A Cost-effective, Modular, Under-actuated, 3D Printed and Adaptive Prosthetic Gripper

Hang Sun, Sherry Cheng and Botao Dong

Abstract— **Most amputees express disappointment regarding the high cost, weight, and repair difficulties associated with commercially available prosthetic hands. This fear of damage leads them to resort to simpler alternatives for everyday tasks, reserving expensive prostheses for special social occasions. This paper introduces a cost-effective, modular, 3D-printed, and adaptive gripper to address this challenge. The gripper employs a modular design, greatly simplifying maintenance. Its adaptive functionality enables it to replicate the capabilities of commercial prostheses while being more cost-effective and compact. The proposed design is experimentally validated through two tests: i) grasping experiments with everyday objects, and ii) force exertion experiments using a dynamometer.**

I. Introduction

The robotic prosthetic market size was valued at USD 1.4 billion in 2022. This growth is primarily driven by the enhancement of functionalities, which benefits from wide application of artificial intelligence (AI) in robotics for prosthetic manipulation [1]. The deployment of AI in prosthetic hands indicates great potential for innovations in precise prosthesis control through signal analysis. To translate the analyzed signals into dexterous movements, the prosthetic hand market currently relies on fully-actuated, heavy, and expensive devices. These devices are capable of performing numerous gestures due to their fully-actuated mechanism, wherein each Degree of Freedom (DoF) has its own motor. However, this design inevitably results in a high price and significant weight. Common prosthetic models, such as the Ability Hand, Adam's Hand, the Michelangelo arm, and the Ottobock bebionic arm, can cost anywhere from USD 28,000 to 65,000 [2] [3]. Consequently, many amputees are disappointed by the high cost of purchase and maintenance. The fear of damaging these prostheses often leads amputees to wear simpler hooks in their everyday lives, reserving the expensive prostheses for special social events. As a result, these advanced prosthetic devices spend most of their time stored away in a drawer. Therefore, there is a clear need for an affordable, easily maintainable, light-weight and aesthetically pleasing solution.

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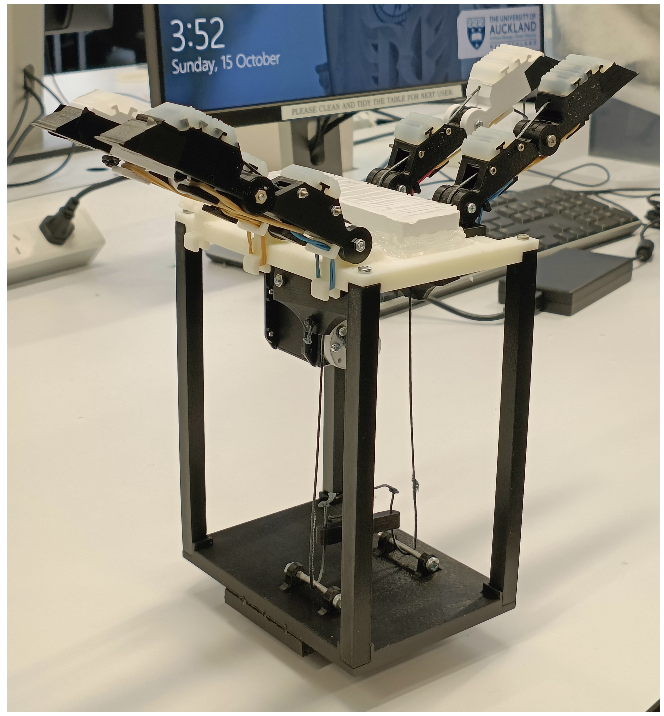

Fig. 1. The proposed highly underactuated four-finger prosthetic gripper

In this paper, we focus on the development of an under-actuated and adaptive four-finger gripper capable of grasping everyday objects. The gripper is both affordable and easily maintainable, due to its modular design and 3D printed manufacturing process.

The paper is structured as follows: Section II presents related work in this field, Section III illustrates the gripper's design, Section IV presents the gripper's performance, and Section V concludes the paper, discussing future directions.

II. Related Work

Ma et al. [4] developed an affordable underactuated prosthetic gripper using 3D printing. The gripper features flexure joints fabricated through Hybrid Deposition Modeling (HDM), enhancing its capacity to adapt to irregular object surfaces. It consists of four fingers, suggesting that two differentials will suffice for transmitting equal forces and ensuring simultaneous motion. However, despite the authors' description of HDM as a technique for rapid prototyping, the curing process can take approximately 24 hours to complete, which is a significant disadvantage when compared to using pins. Furthermore, the stiffness of the fingers remains fixed in this design, making reconfiguration uncontrollable. The gripper demonstrated a gripping force of 10N, making it unlikely to handle heavy objects effectively.

Kontoudis et al. [5] introduced a cost-effective underactuated anthropomorphic hand with a lockable differential mechanism. This hand can smoothly transition between various gestures by selectively locking its fingers, offering a high degree of dexterity at a low cost. It has proven its ability to grasp everyday objects effectively. However, controlling the hand is non-intuitive and complex; users are required to manually lock the differentials in order to switch between gestures, which makes the entire process cumbersome.

Leddy et al. [6] proposed a novel myoelectric underactuated anthropomorphic hand design. The hand has three grasp types that can be manually swapped to enable grasping different objects. This hand uses a cheaper motor, the Faulhaer 1524 SR, which makes it more affordable than Kontoudis's design. However, this hand has limited gestures, making it less dexterous. The fingers use torsional springs for passive expansion, which increases the complexity of tuning their stiffness.

Weiner et al. [7] introduced an innovative myoelectric under-actuated anthropomorphic hand design. This hand is operated by two motors, where one motor controls the thumb, and the other is responsible for actuating the remaining fingers. Notably, it integrates tactile sensors, a camera, distance sensors, and Inertial Measurement Units (IMUs), which collectively provide essential information about force, position, orientation, vision, and distance. The male prosthesis demonstrates a strong average grasping force of 24.2N, indicating its potential for handling heavy objects. However, it's worth noting that the paper does not elaborate on the processing of Electromyography (EMG) signals, leaving a gap in understanding how these signals are utilized. Additionally, it does not convincingly demonstrate the benefits of incorporating a camera, distance sensor, and IMU. Another limitation to consider is the absence of a lockable mechanism, which restricts the hand's dexterity.

III. Designs

A four-finger gripper, as demonstrated in Figure 1, has been developed. This section provides a detailed explanation of the gripper's design.

A. Gripper Fingers

As presented in Figure 2, a tendon-based approach using Dyneema rope has been employed for rapid iteration and minimal size. Each finger measures 13.3 cm in length, 2.4 cm in height, and 1.8 cm in width. A simplistic tendon routing strategy is chosen to minimize friction. A minimum distance of 8 mm from the joint pins to the tendon is guaranteed for greater torque generation. The pivot-based joints enable rapid iterations and stronger force exertion in comparison with HDM, which is time-consuming and disadvantageous when grasping heavy and slippery objects, such as a 1.5L water bottle.

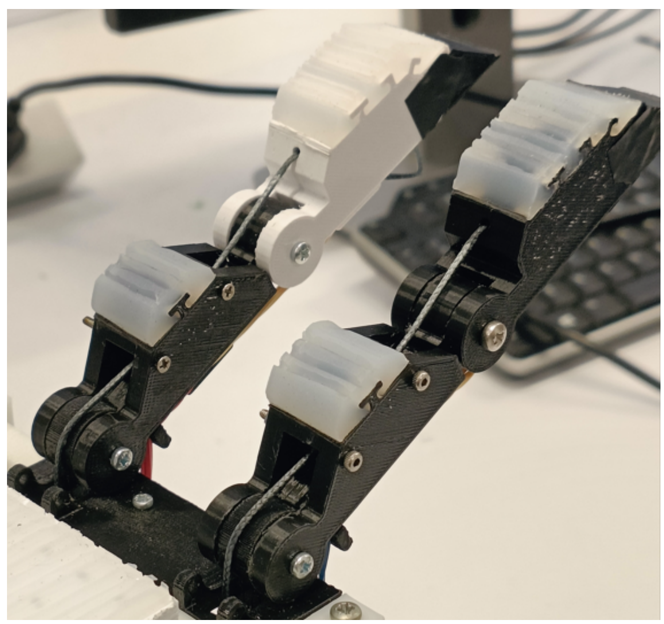

Fig. 2. Finger Design

Figure 3 shows the side view of the finger design. Each phalanx has a finger pad made using the HDM technique with Dragonskin 10 to increase friction. Manual dents have been carved to further enhance grip when grasping. A modular finger nail design has been developed, enabling rapid nail iteration through a press-fit mechanism. Notably, a protrusion is incorporated

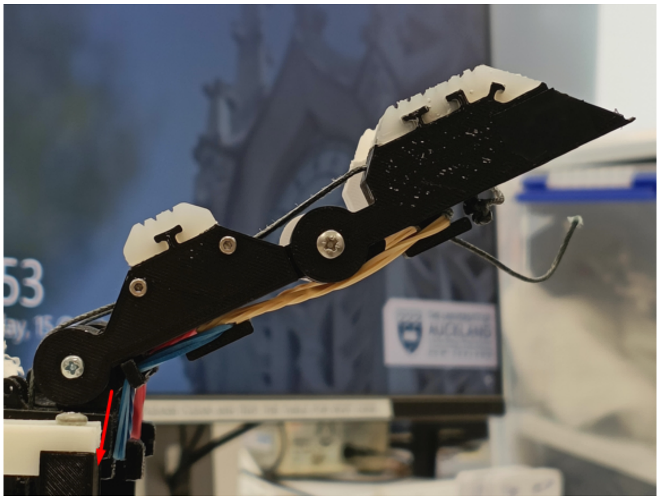

Fig. 3. Finger Sideview

into the finger nail to facilitate the easy grasp of thin, flat items like credit cards and washers. The backs of the fingers are equipped with rubber bands for convenient stiffness tuning, as an alternative to using springs for passive expansion. The two-phalanx design also allows for easy stiffness adjustment. At the proximal joint, a guide has been added to enable vertical force transmission through the rubber band, enhancing efficiency. However, this finger design faces challenges when grasping objects with a large diameter and a slippery surface, leading to early reconfiguration of the grip. The finger swaps from a form gesture to a force gesture using the distal phalanx.

B. Gripper Differential

Figure 4 illustrates the side view of the gripper. In this design, the differentials employed consist of a combination of a pulley and a whiffle tree. Since an even number of fingers is used, two differentials are sufficient to ensure balanced force distribution and simultaneous finger movement.

The Dyneema cable is rerouted at the base's bottom through a rod to a whiffle tree, which is directly driven by a Dynamixel MX-64AR motor. This rerouting approach allows for the motor's placement under the palm, effectively saving space compared to positioning it at the bottom. Furthermore, the motor shaft is designed with a small diameter of 1.05cm, thereby exerting more force while applying the same amount of torque. To prevent fractures, a 50% infill is utilized during the 3D printing process.

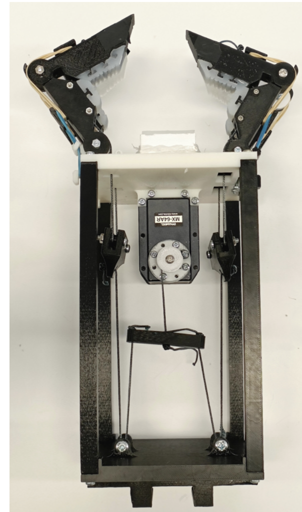

Fig. 4. Side view of the gripper

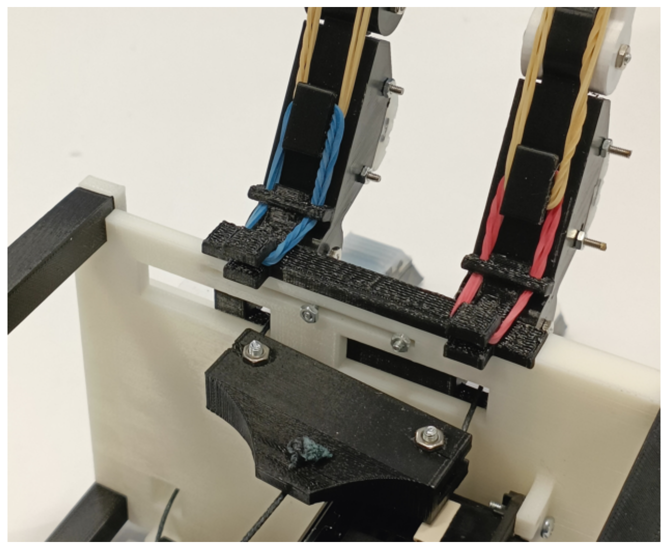

Fig. 5. Sliding Mechanism

C. Gripper Base

A palm measuring 1.7 cm in size has been developed on top of the base to shorten the travel distance of the fingers. The palm pad, made using Dragonskin 10, also enhances friction, enabling a better grip on slippery objects. A sliding mechanism has been designed to facilitate the transition between form closure and force closure, as displayed in Figure 5. The top of the base has five slots for finger installation, which are 5 cm apart, leaving sufficient space for interlocking. Although a base height of 15 cm would be sufficient for achieving full finger form closure, the base height has been set at 18 cm. This additional 3 cm allows for more force exertion, as it provides the motor with a greater range of motion to pull up the whiffle tree.

IV. Experiments and Results

In the grasping challenge, the gripper is attached to a UR5 cobot for positioning. The following items are used:

- Washer
- Gift card
- Fork
- Wrench
- Chain
- Drill
- 1.5L water bottle
- Hammer

The gripper has successfully managed to grasp all the above items using the *finger steepling* configuration, where the fingertips come into contact with the fingertips on the other side.

Additionally, apart from the grasping challenge, the gripper was tested while being held by a human hand. In this case, the *finger steepling* configuration was only employed for grasping the washer and gift card to achieve force closure, while the *finger interlocking* configuration was used for other larger objects to ensure form closure. The gripper has consistently grasped every item ten times with a 100% success rate. It's also worth noting that when grasping the 1.5L water bottle, the stiffness of the fingers was adjusted to make the distal joint stiffer, preventing early reconfiguration.

The gripper has exerted a maximum force equivalent to 116 N before the whiffle tree fractures, demonstrating promising strength in gripping heavy objects.

V. Conclusions and Future Directions

In this paper, we present a cost-effective, underactuated, and adaptive prosthetic gripper designed with modularity in mind. The gripper has demonstrated impressive grasping capabilities, successfully gripping items ranging from tiny washers to larger objects such as a 1.5L water bottle and a drill. It has been shown to exhibit adaptive behavior, with its fingers conforming to the shape of an object using only one actuator. The gripper's ability to exert force showcases its remarkable capability for gripping heavy objects.

As for future directions, we intend to replace the Dynamixel MX-64AR motor with a more affordable alternative, as a USD 200 motor remains too expensive. Additionally, the motor's interface is not user-friendly. We also plan to make the base more compact and wearable, possibly by implementing better cable rerouting. Lastly, we aim to design an electronic control system using a customized PCB and EMG signals to translate EMG signals into gripper movements.

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