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DESIGN AND CONTROL OF BIOMIMICRY EYE USING SOFT ACTUATOR

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ABSTRACT

The purpose of this study is to investigate and implement biomimicry of the human eye through a 3D printed robotic eye and thin McKibben actuators. The human visual system is important and integral to the survival and evolution of humanity. Thus, we look to it for inspiration in designing a robotic visual system that can be adapted into soft robotic systems. This study proposes an improved method in the design of a 3D printed robotic eye which has two Degrees of freedom. The solution is based on the advantage gained through the implementation of the thin McKibben actuators, with a simpler design of the robotic eye as well as 3D printing to produce a robotic structure which can be quickly design, fabricated and deployed. The approach has several notable merits, namely a reduction in design complexity, reduction in size with 2 degrees of freedom. A comprehensive verification via experimentation was carried out to determine the effectiveness of the concept and design. From the experimentation works, it was found that the 3D printed robotic eye can be actuated via the Thin McKibben actuator with an angular movement of around 40 degrees and with 2 Degrees of Freedom. The result shows that the method shows an improvement to currently pneumatically actuated robotic eye with an increase of 33% more angular movement freedom that can be actuated with 2 Degrees of Freedom as well as small compact design. The method proposed in this paper can be implemented in other types of soft robots as well.

Keywords: *Biomimicry, Biomimetic, Soft Actuator, thin McKibben actuator*

1.0 INTRODUCTION

There are many differences between a hard robot and a soft robot. Hard robots are strong and rigid, but this also makes it less flexible, require precise movements to perform a task and are vulnerable to physical damage such as compression and blunt force [1]. However soft robots are made up of soft materials and could easily navigate through unstructured environments [2] and require less complex simpler mechanisms by exploiting the mechanical intelligence of soft materials. The thin McKibben actuator is a soft actuator that is small in size, with an inner tube diameter of 1.3mm, and yet has a good contraction ratio of around 26% at 400kPa. The paper explores the combination of the soft actuator via the thin McKibben and the hard structure of the biomimetic robotic eye via 3D printing, in order to assess the performance of the robotic eye. The biomimicry of human eyes using soft actuators is a field that has potential for further exploration with the potential of being integrated with a soft robot to produce complex robot that has a higher degree of freedom with visual feedback.

1.1 The Human Eye and Extraocular Muscles

The human eye is a sensory organ that reacts to light and pressure. It is the human organ that grants humans vision or sight, which is the ability to perceive the world through the sensory of light. It plays a very important role in the success and survival of human species, and also the main way in which humans perceive this world. As such, human culture and technology has evolved along with it in mind. The human eye itself is a complex organ, with the various sensors and nerves that process light as images are located within the eyeball, however, the eyeball itself is not capable of movement, as it is the extraocular muscles that are attached to the eyeball (with the recti attaching posteriorly to a tendinous ring) which grants it the ability to move and position itself as required. The direction of the eye is controlled via the extraocular muscles through the four rectus muscles which are the superior, medial, inferior and lateral muscles, and also through two oblique muscles, which are the superior and inferior oblique muscles [3]. These muscles are attached to a tendinous ring surrounding the eye. The medial rectus controls the horizontal movement of the eye (medially and laterally), while the superior and inferior rectus are responsible for the elevation and depression of the eye [4]. The two oblique muscles helps to pull the eye laterally as well as moving it up and down. The muscles work antagonistically and synergistically to produce complex and precise movements [5].

1.2 Biomimicry

Biomimicry or biomimetic is the study of understanding of the design principles that govern the biological systems and extract the components of the biological design into an engineering or research design [6] [7]. It’s a field of study that has many thriving opportunities due to the countless biological systems and design that are available to us. In this project, the concept of biomimicry is applied to the human eye movements and the mechanisms behind it in order to build a working 3D printed robotic eye that is actuated by the thin McKibben actuator.

1.3 Soft Robotics

Soft robots are robots which are built out of compliant materials and exhibit large strains in its normal operation [8]. As they are soft and highly deformable, thus they can make use of the material’s “mechanical intelligence “which they are made from to easily perform tasks that would otherwise require complex control systems [2][9]. Manipulating their characteristics and even their non-linear response, they can accomplish difficult tasks such as grasping a fragile, irregular object by manipulating its ability to distribute pressure evenly over its structure [9], surviving from being run over by a car and can still operate freely without issues [1], simplifying tasks such as grasping objects [10], navigating complex unpredictable environments [2] and so on. Soft robotics is often inspired from the biological mechanical designs of animals, where robotic engineers study on these living organisms developed various structures and mechanics to cope, adapt and survive in their environment and translate it into robot models[10]. This shows a very close relationship between biomimicry of living organism and soft robotics.

Among the notable advantages of soft robots compared to traditional hard robots, is the ability of the soft robot to resist certain type of damages that a hard robot will not be able to endure. Hard robots are vulnerable towards certain damage such as impact and compression while soft robotics and soft actuators are resistant towards tension, compression, tensile strain, compressive strain, impact severe bending, twisting and wadding [1]. The paper written by Ramses et al [1] provides a detailed break down and explanation on this, by detailing and experimenting on 3 types of soft robots, which are the legs of quadrupeds and starfish and also a 5cm piece of soft tentacle. The article then discussed their findings in 4 sections, one for Resistance to Tensile Strain, Resistance to Compressive Strain, Resistance to Transient Pressure (impacts) and also Resistance to Severe Bending, Twisting and Wadding. In each of these sections, the findings of their result were discussed and summarized while also introducing concepts and ways that the soft actuators and soft robot design could be improved to help the robot increase its performance in terms of resistance to physical damage. The article ends by concluding their findings that soft robots are indeed capable of withstanding mechanical damage that would have damaged their hard robot counterpart of similar weight and size.

1.5 The Thin McKibben actuator

First introduced by Takaoka et.al [11], with the aim to design artificial muscle with high redundancy and flexibility. The thin McKibben is made out a rubber tube and knitted fibres covering the rubber tube. One side of the actuator is sealed using an end plug, and the other side has an air supplying tube. The actuator functions through the input of air pressure through the air supplying tube, and this causes the actuator to expand in a radial direction and contracts in an axial direction. This produces a contraction force, which acts as the output of the actuator. There are many advantages of this actuator, among which is in the size aspects of the actuator which could reach the size of as small as 1.3mm (inner-tubing outer diameter) [12]. The actuator could also be bundled up together, producing a bundle of artificial muscles made from thin McKibben actuator, with improved force generation from the muscles that are bundled together [13], which is hard to be done with other types of pneumatic artificial muscles, primarily due to their size.

Furthermore, a paper by Toshiyuki et. al [14] which proposes the usage of thin McKibben actuators to mimic an octopus arm structure, by bundling the McKibben actuators in axial, radial and oblique directions to form an octopus-arm-like structure, that has high flexibility and capable of producing motions like contracting and bending with 4 degrees of freedom. This shows that through different manipulation and bundling of the thin McKibben actuator, different structures can be produced along with new degrees of freedoms, greater flexibility and better strength. The paper by Faudzi et. al [15] which implemented the thin McKibben actuator into a robot structure, proves that potential of the thin McKibben actuator which can be used to produce complex robot motions while being very lightweight. Moreover, the work by Hazwan et. al [16] explores the implementation of the thin McKibben actuators through the pinching motion of a humanoid robotic hand and conducting an analysis of the pinching motion on several different objects of different sizes and weight.

In the paper which was also written by Faudzi et. al [12] in which the thin McKibben is used to actuate a soft manipulator that is inspired by a snake body structure, describes how the different positioning of the thin McKibben actuator on a simple piece of a flexible thin plate can produce complex bending motions. The paper highlights the potential of the thin McKibben actuator to be used as a small, simple but robust actuator that can be fit in small applications to produce complex movement and introduce different degrees of freedom and bending motion to a simple flexible structure by manipulating the positioning and actuation of the thin McKibben actuator within the flexible structure. The paper also provides very important information non the 1.3mm thin McKibben actuator, highlighting its contraction ratio (%) and also its pulling force (N) based on the input pressure given to the McKibben actuator.

1.6 Soft Acuators in Robotic Eye

The paper is written by Wang et.al [17], is closely related to this project. The paper proposed a design of a robotic eye using 6 pneumatic artificial muscles to facilitate its movement and has 3 degrees of freedom. It also offers a kinematic and design analysis and also the computer simulation of the proposed eye model. As the eye is very complex, it lay down the ground rules that are involved in their robotic eye design. However, the paper does not include an analysis of a working prototype of the robotic eye, and instead offer some simulation data analysis of the model

Another paper, which was written by Lenz et.al [18], titled "Cerebellar-Inspired Adaptive Control of a Robot Eye Actuated by Pneumatic Artificial Muscles" author discussed on the implementation of a cerebellar control in a robotic through the use of a pneumatically actuated robot, its challenges and how the authors proposed to overcome those challenges. The authors proposed the implementation of a linear adaptive control scheme based on a model of cerebellar function in a robot eye to stabilize a visual image, under disturbances from a moving platform. The authors explain in-depth on the computational model of the control system, in particular on how it is designed, distributed and also the implementation of a different model component of the system. It also explained how the robotic eyes were designed and controlled pneumatically. However, the robotic eye has only 2 degrees of freedom and from the images given, the feedback sensors and also the design of the robotic eye make the robotic eye very large and bulky.

An interesting work on the robotic eye movement using soft actuator written by Li et al [19], uses three linear dielectric elastomer actuators and by controlling voltages applied to the three actuators, the soft actuators were able to produce horizontal, vertical, and circular motions. The eyeball is attached to the top of the soft actuators and their movements produce motions of the eyeball, mimicking real eyeball movement. While the system is not pneumatically actuated, the analysis on the robot and its design was very interesting and could be applied to the project.

2.0 ROBOTIC EYE DESIGN AND CONTROL SYSTEM

2.1 3D printed eye and McKibben Actuation

The fabrication of the 3D printed robotic eye prototype, followed by the thin McKibben actuator fabrication, actuation and integration into the 3D printed robotic eye was conducted. The study of the thin McKibben actuator and its contraction ratio based on the input pressure was conducted in parallel with the fabrication of the robotic eye via 3D printing. Experiments were then performed to test the prototype robotic eye and gauge its performance.

2.1.1 3D Printed Robotic Eye

The 3D printed robotic eye consists of 5 parts, which are the actuator ring, frontal sphere, rotational joint, rear sphere and the cradle.

Figure 1 shows the breakdown of an assembled robotic eye that has been integrated with the McKibben Actuators. The tubings were directly glued to the Actuator Ring of the robotic eye, while the thin McKibben actuator is glued to the tubing. This enables the change of the thin McKibben actuator in the event that the actuator is damaged or deemed not functional, the link between the actuator and tubing can be broken to allow the replacement of the thin McKibben actuator. The inclusion of Tack-its to the robotic eye, allows light adhesion between the parts which ensures the parts hold together during actuation.

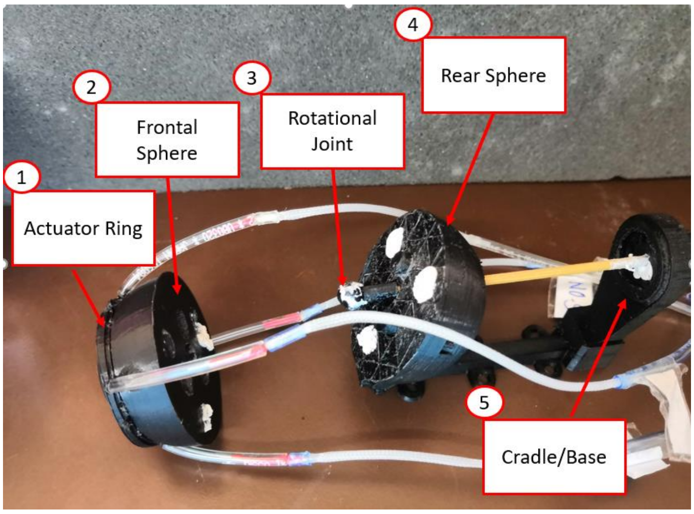

Figure 1 Breakdown of a Fully Assembled Robotic Eye

The functions of the respective robotic eye components are explained below:

2.1.1.1 Actuator Ring

The actuator ring design is inspired by soft tissue around the eyeball where the recti muscles are attached and serves as the connection point between the thin McKibben actuators are attached to the robotic eye.

2.1.1.2 Frontal Sphere

The frontal sphere is where the camera will be housed and also form half of the depression/socket to fit the ball joint. The depression/socket is important as the pulling force of the McKibben actuator against the socket and together with the ball joint, will translate into an angular motion which will turn the eye robot model.

2.1.1.3 Rotational Joint

The part acts as the centre point of the robotic eye, in which its spherical structure together with the depression in the frontal and rear sphere forms a ball-socket joint that helps to translate the pulling motion of the McKibben actuator into the angular motion of the robotic eye. It also acts as a connecting point between the spherical structures of the robotic eye to the cradle. The part will be subjected to the most force in the robotic eye structure, and was designed to be robust and durable enough to withstand the pulling force of the McKibben actuator.

2.1.1.4 Rear Sphere

The part which forms the second part of the depression/socket to fit the ball joint. It also functions to hold and contain the rotational ball joint within the spherical structure of the robotic eye. The design allow the control and limit of the angle of movement of the robotic eye.

2.1.1.5 The Cradle

The function of the cradle is to hold the McKibben actuators in place as well as to position the robotic eye.

2.1.2 Dimension and Actuation of the 3D Robotic Eye

The dimensions of the spherical structure of the 3D printed robotic eye was first determined in order to calculate the length of the McKibben actuator needed to properly actuate the robotic eye.

Figure 2 illustrates the measured diameter, d, and radius, r, of the spherical structure of the robotic eye.

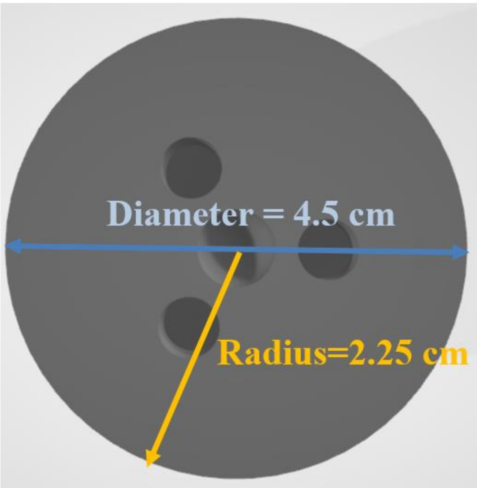

Figure 2 Diameter and Radius of the Spherical Structure of the Robotic Eye

The circumference of the circle is determined based on the radius or the spherical structure and the formula to calculate it is shown in Equation (1):

$$\textit{Circumference of the Circle}, C = 2\pi r \quad (1)$$

Next substitute the radius into equation (1) to obtain the circumference of the Spherical Structure of the Robotic Eye as shown in Equation (2) :

Circumference of the Circle, $C=2\pi r=2\pi(2.25)=14.1372cm$ (2)

The “Half Scale Angular Movement” of the eye ,which is the maximum degrees of movement for the robotic eye, from its initial centre position to its maximum far left or far right of the robotic eye was then determined. Figure 3 (i) shows the half actuation of the robotic eye from the centre to the right, while Figure 3 (ii) shows the half actuation of the robotic eye from the centre to the left. From the experiment, it was determined that the robotic eye has a Half Scale Angular Movement of 40 degrees.

The desired contraction for the thin McKibben actuator during Half Actuation, HA, was determined using the following formula shown in Equation (3):

$$HA= \text{Circumference of the Circle} * (\text{Half Scale Angular Movement})/(360°) \quad (3)$$

Substituting the values in the formula, Equation (4) was obtained:

$$HA=14.1372cm * (40°)/(360°)=1.571cm\approx 1.6cm \quad (4)$$

From the paper written by Faudzi et.al [12], a 1.3mm thin McKibben actuator has a contraction ratio of approximately a minimum of 23% contraction at 400kPa air pressure. Thus using this information, the formula to obtain the appropriate thin McKibben actuator length for half actuation, LH, is shown in Equation (5):

Length of Thin McKibben for Half Actuation , $LH=HA/0.23$ (5)

Substituting in the values, Equation (6) was obtained:

$$LH=1.6cm/0.23=6.96\ cm \approx 7\ cm \quad (6)$$

The Full Actuation, FA, which is the angular movement of the robotic eye from the one far end to the other, can be obtained by doubling that of the Half Scale Angular Movement to obtain the Full Scale Angular Movement, which is 80 degrees.

The desired contraction for the thin McKibben Actuator during Full Actuation, FA, was determined using the following formula shown in Equation (7):

$$FA= \text{Circumference of the Circle} * (\text{Full Scale Angular Movement})/(360°) \quad (7)$$

Substituting the values into the formula, Equation (8) was obtained:

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$$FA = 14.1372cm * (80°)/(360°) = 3.142cm \approx 3.2\ cm \quad (8)$$

The formula to obtain the appropriate thin McKibben actuator length for full actuation, FH, is shown in Equation (9):

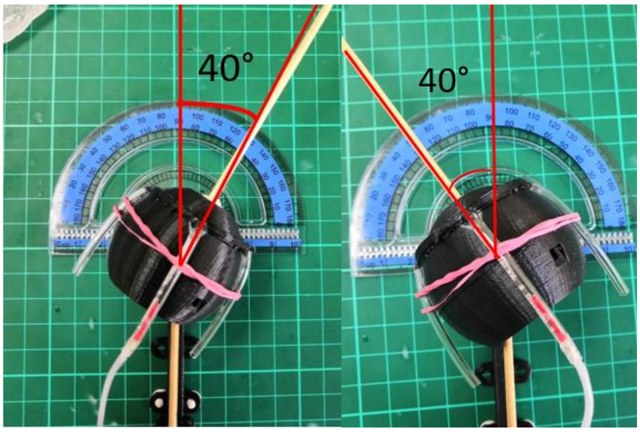
$$\text{Length of Thin McKibben for Half Actuation}, FH = FA/0.23 \quad (9)$$

Equation (10) was obtained by substituting the respective values,

$$FH = 3.2cm/0.23 = 13.913\ cm \approx 14\ cm \quad (10)$$

Thus, in summary, for the prototype to move at half actuation, a thin McKibben actuator of 7cm in length is required, and for the prototype to move at full actuation, a thin McKibben actuator of 14cm in length is needed.

For the prototype build, the thin McKibben actuator of 7cm in length will be used for the prototype robotic eye to assess the functionality of the model.



(i) (ii)

Figure 3 (i) Half Actuation from The Centre of the Robotic Eye to the Right
(ii) Half Actuation from The Centre of the Robotic Eye to the Left

2.2.1 Controller Design

The proposed controller design will control the input pressure that is supplied to the McKibben actuator and thereby control its contraction ratio. This will translate into different movements in the robotic eye. The controller will be based on an Arduino microcontroller, and connected to a computer with the serial monitor turned on. The block diagram of the control system is shown in Figure 4 below.

Figure 4 Open Loop Block Diagram of the Robotic Eye Control System

The control system for the robotic eye will be an open-loop control system in which the Arduino controller will receive the directional input to tell in which direction that the robotic eye should move. The Arduino controller together with the Darlington pair array will control the air pressure valve and activate the thin McKibben actuator necessary to actuate in the desired direction.

3.0 RESULTS AND DISCUSSION

3.1 Thin McKibben Actuator Testing

A total of 9 thin McKibben Actuators of 1.3mm size are assembled and built for this experiment. During assembly, precautions and careful application of the epoxy on the thin McKibben actuator have to be made to prevent from assembling faulty or bad actuators. The actuators were each labeled according to their assigned numbers for identification purposes as shown in Figure 5.

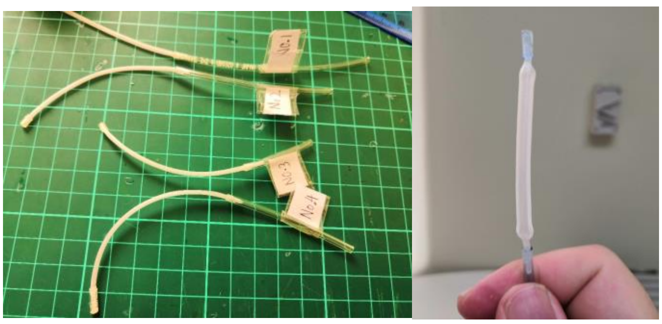


Figure 5 The Assembled and Labeled Thin McKibben Actuator and McKibben Actuator at 350kPA

The Thin McKibben Length Contraction Testing and Measurement Setup was set up as shown in Figure 6. One end of the McKibben is securely taped to a ruler and measurement of the un-actuated Thin McKibben Actuator (At 0 kPa) is measured. An important caution that must be taken during measurement of the un-actuated Thin McKibben Actuator, is that the length of McKibben actuator in which it has been exposed to the epoxy at both ends must also be measured and discounted from the total length in order to obtain the true length of the McKibben actuator.

Figure 6 Thin McKibben Length Contraction Testing and Measurement Setup

Note the slight unevenness of the McKibben that has been pointed at by the red arrow in Figure 6. Such areas must be gently pushed down so that the McKibben actuator is parallel to the ruler to enable an accurate measurement of the length of the McKibben actuator when it is actuated. The data was then gathered and tabulated into a chart, as shown in Figure 7.

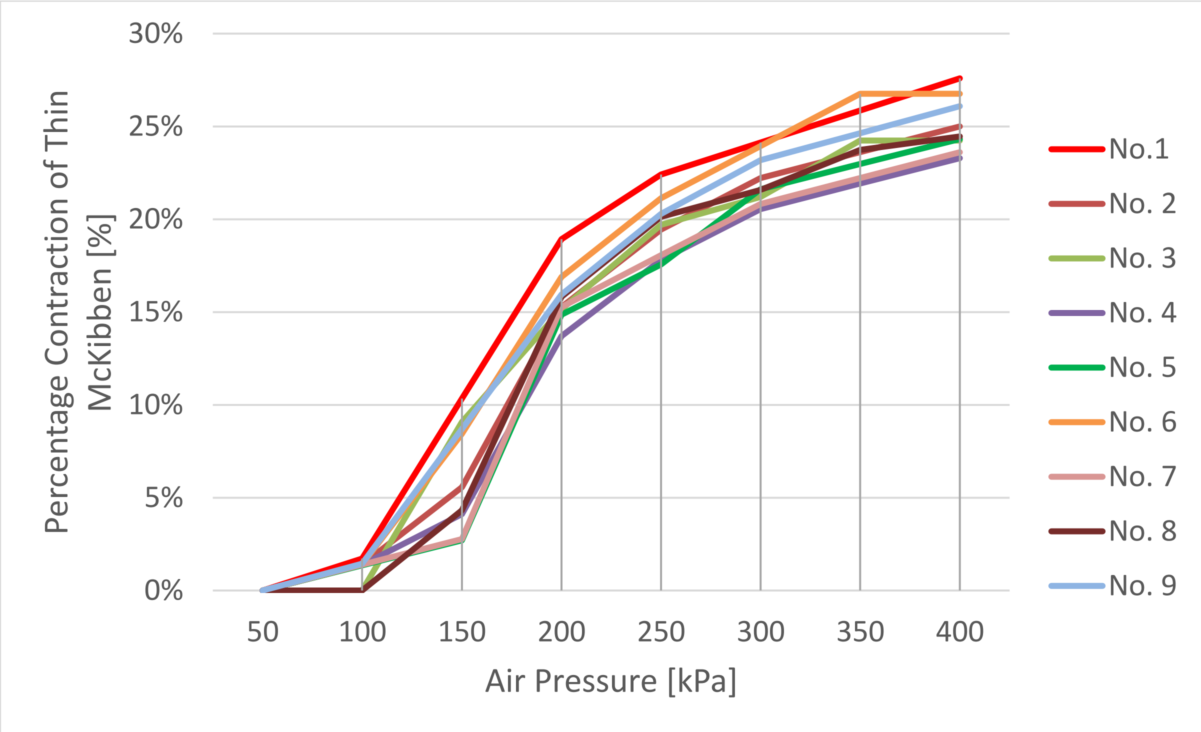


Figure 7 Graph of Percentage of Contraction of the Thin McKibben against Actuated Pressure

The graph in Figure 7, was compared directly with the work of Faudzi et.al [12] which also uses a similar 1.3mm thin McKibben actuator. The results were similar to the experimental findings where at 400kPa, the actuators are at around 23% to 27% percent contraction which is similar to the findings from the paper.

Among the 9 McKibben actuators, only 4 thin McKibben actuators was selected to be used in the prototype build. The selected McKibben actuators performance are shown in Figure 8. Actuator No1 and No5 are selected to be used in the prototype build as their true length is similar to each other and thus are suitable to be used as a pair for the prototype build. Meanwhile, actuator No7 and No9 are chosen as they not only have the same length, but also an almost similar contraction ratio. In short, No 1 and No 5 will be used as a pair of the Up and Down actuators for the robotic eye, while No 7 and No 9 will be used as the Left and Right actuators of the robotic eye.

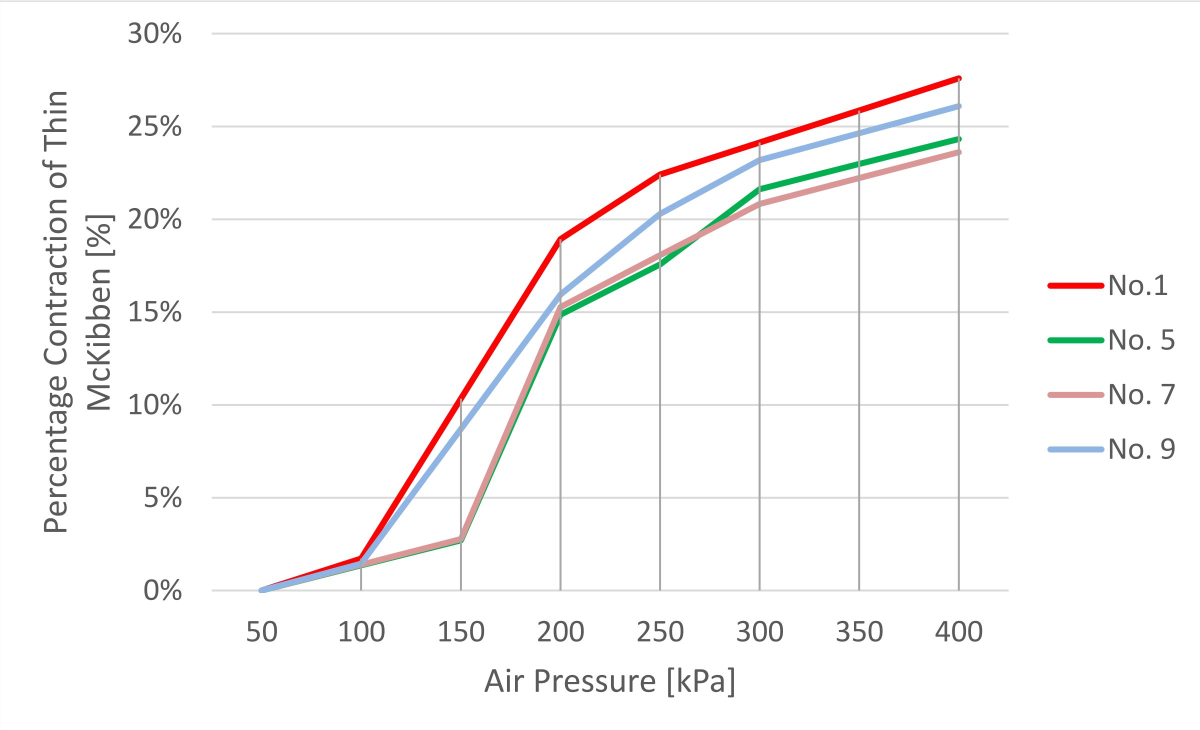


Figure 8 Graph of Percentage of Contraction of the Selected Thin McKibben Against Actuated Pressure

3.3 Printed Robotic Eye Actuation Experiment

The robotic eye then undergoes an experiment to check its functionality. Figure 9 shows the result of the experiment for the half actuation of the robotic eye. From the result, it can be seen that when actuated at 400kPa, the robotic eye is successfully actuated in the Up, Down, Left and Right direction, and has no issues with translating the pulling force from the actuator into angular movement of the robotic eye. The experiment proves that the concept of the robotic eye is feasible and suitable for further development in the future.

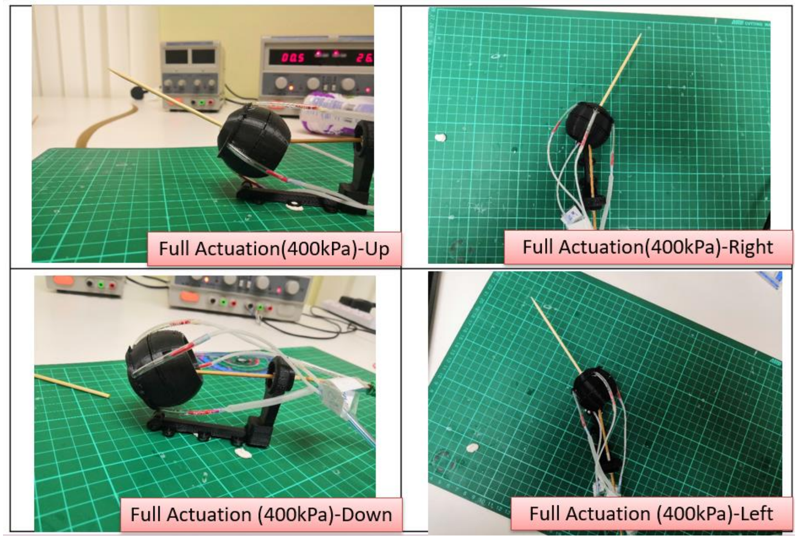


Figure 9 Robotic Eye Half Actuation Results Using 400kPA

4.0 CONCLUSIONS

The prototype 3D printed eye was successfully designed and actuated with thin McKibben actuator. It is also functional, though there will be some work needed before the final product is obtained. The experimentation results shows that the idea is feasible with further redesign needed to be made to the mechanical structure of the 3D printed eye and its cradle.

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