Adaptive, Tendon-Driven, Affordable Prostheses for Partial Hand Amputations: On Body-Powered and Motor Driven Implementations

Geng Gao, Lucas Gerez, and Minas Liarokapis

***Abstract*— Adaptive, tendon-driven and affordable prosthetic devices have received an increased interest over the last decades. Prosthetic devices range from body-powered solutions to fully actuated systems. Despite the significant progress in the field, most existing solutions are expensive, heavy, and bulky, or they cannot be used for partial hand amputations. In this paper, we focus on the development of adaptive, tendon-driven, glove-based, affordable prostheses for partial hand amputations and we propose two compact and lightweight devices (a body powered and a motor driven version). The efficiency of the devices is experimentally validated and their performance is evaluated using two different types of tests: i) grasping tests that involve different everyday objects and ii) tests that assess the force exertion capabilities of the proposed prostheses.**

I. Introduction

The dexterity of the hand allows humans to execute a wide range of dexterous tasks that no other being is capable of. Loss of one or more fingers compromises some of the capabilities of the human hand and this has a tremendous impact on the lives of amputees. According to [1], more than 60 % of the upper limb amputations are transcarpal. In many cases of partial finger amputation (e.g., thumb amputation, multi-finger amputation), the amputation impedes the execution of important grasps needed to perform activities of daily living (ADLs). Most of these grasps are executed using the thumb, index and middle fingers, while the ring and pinky fingers have a subsidiary role [2].

In this paper, we propose two compact, lightweight, and affordable prostheses for partial hand amputations (see Fig. 1). The first device uses a body-powered mechanism while the second device is an underactuated, externally powered solution. The devices are experimentally tested and their efficiency is validated using two different types of tests: i) grasping tests that involve different everyday objects, ii) force exertion capability tests that focus on the finger forces that can be exerted while using the prosthetic devices.

The rest of the paper is organized as follows: Section II presents the related work, Section III focuses on the designs of the devices, Section IV details the experimental setup used for the tests and presents the experimental results, Section V concludes the paper, and Section VI discusses some future directions.

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Geng Gao, Lucas Gerez, and Minas Liarokapis are with the New Dexterity research group, Department of Mechanical Engineering, The University of Auckland, New Zealand. E-mails: ggao102@aucklanduni.ac.nz, lger871@aucklanduni.ac.nz, minas.liarokapis@auckland.ac.nz

Fig. 1. The proposed prosthesis has been designed to support both a body-powered actuation scheme (subfigure a) and an externally powered, motor driven actuation scheme (subfigure b).

II. Related Work

Despite the significant percentage of finger amputations compared to other upper limb amputations, active prosthetic fingers have not received the required attention from researchers due to the high level of customization needed to fit the design to the patient's hand [3], as well as due to difficulties to embed sensors and actuators to the device if compared to active, full hand prosthetic devices. On the other hand, numerous passive prosthetic fingers have been proposed to replace lost fingers. In [4] and [5], the authors propose prosthetic fingers made out of silicone rubber that mimic the human fingers. These solutions are aesthetically pleasing, however, the finger is rigid and not capable of bending. In [6], the authors present an osseointegrated implant with finger prosthesis, a direct attachment to the bony stump. In [7], the authors describe a method to optimize the fitting of prosthetic fingers for distal amputations. Although the aforementioned solutions certainly provide user satisfaction, the improvement on the grasping capabilities is limited.

Active prosthetic fingers are more functional, enabling the user to execute most of their daily activities [3], and they can be either body-powered or externally powered. In [8], the authors present an overview of the existing surgical and technological solutions for treating partial hand amputations. Regarding body-powered prosthetic fingers, in [9] and [10], the authors propose a linkage-based, wrist-driven prosthesis

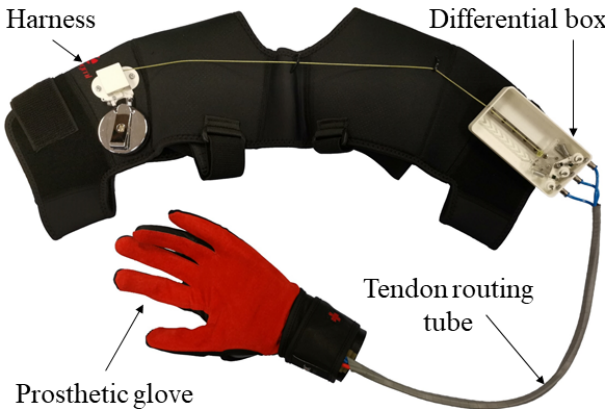

Fig. 2. The body-powered prosthesis consists of a harness, a differential box, and a prosthetic glove. The harness houses a tensioner located on the left shoulder and a differential box on the right shoulder. The differential contains a linear ratchet for locking the tendon, a whiffle tree for distributing the forces across the prosthetic fingers, and an individual tendon tensioners for each prosthetic finger. The prosthetic glove houses a fake amputee hand and three prosthetic fingers (index, middle, and ring). The fingers are connected to the differential box through tendons guided through tendon routing tubes. The device can be customized to different types of amputations (housing less or more fingers).

for amputees with disarticulation of the thumb and index finger. In [11], the authors demonstrate a wrist-powered partial hand prosthesis using a continuum whiffletree mechanism. Other body-powered solutions are the X-Finger (Didrick Medical, Naples, FL) [12], which is a custom fit prosthetic finger that allows flexion and extension of the finger in order to restore dexterous manipulation and the M-finger (Partial Hand Solutions LLC), which is a tendon-driven prosthetic finger. Body-powered devices are usually simple, affordable, and easy to operate, however, the rejection rate of these devices is higher and the harnesses might be uncomfortable if compared to externally powered devices [13]. Regarding externally powered prosthetic fingers, in [14], the authors propose an electromyography (EMG) controlled prosthetic robot finger that can be attached to the end of the finger root bone. The force is transmitted through a linkage system and is controlled using a linear actuator. In [15], the authors present an EMG prosthetic hand for amputees with remaining fingers. In [16], the authors describe a partial hand prosthesis that is actuated by a DC motor combined with a gearhead. A commercially available, externally powered prosthesis for partial hand amputations is the I-digits Quantum (Touch Bionics, Hilliard, OH) [17], a multi-articulating device that can be controlled with simple gestures. Although powerful and attractive, externally powered prosthetic devices are still expensive, heavy, bulky, and have limited autonomy.

III. Designs

In this section, the designs of the body-powered and the externally powered, motor driven prostheses are presented, and their functionalities and operation are discussed.

A. Body-powered Partial Hand Prosthesis

The body-powered device was designed to improve the grasping capabilities of the amputee by providing an intuitive, robust, and lightweight solution. The design is based on the well-known, body-powered mechanism that transmits the forces of the upper body (e.g., shoulders) to the prosthetic fingers [13], [18]. The proposed body-powered device is composed of three main parts: the harness, the differential box, and the prosthetic glove (which includes the prosthetic fingers), as shown in Fig. 2 and described in [19]. The final body-powered prototype weighs only 553 g.

In order to operate the device, the amputee must execute simple movements that increase the tension of the cable connecting the harness to the differential. When the cable is tensioned, the differential box distributes the tendon force to the prosthetic fingers through artificial tendons made out of a low friction braided fiber of high-performance Ultra-High Molecular Weight Polyethylene (UHMWPE). Polyurethane tubes that connect the differential mechanism to the glove are used for tendon routing. The routing tubes are attached to the glove through aluminium connections. The glove is used to keep the fingers in place (the prosthetic fingers are stitched to the glove to avoid undesired motions). The device can be adjusted to different body types and sizes. The device personalization occurs only for the prosthetic fingers and the harness, as these components depend on the user's body dimensions. Appropriate anthropometry studies can be employed to derive the finger link lengths from the overall hand length [20], [21]. Alternatively, the finger link lengths could be measured on the intact hand (if available).

The differential box allows tendon tensioning, force distribution, and position locking of the fingers using as input the force originated from the shoulders. When the main cable is tensioned the finger tendons are pulled and the whiffletree differential distributes the force among the three fingers. Differential mechanisms are widely used in prosthetic devices to evenly distribute the forces [11], [22]. The linear ratchet on the differential box guarantees that the fingers can be locked at any desired position due to a lever that locks the motion of the system when moved into one of the channels of the linear ratchet. The circular ratchet clutch mechanisms on the whiffletree provide tendon tensioning and length adjustment [23]. When the main tendon is pulled for a second time the lever is disengaged, the system goes to its starting point, and the fingers return to their initial positions. The harness is not only used to connect the main tendon and the differential, but also to maintain the shoulders aligned in a comfortable and anatomically correct manner.

B. Externally Powered Partial Hand Prosthesis

The externally powered, motor driven prosthesis was designed to provide the amputee with a solution that offers precise object grasping, requiring minimal user effort. The prosthesis was designed to operate up to two fingers independently and is composed of a motor box with two motors, a control module and a prosthetic glove (which includes the two prosthetic fingers). The motor box and the control module are attached to the wrist strap of the glove. The final prototype weighs only 260 g.

Fig. 3. The externally powered, motor driven prosthesis contains a motor box with 2 motors as seen in the front view of the hand (subfigure a). The back view of the hand (subfigure b) shows the location of the control module and the EMG sensor of the device. The flex sensor of the externally powered partial prosthesis is located inside the glove at the pinky finger.

The control module accommodates a motor controller, a microcontroller (Arduino Nano) and two 500 mAh Li-Po batteries, while the motor box accommodates two DC motors with encoders and two gearboxes. Two different sensors were connected to the microcontroller in order to control the prosthetic device: a flex sensor and an EMG sensor. Only one of these sensors is needed to operate the prostheses, however, two sensors were added in order to improve the user experience and robustify the operation of the device. The flex sensor is positioned in the inner side of the glove on one of the remaining fingers (for the experiments performed, the flex sensor was mounted on the pinky finger). When the intact finger bends, the flex sensor detects the angle variations of the finger joints and the prosthetic fingers are controlled to follow a similar trajectory (using a synergistic approach) employing a PID controller. If the amputee does not have any remaining fingers that can be used to control the prosthetic fingers, the EMG sensor is used. The EMG sensor is located on the skin of the amputee's forearm in order to capture the myoelectric activations of the muscles (*Flexor Digitorum Superficialis* area). The muscle activities that are related to grasping are detected by the EMG sensor board (MyoWare muscle sensor) and the signals are sent to the microcontroller where they are processed and the motor is controlled through simple thresholding. The whole device is depicted in Fig. 3.

C. Prosthetic Fingers

The prosthetic fingers were designed to replace the amputees missing phalanges and to assist the remaining phalanges in the grasping process. The fingers were designed to be slim and compact while maintaining an anthropomorphic appearance in order to be accommodated by a glove. Alongside this, the fingers were designed to be modular to allow amputees to easily replace key components of the prosthetic fingers being the phalanges, the interfacing

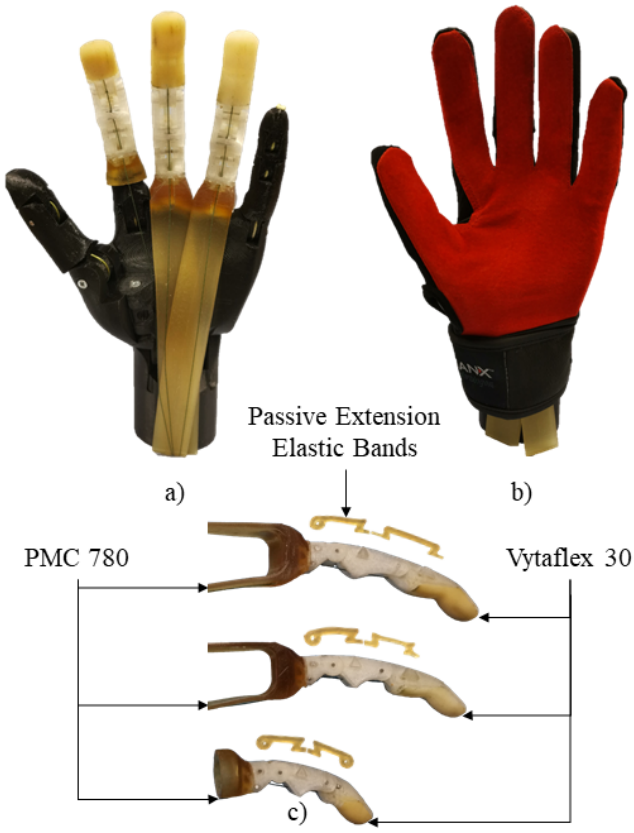

Fig. 4. The tendon driven prosthetic fingers are attached to a paradigmatic, 3D printed amputee hand, which is missing the index finger's distal and middle phalanges with the middle, and ring fingers being fully amputated (subfigure a). Subfigure b, shows the compatibility and fit of the prosthetic fingers with the paradigmatic hand inside the glove. Subfigure c, presents the structure of each prosthetic finger and the passive extension elastic bands. The fingers are built using the concept of Hybrid Deposition Manufacturing [24] and they combine 3D printed parts with elastomer materials (SmoothOn Vytaflex 30 and PMC 780 polyurethane rubbers).

base, and the passive extension elastic bands. Two joints are used per finger instead of the three joints of human index, middle, ring and pinky fingers, with one joint being the metacarpophalangeal (MCP) joint and the other one being the proximal interphalangeal (PIP) joint. The absence of the distal interphalangeal (DIP) joint allows the fingers to have an increased finger pad area for grasping, while also maintaining a compact and slim form factor. The actuation of the fingers is based on a tendon driven system as seen in [25], allowing the fingers to be underactuated and to exhibit an adaptive grasping behaviour. The finger structure is manufactured from 3D printed PLA plastic and polyurethane elastomers (Smooth On Vytaflex 30 and Smooth on PMC-780). The softer polyurethane elastomer (Smooth On Vytflex 30) was incorporated into the finger pads to improve conformability of the fingers on the grasped objects while the stiffer polyurethane elastomer (Smooth on PMC-780) was implemented into the passive extension elastic bands and the interfacing bases of the prosthetic fingers. Two types of prosthetic fingers were designed and developed as shown in Fig. 4 (subfigure c).

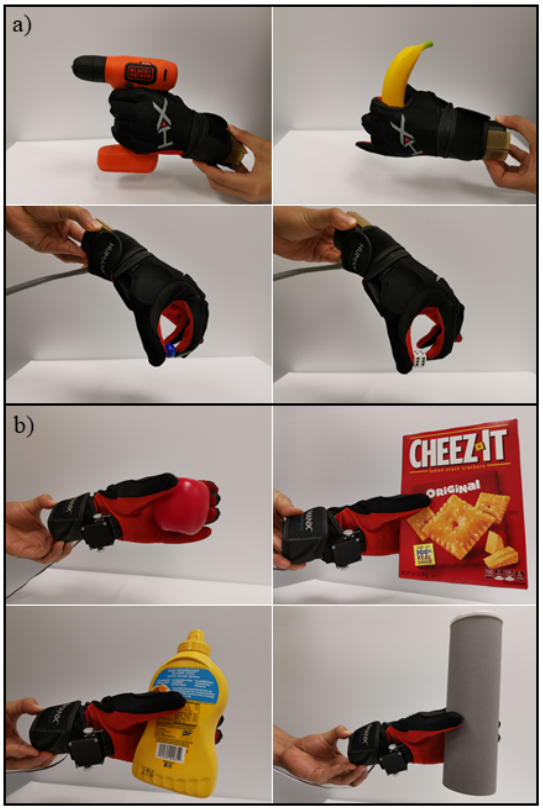

Fig. 5. The grasping experiments involved eight objects of the YCB object set [26] and they were used to evaluate the grasping capabilities of both the body-powered device (subfigure a) and the externally powered, motor driven device (subfigure b). The objects used are a drill, a banana, a marble, a dice, an apple, a box, a mustard bottle, and a chip can.

In Fig. 4, The first example is a full prosthetic finger, while the second one is a partial prosthetic finger for amputees that are missing the first two phalanges of their finger (middle, and distal). The prosthetic finger link lengths were modelled after the human hand employing hand anthropometry studies [20] with a hand length of 190 mm, as reported in Table I.

TABLE I

THE PROSTHETIC FINGER CHARACTERISTICS OF THE INDEX, MIDDLE, AND RING FINGERS FOR HAND LENGTH OF 190 MM. THE PROXIMAL LINK LENGTH OF THE PROSTHETIC FINGERS IS MEASURED FROM THE BASE OF THE INTERFACING PART TO THE PIP JOINT.

Fingers	Weight (g)	Length of Phalanges (mm)		
		Proximal	Middle	Distal
Index	23.90	-	27.10	18.43
Middle	39.46	50.54	32.30	20.52
Ring	37.24	46.36	31.35	20.33

IV. EXPERIMENTS AND RESULTS

The experiments that were conducted to assess the performance of the body-powered and the externally powered, motor driven prosthetic device, were divided into two parts. The first part focused on evaluating the grasping forces and the hand configurations, while grasping different objects. The second experiment focused on measuring the grasping forces

Fig. 6. The force experiments were conducted with the partial prosthesis executing a pinch grasp (subfigure a) and a power grasp (subfigure b) on a SS25LA dynamometer (by Biopac Systems, Inc., Goleta, California).

(in different configurations) that the devices can exert. To execute the experiments, an adapted 3D printed paradigmatic amputee hand was positioned inside the glove to act as a simulated amputee's hand. This anthropomorphic model hand has a fully articulated thumb and pinky finger, a partially amputated index finger that has only a metacarpophalangeal (MCP) joint, and two fully amputated fingers (middle and ring fingers). This hand configuration was chosen in order to be able to test both types of prosthetic fingers designed. Three prosthetic fingers are enough to test both devices, since the body-powered device can actuate up to three fingers and the externally powered, motor driven device only two. A fully articulated finger on the model hand was chosen to simulate the remaining finger of the amputee's hand, so as for the flex sensor to operate appropriately (in this case, the sensor was connected to the pinky finger).

A. Object Grasping Performance

The first experiment was executed to evaluate the grasping performance of the proposed prosthetic devices. All eight everyday objects used in this experiment were selected from the YCB object set [26], an object set designed for facilitating benchmarking in robotic grasping and manipulation. The experiments conducted can be seen in Fig. 5.

TABLE II

THE MAXIMUM GRASP FORCES EXERTED ON THE DYNAMOMETER. FORCES WERE MEASURED FOR BOTH PINCH AND POWER GRASPS.

Device	Grasp Forces (N)	
	Pinch Grasp	Power Grasp
Body-Powered Prosthesis	3.8	10.4
Externally Powered Prosthesis	8.2	18

B. Finger Force Exertion Experiment

The second experiment focused on measuring the amount of grasping force that can be exerted by the devices. The grasp force results can be seen in Table II. Two different grasping types were tested: pinch grasp and power grasp (see Fig. 6). The force measurements in each scenario were collected using a Biopac MP36 data acquisition unit (Biopac Systems, Inc., Goleta, California) equipped with the SS25LA dynamometer. For the body-powered device, the power grasp

involved the three prosthetic fingers (index, middle, and ring). For the motor driven device, since the motor box is connected to the middle and ring fingers, the pinch grasp was executed using the thumb and middle fingers, while the power grasp was executed using the middle, ring, and thumb.

C. Devices Demonstration Video

A video containing the description of the devices and some experiments can be found at the following URL:

http://www.newdexterity.org/prosthetichands

V. Discussion and Conclusions

In this paper, we presented two adaptive, tendon-driven, glove-based, affordable prostheses for partial hand amputations, a body-powered and an externally powered, motor driven version. Two different experiments were executed to assess the efficiency and the grasping performance of the devices and the results demonstrate that the proposed solutions can efficiently assist amputees in executing a plethora of activities of daily living. Although the body-powered device is heavier and larger than the externally powered device (due to the harness), it is still lightweight, simpler than the motorized device, more affordable and it does not rely on a battery or other electronics, having unlimited operation time. The underactuated, lightweight, externally powered, motor driven prosthesis relies on various sensors and electronic components, and it offers precise grasping requiring minimal user effort. Both partial hand prostheses are designed in an amputee specific manner offering increased personalization.

VI. Future Directions

Regarding future directions, we plan to test both devices in clinical trials involving amputees and to redesign them according to the trials feedback. For the motor driven device, we plan to increase the number of motors, to develop multiple versions for different types of partial hand amputations, and to increase the battery life of the prosthetic device by performing an optimal motor selection and energy consumption optimization.

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