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Human-like Robotic Pinching End Effector (HRPEE) Using McKibben Muscles on UR5 Robotic Arm

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ABSTRACT

This paper proposes a design of a human-like robotic pinching end effector using thin McKibben muscles integrated with a robotic arm for pick and place operations. Unlike conventional grippers, this design considers safe interactions with the environment while maintaining the pick and place success rate. This is achieved by mimicking the human counterparts anatomically for pinching and replacing them with soft materials for the structure and actuating system. The performance of the proposed gripper is evaluated in three phases, flexion experiment, pinching experiment, and pick and place experiment. From the pinching experiments, the proposed gripper is observed to successfully pick objects such as a pen, cutter, and a sponge. The results from the pick and place experiments indicate the proposed gripper can perform pick and place operations ten times consecutively with a 100% success rate similar to a rigid conventional gripper. It is envisaged that the proposed work can be particularly useful for industrial pick and place operations as it is less hazardous and has a high pick and place success rate.

Keywords:
Soft robot; bio-inspired; robotic hand

1. Introduction

Robotic arms are widely used in the manufacturing sector for pick and place operations. Automating the pick and place operations helps to increase production rates in the product assembly process. This process involves picking an object from one station and placing the object at another

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station. For this process, the robotic arm is usually assembled with a mechanical gripper as an end effector which is inspired by the human hand. Nowadays, vigorous research is carried out on developing robotic hands to imitate the dexterous motions of the human hand which have ability to carry out pick and place operations. Various robotic hands are aimed at task-based operations including KITECH-Hand [1] and EthoHand [2]. Other work aims at designing anthropomorphic robotic hands to restore lost hand dexterity. Xu *et al.,* [3] developed a highly biomimetic anthropomorphic hand by including the extensor hood mechanism which is actuated by DC motors. The ACT hand is one of the early available research projects with the same objective to replicate the human hand on an anatomical level [4]. The goal of the ACT hand is to examine the biomechanics of the human hand and as an experimental test bed. Extensive results have been presented in the anatomical study on the extensor mechanism [5] and the capability of the hand to play a musical instrument [6]. However, these robotic hands use motors as actuators which increase the weight and have low compliance.

Pneumatic artificial muscle (PAM) is characterized by its similarity with human skeletal muscles of interest. Due to these similarities, PAM is increasingly popular in research and industrial application such as rehabilitation, robotic manipulators, and exploration [7]. The actuator also has passive and natural compliance, which follows the nature of skeletal muscles. These muscles are a type of actuation in soft robots [8]. The PAM structure usually contains an inflatable inner elastic tube enclosed in braided mesh sleeves and fittings are used to secure the ends. When pressurized air is pumped into the PAM body, the inner tube expands in the radial direction and contracts axially, thus producing an axial contractile force used for actuation. PAM actuators are used for their high power-to-weight ratio, are highly compliant, and their soft body allows safer interaction with the environment [8].

Thin McKibben muscles (TMMs) are a type of PAM developed by [9] to further enhance the capabilities of conventional PAM actuators in terms of flexibility, compactness, and are significantly lighter in weight [10]. Applications of TMM include continuum manipulators [11], wearable devices [12], and bio-inspired robots [13]. Authors from [14] presented an index finger of a human-like robotics hand which intends to closely replicate the human finger. One main advantage of using such a structure is the ability of the robot to produce safer interaction with objects due to the soft materials used [8]. Even though there exist various research on development of human-like hands using thin McKibben muscles, however there is less evidence that the current robotic hands can perform in pick and place operations. Taking everything into consideration, this paper contributes to the expansion of knowledge in this field by addressing three important issues. Firstly, the development of an end effector for a UR5 using soft materials that closely mimic the human hand. Secondly, the integration of the soft end effector with UR5, and finally pick and place experimental validations of the proposed end effector. In addition, the fabrication steps and UR5 integration method are shown.

2. Development of Human-like Robotic End Effector (HRPEE)

The Human-like Robotic Pinching End Effector (HRPEE) (Figure 1) is designed to mimic the basic precision grip of the human fingers known as pinching. This function involves two fingers which are the index finger and the thumb from the metacarpal joints to the distal phalanges. A pinching function involves the flexion and extension motion of the two fingers to apply force on an object and thus lifting the object. To achieve the minimum capability for pinching motion, only the muscles involved in the flexion-extension motion of the two fingers are fabricated. The fingers will then be secured on a 50 cm rod and attached to the Universal Robot 5 (UR5) which will be used to mimic the function of the human shoulder, elbow, and wrists for the pinching motion.

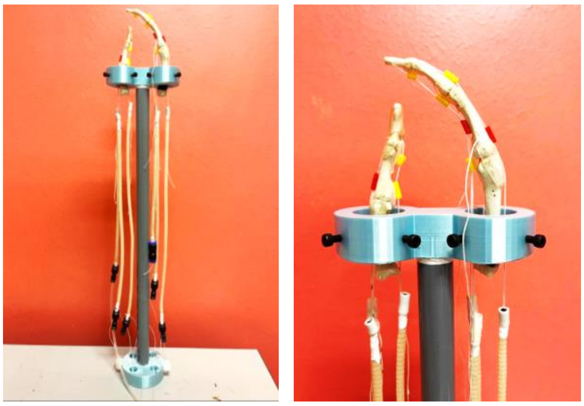

Fig. 1. Human-like robotic pinching end effector

2.1 Muscles, Limbs, and Tendons of Fingers

For the Index Finger, only the muscles that contribute to the flexion-extension motion of the fingers are preserved. These muscles include the Flexor Digitorum Profundus (FDP), Flexor Digitorum Superficialis (FDS), Extensor Digitorum Communis (EDC), and Extensor Indicis (EI) [13]. Although EI contributes to the extension motion of the index finger, it provides a similar function to the EDC and will be neglected in this experiment. Therefore, the index finger will comprise of 3 extrinsic muscles. The muscles will be threaded along the metacarpal joints from the bones and attached to a 3D printed base to be mounted to the UR5.

There are 3 joints and 4 bones in the fabrication of the index finger (Figure 2). The 4 bones include the Metacarpal, Proximal Phalange, Middle Phalange and Distal Phalange. The first joint is known as the Metacarpophalangeal joint (MP) which acts as the saddle joint connecting the Metacarpal bone with the Proximal Phalange. It is commonly known as the knuckle joint. The Proximal Interphalangeal Joint (PIP) links the Proximal Phalange with the Middle Phalange while the Distal Interphalangeal (DIP) links the Distal Phalange with the Middle Phalange. The muscle joint at each joint is tabulated in Table 1 along with their range of motion (ROM). The ligaments are made of 2 mm thick silicon which is sufficient to secure the joints while providing stiffness to the finger [14]. The tendons connecting the muscles and the bones are made of 0.53 diameter Dyneema (high density polyethylene) manufactured by Hayama Ind. Co., Ltd (Nagahama, Japan) with part number DB-8HE. Loctite® 401TM (Dusseldorf, Germany) is used to secure the tendons and ligaments in place.

Table 1
Specifications of Joint and muscles on index finger [14]

Joint on finger	Associated muscles and tendons	Range of joint
Distal Interphalangeal (DIP)	Terminal Extensor (TE) Flexor Digitorium Profundus (FDP)	Extension-0° Flexion-60/70°
Proximal Interphalangeal (PIP)	Central Slip (CS) Lateral Band (LB) – Radial and ulnar Flexor Digitorium Superficialis (FDS)	Extension-0° Flexion-110°
Metacarpophalangeal (MP)	Extensor Digitorium Communis (EDC) Medial Band (MB) Extensor Indices (EI) Dorsal Interossei (DI) Palmar Interossei (PI) Lumbrical (LUM)	Extension-45° Flexion-90° Ulnar deviation-30° Radial deviation-20°

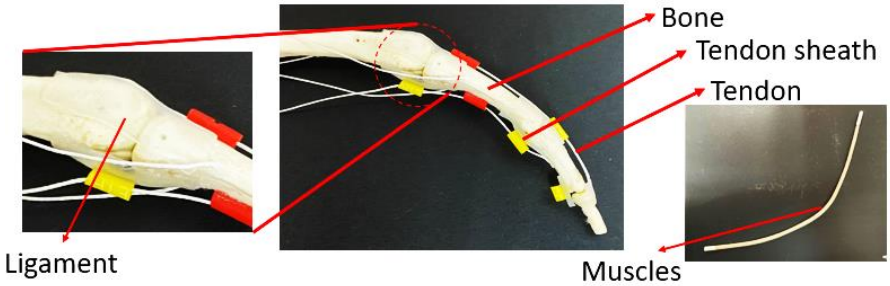

Fig. 2. Components of the index finger

In our initial work [14], the ROM of the fingers are evaluated using a tracker software and compared to meet the requirements of the ROM. The thumb is fabricated using the similar method for the ligaments and tendons. In the case for the thumb, muscles that contribute towards the flexion and extension of the thumb are preserved. The muscles involved include the Extensor Pollicis Longus (EPL), Extensor Pollicis Brevis (EPB), and the FPL.

2.2 Pinching End Effector Structure

Starting from the base, the UR5 Mounting was designed based on the given specifications of the UR5 (Figure 3). The design was modified to allow a 50 cm PVC pipe to be inserted at the centre which will represent the radial and ulna bones of the human hand. This design is 3D printed using Polylactic Acid (PLA) at 20% filling. On the other end of the HRPEE, the finger holder will comprise of two circular structures with 4 holes for the 4 mm head screws to hold the finger in place, as shown in Figure 4. Based on [15], the average length between the knuckles of the index finger and thumb for a 161 cm height male is 5cm. Thus, the design for the finger holders is as shown in the figure below.

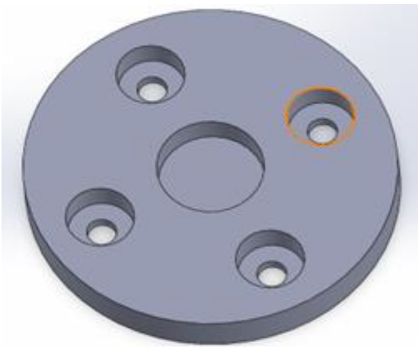

Fig. 3. Mounting base for HRPEE

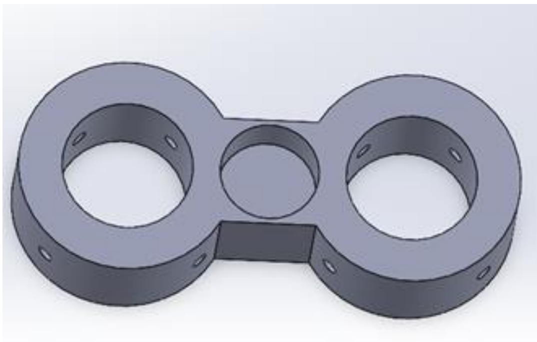

Fig. 4. Finger holder for HRPEE

The entire structure is then assembled, and a 50 cm PVC pipe is used to connect the finger holder with the UR5 mounting. The PVC pipe represents the radial and ulna bones of the human arm where the finger muscles originated.

3. Control Circuit and Pneumatic System Design
3.1 Electrical Circuit for Pinching Function

Starting from the electrical circuit, the main controller of the system is an Arduino MEGA 2560. Since each muscle has a different contraction force for each function, the amount of pressurised air in each TMM would differ. Hence, from the PWM pinout of the Arduino MEGA, it is then connected to a PWM to Voltage converter. The output is then connected to the Pneumatic Valve EVT 500 T30R

Series. This connection applies to every individual muscle; thus, there are 6 PWM to Voltage converter for all 6 muscles. The MEVT pneumatic valve requires 24V power supply while the PWM to Voltage converter requires 12V to 30V. A 24V power supply is then generated by using the WX-DC2416 power supply module which is directly connected to 240VAC power supply, as shown in Figure 5.

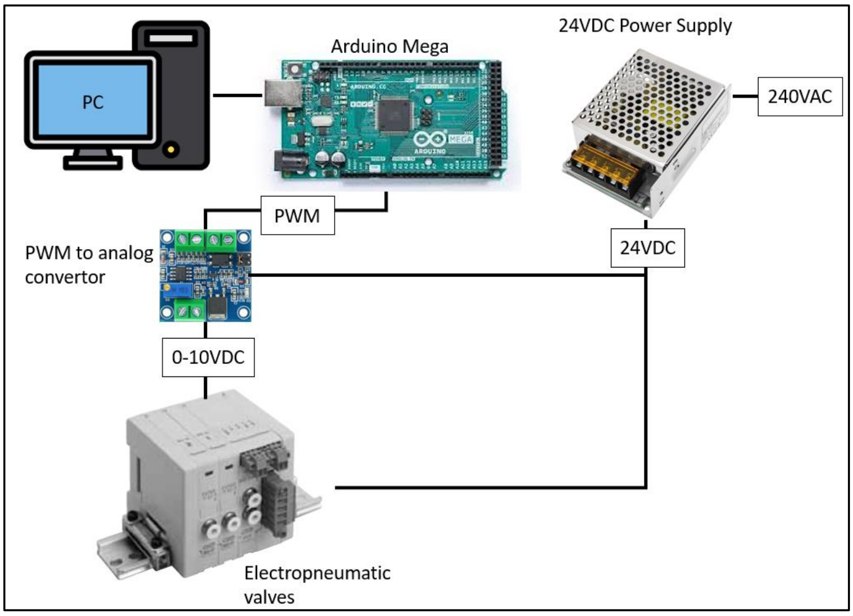

Fig. 5. Electrical circuit to generate control input for HRPEE

Each output of the PWM is connected to one of the 8 available pneumatic valves. A size 4 pneumatic tube and a size 4 fitting is used to connect the pneumatic valve to the open end of the muscles. All PWM converters are calibrated to achieve a 6V output signal to the pneumatic valve which grants a control pressure of 0.3. This eases the tuning process when controlling the amount of pressurised air in the muscles. Figure 6 shows the valve input signal.

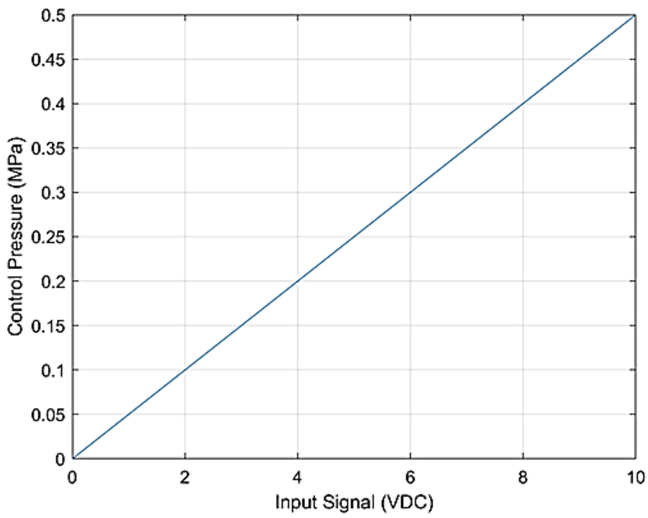

Fig. 6. Valve input signal

3.2 Universal Robot (UR5) Integration

To validate the pinching function of the HRPEE, the UR5 is used to mimic the movement of the shoulder, elbow, and wrist of the human hand in a pick and place function. This program of the UR5 robot is done through the polyscope user interface developed by Universal Robots which is directly programmed to the UR5. The digital output of the UR5 is connected to the Arduino MEGA to trigger the fingers flexion, extension, and rest function. Two adjustable buck converters are used as a step-down transformer from the 24V of the UR5's digital output to the 5V Arduino input. The position of the pick and place functions are fixed on a table. By identifying the waypoint of the object's position, the UR5 can be programmed to attend to the waypoint. The digital outputs trigger the 3 types of motion that cause the HRPEE to open (extend), close (flex) and rest.

The pick and place program for the UR5 starts with the HRPEE at a start position. Next, the HRPEE moves to the ready pick position which is vertically above the pick position. Then 24 V output is used to control extension of muscles of the HRPEE. The UR5 then moves down to pick the object at the pick position set and 24 V is exerted to flex the HRPEE muscles for picking the object. The UR5 is then programmed to bring the pinched object to a place position for release. The detailed flow of the UR5-HRPEE program is shown in Figure 7.

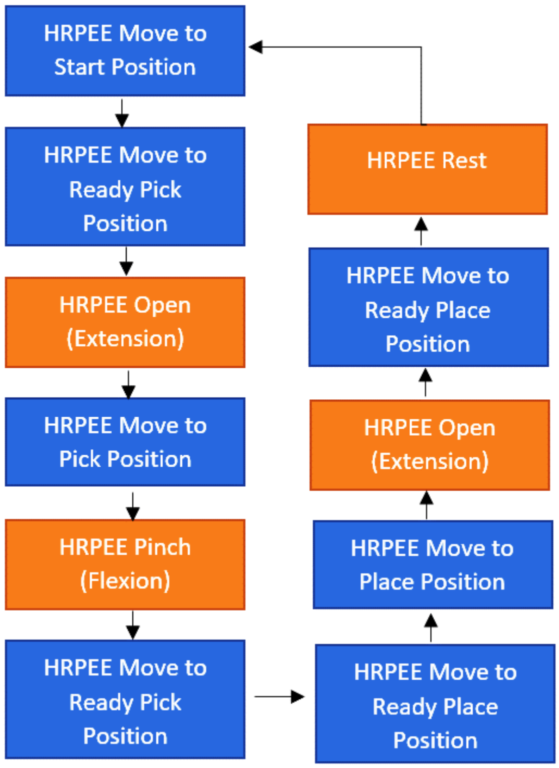

Fig. 7. Flowchart of pick and place operation

3.3 MATLAB-ARDUINO Integration

Using Simulink, the code for the finger's functions can be generated, built and sent to the Arduino. The Simulink block diagram displays the 6 analog outputs of the Arduino and displays the range of pressurised air in each finger muscle. A subsystem is included to the FDS muscle to naturalize the finger motion and allow the pinching function to occur. This subsystem would cause the flexion of the FDS muscle to occur slower by increasing its output per step time. The tuning of the pressurized air is executed according to the length of the muscle. A longer muscle would have a higher contraction force than a shorter muscle. A manual override is included in the Simulink block diagram using a manual switch. This is a safety feature added to prevent further damage to the HRPEE. Similarly, the rest motion can also be triggered in case of emergencies as its function would override the flexion and extension functions. The blocks highlighted in red are the tuning blocks which indicates the amount of pressurized air in each muscle. The teaching pendant of the UR5 is then used to start the pick and place functions which includes the triggering of the muscles. The overall Simulink program for the HRPEE is shown in Figure 8.

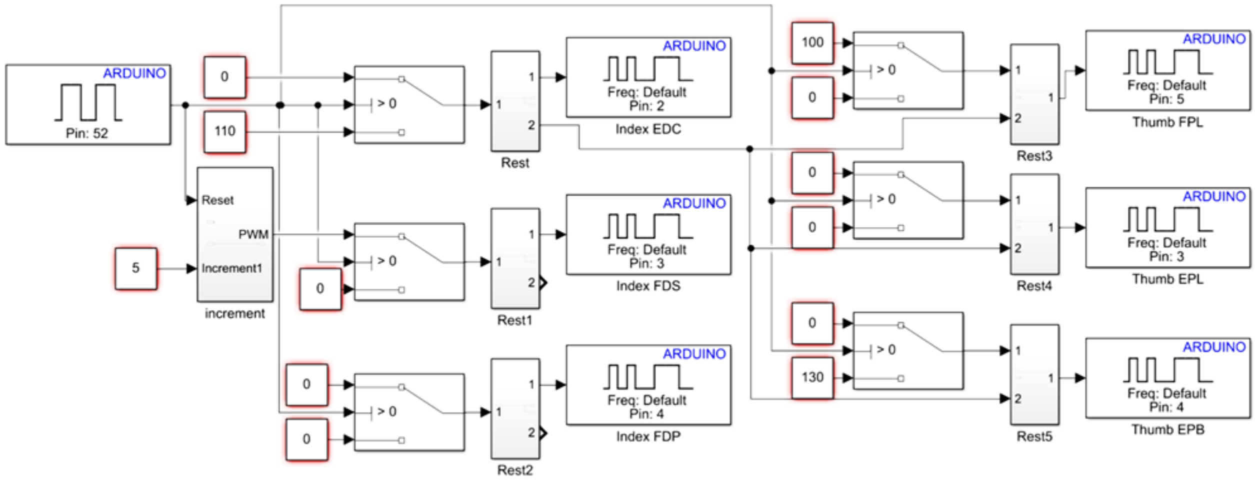

Fig. 8. Simulink program for muscle control

4. Results

This section presents the outcome of the HRPEE design for the flexion-extension function and its integrated system with the UR5 for the pick and place function.

4.1 Pinching Function of HRPEE

In Figure 9, the HRPEE can achieve the flexion motion with an input range of 125 at the FDS and 100 at the FPL. This range can be further increased up to the maximum of 153 for higher flexion force.

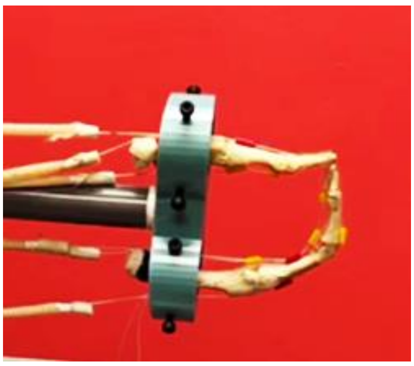

Fig. 9. Pinching of HRPEE

A few objects were then placed to determine the HRPEE's ability to pinch objects of various weights and surface structure. The sponge was the easiest of the 3 objects as it is light and the spongy texture which allowed the HRPEE an easier grip. The toughest of the 3 items was the pen as the circular design requires precise pinching point to be able to pick the object. Details of the objects are shown in Table 2 and the capability of the HRPEE to pick up the objects are as shown in Figure 10.

Table 2
Details of objects

Object	Weight (grams)	Surface
Pen	50	Smooth and slippery
Blade	72	Rough
Sponge	3	Rough

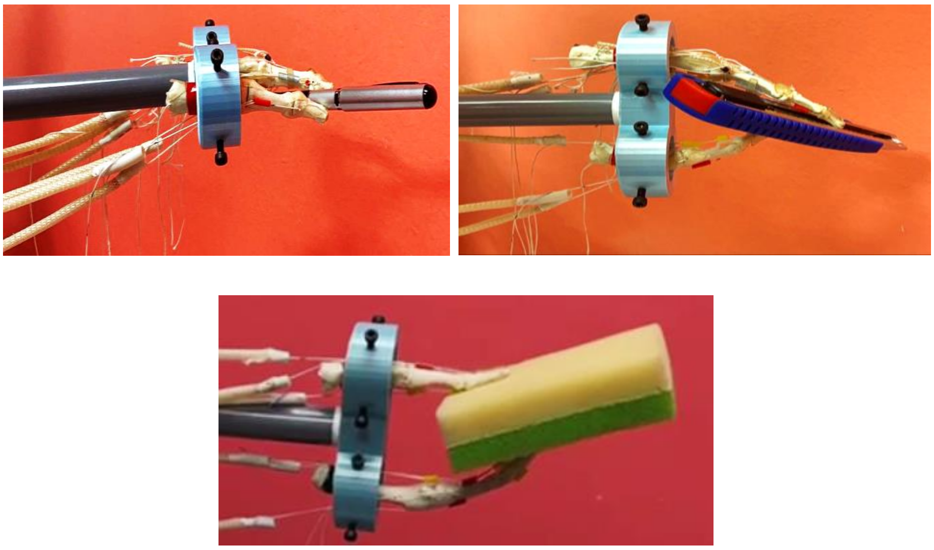

Fig. 10. HRPEE pinching various objects

4.2 Pick and Place Function of HRPEE

A pick and place experiment are conducted to test the effectiveness of the developed HRPEE. The UR5 is programmed to move an object from a pick position to a place position. The experiment is conducted using the HRPEE and the ROBOTIQ Gripper with part number 2F-85. The programme is run ten times and the success picks are evaluated. Results from the experiment are shown as Figure 11.

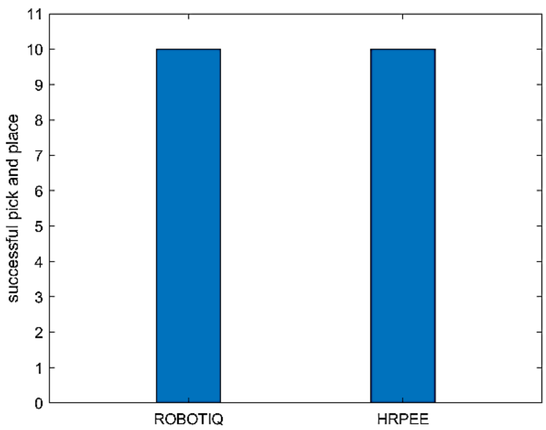

Fig. 11. Evaluation results for pick and place experiment

From Figure 11, it can be observed that both grippers have a 100% success rate in the pick and place experiment. This shows that the HRPEE can perform pick and place operation similarly to a rigid gripper. This proves that the proposed gripper is able to maintain pick and place success rate while being fabricated by soft materials. The pick and place functions of HRPEE can be seen in Figure 12.

Fig. 12. Pick and place function of HRPEE

The finger extension and flexion can be tuned according to the weight of the object and size of the object. A larger object would require a wider extension of the fingers while a heavier object would require more muscle contraction on specific muscles. Figure 13 shows a close-up view of the HRPEE's flexion and extension during the Pick and Place Function.

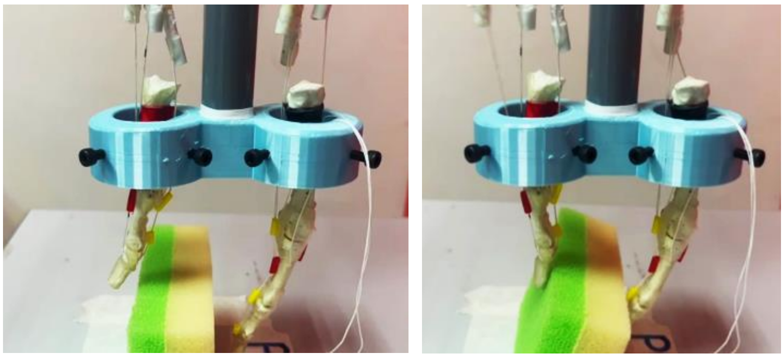

Fig. 13. HRPEE pinching for pick and place function

5. Conclusions

In this paper, the development of the HRPEE using thin McKibben muscles integrated with the UR5 is presented. One of the significant key findings in this study is the ability of the soft robotic gripper to pick various objects. The HRPEE is observed to maintain pick and place performance and can be programmed directly into the UR5 similar to the rigid ROBOTIQ gripper. Since the proposed gripper is made from soft materials, it can reduce hazardous operations for industrial pick and place applications. Moreover, the HRPEE's design effectively isolates the electrical components within the control unit and the end effector, eliminating the need for potentially vulnerable waterproofing elements on the end effector, such as O-rings and sealants, thereby enhancing the system reliability and durability in underwater environments. Due to this advantage, it would be interesting to extend the capabilities of the HRPEE to integrate with a remotely operated vehicle (ROV), where the soft gripping mechanism would be ideal for tasks requiring precision and care in underwater environments such as conservation of giant clams.

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