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PINCHING FUNCTION OF HUMAN LIKE ROBOTIC HAND USING MCKIBBEN MUSCLES

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ABSTRACT

The function of human hands to form multiple gestures is unique which requires perfect coordination between its anatomical parts, bone, ligaments and muscles. The current available robotic hands simplified the hand's function which limits the number of DOF and mainly controlled using DC motor. In this article, index and thumb fingers of Human-like Robotics Hand (HR-Hand) is proposed for experimental study. The hand design is intended to closely replicate the human finger anatomy in terms of bones, ligaments, muscles, tendon and pulley system. Thin multifilament McKibben actuators administrated to replicate the muscles for the hand actuation in the experimental procedure with up to 300 kPa pneumatic pressure. The total numbers of extrinsic muscles according to the anatomy of these fingers are 7 muscles. The fabricated finger motion is validated by experimental analysis for pinching gesture. Three objects with different sizes and weight are used for the pinching gesture experiment and force required are recorded. Using the developed HR-Hand, one can better understand the human fingers pinching function and may use it for training and for modelling the human fingers and proposing rehabilitation devices.

Keywords: Human Robotic Hand, McKibben Actuator, Pinching Gesture, Biologically-Inspired Robot, Soft Material Robotics

1.0 INTRODUCTION

The human hand has ultimate dexterity and flexibility as it is very vital in our daily life tasks such as driving, wearing clothes and even playing musical instruments. The main reason behind achieving these dexterous motions of the hand is the biomechanics of the hand and the muscle associated with it [1]. These dexterous tasks of the hand are made possible because of the intrinsic and extrinsic muscles as they contract and extend. Currently, research on developing robotic hands are vigorously carried out where most of the available robotic hands are said to be task-based hands as they are developed to perform certain task [2]. These tasks based robotic hands are suitable to perform repeating tasks as factory automation which traditionally use operators manually doing repeated task. These robotic hands lack dexterity and have lower degrees of freedom compared to the actual human hand. The KITECH Hand is an example of a task based robotic hand. The 4 fingered robotic hand uses servo motors to actuate the flexion and extension movement [9 to 3].

The hand also has a rolling motion which allows the fingers to rotate which is non-existent in real human hands. The design is compact and lightweight which does mimic the human hand and showed high level of dexterity. However, the absence of abduction and adduction movement prevents a higher level of dexterity where the hand is not able to adjust gap length between fingers and may restrict poses for some human tasks such as typing. The absence of the little finger also brings differences compared to the real human hand. Anthropomorphic hand is a type of robotic hand designed to mimic the real human hand, yet it is not an easy task to closely mimic the human hand due to some limitations of copying the dynamics, degree of freedom and even the weight of the human hand [10 to 4, 11 to 5].

The monolithic thumb is a prosthetic hand design where it addresses the significant role of flexion/extension and abduction/adduction movement and aims to build a lightweight hand by reducing the number of actuators [3 to 6]. The reduced number of motor allows for a lighter weight hand but as the structure design of the hand uses hinge joints and the shape of the hand as stoppers, the range of motion (ROM) is different as the human hand as the ROM of the human hand depends on the human bone structure. Zhu Xu et al. [4 to 7] developed a highly biomimetic anthropomorphic hand by first identifying biomechanical information on the human hand then closely mimicking the human hand. The hand structure is made of 3D printed bones of cadaver skeleton dimensions captured using laser/MRI scanner. Ligaments are replaced with silicone rubber and servo with elastic pulley system are used for actuation. Extensive results have been presented on anatomical study of the extensor mechanism and the ability of the hand to play musical instruments showing high dexterity of the robotic hand [5 to 8]. A new challenge is not only to mimic the dexterity of the finger by design but also to mimic other parts including the actuation to follow the biomechanics of the human hand [14 to 9].

McKibben actuators which has passive and natural compliance is now widely used in the field of robotics. A soft manipulator using McKibben muscle allow for smooth snake-like motions that perform pick and place [15 to 10]. The six-legged Giacometti hexapod also uses the McKibben muscle to create gait motion for movement of the robot [16 to 11]. These actuators have become an area of interest as they have high matching analogy with human skeletal muscles. The actuators are built of silicon rubber tube from the inside wrapped with braided fabric material which result in the contraction as it is pressurized. The McKibben has the advantage of being used to replicate the biological muscles of the real human muscles as it falls under pneumatic artificial muscle category [6 to 12 , 12 to 13].

The Index Finger of Human-like Robotic Hand (HR Hand) developed by Faudzi *et. al* mimics the human hand closely in terms of bone structure, ligaments, tendons, and muscles [7 to 14]. The bone structure of the human hand is mimicked by using upper limb model from 3B

Scientific with part number A45. Hyperelastic materials from soft McKibben muscle silicon is used to replace human ligaments. Silicone thickness of 1 mm was used as to attain similar stiffness equivalent to human ligaments [7]. The intrinsic muscles were replaced by using 1.3 mm soft McKibben muscles tied to Dyneema as having a small diameter, this allows the muscles to be inserted at the exact insertion point of the muscle. Extrinsic muscles are replaced by using 4.0 mm McKibben muscles and sealed with 3D printed caps. As the pinching motion not only desires the index finger but also requires actuation of the thumb. This study focuses on the additional thumb following the design of Faudzi *et. al* to allow for pinching motion and fabricate the HR-Hand index and thumb actuators using McKibben muscles [7, 13 to 15]. Experiment is carried out to study and analyze angle of motion of each finger when McKibben muscle actuated below 300 kPa and muscle and force actuation for selected pinching gestures.

1.1 PINCHING ANALYSIS

The pinching motion requires a certain flexion, extension, adduction, and abduction of the finger joints. To propose an experimental set up, every joint of the index finger must be flexed a certain angle degree while the same goes to the thumb finger where a certain degree of flexion is required in addition to some abduction motion performed at the CMC joint, as shown in Figure 1.

Figure 1 Pinching Function of a Simulated Human Hand

For the fabrication process, the muscles, tendon and bones follow the HR hand index finger by [7] and the same fabrication methods are used in this work. This fabrication process employs 4.0mm outer diameter McKibben muscles which are used to replicate extrinsic muscles while the intrinsic muscles uses the 1.3mm outer diameter McKibben muscles. The muscle length differs for each muscle where the selection is based on required contraction with 18% contraction ratio as stated in Equation 1.

$$\text{Muscle length (L)} = \frac{required\ contraction * 100\%}{18\%} \quad (1)$$

The bones are mimicked using upper limb model from 3B scientific with part number A45 which is already available. It involves carpal bones and phalanges. The bone structure is

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made from natural cast and molded from an actual specimen of a 160 cm male adult. The length of bones used are as in Table 1.

Table 1 Bones length

Finger	Bone Name	Length (mm)
Index Finger	Distal	16
	Middle	24
	Proximal	38
	Metacarpal	70
Thumb	Distal	24
	Proximal	31
	Metacarpal	48

All ligaments in this work were mimicked by using hyperelastic materials that we extract from the McKibben soft Muscles. The most suitable thickness to attain a similar stiffness to that of human hand is 1 mm. Figure 2 demonstrates the structure of ligaments of both thumb and index finger joints which were created between proximal phalanx, middle and distal phalanx. Loctite 401TM (Düsseldorf, Germany) glue is used to paste the silicon ligaments on the bones. As the silicon can take after the form of the bone, procedure of settling is simple. We create the ligaments after the real joint structure of the human beings.

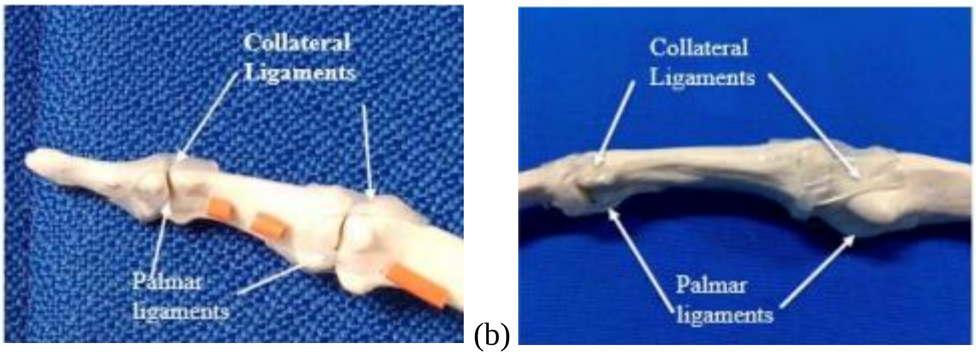
(a) (b)


Figure 2: (a) ligaments of thumb, (b) ligaments of index finger

The tendon sheaths anatomy is according to [8 to 16] in term of the insertion point on the phalanges. The material used for the tendons of all extrinsic muscle is Dyneema DB-8HE with diameter of 0.53 mm. The Dyneema is attached by either drilling a hole on the bone or pasting using Loctite 401 glue. For the pulley system, 3.0 mm polyethylene tube is used to fabricate the synovial sheathes which surround and enclose these tendons.

The HR Hand is tested on pinching 3 objects with different diameter, length and weight. These objects are a 15 g cutter, 100 g wood rod and a 9 g pen. As the dimensions and weight of the object vary, for every pinching gesture, certain muscles are actuated with different input pressure value. The pressure varies based on the weight and the diameter of the object.

2.0 EXPERIMENTAL SET-UP

An experimental set up considered in this study and the overall design block diagram is shown in Figure 3. Air compressor is the main supply whose output is relatively high which requires an air regulator to control the air flow. To supply the exact predetermined pressure, a pressure sensor is always applied to read the value of the pressurized air with the maximum amount of 300 kPa. The varying of air pressured received by the actuator is being controlled by the analogue pneumatic valve. Electro-pneumatic regulator (EVT500 series) is used in this design. To turn on the valves, a 24 DCV supply is required. The pressure is controlled by adjusting the input signal which has the range from 0-5 VDC. The voltage is controlled by potentiometer at which the supply will be fully delivered to the actuator at 5 VDC where the supply at this voltage will be 300 kPa.

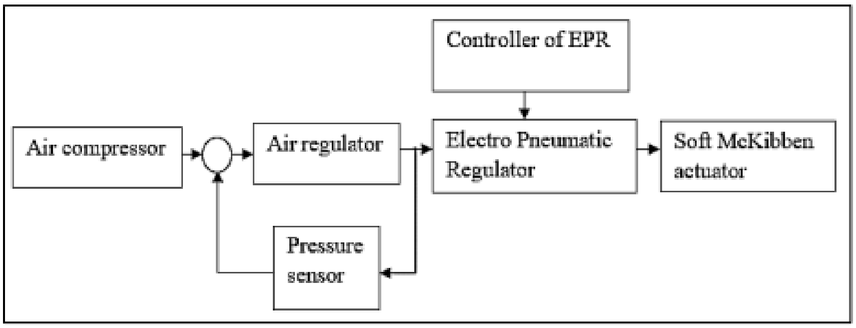


Figure 3 Block diagram of the overall system design

Figure 4 shows the system including all the aforementioned elements. Figure 4(a) shows the main air supply and Figure 4(b) is the electric circuit of the input signal along with the pneumatic valves. The output from the pneumatic valves goes directly to the McKibben muscles which drive the fingers motion. The muscles length is calculated according to the maximum contraction required for each actuation and tabulated in Table 2.

Table 2 Extrinsic muscle length based on required contraction

Finger	Muscle	Contraction (mm)	Length(mm)
Index	FDP	26	145
	FDS	21	117
	EDC	16	89
Thumb	FPL	25	139
	APL	8	45
	EPB	6	33
	EPL	10	56

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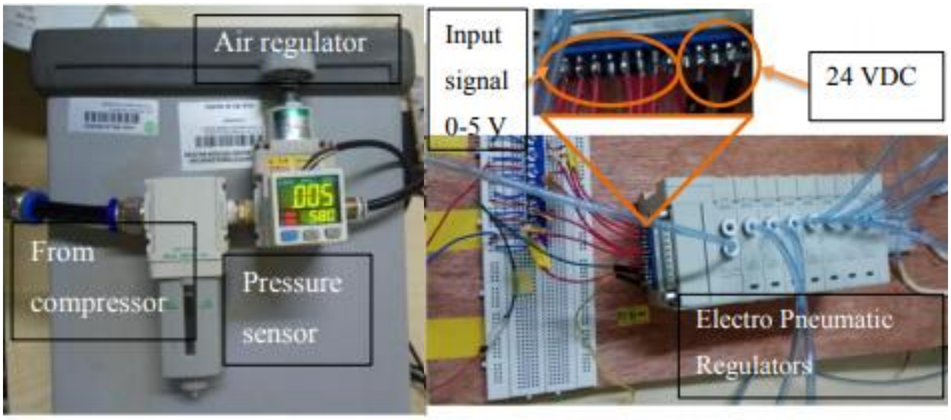
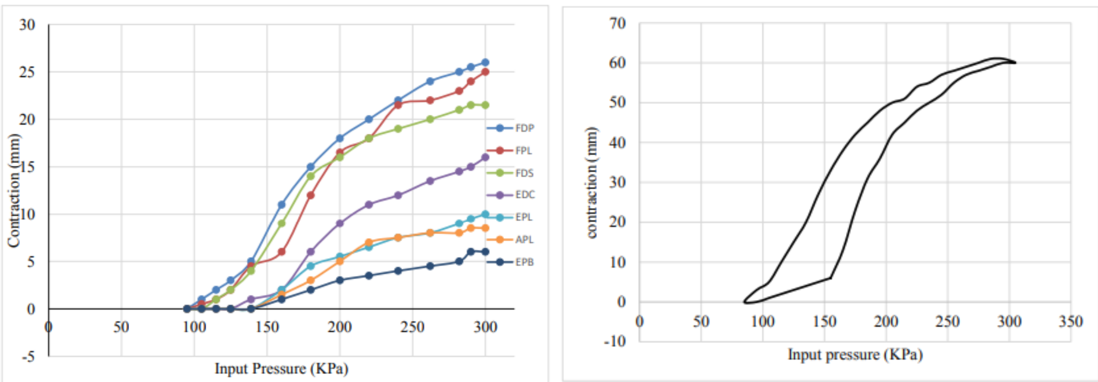


(a) (b)

Figure 4 (a) The design of the overall system. (b) Air regulator and pressure sensor and Electro pneumatic regulators with 0-5V input signal from potentiometer and 24V from power supply.

3.0 RESULTS AND DISCUSSION

The HR hand was tested by measuring the contraction of each individual muscle. Hysteresis of McKibben was also tested where a 350 mm muscle at 300 kPa was used as shown in Figure 5. Flexion Motion of Index finger and thumb were recorded and evaluated using tracker software. Force analysis was carried out on muscles of FPL and FDS of index finger. Pinching gesture of the HR Hand was tested using 3 different objects which are 15 g cutter, 100 g wood and 9 g pen and the muscles actuated, pressure used, and force is recorded.



(a) (b)

Figure 5 (a) Contraction vs input pressure of individual muscles, (b) Hysteresis of McKibben muscle

The origin of the X-Y aces is placed at the metacarpal joint which is the last movable joint of the index finger towards the wrist. The flexion motion shown in Figure 6 is due to the contraction of FDP and FDS muscles. These two muscles are being actuated in parallel up to

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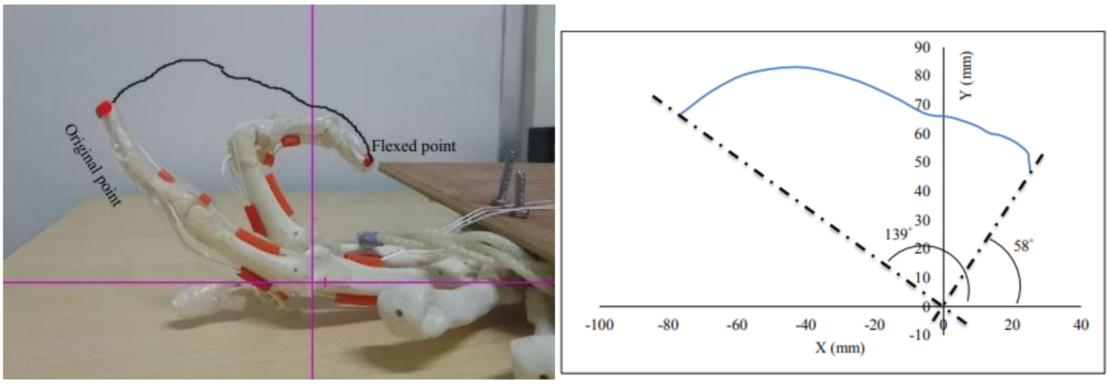
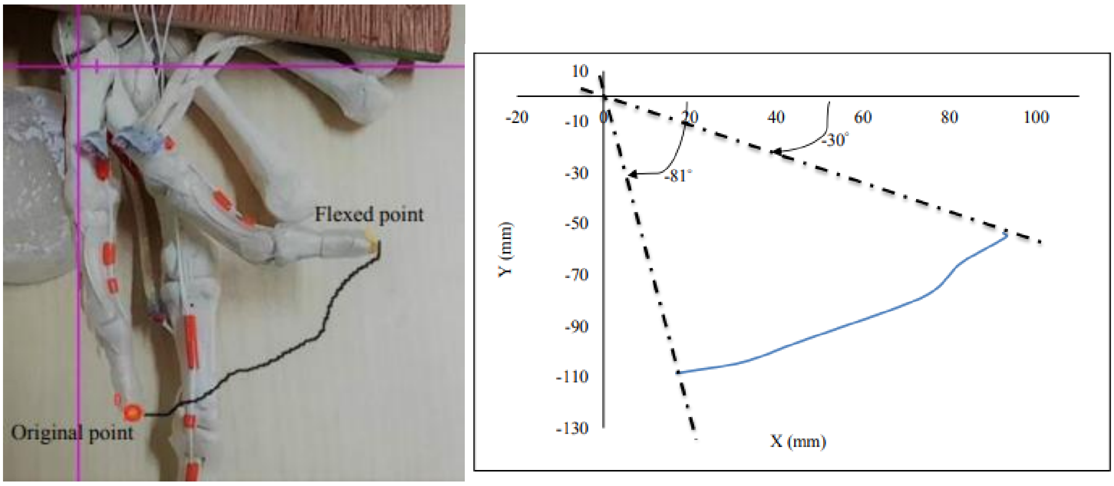
the maximum input pressure value. The location of the index finger when there is no actuation is at 139° which is considered as the resting point of the finger as shown in Figure 7. According to the predetermined specifications, the index finger can flex down to 58° which accumulates an angle of -81° as the range of flexion motion.



(a) (b)

Figure 6 (a) Flexion motion of the index finger, (b) flexion and angle range of index finger



(a) (b)

Figure 7 (a) Flexion motion of the thumb finger, (b) Flexion and angle range of thumb finger

The origin of the X-Y aces of the thumb finger is placed at the carpometacarpal (CMC) joint. At the CMC joint, different types of motion can occur. However, we are focusing on the flexion motion which is occurred due to the contraction of the FPL muscle. Figure 7(a) shows the flexion motion of the thumb finger as the FPL is being pressurized up to 300 kPa. The thumb on the other hand has a flexion range of 51° as it is resting at -81° with respect to the origin as shown in Figure 7(b). When FPL muscle is actuated, the thumb can flex up to -30°. Figure 8 shows the fingertip force curves for FPL and both FPL and FDS.

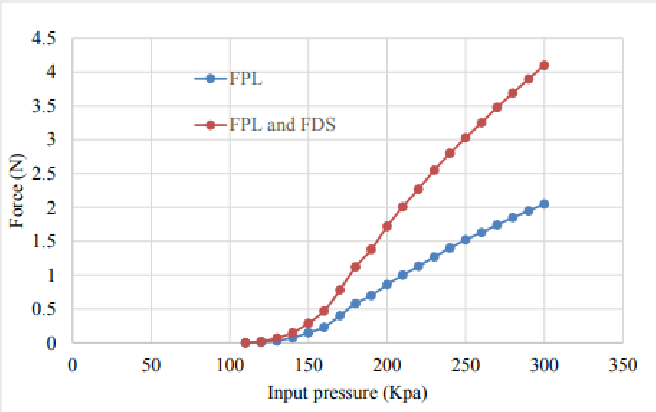


Figure 8 Fingertip force curves

The pressure and muscles actuated for each object is tabulated in Table 3. It can be observed that muscle actuation and even pressure and force for each muscle vary when pinching objects with different size and weight.

Table 3 Pinching Motion Joints Angles vs Muscles Tendon Forces

Muscle	15 g cutter		100 g wood rod		9 g pen	
	Pressure (KPa)	Force (N)	Pressure (KPa)	Force (N)	Pressure (KPa)	Force (N)
FDS	220	1.13	250	1.52	180	0.58
FPL	203	0.9	300	2.02	150	0.15
APL	155	0.18	195	0.75	155	0.2
EPL	160	0.23	160	0.23	-	-
EDC	300	2.01	300	2.02	300	2.02

4.0 CONCLUSION

A Human-like robotic hand focusing on index and thumb is presented in this work. Seven extrinsic muscles using McKibben actuators are used to drive the thumb and the index fingers considering the hysteresis effect of actuators. The length of the McKibben muscles is chosen based on the desired range of motion. The force at the fingertip of the index finger was measured with FDP actuated solely and FDP and FDS actuated together. The maximum force produced at the fingertip was from 2 N when one muscle acting alone and 4 N when two muscles are actuated together. The hand was then tested with pinching several objects where the pressure supplied to each muscle involved with the required pinching motion is recorded. From the experiment we can conclude a motion of 81° flexion for the index finger and 51° flexion for the thumb. This motion is enough to produce pinching gesture for the 3 different objects. Collected data from this study shall be used for help in proposing rehabilitation hand for future work.

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