OLYMPIC: A Modular, Tendon-Driven Prosthetic Hand With Novel Finger and Wrist Coupling Mechanisms

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***Abstract*—Prosthetic hands, while having shown significant progress in affordability, typically suffer from limited repairability, specifically by the user themselves. Several modular hands have been proposed to address this, but these solutions require handling of intricate components or are unsuitable for prosthetic use due to the large volume and weight resulting from added mechanical complexity to achieve this modularity. In this letter, we propose a fully modular design for a prosthetic hand with finger and wrist level modularity, allowing the removal and attachment of tendon-driven fingers without the need for tools, retendoning, and rewiring. Our innovative design enables placement of the motors behind the hand for remote actuation of the tendons, which are contained solely within the fingers. Details of the novel coupling-transmission mechanisms enabling this are presented, and the capabilities of a prototype using a control-independent grasping benchmark are discussed. The modular detachment torque of the fingers is also computed to analyse the trade-off between intentional removal and the ability to withstand external loads. Experiment results demonstrate that the prosthetic hand is able to grasp a wide range of household and food items, of different shape, size, and weight, without resulting in the ejection of fingers, while allowing a user to remove them easily using a single hand.**

***Index Terms*—Prosthetics and exoskeletons, tendon/wire mechanism, mechanism design, multifingered hands, grasping.**

I. Introduction

THE lack of specialist repair services in many parts of the world presents the need for prosthetic hands that allow self-maintenance by a non-expert user. Previous studies have shown that the main cause of concern for amputees looking to use myoelectric prostheses were their initial upfront and ongoing maintenance costs [1], [2]. For owners of these prostheses, some reported choosing not to wear them due to fear of damage while performing physically demanding tasks [3]. To solve these issues, many open-source, low-cost prosthetic hands, designed for manufacturing at home using 3D printing technology have been proposed [4]–[6]. These hands are intended to be affordable and simple to build. Hence, durability and long-term maintenance are often not considered. While these hands can be easily manufactured with given time, handling of multiple parts and tools during assembly can be a challenge to amputees with their remaining hand. Amputees are also expected to own 3D printers or have access to services for printing these prostheses, which may not always be a possibility.

The idea of modularising robotic and prosthetic hands with the intent of improving ease of maintenance is not a new one. Modularity provides the opportunity for mass production and customisation at a lower cost, which is not currently possible

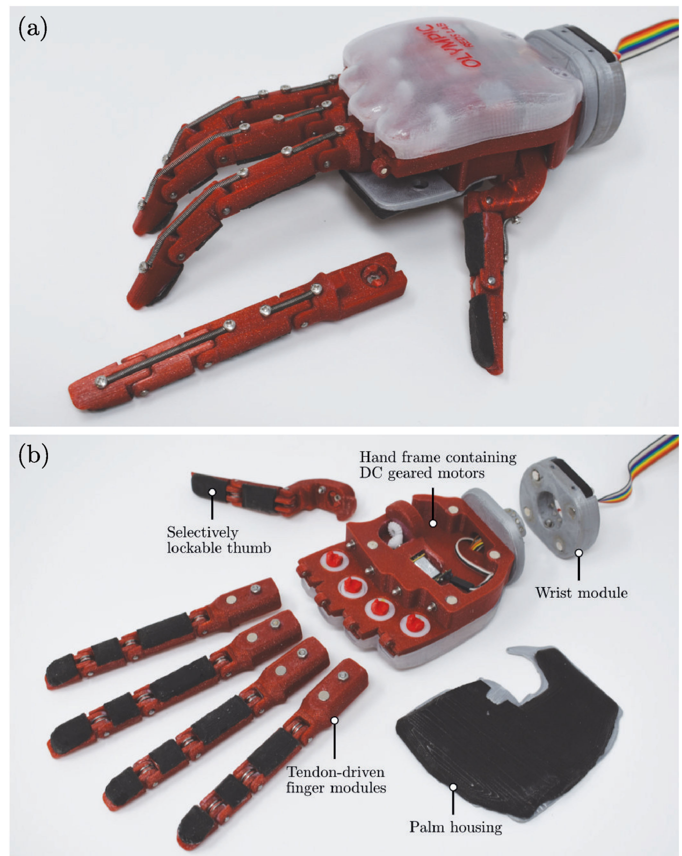

Fig. 1. The proposed tendon-driven prosthetic hand with finger and wrist level modularity. Assembled dorsal view (a) and disassembled palm view (b).

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TABLE I
COMPARISON OF THE DESIGNS AND LIMITATIONS OF MODULAR PROSTHETIC AND ROBOTIC HANDS

Modular Hand	Actuation	Modular Connections	Requires Re-tendoning	Requires Re-wiring	Requires tools to disassemble
HIT V *Harbin Institute of Technology* [9]	DC motors (located in the fingers) with worm-gears and tendons	Fingers-Palm Thumb-Palm	No	Yes	Yes
Galileo Hand *Galileo University* [6]	DC motors (located in the palm) with tendons	Fingers(grouped)-Palm Thumb-Palm	No	Yes	Yes
OpenBionics *National Technical University of Athens* [10]	Servo motor (located in the palm) with tendons	Fingers-Palm	Yes	No	Yes
i-Limb *Touch Bionics* [8]	DC motors (located in the fingers) with worm gears and belt	Fingers-Palm Thumb-Palm Wrist-Palm	No	No	Yes
Sandia Hand *Sandia National Laboratories* [11]	DC motors (located in the fingers) with tendons	Fingers-Palm Thumb-Palm	No	No	No
Eagle Shoal Hand *Intel Labs China* [12]	DC Motors (located in the fingers) with worm-gears	Fingers-Palm	No	No	Yes

in the prosthetics industry [7]. Multiple authors have proposed modular designs, with varying levels of modularity, as summarised in Table I. However, often these designs, such as the i-Limb [8] and HIT V [9] hands, still require the use of tools to remove fasteners holding components together, requiring a user to deal with intricate components which are difficult to access for repairs and replacement. As a result, repairs have to be performed by a certified clinician or engineer. Other designs have intrinsic actuation, with motors located in the palm, and require reconnection of tendons and/or wires before they are operational [5], [6]. Currently, the most advanced modular robotic hand is the Sandia Hand [11], which does not require reconnection of tendons or wires, or tools to disassemble. The modular fingers allow easy removal of the outrunner motors which are located on a separate module from the planetary gearheads, tendon actuation system and electronics. This internal modularity enhances maintenance and replacement of parts. However, it contributes significantly to the volume and weight of the hand, which is allowable for industrial robotic applications, but unsuitable for implementation in prosthetic devices.

Many developed prosthetic hands are tendon-driven (*e.g.*, [8], [9], [13]–[16]) due to the benefits regarding low-cost production, lightweight, and the implementation of self-adaptive underactuation [17]. Tendon-driven systems also allow actuators and electronics to be placed remotely from the moving parts of the hand [18], thus facilitating the development of a more compact prosthetic hand with a size similar to that of a human's. However, tendon routing is considered one of the most challenging and time-consuming processes in the assembly of anthropomorphic robotic hands [17]. An alternative method for transmitting force is the use of linkages, such as in [19]; while able to transmit greater fingertip forces in comparison to tendon-driven fingers, they are often bulky which may obstruct grasping ability and impact user comfort in prosthetic use. Moreover, the rigidity of a linkage system also makes them prone to mechanical failure, mainly due to accidental impacts [20].

To the authors' knowledge, the problem of tendon reconnection in the mechanical design of tendon-driven hands has not been thoroughly investigated either commercially or in the literature. To solve this issue, we introduce in this letter a fully modular prosthetic hand with coupling mechanisms that allow the tendons to be externally actuated from the palm, thus creating independent tendon-driven finger subsystems from the whole hand. The proposed prosthetic hand, named OLYMPIC (OperationalLY Modular ProsthetIC), is an affordable transradial device with modules that can be intuitively and quickly interchanged and assembled by an amputee without need for tools, as shown in Fig. 1; indeed, the hand introduces novel joint coupling mechanisms to allow finger and wrist level customisability. The assembly time of the hand is 8 hours by a single person (60 hours manufacture time on a standard desktop 3D printer), and the overall cost is £170. This cost includes the materials, mechanical components, geared motors and electronics.

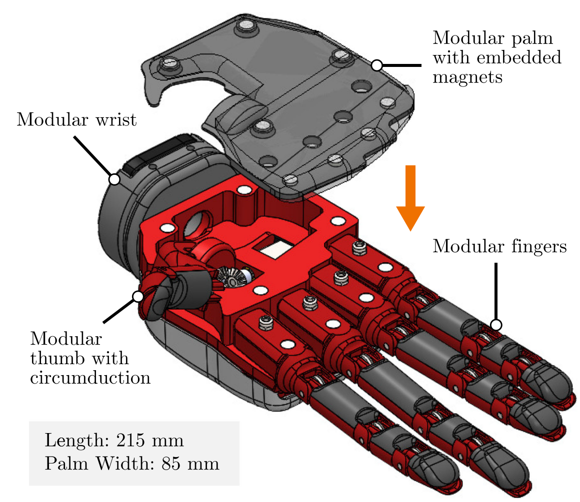


Fig. 2. Design overview of the OLYMPIC prosthetic hand, indicating modular components and general dimensions.

The rest of this letter is organised as follows. Section II details the design and development of the mechanical and actuation systems of the proposed modular prosthetic hand—OLYMPIC. Section III assesses the performance of the introduced design

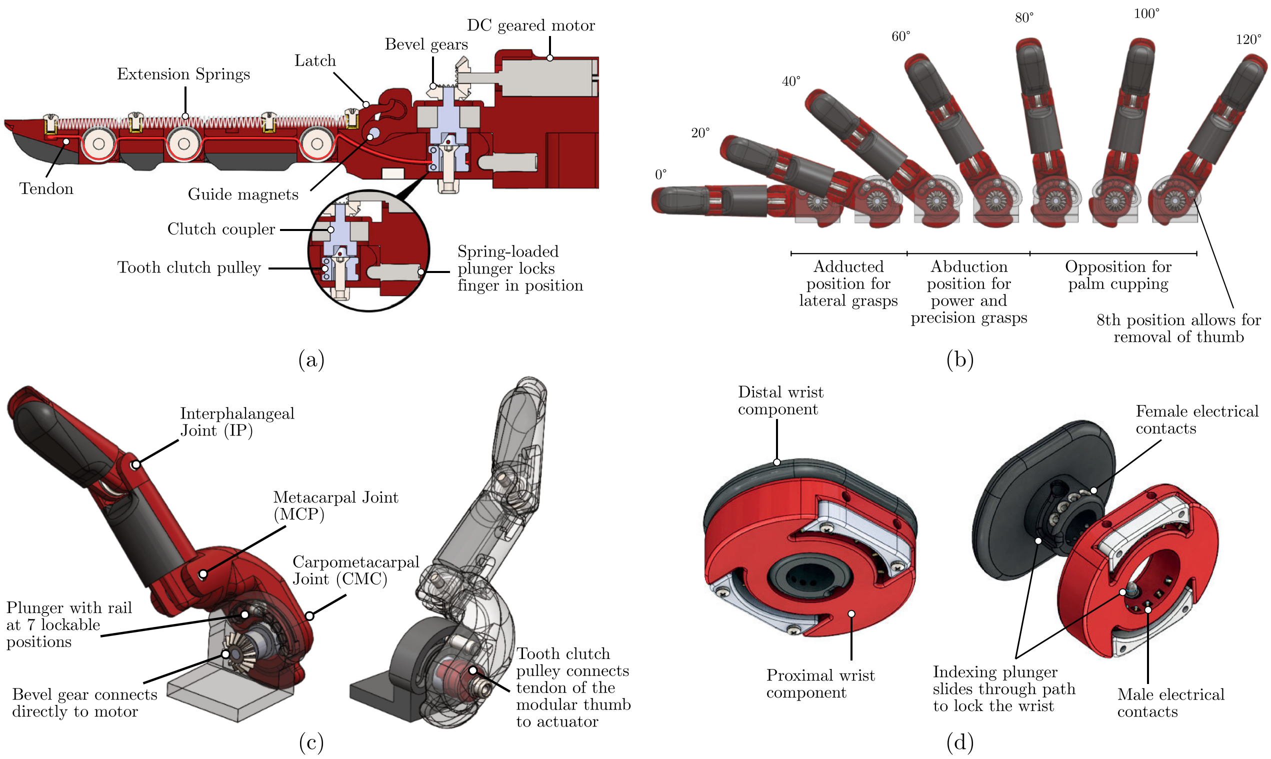


Fig. 3. The modular components of the OLYMPIC prosthetic hand. Section view of modular finger coupling mechanism (a), range of thumb circumduction angles for different grasp types (b), design of the modular thumb coupling and circumduction mechanism (c), and modular connection of the two components of the wrist (d).

in terms of its grasping capabilities and modularity, with results detailed in section IV. In section V, we provide a discussion of the experiment results, presenting insights into the measured performance of the hand. Finally, we conclude in section VI.

II. Development of Modular Prosthetic Hand

The hand has an overall length of 215 mm (from the palm base to end of the middle finger) and palm width of 85 mm, with a length of 92 mm, 102 mm, and 82 mm from metacarpophalangeal (MCP) joint to fingertip for the index and ring, middle, and little finger respectively, based on the dimensions of a medium size male hand (see Fig. 2). The prototype of the hand was 3D printed in PLA (Polylatic Acid) and PETG (Polyethylene Terephthalate). Due to frequent loading of the fingers and frame of the hand, PETG was specifically chosen for greater strength and durability.

A. *Finger Design and Modular Coupling Mechanism*

The hand has five fingers with a total of 15 joints. The fingers have metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints to allow flexion and extension of the fingers. The thumb consists of a carpometacarpal (CMC), metacarpal (MCP), and interphalangeal (IP) joints. The CMC joint allows circumduction of the thumb about the axis parallel to that of the wrist axis.

DC geared motors were selected due to their low weight, cost, and compactness, allowing them to be packaged in the hand. Four DC motors are located on the dorsal side of the hand for actuation of the index, middle, ring, and little fingers, with another motor located in the palm to actuate the thumb, as shown in Fig. 1b. Rotational motion of the motors is transmitted to the fingers through a set of bevel gears of ratio 1:1, which are placed perpendicularly to each other (see Fig. 3a). Given the closing speed (closing time 1.0–1.5 s [21]) expected in anthropomorphic prosthetic hands [22], we selected five DC brushed geared motors with gear ratio 298:1 and speed of 75 rpm at 6 V. The closing speed was estimated using the speed of the motor, clutch diameter, and length of tendon, while the torque was estimated from the length of each finger and the moment experienced around the base joint. This high gear ratio prevents back-driving and allows the hand to maintain grip on an object without power being supplied to the motors. The maximum current draw of each motor was 150–250 mA. In many prosthetic hand designs, backdriving is often solved by implementing a worm-and-wheel drive system with limits. However, worm-and-wheel drives can take up more space within the hand.

Details of the modular finger coupling mechanism can be seen in Fig. 3a. To connect the fingers to the hand, they must first be positioned correctly. Through the use of integrated magnets as guides, the finger modules are attached to the frame of the hand in a smooth swinging motion, as indicated in Fig. 4. A pivot latch located on the knuckles of each finger is first mated with a socket on the hand's frame. This mechanism then allows the finger to

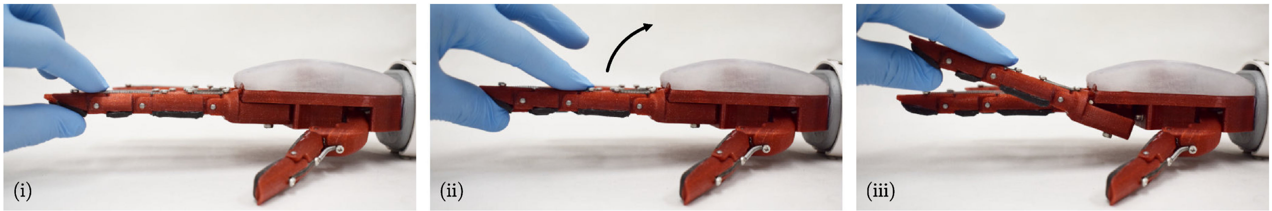


Fig. 4. Method of removal of modular fingers: (i) Finger is grasped at the tip, (ii) force is applied bending the finger backwards, and (iii) once enough force is applied the finger detaches from the hand. To reattach the fingers the method is reversed, with the base of the finger pressed into the hand.

pivot about an axis located at the base of the MCP joint and rotate into the locking mechanism. A spring-loaded plunger is used to lock the finger in position, preventing detachment during operation.

A groove on the base of the finger is included to guide the plunger to smoothly slide into place. The plunger is orientated horizontally, to resist the vertical forces exerted by the actuator during motion, which may cause the clutch to misalign and separate, resulting in the finger to eject from the frame. To remove the finger, the user has to place an upward force on the underside of the phalanges to release it. A balance was necessary for the design of the groove's radius, as sufficient contact was needed to ensure that the plunger does not slide during motion, to preclude the unintentional detachment of the fingers. However, the user should still be able to easily remove each finger with the minimum amount of force. As a safety measure during usage of the prosthesis, a modular palm plate was introduced, as in Fig. 2. The plate attaches onto the palm of the hand and the base of the fingers with the use of magnets, resulting in a distributed holding force preventing unwanted removal of the fingers.

The tendons in the finger are actuated externally via the rotation of the clutch and pulley (Fig. 3a). This innovative mechanism allows the motors to be placed on the back of the hand at a remote location from the fingers, allowing the hand to be compact and slender. The pulley acts as a clutch, which engages with the bevel gears when the finger is attached. The motor winds the tendon around the pulley, which flexes the finger. The pulley design allows pretension of the tendon; however it relies on the tendon being manufactured at the exact length. The tendon of each finger is terminated at the distal end, wrapped around a bolt fixed with a threaded insert. Extension springs across the phalanges act as a passive mechanism to allow the fingers to retract when the tension in the tendon is removed. Limits on each finger joint prevent the extension of the fingers beyond their allocated range of motion when overloaded to avoid damage to the fingers.

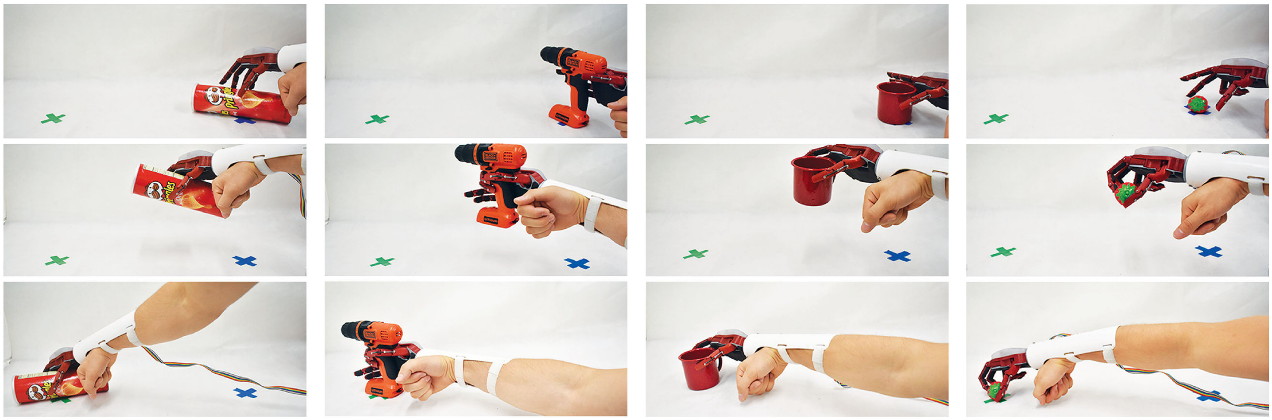
The fingers themselves do not contain any electrical components, thus reducing the cost for manufacture and replacement. As the fingers are independent to the rest of the hand system, it allows easy transition between different finger designs, without need to change the design of the hand's frame. The modular finger connectors provides the opportunity to implement fingers of various geometry, dimension, materials, and tendon routing paths to modify the functionality of the hand.

For the current proposed design, 3D printed PETG fingers with silicone moulded pads were selected. The use of soft silicone material on the fingers, as well as on the palm, provide improved grasping and slip resistance of the hand. A rigid fingernail was also added to the end of each finger. These allow for a better grip when handling small and intricate objects during precision grasping. To underactuate the fingers, a common tendon routing topology was used, in which the tendon was wound around the V-groove pulleys at each joint before they are drawn through a horizontal path behind the phalanges, as shown in Fig. 3a. The V-groove pulleys were introduced to reduce friction against the tendons.

B. *Thumb Design and Circumduction Mechanism*

The thumb accounts for 40 percent of the capabilities of the human hand and plays an important role in the manipulation of objects against the rest of the fingers while maintaining the stability of the grasp. The thumb is often associated with three main configurations to perform: (1) precision and spherical grasps, whereby the thumb opposes the index and middle fingers, (2) cylindrical grasp, whereby the thumb is offset from the rest of the fingers to avoid interference, allowing the object to be fully enclosed and (3) lateral grasp, in which the thumb is abducted (in-plane) with the rest of the fingers. Our design implements a selectively lockable thumb which can be manually repositioned to seven different opposition configurations to achieve these grasps. The thumb allows a circumduction angle between 0 to 120° (shown in Fig. 3b), which enables the hand to swap between precision and power or lateral grip. This is beyond the average human circumduction motion of 90.2°. Similar to most prosthetic hands, such as the i-Limb and Bebionic with manually repositionable thumbs, our thumb's circumduction axis is parallel to the axis of the wrist.

Similar to the locking mechanisms of the rest of the fingers, the thumb utilises an spring-plunger which slides through a rail located on the thumb holder block, as shown in Fig. 3c. The thumb can be rotated with ease by the user, but remain completely rigid during actuation of the finger. This is to ensure that torque exerted by the motor does not result in a displacement of the thumb. For this reason, this locking mechanism is advantageous over friction-based mechanisms [23] which are prone to result in the accidental reorientation of the thumb by external forces. This locking mechanism also benefits over a previous suggested



(a) (b) (c) (d)

Fig. 5. Power grasps: (a) cylindrical grasp of a chips can and (b) medium wrap grasp of a drill. Precision grasps: (c) tripod grasp of a mug and (d) pinch grasp of a strawberry.

design [24], as it requires minimal assembly and parts while facilitating the modular design of the thumb. The design is also more intuitive for the user as the thumb could be rotated and locked in a single motion. Tension of the tendon changes when the configuration is changed, and hence, recalibration of the initial position of the thumb is ideal, but not required prior to usage. The transmission system of the thumb is similar to the rest of the fingers. The thumb can be removed by rotating the thumb clockwise. The plunger slides to the end of the rail, allowing the release of the thumb.

C. Wrist Electrical Connector Design

The locking mechanism of the wrist uses a spring-plunger, the same as those used for the fingers, on the proximal component of the wrist, as in Fig. 3d. When the two distal and proximal components are pushed together, the plunger slides along a path on the distal component. This creates a twist-and-lock motion for the wrist and allows the male and female electrical contacts to engage with one another upon locking. Electronics and surface electromyography (sEMG) sensors could be placed in the forearm and socket as a result, as they contribute to the majority of the cost in myoelectric prosthetics, without need for rewiring when replacing aspects of the hand. The wrist coupler was also designed to have the contacts situated internally and shielded by the plastic enclosure to limit exposure to moisture. The weight of the proposed prosthetic hand, including the modular wrist, is 546 g, close to an ideal prosthetic weight of 500 g [22], [25], [26].

III. Performance Evaluation of the Modular Hand

The focus of our research was on the hardware design of the modular hand, not the control. As most prosthetic evaluation tools, such as the Box and Blocks test, 9-hole-peg test, and the Southampton Hand Assessment Procedure (SHAP) are influenced by time, and thus the control method of the hand, we have proposed a new protocol and benchmark to assess the grasping ability of prosthetic hands with objects of different sizes and shapes from the Yale-CMU Berkeley (YCB) Object set [27], a standard object set specifically for robotic hands. Food, kitchen items, and tools were chosen as benchmarks because eating and housekeeping are considered the most important activities for daily living (ADLs), as exemplified in Fig. 5, as these were the objects a prosthesis user would most commonly interact with. These objects are also commonly used in previous prosthetic evaluation tests and are easily attainable through purchase.

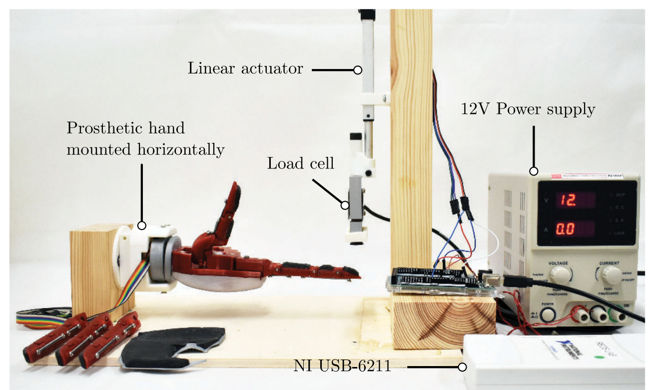


Fig. 6. Experiment setup to evaluate the detachment torque required to remove the fingers from the hand.

The prosthesis was attached to a splint mounted on the right forearm of an able-bodied experimenter, powered by a bench power supply, and teleoperated to allow individual control of the fingers for tasks requiring precise gripping and object manipulation. On a planar surface, two ‘X’ marks were placed 500 mm apart. Food items, kitchen objects, and tools from the YCB object set were presented 10 times on the first marked ‘X’. All motors were driven with the same speed until the fingers made sufficient contact with the object. In first performing a grasp, small manipulations by the prosthesis were allowed to aid a stable grasp, particularly for objects with irregular shapes, as long as they remain within the marked ‘X’. Each object was lifted vertically above a minimum height of 100 mm and subsequently moved horizontally across the surface, before being placed on the second marked ‘X’. Once moved, the object was released into

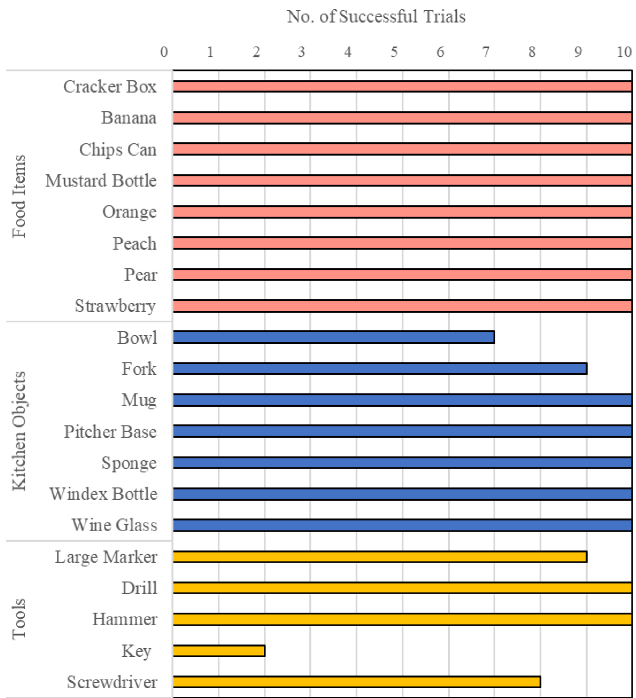


Fig. 7. Number of successful transfers of objects specified in the proposed prosthetic hand grasp assessment based on the YCB object set, including different food items, kitchen objects, and tools.

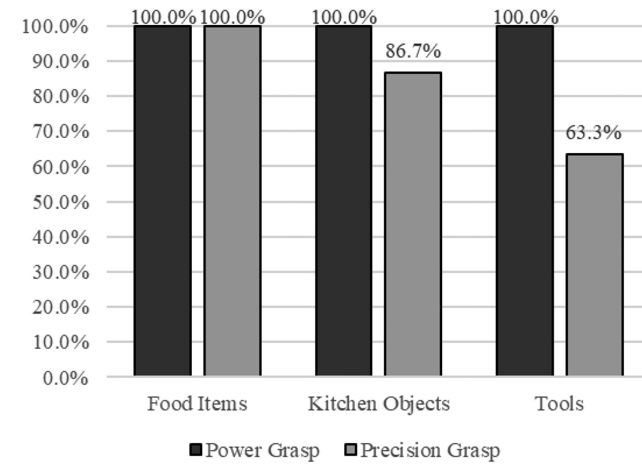


Fig. 8. Percentage grasp success for precision and power grasp of the objects grouped by object category

a stable position. The number of successful grasps and transfers for the 20 selected benchmark objects was measured, with a single point being awarded for each. Therefore, the total score for successful grasping and transfer for all objects is 200.

In order to evaluate the maximum loading force of the modular fingers, the hand was mounted horizontally with fingers fully outstretched as shown in Fig. 6. A linear actuator (Actuonix L12-100-100-12I) with a single-axis load cell (DBBSM 5 kg S-Beam) was mounted perpendicularly to the hand on a rigid beam. The modular fingers (index, middle, ring and little) were loaded on their middle phalange, with the load cell pressing against the fingers with increasing force until the fingers detached. Force-time data was collected through a DAQ (NI USB-6211) and DAQExpress software. This was performed ten times for each finger, where the peak force experienced was measured as the detachment force. By multiplying by the distance from the rotational pivot to the centre of middle phalange, we obtained the ejection torque required to detach each finger. We also tested a single finger locked in position with the magnetic palm to failure, determining the maximum force and torque the fingers are capable of withstanding.

IV. Experiment Results

Results of the YCB object grasping and transfer task of the 20 household objects are shown in Fig. 7. The hand achieved a score of 185 out of a total score of 200, using a combination of power and precision grasp types for the different objects. The hand successfully grasped and transferred the majority of the objects, with only the key failing to be grasped a significant 8 number of times. The hand achieved a full score out of 10 for all the food items, which includes the cracker box, chips can, mustard bottle and the plastic fruits. For kitchen objects, the bowl proved slightly more challenging for the hand to grasp, which resulted in a score of 7. The hand, however, performed extremely well for spherical and cylindrical objects with a diameter similar to that of the palm, which allowed for full force closure, for such objects as the cracker box, chips can, and Windex bottle. Small diameter cylinders such as the large marker and screwdriver scored a 9 and 8 respectively. The usage of the palm allowed grasping of the objects in all 200 trials without experiencing any unwanted ejection of the fingers.

To investigate the differences in measured force/torque between fingers, the finger loading test was performed. The peak force experienced during the detachment of the fingers was measured for the ten trials and averaged. The torque required to detach the finger was therefore calculated by combining the averaged peak forces experienced during the detachment of the fingers with the length of each finger. From this measured torque, the results are displayed in box plots in Fig. 9, with the range of values for each finger indicated by the dotted black lines, interquartile range (IQR) denoted by the blue box, and median shown by the red line. The results show an average median torque of 0.39 Nm is required to detach the fingers, with the data showing a range of values distributed between maximum and minimum torques of 0.50 Nm and 0.33 Nm. To understand the maximum force capabilities of the finger, a single finger (little finger) with the attached magnetic palm was continuously loaded until failure occurred at a maximum torque of 2.73 Nm (14.4 N), as shown in Fig. 10. During the entire loading sequence, the finger did not eject from the frame, demonstrating it was capable of sustaining a significantly greater force in comparison to when the palm was removed.

V. Discussion

The results from the proposed prosthetic grasping test were grouped according to grasp type used for each object (power and precision), which can be seen in Fig. 8. Overall, an equal number

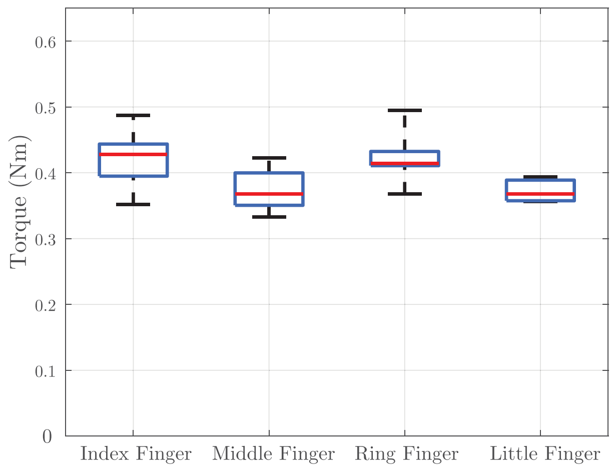


Fig. 9. Results of the torque required to remove each finger, calculated from the force required and finger length.

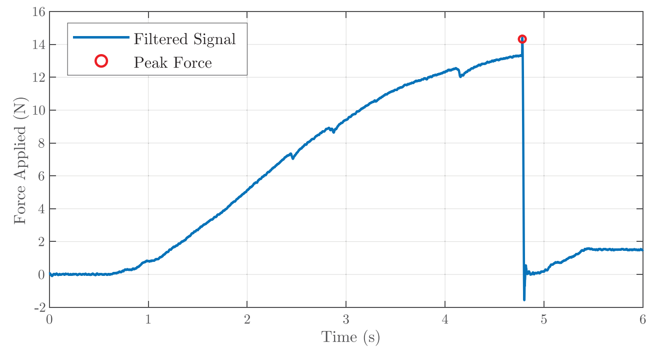


Fig. 10. Force-time plot showing a single finger loaded until mechanical failure (peak force of 14.4 N), with magnetic palm restricting the removal of the finger.

of power and precision grasps were used. Power grasp showed a higher success in grasping, as it allowed the fingers of the hand to wrap around in a stable configuration around the objects. In measured success, the power grasps performed a perfect score of 100% for all three categories of food items, kitchen objects, and tools. Precision grasps achieved a score of 100% and 86.7% for food and kitchen objects respectively. The hand scored the lowest for precision grasping of tools, making a success rate of only 63.3%, mainly due to its difficulty in manipulating the key.

Precision grasps were mainly used for smaller objects such as the plastic pear, peach, and strawberry, as the hand could not achieve a stable closed grasp around the object from the initial object position in the experiment. On average, for grasps requiring precision, the hand demonstrated the success of 85%. Pinch grasps were particularly difficult to achieve due to the lack of contact surfaces between the fingers and the small objects. This is also true for flat objects such as the key, which require additional manipulation before grasping. To grasp a key from the table, one must typically be able to first lift one side of the key off the surface by using their fingertip as a wedge. The key can then be reorientated into a stable grasp such as a lateral or pinch grasp. An object that required a similar manipulation was the bowl, in which the hand had to tilt bowl to distribute the fingers evenly over the object. The hand showed difficulty in manipulating objects on a surface, due to the limited control of the fingers, and as such the hand was often unable to perform the first part of this grasp, specifically for the key. The current kinematic design of the hand also presents minor difficulties in grasping small cylinders, such as the fork, large marker, and screwdriver. This can also be explained by the limited manipulation required for a power grasp around a small cylinder, as well as the hand's limited ability to interdigitate and enclose completely around the tools. Despite these difficulties, the hand showed success in the majority of objects, overall showing a success rate of 92.5%.

In the design of the fingers, various trade-offs were considered. The modular fingers should allow for intentional removal with a single hand, but should still be able to withstand external loads experienced during grasping without ejecting. For a typical user, the maximum pronation torque they can exert with a single hand is 5.88 Nm (60 kgcm) [28]. To allow for ease in removal, we assume a maximum allowable force of 14.5 N (1 Nm).

The measured force to detach each finger ranged from 3.96 N to 7.09 N. This is lower than the limit of a user, allowing easy removal of the fingers. The finger loading results indicate that the modular fingers show similar ejection torques, with the median torque required to eject the index, middle, ring, and little fingers calculated to be 0.43, 0.37, 0.41, and 0.37 Nm respectively– results of an additional test of 20 cycles for the index finger showed no decrease in ejection force over time. As shown by the box plots in Fig. 9, the distribution of measured torques was small, indicated by the condensed inter-quartile ranges (IQRs). The minor differences measured in ejection torques for the four fingers may be explained by manufacturing tolerances of the locking mechanism, as well as the variations in finger length altering the position at which the force is applied.

By attaching the magnetic palm, the force required to detach the fingers increased, and a force of up to 14.4 N was experienced by a single finger before failure, as shown in Fig. 10. A typical prosthetic should aim to be capable of exerting 45 N of force in a grasp [25], [29]. From this test to failure, the hand was estimated to be able to sustain up to 57.6 N of load at the fingertips. For comparison, an average bottle of wine weighs $\sim$12 N. In a real-life situation, the expected 45 N would not be distributed at the fingertips, nor directly perpendicular to the finger latch mechanisms. With the attached magnetic palm, the hand was able to successfully grasp and transfer all objects without resulting in the ejection of the fingers. This includes the heaviest objects, which are the drill and hammer of 895 g and 665 g respectively.

VI. Conclusions

We have addressed the design issues and limitations of current modular commercial and research prosthetic hands. In this letter, we present a fully-modular anthropomorphic prosthetic hand with interchangeable tendon-driven finger modules for the purpose of self-maintenance without tools. We introduce a novel finger coupling and transmission mechanism, which eliminates the need for tendon reconnection and rewiring of the hand. The modular fingers themselves do not contain any electronics and are actuated remotely by DC motors located in the palm. This reduces the time and cost of manufacture of these fingers, allowing the fingers for affordable replacement without need to alter or re-manufacture the rest of the hand. The fingers are attached to frame of the hand containing actuators through a swinging motion about a pivot located on the base of the fingers' MCP joints and are locked in place with a spring plunger. A magnetic palm prevents the fingers from undergoing unwanted detachment. A selectively lockable mechanism was implemented with the modular thumb, enabling eight different opposition configurations for power, precision, and lateral grasping. The design allows the thumb to be easily manually repositioned by the user, but remain stiff during actuation. The design of the modular wrist and its electrical contacts was also discussed. The functional capability of the hand was validated experimentally through a series of grasping tests with the YCB object set, consisting of 20 kitchen objects, food items, and tools of a variety of shapes, sizes, and weights. The hand showed a good performance (92.5% success) in grasping and was able to lift the heaviest object, the drill (895 g) with ease. Results from the fingertip loading test have shown that a torque between 0.37–0.43 Nm is required to eject the fingers from the locking mechanism. This allows the fingers to be easily removed by the prosthetic user using a single hand without worry about damaging the fingers.

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