Open-Source, Low-Cost, Compliant, Modular, Underactuated Fingers: Towards Affordable Prostheses for Partial Hand Amputations

Minas V. Liarokapis, Agisilaos G. Zisimatos, Melina N. Bousiou and Kostas J. Kyriakopoulos

***Abstract*— In this paper we present a series of design directions for the development of affordable, compliant, modular, underactuated robot fingers, that can be used as prostheses by amputees that suffer from various partial hand amputations (index to pinky fingers are considered). Our design is based on parametric models that have been derived from hand anthropometry studies. Various interfaces have been considered in order to control the prosthesis, depending on the type and level of amputation. More precisely: 1) An Electromyography (EMG) based interface is used to control the robot fingers employing the EMG signals of the human forearm muscles 2) A flex sensors based interface is used to record the motion of the intact finger/fingers and predict the motion of the prosthesis implementing a synergistic behavior in an efficient manner, 3) A body powered interface is used for those that want to achieve even lower cost, with robust intuitive operation. Following the proposed design directions, an amputee will be able to replicate our fingers and develop personalized, affordable, light-weight but yet efficient prostheses.**

Index Terms: **Prostheses, Open-Source Design**

I. Introduction

The human hand, the most versatile and dexterous end-effector known, inspires robot hand designers and prosthetists over the last fifty years. Nowadays the state-of-the-art of both robot and prosthetic hands follows the road to increased performance and humanlikeness [1] and [2]. Such a design direction leads also to increased complexity and cost, as most anthropomorphic robot hands and myoelectric prostheses cost several thousands of USD. The cost is increased due to the materials used, the sophisticated actuators and the advanced sensing elements.

The idea of low-cost, light-weight prostheses is not a new one [3]. In recent studies [4], the amputees expressed their disappointment for the large initial and maintenance costs of the prostheses, the weight and the difficulties they face with repairs. The same studies, showed that when the amputees are involved in the selection and/or development of a prosthesis, the likelihood of prosthesis acceptance increases 8 times. Moreover, most amputees confessed that the fear of damaging the prosthesis forces them to avoid to use it on a daily basis or for difficult/dangerous tasks.

Minas V. Liarokapis, Agisilaos G. Zisimatos and Kostas J. Kyriakopoulos are with the Control Systems Lab, School of Mechanical Engineering, National Technical University of Athens, 9 Heroon Polytechniou Str, Athens, 15780, Greece. Email: mliaro@mail.ntua.gr | el08087@mail.ntua.gr | kkyria@mail.ntua.gr

Melina N. Bousiou is with the Department of Mechanical Engineering and Aeronautics, University of Patras, Greece. Email: melina.boussiou@gmail.com

This work has been partially supported by the European Commission with the Integrated Project no. 248587, THE Hand Embodied, within the FP7-ICT-2009-4-2-1 program Cognitive Systems and Robotics.

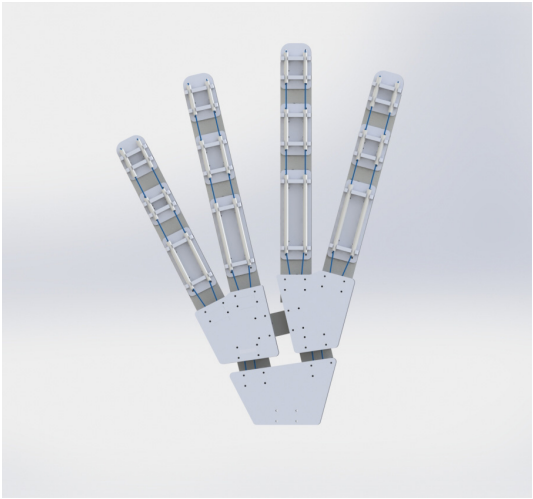

Fig. 1. The model of the prosthetic device with four fingers attached, is depicted.

During the last decades several researchers have focused on low-cost robot hands based on elastomer materials [5], providing open-source solutions [6]. The SDM [7] is a cable-driven hand, with viscoelastic flexure joints, stiff links, soft fingerpads and a set of movable pulleys (differential mechanism). Another underactuated robot hand with force and joint angle sensors, as well as a movable block differential mechanism, was proposed in [8]. A third example of an underactuated, compliant robot hand, is the i-HY (iRobot-Harvard-Yale) hand [9], which has flexure joints and integrated tactile arrays. The aforementioned studies have made progress towards the goal of reducing both the hand cost and weight. An overview of the mechanical design and performance specifications for various anthropomorphic prosthetic hands, is conducted in [10].

Recently we proposed a series of open-source, affordable, light-weight, modular, compliant, underactuated robot hands [11], through the OpenBionics initiative [12]. These hands are very efficient in grasping a series of everyday life objects with various geometries and weights. In this paper we extend this latter study, proposing a new design approach for the creation of affordable (cost less than 100 USD), light-weight (weigh less than 200 gr | 0.44 lbs, including the servo motor), intrinsically-compliant, underactuated prostheses. These prostheses can be easily reproduced with off-the-shelf materials and can help people with partial hand amputations regain lost dexterity.

The rest of the paper is organized as follows: Section II focuses on the hand anthropometry studies used for our analysis. Section III presents the open-source design and the different components used for robot hands replication, Section IV presents the different types of prostheses and interfaces that can be used, while Section V concludes the paper.

II. Hand Anthropometry Studies

Our design is inspired by the kinematic model of the human hand, which consists of 25 DoFs, five DoFs for the thumb, four DoFs for index and middle fingers and six DoFs for each one of the ring and pinky fingers. We consider 6 DoFs for each one of the ring and pinky fingers, in order to take into account the mobility of the carpometacarpal bones of the palm. The motion of these bones results to varying positions for the fingers base frames and increases human hand dexterity.

Human hand digit lengths can be easily measured, but expressing the base of each finger relatively to the base of the wrist, is a difficult problem that requires advance imaging techniques such as fMRI [13]. In this paper we choose to use hand anthropometry studies in order to derive the parametric models for each human digit [14], [15] and [16]. Such parametric models, define the lengths for all phalanges of the human hand relatively to specific human hand properties. These properties are the hand length (HL) and the hand breadth (HB). For an amputee with partial amputation of one of the two hands, HL and the HB parameters, can be computed from the intact hand and can be used for the creation of a personalized prosthesis.

The parametric models used for the creation of the prosthetic fingers and the fingers basis are expressed relatively to HL and HB in Tables I and II.

TABLE I
Finger Base Frames Coordinates

Finger Basis	Coordinates Relatively to the Wrist
Index	$(-0.251 \times HB, 0.447 \times HL)$
Middle	$(0 \times HB, 0.446 \times HL)$
Ring	$(0.206 \times HB, 0.409 \times HL)$
Pinky	$(0.402 \times HB, 0.368 \times HL)$
Thumb	$(-0.196 \times HB, 0.073 \times HL)$

TABLE II
Phalanges Bones Parametric Lengths

	Phalanges		
Fingers	**Proximal**	**Middle**	**Distal**
Index	$0.245 \times HL$	$0.143 \times HL$	$0.097 \times HL$
Middle	$0.266 \times HL$	$0.170 \times HL$	$0.108 \times HL$
Ring	$0.244 \times HL$	$0.165 \times HL$	$0.107 \times HL$
Pinky	$0.204 \times HL$	$0.117 \times HL$	$0.093 \times HL$
Thumb	$0.196 \times HL$	-	$0.158 \times HL$

III. Open-Source Design

A. Bioinspired Design of Prosthetic Fingers

The design of the robot finger follows the bioinspired paradigm that was first proposed in [11] (for the creation of affordable robot hands) and is based on a simple yet effective idea: to use agonist and antagonist forces to implement flexion and extension of robot fingers. This design employs, steady elastomer materials that implement the human extensor tendons counterpart, as well as cables (strong fishing lines) driven through low-friction tubes that implement the human flexor tendons analogous.

The phalanges lengths as well as the positions of the finger base frames have been chosen so as to optimize anthropomorphism, maximizing the metric proposed in [17]. More specifically, in this latter study we proposed a complete methodology for the quantification of anthropomorphism of artificial hands, that uses set theory and computational geometry methods to compare human and robot/prosthetic hands. The derived score, can be used in order to extract specifications for the creation of the next generation of human-like robot hands and prosthetic devices.

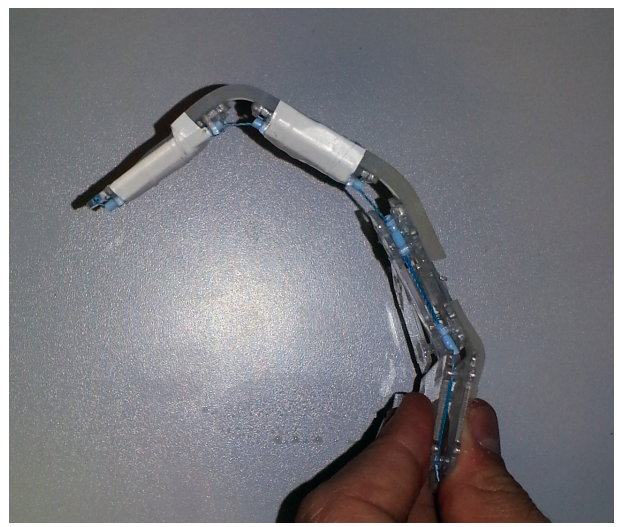

Fig. 2. A prototype of a prosthetic finger is depicted.

B. A Modular Finger Basis

The proposed prosthesis uses a modular fingers basis that complies to the motion of the carpometacarpal bones of the human palm, being also able to accommodate a total of four fingers (index, middle, ring and pinky fingers can be considered). In Fig. 3 the modular fingers basis is depicted with the possible finger locations annotated. The basis consists of three parts, namely Part A, B and C. Part A, is parallel to the plane defined by the index and middle carpometacarpal bones. Part B complies to the motion (flexion/extension) of the ring and pinky carpometacarpal bones. Finally Part C is used only for tendon routing and to accommodate the pulleys and the whiffle tree (or seesaw) based differential mechanism [18], required for prostheses with multiple fingers.

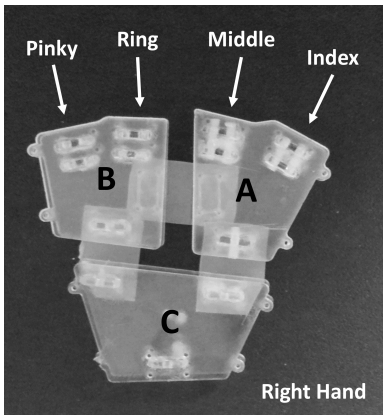

Fig. 3. A modular fingers basis is depicted, that complies to the motion of the carpometacarpal bones of the palm and which can accommodate a total of four fingers (all human fingers with the exception of thumb).

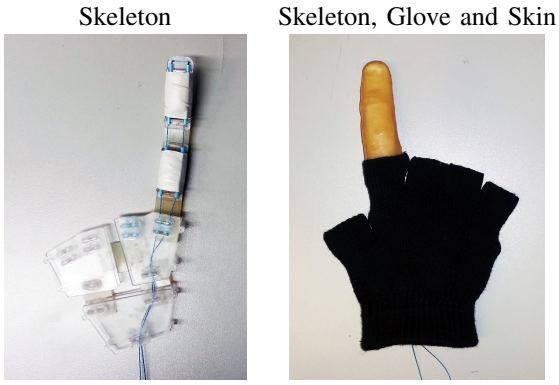

Fig. 4. A prosthesis that consists of the finger basis and only one finger is depicted. Two different stages can be distinguished. The first stage represents the prosthesis structure/skeleton. At the second stage the prosthesis is covered with a glove which is worn by the user (that covers only the proximal phalanges) and appropriate latex-based skin.

C. Humanlike Appearance with Artificial Skin

In order to maximize anthropomorphism of the proposed prosthetic fingers, we chose to create an artificial skin that covers the finger skeleton. For doing so we use natural pre-vulcanized latex. The artificial skin is prepared in two different stages. A first thin skin is created covering an actual human finger - of similar proportions - with the liquid latex. Then we let this first layer to dry as depicted in Fig. 5, we dismount it (from finger surface) and we repeat the same procedure until the artificial skin gets adequately thick.

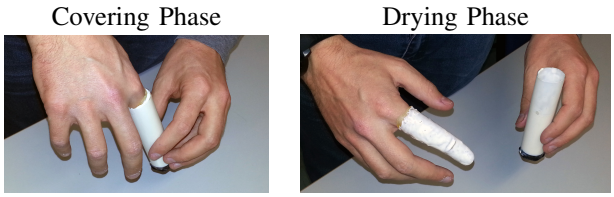

Fig. 5. The different phases for the creation of the prosthetic fingers latex based skin, are depicted. The same procedure is repeated several times in order for the skin to become adequately thick.

D. Off-the-Shelf Low-Cost Parts

The proposed design is based on low-cost, off-the-shelf materials that can be easily found in hardware stores around the world. The different materials used for the replication of the prosthesis are listed in Table III. Plexiglas (acrylic) is the main material used, as it is low-cost, light-weight, has good durability, adequate density, can be easily found and can be easily cut with laser machines or other machinery (even with hand-held rotary tools) in 2D.

TABLE III
PARTS USED FOR THE CREATION OF THE PROSTHESIS

Material	Characteristics
sponge-like tape	width: 1.8 mm
Dyneema fishing line	strength: 41.5kg (91.5 lb)
low friction tubes	d: 2 mm D: 2.5mm
pulleys	d: 3mm, D:12mm, W: 4mm
silicone sheets	3 mm - 4 mm
fasteners	width: 3mm
Plexiglas sheets	2 mm - 4 mm
liquid latex	pre-vulcanized

Finally it must noted that the proposed design can be replicated with any type of plastic or other material wanted and of course with the desired dimensions.

E. Electronics

The proposed prosthesis can be actuated by a servo motor or by the body powered interface, described in Section IV. In case that we choose to use a servo motor actuated interface, we control it using as low-cost, light-weight and small-sized solution the Arduino Micro platform [19]. In case that the prosthesis is meant to be controlled with an EMG based interface, an appropriate low-cost surface Electromyography (sEMG) sensing kit (Advancer Technologies) [20] compatible with the arduino platform, is used. Standard printed circuit boards (PCB) modules have been developed on purpose. The PCBs connect the arduino platform, with the servo motor and other sensors (e.g., flex sensors).

IV. Use Cases, Types of Prostheses and Interfaces

A. Types of Prostheses and Interfaces

Depending on the different types of amputations (e.g., number of fingers missing), different interfaces can be considered. Namely the possible interfaces are the following:

- A flex sensors based *Synergistic Interface*.
- An EMG sensors based *EMG Interface*.
- A *Body Powered Interface* that uses a series of pulleys and cables.

More specifically for those cases that one or more fingers are intact, the amputee can use either the synergistic interface or the body powered interface. The synergistic interface captures the motions of the MetaCarpoPhalangeal (MCP) joints of the intact finger or fingers (with flex sensors) and produces appropriate synergistic motions for the missing fingers, following the directions provided in [21]. The body

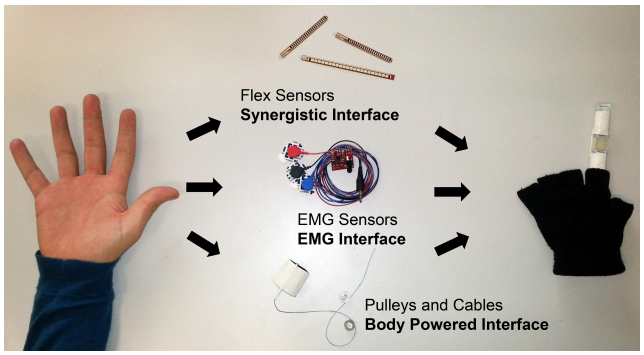

Fig. 6. The different interfaces that can be used for the control of the proposed prosthetic device, are depicted. A flex sensors based, *Synergistic Interface*, an EMG sensors based *EMG Interface* and a *Body Powered Interface*, that uses cables and pulleys.

powered interface uses the motion of an intact finger to drive the prosthetic finger, in a similar with the synergistic interface fashion. The main difference is that with the body powered interface, the prosthetic finger is actually actuated by one of the intact fingers, thus it doesn't require a motor or any other electronics. For doing so the ring that appears in Fig. 6 has been created. This latter ring is worn in the proximal phalanx of an intact finger and the whole interface uses a series of cables and pulleys to facilitate motion transmission from the intact finger to the prosthetic one. It must be noted that the body powered version of the proposed prosthesis in inherently water-proof as it doesn't contain any electronic elements. Finally, the EMG interface is usually the only option for severe amputations. For example, if all fingers except the thumb are missing (thus, we cannot employ a synergistic, or a body powered interface), EMG electrodes can be used to decode from myoelectric activations of human muscles, the human hand motion.

The proposed open-source design will be available through the OpenBionics initiative website [12]. Adequate instructions, will also be provided in terms of an assembly guide, to facilitate reproduction.

V. Conclusions and Discussion

In this paper we presented an open-source design for the creation of affordable, compliant, modular, underactuated prosthetic fingers, that can help amputees that suffer from partial amputations (e.g., amputations of one or many fingers of human hand, with the exception of thumb), to regain lost dexterity. The proposed design has been based on parametric models of the human hand that have been derived from hand anthropometry studies. Various interfaces have been considered for controlling the proposed prostheses. The efficiency of each interface, depends on the type of amputation.

Regarding future directions we plan to experimentally validate the efficiency of the proposed design with human subjects (i.e., amputees with different types of amputations) as well as to design new devices for thumb or whole hand amputations, developing a variety of subject-specific, open-source, affordable, myoelectric prostheses.

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