Bio-Inspired Hybrid Soft Actuator as a Sixth Finger

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***Abstract*—This paper provides details on the design, fabrication and experimental validation of a proposed hybrid bending actuator inspired from the biological mechanism of a shrimp and how such an actuator can be used as a "Sixth Finger", i.e a rehabilitation device for chronic stroke patients. This sixth finger is attached to the forearm of the patient where combined with the patient's paretic hand it acts as a gripper. The study also presents an analytical model and FEM to better represent and understand the actuator during its operation. Our design uses a soft elastomeric tube on which a series of rigid shells are pinned together. The performance was evaluated experimentally using force, response time and bending angle experiments. When actuated using pneumatic pressure, the biomimetic actuator was able to produce an average force output of 10 N at 135 KPa with a response time of 1037ms. Finally, the designed actuator is evaluated as an actuated human controlled sixth finger using both quantitative and qualitative factors. In the end results showed that the hybrid bending actuator can be used as a "Sixth Finger" for rehabilitative purposes.**

***Index Terms*—Hybrid actuator, bio-inspired design, pneumatic actuation, sixth-finger**

Fig. 1. The hybrid sixth finger being used to grip a water bottle an then unscrew its cap.

I. Introduction

In the field of robotics, soft robots have emerged as an answer to the need of safer robot interactions in delicate environments. Soft robots incorporate soft actuators within their structures. These soft actuators are varied in their designs and can be categorized in many ways. Most soft actuator designs are bio-inspired taking their inspiration from Octopus arms,[1,2] caterpillars,[3] or even worms.[4] They can be differentiated upon their main element of construction; some are based upon compliant elastomers.[5,6] Whereas others utilize smart materials such as hydrogels,[7–9] dielectric elastomers,[10] conducting polymers[11] and shape memory alloys.[2,12–15] The main discrepancy between soft actuators exists as a result of their actuation stimuli. A substantial number of them are have a hollow cavity that is pneumatically actuated. These pneumatic actuators can be mostly associated to Mckibben Muslces,[16] Pnue-Nets[17] or fiber reinforced actuators.[18] Mckibben Muscles consist of an elastomeric tube enclosed in a braided mesh which when pressurized allows it to expand radially and contract longitudinally. Pneu-Nets consists of multiple chambers which are responsible for the movement generation. Finally, fiber reinforced actuators consist of an elastomeric tube encased in an inextensible fiber. Some fiber reinforced bending actuators also included an inextensible layer to assist with actuation.[19] These types of actuators can also be mechanically programmed for different motions by varying the helix angles of their enclosing fibers.[20]

In addition to pneumatic actuation other actuation methods include using tension cables[1] or utilizing hydraulic and electrostatic forces.[21] More unique methods, such as combustion[22] or chemical reactions[23] can also be used as an actuation source. Finally, these actuators also differ from one another on the basis of their fabrication methods. Some utilize the more traditional method of vacuum molding[24] where as others employ 3D printing as it is faster and easier for prototyping purposes but may be limited due to readily available technology. In terms of their application, plenty of soft actuators are made for rehabilitative purposes and HRI (Human Robot Interaction) such as soft exoskeletons for hands[25] and shoulders[26], gloves for stroke patients[27–30] and soft robotic sixth finger.[31,32]

Stroke patients often suffer from hand impairment as a consequence of their neurological disorder. They become unable to use theirs hand to perform activities of daily living (ADLs).[1] However, studies have shown that through rehabilitation programs involving repetitive tasks, hand function can be improved.[2] Improved hand function also results in the improvement of the paretic upper limb.[3,4] And overall this results in the improvement of the performance of ADLs. A number of robotic devices have been with the purpose of rehabilitating stroke patients.[37,38] One such class of assistive devices as mentioned above are hand exo-skeletons[39] but

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these focus most on early recovery and not suitable for chronic patients. In such cases sixth finger[40] provides a novel approach for the improvement of hand impairment of chronic stroke patients. This approach involves wearing an extra sixth finger on the paretic forearm. The impaired hand and the sixth finger act as the two ends of a gripper. The sixth finger may be useful in cases where exoskeletons may fail. However, current iterations of the design are rigid bodied and bulky due to the presence of servo motors. As a result, they become incompatible for tasks in unpredictable environments or humans; such traditional robots are not suitable due to the high speed movements of their stiff bodies. For safer human robot interaction and intricate work spaces soft robots are more suitable as a result of deformable and conforming bodies.[41]

However, looking at all the soft robots and actuators mentioned above most of them focus their design on maximizing conformability and deformability but as a result lose some of their repeatability, controllability, precision and programmability when compared with their rigid counterparts. They also become more vulnerable. And so as this application requires a middle ground, a different type of actuator is needed known as hybrid soft actuator.[42] In this work we present a study on this hybrid actuator to evaluate it on the basis of its characteristics and its suitability as a sixth finger. The design of this pneumatic hybrid actuator was inspired from shrimp and lobsters which have rigid exoskeletons coupled with soft muscles. Similarly, the hybrid actuator combines rigid and soft elements by integrating an elastomeric tube with plastic shells pinned to each other serially. In this paper different design iterations were looked at, a couple of modeling methods were analyzed and a number of construction methods were analyzed. The goal was to give an outlook to this hybrid actuator, give an account of its advantages and shortcomings. And discuss its viability as a sixth finger.

II. Materials and Methods

A. Design and Modelling

As mentioned earlier this actuator was designed by Chen et al.[42] Its design was inspired by the working principle of the abdominal segments of shrimp and lobsters more specifically their abdominal muscles and rigid exoskeletons. It comprised of a rigid exoskeleton sitting on top of its soft body as displayed in Fig. 2. Shrimps usually swim by rapidly contracting and retracting their abdomen towards their body.[43] This motion allows them to propel themselves in water both forward and backward. Mimicking their anatomy[44], a soft inner structure was made out of silicone and fitted within a series of modular shells. Following the afore mentioned principle, the exterior rigid exoskeleton was powered by the muscles it enclosed. Once pressure was applied to the soft chamber, due to expansion, it pushed against the shells that acted as levers and as a result produced a rotary motion similar to that shown by a shrimp. Specifically, the soft tube was in the form of a series of hemi-spheres. This was due to the fact that the exterior shell flaps were positioned above the depressions between the hemi-spheres which during expansion transfers momentum from the expanding tube to the shell. It

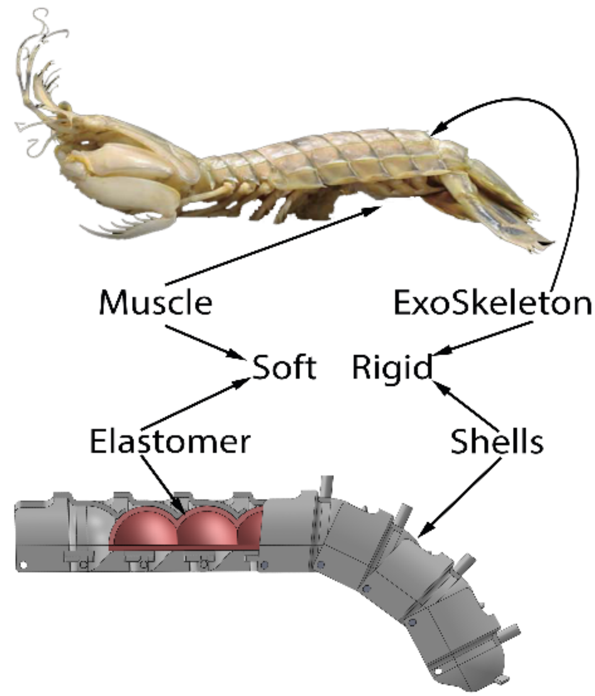

Fig. 2. The rigid shells were analogous to the exterior abdominal segments while the soft elastomeric tube played the role of the soft muscle.

should be noted that the rigid shells used while designing the hybrid actuator also had advantages as those demonstrated by a shrimp. The exterior shells on the abdomen of shrimp provides it with protection from predators and are used to propel them in water at surprisingly rapid speeds over a short interval. This provided us with a structure that was intrinsically powered by soft means but had the advantages of traditional rigid mechanisms as well.

To model the actuator for its various characteristics such as end-effector position, tip force and bend angle, it had to be separated in terms of rigid and soft components. The rigid shells were modeled as a finite link manipulator by forward kinematics to generate position data as shown by Chen et

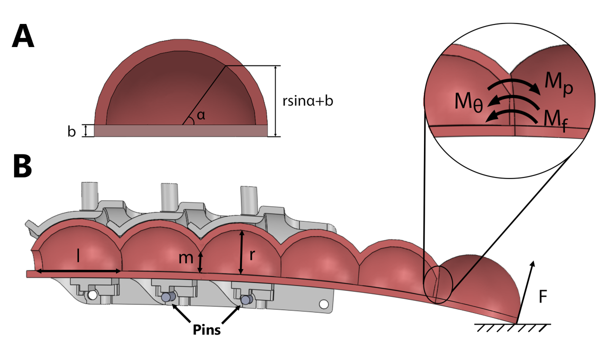

Fig. 3. (A) Cross sectional view of tube (B) The rightmost hemi-sphere of the tube was completely filled with silicone. A tip shell was designed and later pinned for ease of force measurements.

al.[42] Similarly to generate the total bend angle of the actuator, individual bend angles of the smaller segments were calculated and using traditional robotic theory and again considering the actuator as a robotic manipulator the sum of these individual angles becomes equal to the total bend angle. To calculate the bend angles of the individual segments the soft continuum was modeled as an incompressible Neo-Hookean material and a moment equilibrium was established in free space between the torque generated by the internal stretches of the elastomeric layers and torque generated by the inducting pressure as shown by Polygerinos, et al.[28] In this case due to linear model assumptions an explicit equation could not be formed. And so to generate the angles a lot of time and effort would have been required. To bypass this an alternate way was used suggested by Drotman D et al.[45] The extension Δl in the top soft layer was related to the bend angle by:

$$\theta = \arctan(\frac{\Delta l}{r}) \tag{1}$$

This solution however does not consider the frictional losses in the pinned joints and surface interactions. These overestimations were minimized through rigorous polishing of the interacting surfaces. Now for the tip force it was assumed that the actuator is held in place to generate a maximum blocked force. Again at first we established a moment equilibrium between the torque due to pressure and torque due to contact with the blocked surface Fig. 3. to generate an explicit equation for the tip or blocked force as shown by Chen et al.[42]

$$F = \frac{2P_{in}\int_{\mathbf{0}}^{\frac{\Pi}{2}}(r\sin\alpha + b)r^2\cos^2\alpha d\alpha}{l} \tag{2}$$

B. Finite Element Analysis

In reality analytical models don't capture certain aspects of the response of the actuator such as the interaction of the solid and the rigid parts while actuation. To get a realistic representation of the nonlinear response of the system, a FEM model was used. The Yeoh[46] material model with material coefficients C_1 = 0.11MPa and C_2 = 0.02MPa for Elastosil M4601 was used. ABAQUS (Simulia, Dassault Systemes) was chosen for better understanding the performance. The shells as well as the pins were modeled as ABS plastic with a mass density of 1.07 g/cm^3 and a poison's ratio of 0.3. Firstly, for validation of the proof of concept a 2 hemispherical section tube was fitted with 3 shells. One shell was fixed, while a certain pressure was applied inside the tube. As expected, the tube expanded and due to the shell restriction the only motion that was generated was the bending about the pins of the successive shells.

Next, two different shell designs were evaluated at a pressure of 80kPa. The geometrical simplifications were set as to closely match the fabricated actuator. Both the elastomeric tube and the shell was modeled using solid 8-node hexagonal linear elements with reduced integration (Abaqus element type C3D8R). Due to geometric symmetry and repeatability a simple assembly of 3 shells and an elastomeric tube of 2 hemispheres. The first shell was encastered while the rest were free to move. One design was made to fully cover all the sections of the tube by the 3D printed shells. This resulted in maximum transfer of the strain induced due to the pressure (60Kpa). One drawback of this was that due to the introduction of the flap, a component of force contributed in pushing the pins in the axial direction. This resulted in less bending angle achieved for an actuation pressure compared to no flap. On the other hand, force output when the actuator was restricted was more when compared to the one with no front flaps output force was more desired while the design process, the design with the flap was chosen.

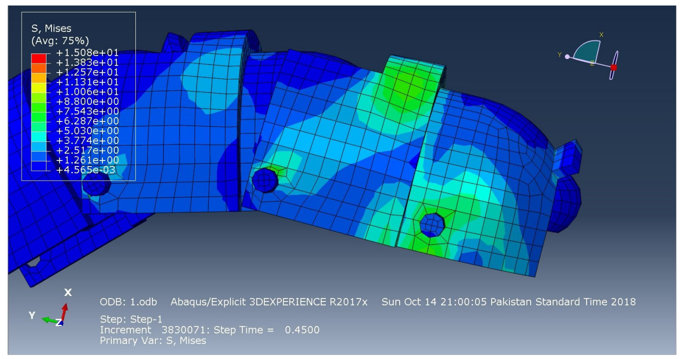

Fig. 4. The first design of the shell that was analyzed. A pressure of 60 Kpa. was applied which resulted in the shown bending after a time step of 0.45 seconds.

C. Construction

A number of materials were shortlisted for the fabrication of the soft elastomeric tube including Elastosil M4601 (Wacker Chemie AG, Germany), Dragon Skin 10 (Smooth-On Inc.), EcoFlex 00-30 (Smooth-On Inc.) and HY-625 RTV-2(Shenzhen Hong Ye Jie Technology Co., Ltd.).

The first prototype for proof of concept of the phenomenon was made using HY-625 RTV-2 due to its local availability and cheap price. The drawback of making the elastomeric tube out of HY-625 RTV-2 was the prerequisite of high pressures for actuation and instability while the curing process due to low processing time. It also presented 75% less elongation at break compared to the chosen material i.e. Elastosil M4601. EcoFlex 00-30 by Smooth-On Inc. has been used for developing many soft robots. The only factor that undermined it was its low capability of handling pressures and strains at the same dimensions compared to the chosen candidate. After testing all four, Elastosil M4601 was used as the actuation pressures and the stresses induced as a result were as desired.

The fabricated of the soft elastomeric tube consisted of a simple 2 step molding process as shown in Fig. 5. First, the top semi-spherical part of the tube was molded using a 3D printed mold and core. Uncured silicone was poured into the mold of the bottom plate and the previously cured top layer was placed on top. After curing the top and bottom layers firmly bonded together. A nozzle was inserted in the cured soft tube and the opening was sealed using a cable and silicone to prevent leakage. On the opposite end the last hemi-sphere was completely filled with silicone in order to create a rigid and non-compressible point of contact for the

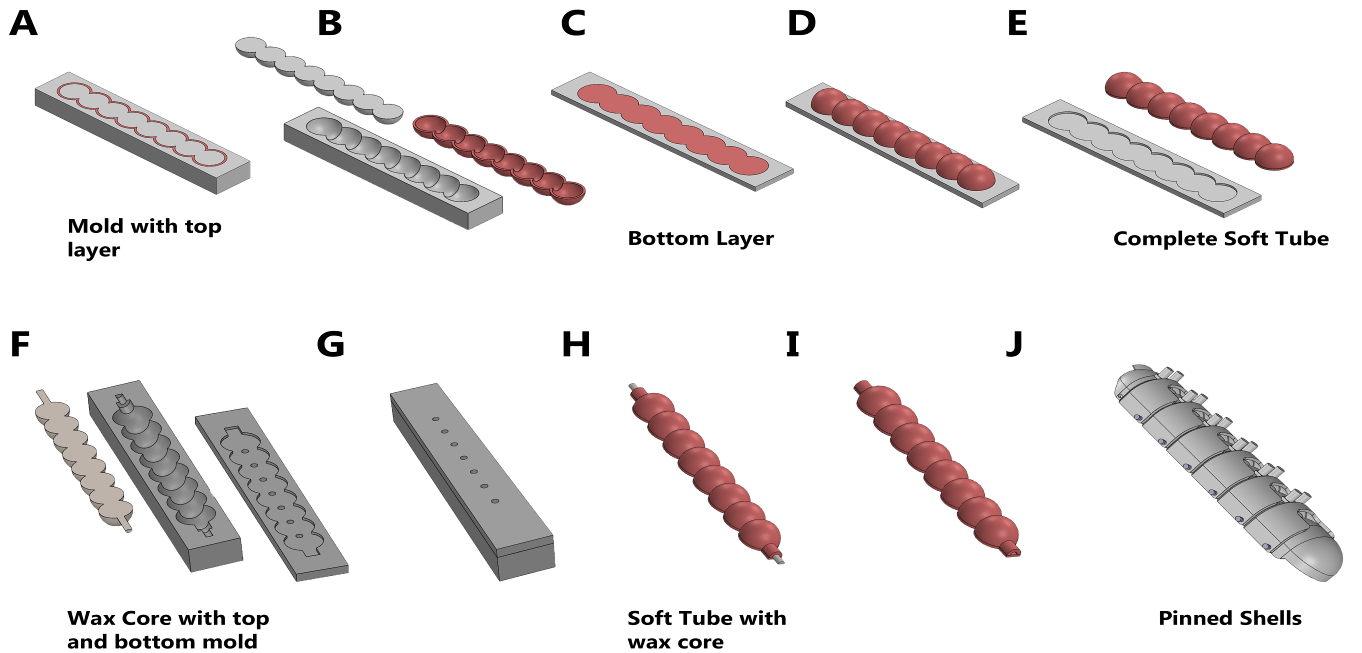

Fig. 5. (A) Two part RTV curing silicone Elastosil M4601 was poured into the mold (B) The cured top layer taken out of the mold (C) (D) The uncured silicone was put in the bottom layer and then the top layer was put on top. (E) Removal of the inner soft tub (F) Preparation of the mold and the wax core. The wax core was reinforced with metal strips to avoid breakage while handling (G) The silicone is allowed to cure inside the 3D printed mold (H) The cured silicone with wax core was separated and excess silicone was removed via surgical blade (I) Silicone was put in hot water for the wax to be liquefied (F) 3D printed rigid shells were placed and pinned onto the soft tube. A tip shell was used at the end.

complete transference of forces. 3D printing was used for the rapid and low cost prototyping of the rigid shells. The shells were slid onto the tube such that the pin holes were aligned. To ensure that there was not any unwanted expansion, the tube was secured from the below using bottom plates were which could easily fit onto the shells. Finally, the shells were pinned together, creating a bending actuator having a specified number of links.

In most cases the downside of the procedure explained above for the fabrication of soft robotics is that due to the multi-step process it is susceptible to de-lamination. For these reasons, we opted for an alternate method also known as lost-wax casting as part of the fabrication process for the soft inner tube of the hybrid actuator. Using this, the inner tube could be prepared in a single step process, therefore eliminating the number of steps and time used for fabrication process. The Fig. 5 illustrates the lost-wax fabrication process for the inner tube. In Fig (F), a wax core was prepared using Paraffin wax. As the density of the elastomer was 25% than that of the wax used, small metal bars were embedded into the wax. This ensured that once the uncured elastomer was poured, the wax core would not rise. Furthermore, the point at which the two half spheres of the inner the intersected laced mechanical strength and could easily break during the fabrication process. Hence, the inlay of the metal bars provided reinforcement to the wax core. In (G), Elastoil M4601 was prepared and poured into the mold. To facilitate the ease of removal of the silicone from the wax, a mold release spray was applied to the wax core. The silicone was allowed to cure. After curing (H), the tube taken out and excess silicone from the geometry was removed via a surgical blade. In the next step (I), the tube with the wax inside was put into water at 50°C for the removal of the wax core inside the elastomeric tube. The metal bars and wax were easily separated from the elastomer as the wax is liquefied at this temperature, resulting in the desired soft part of the actuator. All the geometric parameters of the actuator can be specifically tuned to meet a desired result. The values used in this study was chosen while keeping in mind the design of a hybrid robotic Sixth Finger for assistance of stroke patients.

D. *Experimental Setup*

We experimentally evaluated the performance of the proposed hybrid actuator using a number of tests. A 9 segment actuator excluding the tip shell was used for experimentation as it was the optimal design to be used in developing the sixth finger.[42] The experimentation platform consisted of a compressor (Jun-Air Model 6-25) whose output pressure was modulated via a manual pressure regulator (Festo LR-D-MINI) to the soft tube encapsulated inside the abdomen shells.

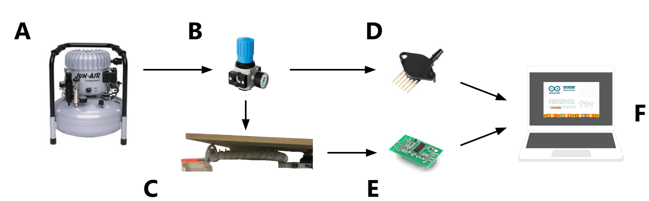

Fig. 6. Experimental Setup (A) Air Compressor (B) Pneumatic Valve (c) Blocked Actuator (D) Pressure Sensor (E) Amplifier (F) Computer/Arduino

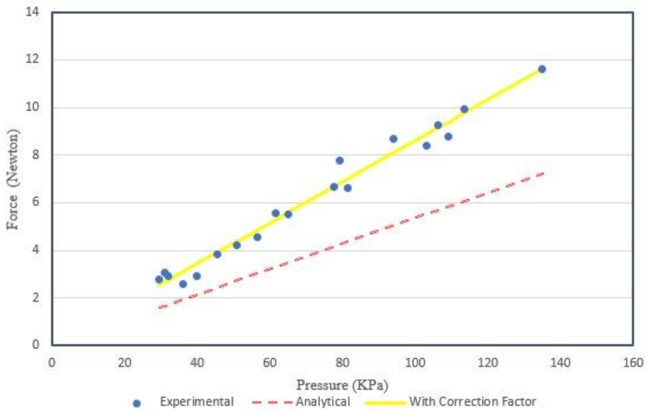

Fig. 7. The Experimental values compared with the Analytical data for tip/bending force.

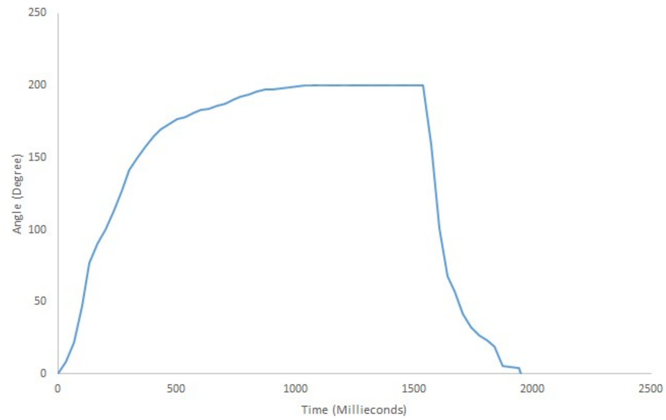

Fig. 8. Bending Angle vs Time. The oscillations at the end occurred because the air was being evacuated to atmospheric pressure.

A Pressure sensor (MPX-5700) was used to determine the pressure of the inner tube while actuation and a Load Cell (TAL221) was used in conjunction with an amplifier (HX-711) to calculate the tip forces. Both were connected to a microcontroller (Arduino) for Data Acquisition as shown in Fig. 6.

III. Results

A. Characteristics of Hybrid Soft Actuator

1) Tip/Blocked Force: The actuator delivered a distributed force along it length. To determine the force capabilities of such bending actuators the tip force was evaluated.[47] The actuator was held in a horizontal position with the tip shell pressing down on a load cell. Due to the curling of the actuator it tends to slip which in turn creates non-linear effects (resulting in inaccuracies while measurement). A micro-controller (Arduino) was used to measure pressure and load cell readings. To ensure that there were no unwanted errors, a constraining platform as shown in Fig. 6. was used to reduce undesirable bending of the actuator while taking measurements. The constraining platform ensured the tip shell to exert force directly onto the load cell. The load cell was calibrated such that at no input pressure the value on the load cell was 0 Newton. This ensured that the force due to gravity was accounted for in the obtained values.

A group of experiments were conducted and results from each group were repeated to eliminate the effects of random error. Pressure was gradually increased so that a quasi-static state was maintained while testing. The pressure was slowly increased and the readings from the load cell were plotted. The proposed actuator was able to deliver forces up to 11.5 N at 135 KPa, demonstrating that it could be used in the proposed application. For the pressure range of 0-20 Kpa, the forces were considerably low due to strain energy absorption by the elastomeric material and the friction of the pin joints. The analytical model and the experimental results are shown in Fig. 7. The results obtained from the experiments showed higher values than that obtained from the analytical model discussed above. This was due to the fact that the model did not account for the following factors:

- On the bottom of the actuator gaps were left between the bottom plates to allow for bending. But due to the high the tube could expand from the respective areas leading to change in thickness.
- The height of the top layer continuously changed due to the hemi-spherical geometry of the elastomeric tube.
- The axis of bending in the analytical model was considered at the bottom layer while in our case the pins had been positioned at a certain distance below the bottom layer of the tube.

Based on the two reading, a correction factor called FUI factor in terms of ‘r’ was calculated that equated for the difference between the analytical and experimental results and when used in the analytical model resulted in a representation of the force response of the proposed actuator. The above mentioned Equation (2) becomes;

$$F = \frac{[2P_{in}\int_{\mathbf{0}}^{\frac{\mathbf{\Pi}}{\mathbf{2}}}(r\sin\alpha + b)r^2\cos^2\alpha d\alpha] + \kappa}{l} \tag{3}$$

Where the FUI factor (κ) came out to be 6.55r^2 - 0.758r + 0.0037 for the given dimensions. This gave an average percentage error of 6.4%. Certainly more detailed analytical models on the operation of the hybrid actuator would produce more accurate results but would also increase the time and effort considerably. Thus the correction factor provides a good compromise.

2) Response Time: The response time of the actuator was obtained using a tracker software (Tracker 5.0; Open Source Physics) Fig. 8. A dot was placed at the base of the actuator and another in the tip and by placing a co-ordinate frame the relative angle of the tip was measured as actuation took place. The actuation footage was recorded on a high speed digital camera at 120fps (GoPro Hero 3). The response time came out to be 1037ms. This actuation was recorded at 130kPa which shows the actuator has a very good response time. However, the time to return to the initial position was 432ms. The oscillations at the end were due to the fact that the pressure difference for the evacuation of air was with respect to atmosphere and not vacuum.

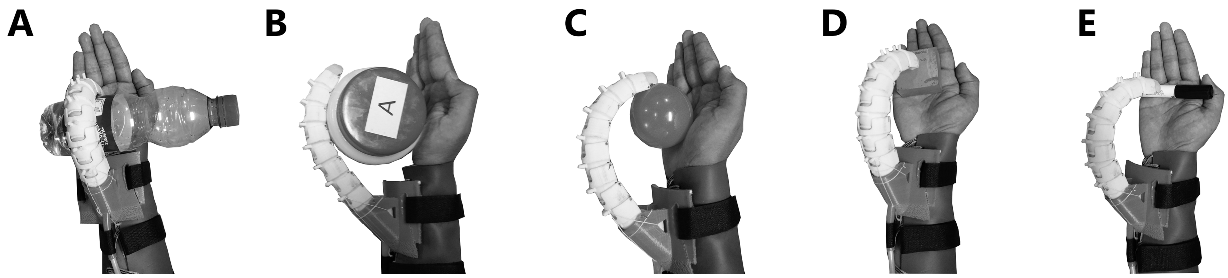

Fig. 9. Sixth finger rehabilitation device (A) Bottle (B) Plastic jar (C) Plastic ball (D) Acrylic cube (E) Marker.

3) Bending Angle: For calculating the bending angle, the shrimp inspired actuator was placed such that the component of gravity was opposite to the bending motion of the actuator. A video was recorded and then analyzed again using a tracking software Tracker (Tracker 5.0; Open Source Physics). The tip shell was marked with a black spot for facilitation in tracking its movement in post-video processing. The initial angle with respect to the horizontal axis was calculated and taken as reference for all the subsequent bending angles to account for the discrepancies arising from tight fitting the shells onto the tube. The actuator was actuated to pressure of 130kPa at 10 Pa intervals. The maximum desired bending angle for use as a sixth finger was no more than 180 degrees Fig. 10. Further bending did not provide any advantage in grasping abilities during its usage as a sixth finger [40].

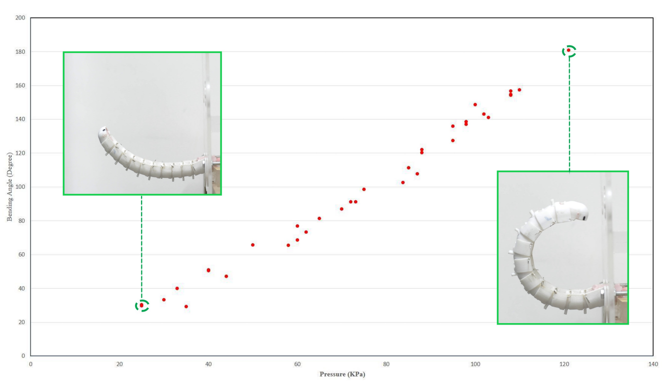

Fig. 10. Bending Angle vs Pressure. The angle was take respective to the shell after the one screwed with the acrylic plate. Pre-bending at 0 KPa due to tight fit of the shell on the tube was accounted for in the calculated readings.

4) Actuator weight to Payload capacity ratio: Our actuator has a given weight of 112g and the load it can lift under a maximum actuation force of 135kPa is 537g. Thus our hybrid actuator can lift about 5 times its own weight.

B. Application as a Sixth Finger

To be used as a sixth finger, the actuator was mounted on the wrist of the impaired hand of the patient facing the palm in a jaw orientation. This orientation has proved to increase the workspace of the hand[48] allowing better grasping capability and dexterity for the user. Another benefit of employing the hybrid actuator as a sixth finger was that it provided high power to weight ratio with repeatability in control, desired in rehabilitative applications.

The hybrid sixth finger comprised of three components namely, the actuator, mounting plate and a leather brace. There were no changes in the design of the actuator except for replacing its last shell by a mounting plate which oriented the finger at a suitable angle above the wrist of the patient. The mounting plate was 3D printed using ABS and was ergonomically curved at its base to fit the forearm perfectly. For the actuator to be held in place, the mounting plate had a cavity that was pinned to the actuator. The leather brace was manufactured using readily available materials like leather and Velcro straps. It facilitated easy and comfortable attachment of the hybrid sixth finger onto the patient's forearm avoiding any unwanted forces onto the forearm causing any kind of discomfort. An eight DOF actuator was employed as the sixth finger.

Now in order to qualitatively evaluate its usage as a sixth finger, the device has to satisfy a number of ergonomic and functional requirements.[48] Starting with ergonomics, the device should be of low encumbrance such that the patient can wear it without any assistance and should be easy to use. Also, the actuator should be lightweight and portable enough to be used in outdoor environments i.e. it should weigh less than 400g. The setup weighed approximately 200g and did not provide any un-natural forces causing uneasiness and fatigue for the user. The finger was controlled via EMG signals via Myo-Band which eliminated the need for any assistance required by the patient during usage of the device. In the case of functionality, the grip/contact force was the decisive factor which was provided by the hybrid actuator as stated earlier. Tethering to the forearm using the arm brace allowed the finger to successfully couple to the human arm Fig. 9. The actuator also provides robustness as the rigid shells covering the elastomeric tube provided adequate protection from objects likely to rupture the elastomeric tube. Finally, the actuator should be conformable and be able to adapt to different shapes. The proposed hybrid actuator conforms to most shapes due to the fact that its individual links joined are by a continuous soft tube. Additionally, conformability to specific shapes can be increased by locking two or more shells together thus optimizing conformability for a certain shape. The small pins on top of each shell as shown in figure 4 were fabricated for this purpose. Shells can be added or removed to vary the DOF thus allowing additional changes in the shape adaptability.

IV. Discussion

Limitations

Since it lies between soft and rigid robotics, as a product it gets restricted to this general niche. It is quite suited to this category where both types of features are required. However, for use cases where only precision is required or where intractability with human's matters above all else the two general categories of actuators fare much better. Additionally, the construction processes for the elastomeric tubes such as lost wax and molding are not quite suited for prototyping and require better equipment for success. Alternative methods such as 3D printing are more desirable if the equipment can be procured as suggested by Tawk et al.[49]

V. Conclusion and Future Work

In this study we have designed, modeled and constructed a pneumatically actuated bio-inspired hybrid actuator. We have given an outlook on this hybrid actuator. We have demonstrated different design iterations and a number of analytical models and their advantages and disadvantages. We have also demonstrated a few construction methods. And finally we suggested some applications suited to its design. This actuator lies between soft and rigid bodied actuators in terms of its specific characteristics. It combines the robustness and precision of rigid actuators with conformability and adaptability of soft actuators and adds its own specific characteristic 'modularity'. This aspect of its modularity shows much promise as it allows the actuator to adapt to specific tasks at hand and will be looked at in further studies. This actuator provides a response time of 1037ms and an average force output of 10N which is within the required criteria of 8N for palm grasping.[50] So as suggested it can be utilized by stroke patients for grasping day to day objects while they rehabilitating. Or in the food industry for sorting and picking.

Acknowledgment

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Authors Contribution

The actuator was developed by IB, MU and FI. The Simulation was done by IB and FI. FI was responsible for the modelling and MU for the figures. The experimentation and the development of the manuscript was handled by MU and IB. HA, MJ and YA were responsible for the review and revision of the manuscript.

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