Development of Prosthetic Finger using Pneu-Nets Soft Actuator to Mimic Flexion Kinematics

Nilay Joshi[1], Kshitija Joshi[1], Nidhi Kamble[1], Sarvesh Joshi[1], Siddhesh Jejurkar[1], Santosh Joshi[2]

[1]B.Tech. Student, Department of Mechanical Engineering, Vishwakarma Institute of Technology (VIT), Pune, Maharashtra, India
[2]Assistant Professor, Department of Mechanical Engineering, Vishwakarma Institute of Technology (VIT), Pune, Maharashtra, India

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Abstract - *Advancement in the field of robotics has led to the development of soft robots that use innovative techniques to replicate desired motion. Compared to traditional robots, soft robots are made from deformable and conformable materials that withstand harsh conditions. The use of such soft robots has found several applications, a notable one being prostheses. Pneumatically actuated soft robots have been developed to mimic human limb motion. However, existing designs were not often effective enough to capture the complexity of the kinematics involved. Additionally, very few of these devices have reached the final product stage. In this work, a pneumatically actuated soft robotic finger was developed to mimic human finger motion, capable of offering higher freedom over kinematic control while maintaining the benefits of easy and quick manufacturing. The proposed design was studied analytically through simulations to optimize the geometry and explore suitable materials. Further, a prototype was developed to validate simulation results. Good conformance was observed in the analytical and empirical findings. The efforts made in this research were aimed not only towards improving prosthetics but also towards better implementation of soft robotics in product design.*

***Key Words*: soft robots, pneumatically, finger, prosthetics**

1. INTRODUCTION

Injuries to the hand and fingers are a common phenomenon that might lead to amputation of the limbs. It can affect people of all ages and can happen while doing many day-to-day activities like operating doors, knives, power saws, and lawnmowers, being a few common ones, according to a study conducted [1]. Apart from trauma, medical conditions like Buerger's disease that leads to gangrene cause thousands of limb amputations worldwide. Given the importance of fingers in daily activities and a variety of vocations, the impact of an amputation can be traumatic. Loss of application has a significant impact on the daily well-being and, in extreme cases, can even cause depression and anxiety among amputees. Detailed statistics of finger loss and its impact on people's daily life are described here [1, 2]. Such patients need advanced prosthetic devices, and through this work, possible solutions to restore lost limb function using soft actuators were studied.

Soft robots have shown great potential in prostheses applications due to their lightweight, chemically passive materials and compliant and compact designs. They have been used to develop wearable devices that provide a non-invasive alternative to invasive solutions that are still very experimental. Moreover, the manufacturing process's ease and adaptability to suit each patient make soft robotics a compelling solution for prosthetic devices. Pneumatically Actuated soft robots, while maintaining the aforementioned advantages, also provide simpler actuation without the need for complex electronic circuitry. These Pneumatic Networks (Pneu-Nets), originally developed by Whitesides Research Group at Harvard, were chosen as a basis for our device's development.

While soft matter and the possibility to create complex shapes open up many possibilities in the filed of prosthetics, these advanced designs along with the high amount of DOFs also bring challenges to control the kinematics.

This study aimed to harness the highly beneficial properties of soft robots and develop a prototype for a prosthetic finger. Our design was developed to provide improved kinematic control over the bending motion while maintaining simplicity in actuation, an improvement over previous works that did not offer kinematic freedom to mimic the exact bending motion of three jointed fingers. To improve the kinematic flexibility while maintaining simple actuation methods, the geometry itself was optimized to eliminate unwanted motions. Moreover, the rapid prototyping method is used to create mold parts, allowing for quick alteration to the design according to the individual's requirements.

2. LITERATURE REVIEW

Following is a detailed review of the research literature related to the function and anatomy of the human finger, kinematics of bending motion, and the development of soft robots. The section presents initial considerations necessary for designing of the actuator.

A. Kinematics data:

When designing the mechanism for the prosthetic device, it is crucial to evaluate the motion analysis of fingers, mainly the bending motion of joints. Finger kinematic data is vital in enabling this device to perform human-like movement. The human hand is composed of a thumb, index finger, middle finger, ring finger, little finger, and palm, which includes the thenar eminence, the hypothenar eminence, and creases. The fingers contain 19 distal phalanges, middle phalanges, proximal phalanges, and metacarpal bones. Thus, the fingers have metacarpophalangeal (MP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints, whereas the thumb has carpometacarpal (CMC), MP, and interphalangeal (IP) joints.

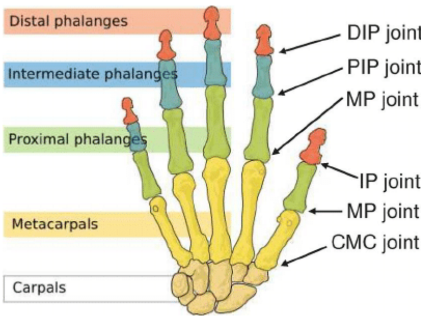


Fig - 1: Joints and bones in human hand. This picture is adapted from [3]

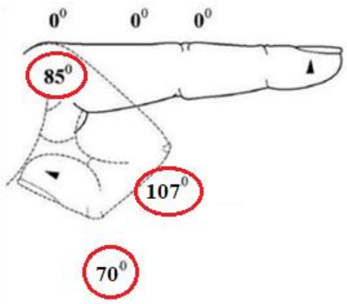


Fig - 2: Mean flexion ROM for the middle finger

The range of motion (ROM) is the most commonly used functional measurement variable. Anatomical measurements and the ROM are usually used to design hand products and rehabilitation. Several studies have measured the flexion range of motion (ROM) of each finger joint. The mean flexion ROM of the DIP, PIP, and MP was 68°, 104°, and 80° for the index finger; 70°, 107°, and 85° for the middle finger, 66°, 107°, and 87° for the ring finger; and 69°, 104°, and 86° for the little finger, respectively [4].

B. Pneu-Nets:

Pneu-Nets (Pneumatic Networks) are a class of soft actuators. They are made of small channels inside elastomeric materials. When pressurized, these channels inflate, producing sophisticated motion with simple control. The nature of this motion is controlled by modifying the geometry of the embedded chambers and the material properties of their walls. When a Pneu-Nets actuator is pressurized, expansion occurs in the most compliant (least stiff) regions. For example, if the Pneu-Net is composed of a single, homogenous elastomer, most expansion occurs at the thinnest structures. Hence, by controlling the wall thicknesses, designers can pre-program the desired motion.

In addition, different materials can be used in combination to enable further control over actuator behavior. If a Pneu-Nets actuator contains layers of materials with different elastic behavior, as shown in fig. 3, the more elastic material expands more when the actuator is pressurized. In this configuration, the more rigid material is called the “strain limiting layer”, as it restricts the amount of strain that can occur. The “differential strain” effect can be used to achieve valuable motions such as bending and twisting.

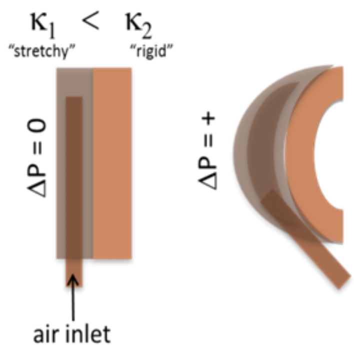


Fig - 3: Differential strain effect [5]

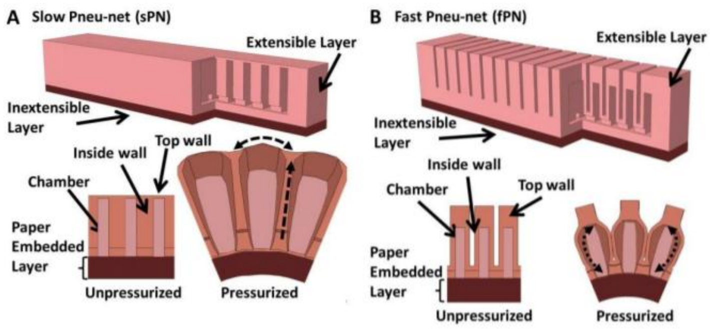


Fig - 4: Slow Pneu-Nets (SPN) vs Fast Pneu-Nets (FPN) [6]

C. Pneumatic Networks for Soft Robotics That Actuate Rapidly:

Although early designs of Pneu-Nets could achieve motion with large amplitudes, they did so slowly (over seconds). A study [6] conducted describes a new design for fast actuating Pneu-Nets (FPN) that reduces the amount of gas that must be transported for inflation of the Pneu-Net, thus increasing its actuation speed. The design achieved an improvement in overall performance showing improvements in 1) speed achieved for a given rate of inflation, 2) force exerted for a given pressure, 3) change in the volume required for a given degree of bending, 4) the number of actuation cycles before failing, and 5) correlation between the pressure in the Pneu-Net and its degree of bending without a load.

Due to its advantages, this new design of Fast actuating Pneu-Nets was used as a basis for our prosthetic device, adopting the improved geometry. Refer fig. 4 to understand new geometry. Similar to the FPN actuator, our device has topographical features along the inside and outside surface of the actuator for high-speed actuation and performance improvement.

3.ACTUATOR DESIGN

The actuator is designed for middle finger, taking appropriate dimensions for phalanges (Distal, Intermediate, Proximal). Geometry of wall thicknesses and internal chamber dimensions were adjusted according to optimization methods mentioned here [7].

The design consists of three layers: top, middle and bottom layers. The middle (enclosing inextensible layer) and bottom layers together form the base of the actuator. The Top layer primarily consists of topographical features on the inside and outside surface. It is provided with internal chambers at three locations along its length to mimic DIP, PIP and MP joints. The bending angle of actuator depends upon the pressure applied at these joint locations. Figs. 5 and 6 show the CAD model of the extensible top layer. Fig. 6 shows the geometric features such as chambers provided for bending and the chambers made to reduce unwanted weight between adjacent joints so that bending due to gravity load can be minimized. The actuator also consists of bonding features added to aid adhesion of top layer with base part.

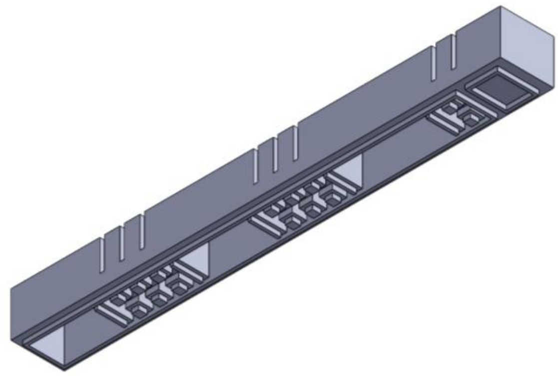


Fig - 5: Top layer design

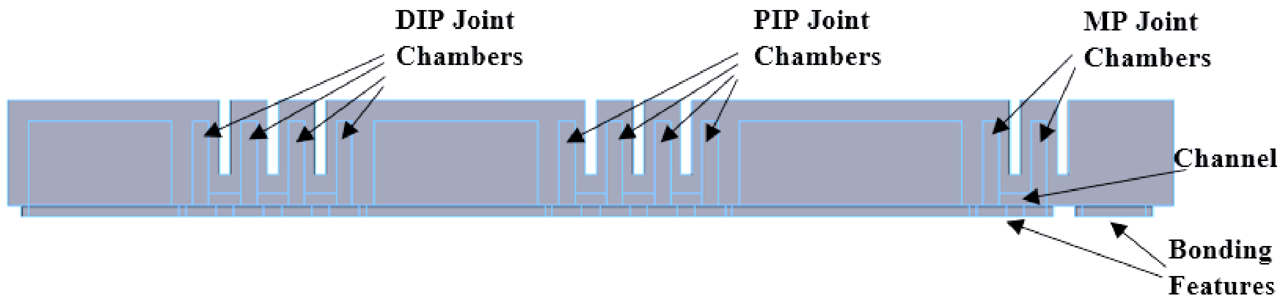


Fig - 6: Top layer geometric features

4.ABAQUS SIMULATION

Simulation of actuators has been carried out using Abaqus software. Two types of loading cases have been simulated, the first is bending of actuator due to gravity, and the second is actuator bending due to application of pressures inside hollow cavities. Gravitational loading indicated unwanted bending that was minimized by adjusting the geometry. Pressure loading inside the internal cavities indicated the pressure vs bending relation upon pneumatic actuation. Simulation parameters were as follows:

- DragonSkin 20 silicone rubber (assigned to extensible parts): Ogden strain energy potential defined by the coefficients

  μ_1 = 1.3077, μ_2 = -2.3497, μ_3 = 1.2075 MPa,
  α_1 = 1.1087, α_2 = -0.0317, α_3 = -1.6291,
  D_1 = 0.4900, D_2 = 0, D_3 = 0 MPa^{-1}, obtained from [8]
  Density of 1080 Kg/m^3, assumed isotropic

- Paper (assigned to inextensible layer): density of 750 Kg/m^3, Young's Modulus of 6.5 GPa, and Poisson's ratio of 0.2

The resultant stress and bending are illustrated in Figs. 7 and 8. Fig. 8 shows the bending trajectory on sequential actuation of MP, PIP, and DIP joints in that order. The maximum stress in the extensible silicone material is below its tensile strength of 3.8MPa, ensuring safe operation. The bending angles at each joint were calculated using specific node coordinates for every pressure step. From this data bending angle against pressure graph plotted to further compare with empirical data. Also, pressures required to attain desired bending angles in each joint were interpolated from the plots. Details are discussed in the results section below.

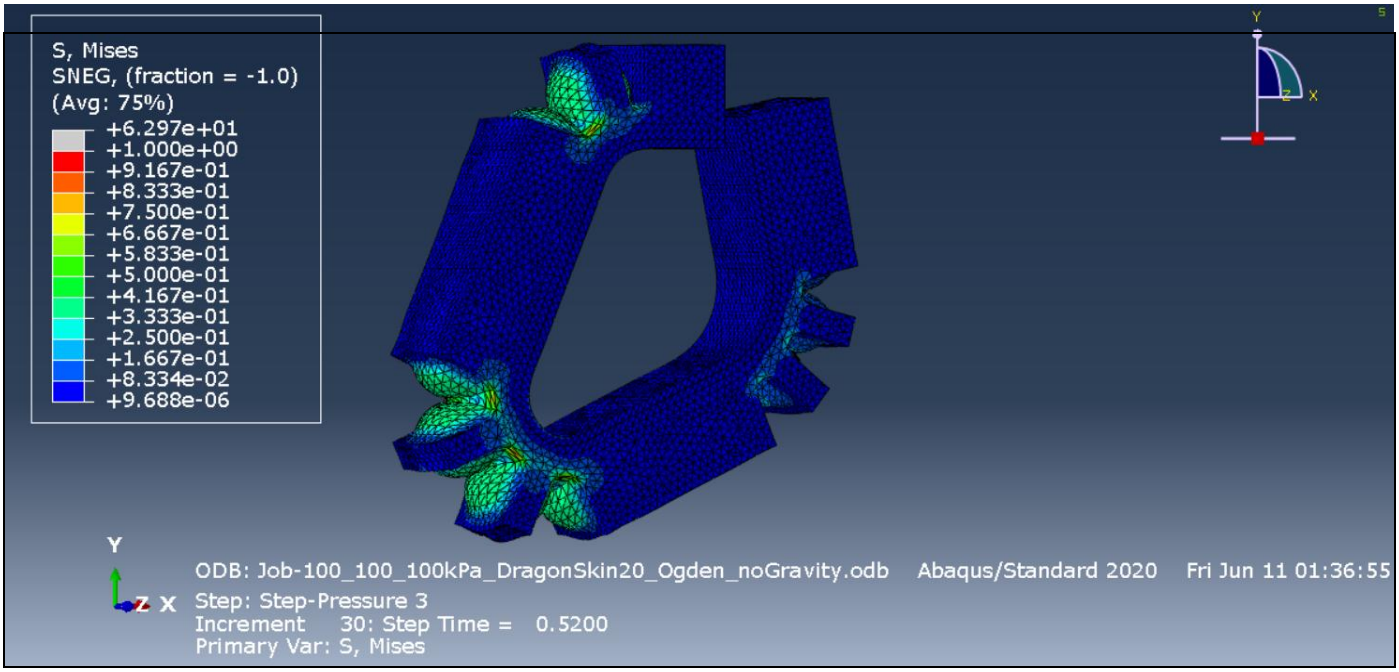


Fig - 7: FEM results

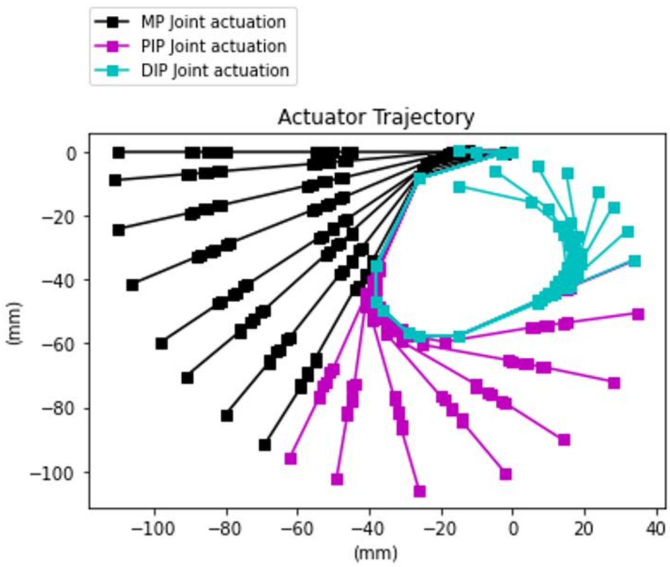


Fig - 8: Actuator trajectory

5.FABRICATION

Casting process used to manufacture the actuator is explained here. Initially, a mold is designed from the actuator geometry, and 3D printed using affordable Polylactic Acid (PLA) filament. Fig. 9 shows the mold parts to be printed; the top part and bottom parts for main body (or top layer of actuator) mold and a base mold for casting the base (consisting of the middle and bottom layer of actuator).

The chamber are fabricated with bio-compatible DragonSkin 20 silicone, in order to guarantee a safe contact with the skin. The rubber comes in two parts: A and B are mixed in the required quantities, and the mixture is deaerated. Removing air bubbles ensures homogenous properties throughout the geometry after hardening and reduces the chances of failure. The mixture is then poured into respective molds and left to harden. The time required for formation was observed to be 1.5 hours for the proposed design. After forming, the actuator parts are separated from the mold parts and combined together with a paper layer embedded between the top and bottom layers. This piece of paper acts as the inextensible layer. Air tubing is inserted between the layers to serve as the inlet to pneumatic power. Finally, a Pneumatic circuit consisting of an air pump, pressure gauge, and tubing is connected for experimental testing.

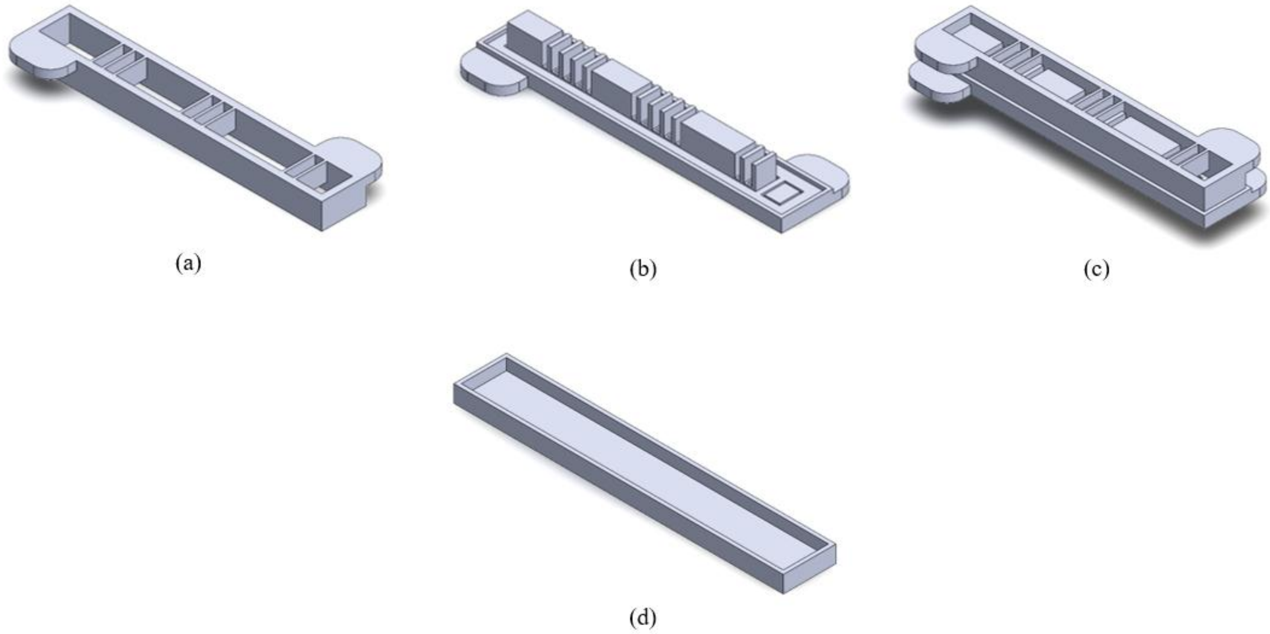


Fig - 9: (a) main body mold - top part, (b) main body mold - bottom part, (c) main body mold - assembly, (c) base mold

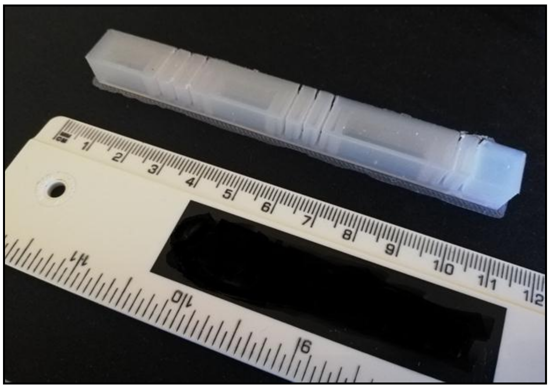


Fig - 10: Casted top layer

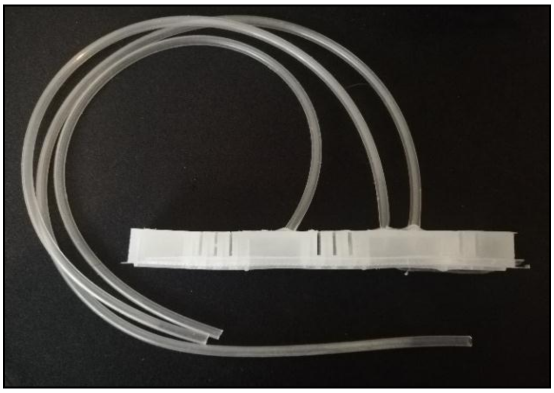


Fig - 11: Top layer with tubing inserted

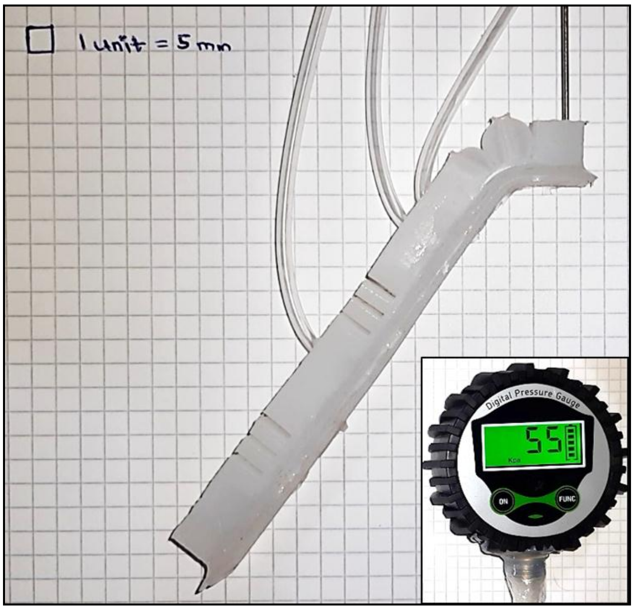
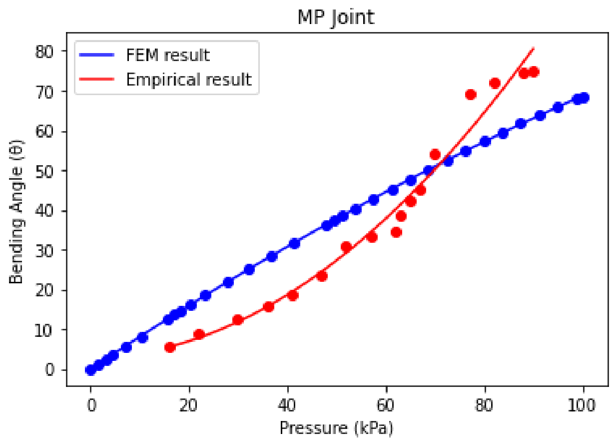


Fig - 12: Prototype actuation (MP joint pressurized); pressure gauge value in kPa

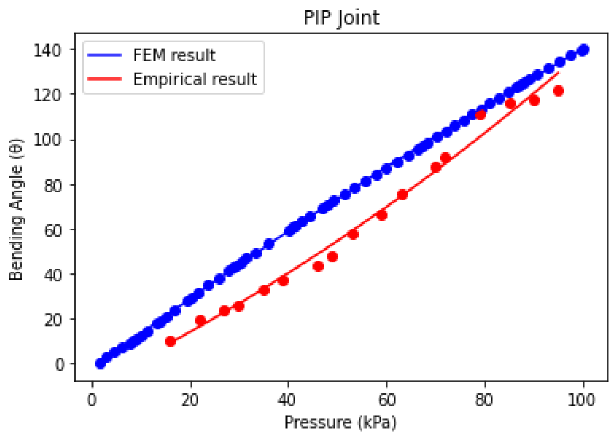
6.RESULTS

The simulation and empirical results obtained are discussed and compared in the following section.

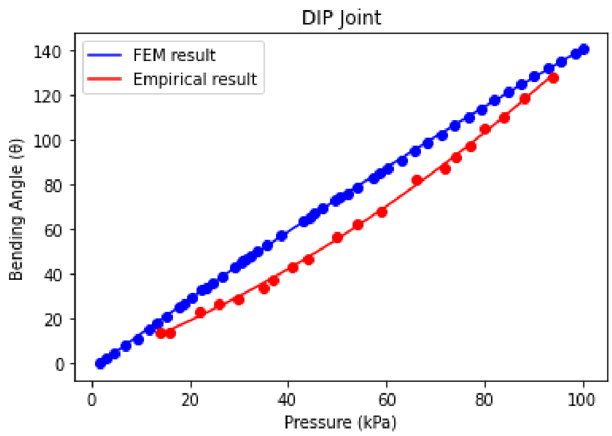
Graphs in figs. 13, 14, and 15 compare the Bending Angles vs. Actuation Pressure trends for simulation and experimental results.



Graph - 1: MP joint - Bending angle vs Pressure



Graph - 2: PIP joint - Bending angle vs Pressure



Graph - 3: DIP joint - Bending angle vs Pressure

Table 1 presents pressure values in kPa required in each joint to obtain corresponding maximum bending angles. The experimentally observed PIP and DIP joints values were more than the FEM results by 10.9% and 25.5%, respectively. This dissimilarity could be due to additional pressure required to overcome unaccounted factors in the simulation, like friction and minor imperfections in the molding process. As for the MP joint, the practical value is less than the FEM value, possibly due to the effect of weight of cantilever mounted actuator that causes it to bend more at the MP joint. These results could be improved upon with more accurate manufacturing, electronically controlled pneumatic circuitry, and precise angle measurement.

Table - 1: Actuation pressure values

Joint	Desired Bending Angle (deg)	FEM Result (kPa)	Empirical Result (kPa)
MP	85°	132.38	92.60
PIP	107°	74.45	82.59
DIP	70°	47.74	59.90

7. CONCLUSIONS

A soft robotic actuator for mimicking human finger movement was studied and developed. The finger kinematics, based on DIP, PIP, MP joints in the finger mimicked, achieving complete flexion range of motion (ROM). The pressure required to actuate was studied through FEM analysis, and based on the data obtained, a prototype was developed to demonstrate the designed model empirically. The important factors considered were material properties, actuator geometry, and manufacturability. The prosthetic device was developed with scalability and affordability in mind. The resulting actuator is cheap, easy to manufacture, and highly compatible with an individual's physique, making it suitable for affordable and novel prosthetic applications of the future.

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