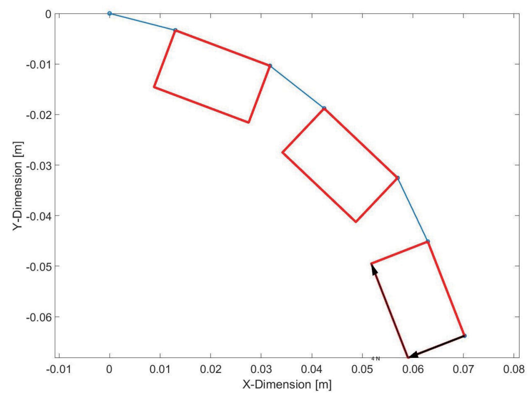

Fig. 4. The final selected trajectory of the finger: The numerical simulations are performed in order to observe the variation of trajectory of the finger in response to percentage of infill density of 3D printing material.

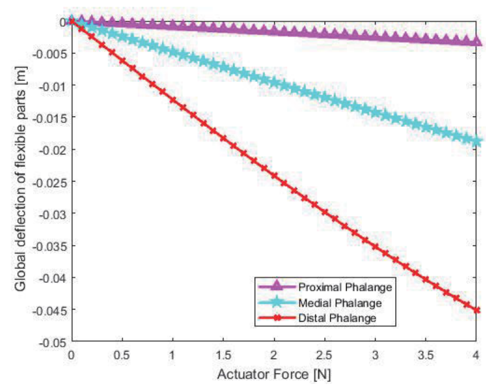

Fig. 5. The simulation results of deflection of each joint with respect to the global coordinates defined at the base of the finger are shown.

IV. Experiments

A. Electromyography based control interface

To control the motion of the prosthetic hand, we developed electromyography based user interface. The interface is developed using a commercially available Myo Armband device to be wear at forearm of the user. The Myo Armband consists of eight electromyographic (EMG) sensors working at frequency of 2200 Hz that detect electrical activity in the forearm muscles which are combined with 9-DoF intertial measurement unit (IMU) working at 50 Hz to recognize gestures of human hand. The interface can detect different posture of human hand which we have associated with the robotic hand to control its motion. The interface has wireless bluetooth protocol. We used the software development kit (SDK) to record the data and its further processing. The EMG data is filtered using notch filters at frequencies of 50 Hz and 60 Hz. Five gestures of the human hand are considered to control the motion of prosthetic hand. The block diagram of the complete system is shown in figure 7.

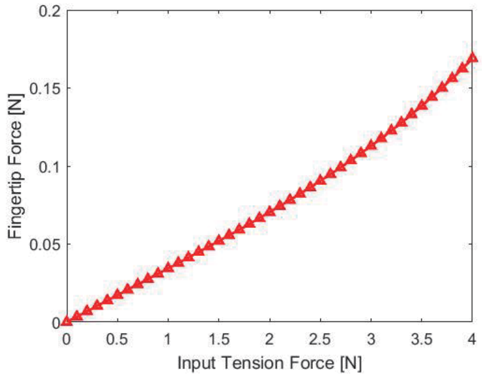

Fig. 6. The numerical simulation plot of the motor applied force versus Fingertip force.

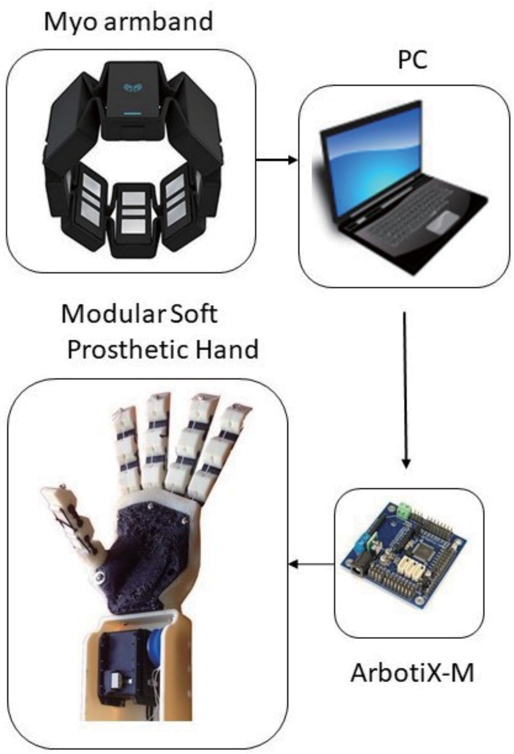

Fig. 7. Main elements of the complete system and control interface of the prosthetic hand. The Myo Armband is connected with the PC. The PC is interfaced with the Arbotix controller which in turns control the motion of our soft hand prosthesis.

The Myo Armband uses Bluetooth communication to communicate with the computer. The MyoMex is used to stream data from the Myo Armband. In order to control the motion of robotic hand, we have used Arbotix-M controller which is connected with the computer through serial communication on which the MyoArm band gestures are recognized. Further more, as low level controller, we have implemented a trigger based Finite State Machine (FSM) to control the motion of the robotic hand. All the gestures were associated to a unique trigger signal. In figure. 8-a, the gesture recognized through the Myo-Armband are shown while in figure. 8-b the different states of the robotic hand are detailed.

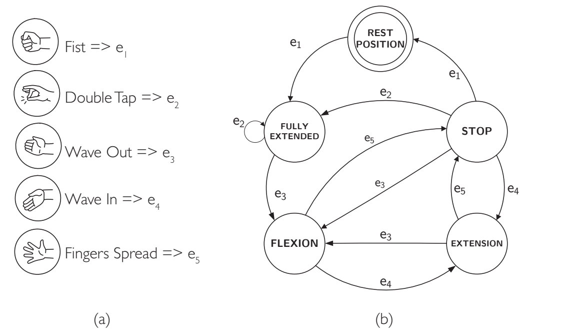

Fig. 8. a) The gestures recognized by human hand and corresponding trigger signals are shown. (b) The FSM for robotic motion control is presented. Gestures are used to switch different states of the motion of prosthetic hand.

Fig. 9. The grasping experiments of prosthetic hand. The experiments involve different grasping objects of various sizes, textures and shapes.

B. Grasping of objects with different shapes

The grasping ability and shape adaptation of the robotic hand are evaluated through qualitative experiments. We grasped various objects of the activity daily living (ADL). The aim of the experiments was to observe how the robotic hand can adapt to the shape of the objects to realize a stable enveloping grasp. The experiments involved the objects of different shapes, sizes, textures, weight and rigidity. During all the tests, we used the myo armband to control the motion of the robotic hand. Figure. 9 shows some snapshots of grasping tasks performed by the prosthetic hand. The hand was able to adopt itself to the various objects' shapes due to its suitable closing trajectory and passive compliance.

V. Conclusion and Future Work

In this paper, we presented the design and evaluation of a tendon driven soft prosthetic hand whose fingers are consist of stiff links and soft joints. The stiffness of the soft joint can be designed and 3D printed to obtain a desired bending trajectory. We presented the static analytical model, analysis and numerical simulation of cable driven flexible fingers using beam theory. Different stiffness values could be obtained during the 3D printing by setting different percentage of material infill density. We used the simulation results to realize the prototype of the soft prosthetic hand. In order to control the motion of robotic hand, we presented electromyography (EMG) based control interface. The development of the hand is achieved through rapid prototyping 3D printing. We believe that new additive manufacturing technologies and materials open a completely new set of design opportunities. In particular, exploiting them in underactuated compliant mechanical structures can be a strategic solution for the design of simple, highly adaptable and robust robotic hands that can effectively be employed in clinical and industrial applications. Currently, we are working on the design and development of a high torque elbow actuator (joint) to be integrated with soft hand for the upper limb prosthesis. In future, we are planning to test the complete upper limb prosthesis for its overall performance characterization and experiments with upper limb amputees for its further evaluation.

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