Toward 3D Printed Prosthetic Hands that Can Satisfy Psychosocial Needs: Grasping Force Comparisons Between a Prosthetic Hand and Human Hands

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Abstract. The advancement in 3D printing technologies appears to be the key toward affordable and functional artificial limbs. The loss of an amputee's capability to do functional tasks like grasping objects has an obvious effect on that individual's psychosocial behavior. In this paper, we investigate whether a low-cost 3D printed prosthetic hand can perform basic grasping tasks. We determine whether the fingertip forces used in grasping various objects are comparable to the grasping forces applied by the hands of 5 research participants. We considered 5 different grasps, namely, lateral pinch, spherical, disk, medium wrap, and thumb-index finger grasps for both the prosthetic and human hands. For each grasp, 25 readings for each finger were considered in the analysis. Results show that there were significant differences in the grasping contact forces recorded on the fingers of the prosthetic hand and the human hands. Since this prosthetic hand and similar 3D printed hands may not be able to reach the grasping forces of human hands, the results of this work open the motivation for addressing other requirements of articulated artificial hands for social interactions and gestures.

Keywords: Social touch · Prosthetics · Artificial hands · Tactile sensing

1 Introduction

The on-going wars in some regions in the world have created one of the biggest tragedies in modern times that are affecting millions of people. Citizens in some of these countries were forced to be either displaced internally or become refugees at neighboring countries. A survey conducted in refugee camps revealed that there are around 9.7% with physical impairment [18]. There is an increasing

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need for low-cost and affordable prosthetics in such places and in the developing countries. There are many affordable and promising upper-limb prosthetics for resource-scarce environments [24]. Simple tasks and functions, such as lifting light objects and pushing buttons, can be achieved with high success with such low-cost prosthetics [15]. The availability of such prosthetic hands does not only provide functional benefits to the amputees, but also help the users psychologically and emotionally.

The work in developing countries is laborious in nature, hence, functionality is very important to accomplish some tasks. Another important aspect is to provide more natural social touch as well as to make various gestures possible [13]. The appearance and the feeling of the artificial hand to be perceived by others play a very important role toward more natural social interactions [11,12,21,25]. Adding more realistic interactions with the artificial hand could be made possible through the implementation of human-like artificial skin [7,8,10,27] along with adding sensing capabilities by embedding skin-like [22] or biocomposite [26] sensors to receive sensory signals similar in functionality to that of the receptors in the human skin [20].

The artificial hands that are currently available might be able to mimic some of the properties, characteristics, and basic functions [1] of the human hand. However, the ability of a prosthetic hand to match the force exerted by the human hand, especially in social touch, is considered a feature that is usually overlooked in the commercially-available designs. The amount of pressure or force applied by the human hands plays an important role in expressing feelings, emotions and providing social cues to others [4]. An earlier work showed the comparisons between the force distribution of human hands and prosthetic hands in grasping a cylindrical object [19]. In that work, the forces were measured from over 20 different positions on the hands. The measurements were taken while the object is being held with a power grasp. The study concluded that the force distribution of the human hands are comparable to that of their adaptive prostheses.

With the advancement of 3D printing technologies, affordable prosthesis is now possible. There are emerging designs and technologies aiming at offering affordable 3D printed prosthetic hands. An example is the Ada Hand (Open Bionics, Bristol, UK; Fig. 1a). In this paper, and as a primary step toward understanding the implication on social touch, we investigate whether the fingertip forces of a 3D printed prosthetic hand used in grasping various objects are comparable to the grasping forces applied by human hands. The next section describes the materials and methods. Section 3 presents the results between the grasping forces of the prosthetic hand and human hands. Section 4 provides the discussion. The concluding remarks are presented in Sect. 5.

2 Materials and Methods

2.1 Participants

Five male subjects (22–25 years old) took part in the experiments. All participants were healthy volunteers as obtained from their self-reports. The procedures

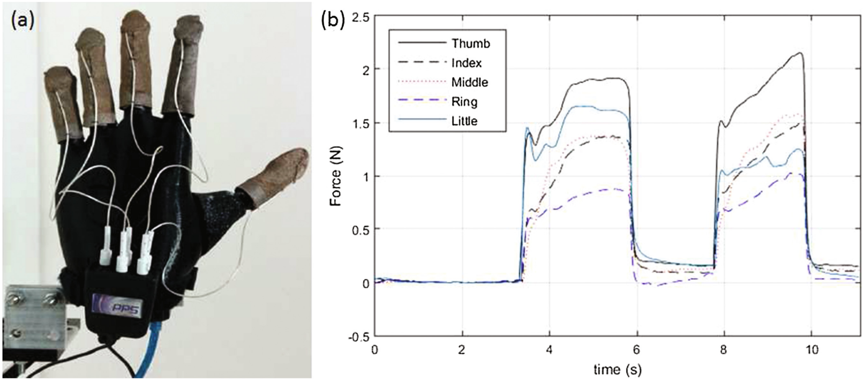

Fig. 1. The low-cost prosthetic hand. (a) With wearable tactile sensors. (b) Changes in the force readings across five fingers for a trial experiment of the human hand grasping on the ball.

did not include invasive or potentially dangerous methods and were in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Data were stored and analyzed anonymously. All participants gave written informed consent and were given course credit for their participation.

2.2 Artificial Hand

The 5-DOF prosthetic hand used in this study was the 3D printed low-cost prosthetic hand (Ada Hand, Open Bionics, UK). The construction procedures to build the artificial hand are openly accessible (https://www.openbionics.com/). The palm was made from flexible filament material (Ninjaflex, NinjaTek, USA) while the rest of the parts were made from either Polylactic Acid (PLA) or Acrylonitrile Butadiene Styrene (ABS). The hand makes use of a custom-made board, the Almond V1.2 with a microcontroller (ATMEGA2560, Atmel, USA). The grasping movements were made possible through 5 linear servo motors (PQ12, Actuonix Motion Devices, Inc., BC, Canada), which pull the strings attached to the tips of the fingers.

2.3 Tactile Sensors

A wearable tactile sensor system (FingerTPS, Pressure Profile Systems, CA, USA) was used in the experiments to measure the grasping forces exerted by the tips of fingers for both the prosthetic hand and the human hands. The tactile sensors were fitted on the prosthetic hand (Fig. 1a) and were calibrated using the accompanying calibration tool. Each finger was calibrated separately and the overall changes of force values across all fingers were displayed by the software (Fig. 1b). The data were stored after every experiment. Similar procedures have been followed for calibrating the sensors when worn by the human hands.

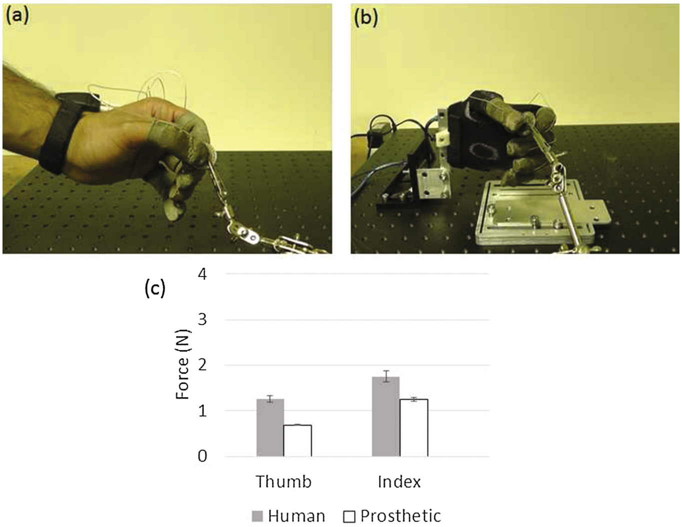

Fig. 2. Lateral pinch grasp. (a) Experimental setup for the human hand. (b) Experimental setup for the prosthetic hand. (c) Average grasping forces exerted by each finger of the left hand for the human hand and the tested prosthetic hand when using the lateral pinch grasp on a coin.

2.4 Experimental Setup

The prosthetic hand was set on a lab bench throughout the experiments. This was open-loop controlled using a laptop with the communication software (Arduino IDE, Italy) to send commands serially to achieve a specific grasp. To achieve best consistency between trials and due to the limitation of the prosthetic hand in performing some grasps without aid, all objects have been fixed. The participants were asked to wear the tactile sensors and to perform the grasping on the given objects. The participants were instructed to apply sufficient holding force on the objects that is needed to lift them. The trials for every grasp type have been done 25 times.

2.5 Data Analysis

The mean forces for the human and prosthetic hands were submitted to a two-way analysis of variance (ANOVA) followed by post hoc Tukey test. Statistical significance was set at $p < 0.05$. All analyses were performed using Origin (Version 2016, OriginLab Corporation, USA).

3 Results

The lateral pinch grasp is a thumb and index finger grasp that is used for holding small objects, such as keys, coins and utensils (e.g. spoons or forks). Therefore, this grasp is very important for functional tasks, such as unlocking a door, eating, or using the vending machine. The average contact forces of the lateral pinch grasp were measured for the prosthetic and human hand while grasping a coin (Fig. 2). There was a significant difference among the mean forces of the fingers, and significant difference among the mean forces of the hand types. The interaction between hand type and fingers was not significant. A post hoc Tukey test showed that the human fingers and prosthetic fingers were significantly different at $p < 0.05$.

The spherical grasp is commonly used to hold spherical objects in the palm of one's hand, for example, a spherical-type doorknob or a tennis ball. The average grasping force on each of the 5 fingers of the left hand was measured while exerting force on a tennis ball by both the human and prosthetic hands while performing a spherical grasp (Fig. 3). There was a significant difference among the mean forces of the fingers, and significant difference among the mean forces of the hand types. The interaction between hand type and fingers was significant. A post hoc Tukey test showed that the human fingers and prosthetic fingers were significantly different at $p < 0.05$.

Disk grasp is a very common type of grasp that involves holding disk-shaped object (e.g. jar lids or CDs) with all fingers wrapped around it. The disk grasp was performed on a lid cover by both the human and prosthetic hand. The average grasping force for each finger was calculated (Fig. 4). There was a significant difference among the mean forces of the fingers, and significant difference among the mean forces of the hand types. The interaction between hand type and fin-

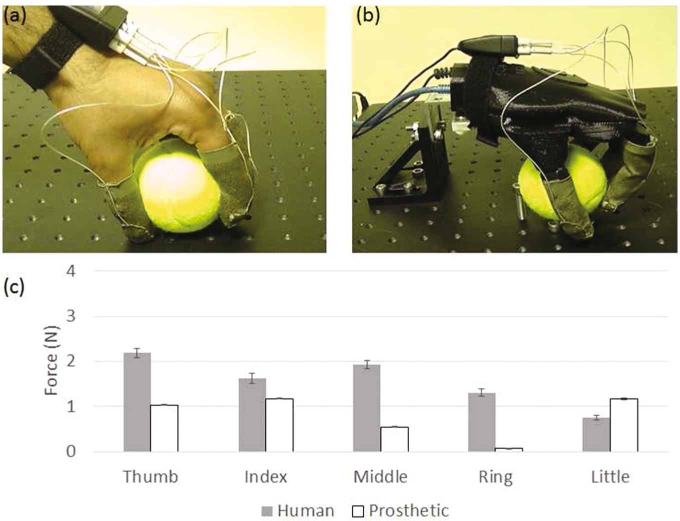

Fig. 3. Spherical grasp. (a) Experimental setup for the human hand. (b) Experimental setup for the prosthetic hand. (c) Average grasping forces exerted by each finger of the left hand for the human hand and the tested prosthetic hand when using the spherical grasp on a tennis ball.

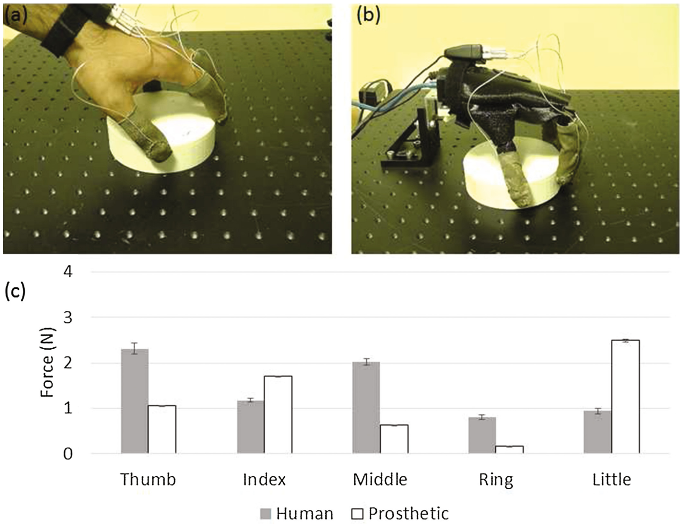

Fig. 4. Disk grasp. (a) Experimental setup for the human hand. (b) Experimental setup for the prosthetic hand. (c) Average grasping forces exerted by each finger of the left hand for the human hand and the tested prosthetic hand when using the disk grasp on a lid.

gers was significant. A post hoc Tukey test showed that the human fingers and prosthetic fingers were significantly different at $p < 0.05$.

Medium wrap grasp involves the curling of all fingers around an object without reaching the palm of the hand. This type of grasp is used to handle objects that are heavy and require more control, such as a water bottle or a torch. The force values across the 5 fingers of the left hand for human and prosthetic hands, were measured while using medium wrap grasp on a water bottle (Fig. 5). There was a significant difference among the mean forces of the fingers, and significant difference among the mean forces of the hand types. The interaction between hand type and fingers was not significant. A post hoc Tukey test showed that the human fingers and prosthetic fingers were significantly different at $p < 0.05$.

Also known as pincer grip, the thumb-index grasp enables a person to hold small objects, such as a pen or a paint brush, using only the thumb and the index finger. The results show the average grasping force that was exerted on a pen by both the human and prosthetic hand during testing using a thumb-index grasp (Fig. 6). There was a significant difference among the mean forces of the fingers, and significant difference among the mean forces of the hand types. The interaction between hand type and fingers was not significant. A post hoc Tukey test showed that the human fingers and prosthetic fingers were significantly different at $p < 0.05$.

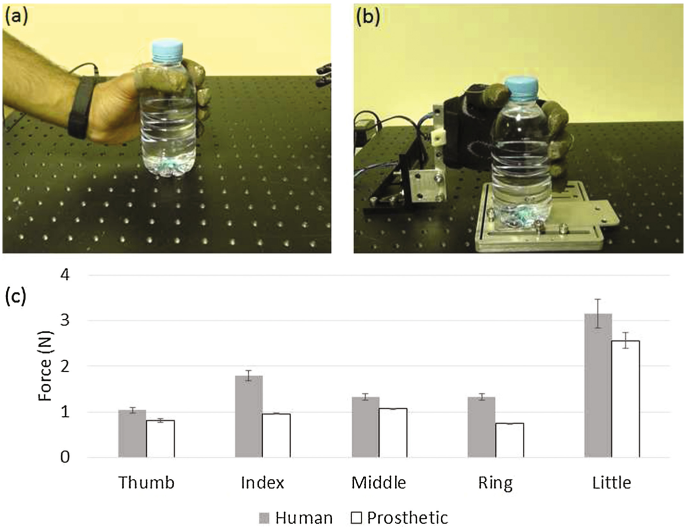

Fig. 5. Medium wrap grasp. (a) Experimental setup for the human hand. (b) Experimental setup for the prosthetic hand. (c) Average grasping forces exerted by each finger of the left hand for the human hand and the tested prosthetic hand when using the medium wrap grasp on a water bottle.

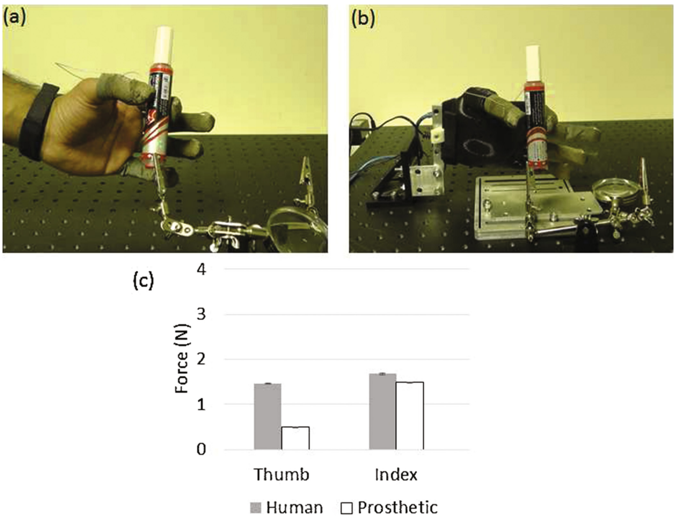

Fig. 6. Thumb-index finger grasp. (a) Experimental setup for the human hand. (b) Experimental setup for the prosthetic hand. (c) Average grasping forces exerted by each finger of the left hand for the human hand and the tested prosthetic hand when using the thumb-index grasp on a pen.

4 Discussions

There are around 33 grasps in the grasping taxonomy of the human hand [17], and the grasps that have been selected in this study, with the exception of thumb-index finger grasp, fall into the 10 most used daily grasps for some professions [2]. The significant difference between the contact forces exerted by the human hand and the prosthetic hand can be explained by the limitation in DOF of the prosthetic hand and the way that the prosthetic fingers were designed and positioned. Furthermore, this limitation is inherent with the actuation mechanism of this hand as some of the joints are underactuated [16].

The grasping mechanism of both the human and prosthetic hands are different. For example, the thumb of the prosthetic hand consists of only one phalange while the human thumb consists of two phalanges. This difference has contributed to the differences between the way contact forces were applied by the human and prosthetic hands. Another contributing factor to the overall reduction in contact forces in the prosthetic hand is the limitation in the range of motion. The difference in DOF between both hands has affected the grasping, and as a result, the contact forces exerted. For example, the lack of DOF has hindered the prosthetic hand from firmly grasping certain objects. Finally, the dexterity of the human hand has enabled it to grasp all objects firmly while maintaining even distribution of contact forces as compared to the artificial hand.

The need for prosthetic hands in the developing countries is not only about being affordable and meeting a certain functionality, but also is about being light weight, easy to operate, and maintain. The selected low-cost prosthetic hand is certainly light weight and has a lot of built in functions, but it is still facing some shortcomings when it comes to maintaining the strings of the fingers at the optimal tension. In an earlier study surveying 60 patients with upper limb loss [23], it was shown that 90% of the participants have used their artificial limbs functionally for less than 6 hours/day. This daily average usage will put a lot of strain on the strings of the Ada Hand, which will require that the maintenance should be more frequent. During the experiments that were conducted in this study, the strings were re-tightened regularly.

From an aesthetic point of view, the prosthetic hand is close to the natural shape that can be easily customized and improved visually for more realistic look for better social interactions when human-like artificial skin is considered [3,5,9]. Finally, future work can investigate how this design can be used for replicating popular hand gestures, for sign languages, and for social touching [4,6,14,28].

5 Conclusions

While the selected 3D printed prosthetic hand is capable of mimicking the grasping mechanism of the natural hand to some extent, it still falls short when the precision of grasping is considered. Increasing the DOFs could increase the dexterity and capabilities of such hand. however, that comes with a trade-off, which then increases the complexity, cost, and weight of the hand. Functionally, this prosthetic hand is not capable of generating comparable fingertip contact forces to that of the human hand. However, such prosthetic hands could still be useful for social touching applications where less forces are applied and required (e.g. caressing or patting).

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