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A novel underactuated multi-fingered soft robotic hand for prosthetic application

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HIGHLIGHTS

- The principle of working of AFPA or ABFPA is based on an anti-Bourdon tube principle.
- Asymmetric actuators give bending performance better than the symmetric actuators.
- Asymmetric actuators can be bent in any direction by rotating the actuator itself to that direction.
- The fingers are made with 2 DOF whereas the general soft hand has 1 DOF in one finger.
- The dynamic modeling will offer an insight into the dynamic system to design a soft robot.

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ABSTRACT

Robotic hand plays a very important role as it is required to hold and place the object at the desired location. There has been a lot of research on the flexible pneumatic rubber or polymer based actuators for soft gripper applications. This paper is investigating asymmetric bellow flexible pneumatic actuator (ABFPA) as a bending joint made of suitable rubber material in the construction of a novel underactuated multi-jointed, multi-fingered soft robotic hand for prosthetic application. The proposed asymmetric actuator has a single internal chamber and is simple, compact and easy to manufacture. Several actuator designs are analyzed and validated experimentally. It is found that the effect of shape and eccentricity of the ABFPA plays an important role in the bending of the actuator. By proper selection of materials and manufacturing of the ABFPA with reinforcement, a versatile dexterous hand can be fabricated. The present work has paved the way for extensive research on this innovative technique as it holds out the true potential for innumerable and very interesting application in various areas.

1. Introduction

The Robotic hands are essential components of any Robotic system as they are required to work as human hand. Robotic or artificial hands, those with four fingers and a thumb, have demanding responsibilities that will improve the efficiency and usefulness of the robot if they can establish a power grasp and precision grip. Nowadays it is more and more important for robots to serve and help people, especially the old and the disabled. There are about 1,000,000 people who had an amputation of a hand or a complete arm worldwide [1]. The main factors for a loss of upper or lower limbs are accidents followed by general diseases and injuries. For diseases and tumors, amputation is a way of stopping the spread of the disease to the rest of the body. About 30 to 50% handicapped persons do not use their conventional prosthetic hands regularly since the hands are heavy in weight, low functionality and limited DOF's cause inability to adapt to the shape of an object [2]. In order to serve them adequately, it is indispensable for the robots to have soft-moving hands. The various artificial hands that are available are essentially based on linkage-mechanisms or hydraulic and pneumatic elements such as wires, cables and chains, belts, artificial muscles etc. [3–6]. The artificial hands presently in use are complicated in design and control structure and also costly to be implemented for robotic or prosthetic applications.

The need for an adaptable hand with flexibility, dexterousness and load carrying capacity analogous to the human hand seems to be the ideal one for robotic or prosthetic application. An extensive research in this area has lead to the design and development of such hands which are becoming more and more complicated in structure, components along with programmable control systems being developed. Several kinds of flexible pneumatic rubber actuators have been developed and reported with two or more internal chambers having symmetric cross section or attached to

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a joint to create bending motion. Also their internal pressures are controlled independently through flexible tubes, which are connected to pressure control valves. Examples of them are Rubber gas actuator driven by hydrogen storage alloy [7], Flexible micro actuator (FMA) [8,9], Pneumatic wobble motor [10], Pneumatic soft actuator [11], Flexible fluidic actuator (FFA) [1,12] and Flexible pneumatic actuator (FPA) [13,14]. Even though the FMAs [8,9] with two or more chambers provide multiple DOF, it requires multiple pressure supplies, valves and sensors as well as complicated manufacturing. Compared with the typical FMAs, the FPA [13] uses spring or wire rather than fiber as its constraint, which results in the bending deformation of the actuator. Also many research groups have developed artificial hands with a fluidic actuator that is called McKibben artificial muscle or Pneumatic Muscle Actuator (PMA) [15,16]. The multi-fingered hands actuated by pneumatic artificial muscle are costly and difficult to miniaturize. Also there is hardly any space left in the socket that covers the stump of the forearm of a handicapped person, to keep the contracting artificial muscle which provides force to the movement of the hand joints. However, grippers having flexible tube like pneumatic fingers constrained by the supporting member such as thin plate or rod along one side have been proposed [17,18]. This may be called as composite material flexible pneumatic actuator (CMFPA). An attempt has been made with dual compartment, differential pressure flexible pneumatic actuators (DPFPA) in the construction of robotic grippers for soft fruit packing [19] but not for the investigation on the multi-jointed multi-fingered prosthetic hand based on asymmetric bellow flexible rubber actuators. The main disadvantage with the above type of grippers is the fingers inability to grasp both soft and hard objects of different shapes, sizes and weights.

In the search for a simple soft robotic gripper design, a new technique altogether different from others yet versatile has been found and developed based on an asymmetric (eccentric) polymer/rubber tube or bellow actuators with or without reinforcement [20,21]. Actuators made of bellows or tubes with asymmetric cross section has been investigated to overcome the disadvantages of FMA and FPAs or FFAs and applied for the robotic soft gripper construction and the same technique is proposed for the development of a dexterous hand [20,21]. It has also been applied to fabricate a micro walking robot [22], robotic fish [23] and a soft gripper [21,24]. Later many research groups further explored our technique with different arrangements of fibers embedded within the actuator wall [25] or by changing the shape and material of the actuator [26–28]. The above research groups use embedded PneuNets (pneumatic networks) channels in elastomers of square shaped tubes and these channels inflate when pressurized, creating motion either by varying the thickness of the walls of the tube [26] or by changing the material of the active and passive layers of the square shaped tube [27,28] or square shaped molded silicone actuator with rounding on one side [29]. The fingers of the hand developed [27,29] are of 1 DOF not resembling the finger joints of the human hand and also it is controlled by external pneumatic components and air supply. A complex construction of fiber-reinforced tubular soft prosthetic hand with stretchable optical waveguides for strain sensing has been developed using external control devices and air supply [29]. A hybrid actuation principle combining both pneumatic and tendon-driven actuators for a soft robotic manipulator has been constructed which needs both external motors and compressor [30]. Comprehensive modeling and construction of such type of complicated fiber-reinforced soft robotic actuator designs were presented [31]. Recently research on bellows to generate bending motion using symmetric thickness actuator [32] and polymer Bi-bellows [33] have been carried out. The above group [32] has not worked on the asymmetricity along the longitudinal direction of the actuators. The problem in the symmetric thickness actuator is that it cannot withstand higher pressure ranges. Also the rubber bonding process using ultraviolet light of 172 nm wavelength could be dangerous and expensive.

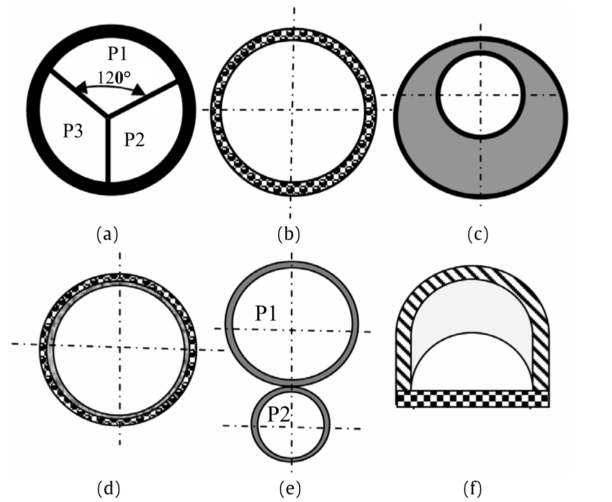


Fig. 1. Cross section design of various Flexible Pneumatic Actuators (a) FMA (b) FPA (c) AFPA (d) PMA (e) DPFPA (f) CMFPA.

Instead of two or three internal chambers in FMA made of rubber or fiber-reinforced rubber, the proposed actuator not only has a single internal chamber but also simple, compact, stable, less in weight and easy to manufacture. It is mentioned that in the case of symmetric actuators (FMA's), there is an unstable phenomenon which occurs while gripping when the pressure of the working fluid reaches some limit [8,9]. The asymmetric actuators can be bent in any direction by just rotating it to the desired angle and thus eliminating the usage of more number of control devices. The AFPAs or ABFPAs show better deflection up to certain amount of eccentricity provided in the asymmetric actuators. The need for totally new approach to achieve flexibility or dexterousness similar to the human hand is felt. The design of robotic hand by an asymmetric nitrile rubber (Acrylonitrile–Butadiene rubber) bellow actuator has been studied [34–36]. The applicability of ABFPA using rubber for the fabrication of a novel underactuated multi-fingered robotic hand has not been investigated. The hand is also known as Amrita Prosthetic Hand. The finite element analysis of the ABFPA has been carried out using Abaqus 6.13 software and the effect of various factors affecting the bending of the actuators are presented. These actuators have the advantages of high force density and relatively simple structure over other types of actuators. The cross section of AFPA or ABFPA is asymmetric as compared to symmetric section of FMA [8], FPA [13], PMA [15,16], DPFPA [19] and CMFPA [17] as shown in Fig. 1.

2. Principle

The principle of working of asymmetric tube or bellow actuator is exactly opposite to that of the principle of actuation of the Bourdon tube. An over simplified statement of this new principle is to dub it as an anti-Bourdon tube principle [37]. The Bourdon tube used is initially in curved form with flat or elliptic cross section which under the application of internal pressure will tend curved tube to open up because of the action of the flat or elliptic section becoming circular under pressure. Contrary to this a straight asymmetric (eccentric) tube or bellow actuator with circular cross section under the application of pressure will become curved and elliptic in cross section. This behavior is exactly opposite to that of the above case.

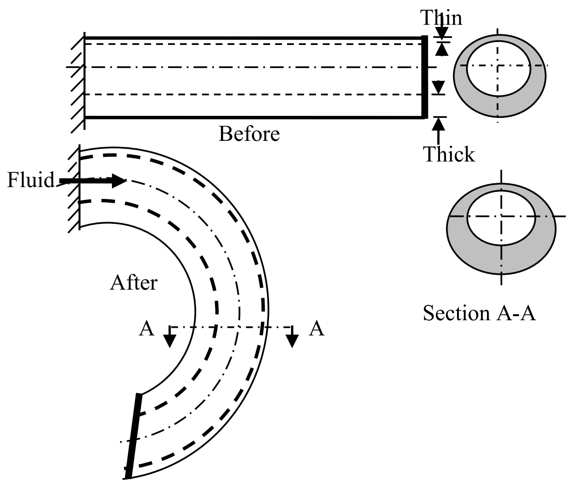


Fig. 2. Bending of AFPA subjected to fluid pressure.

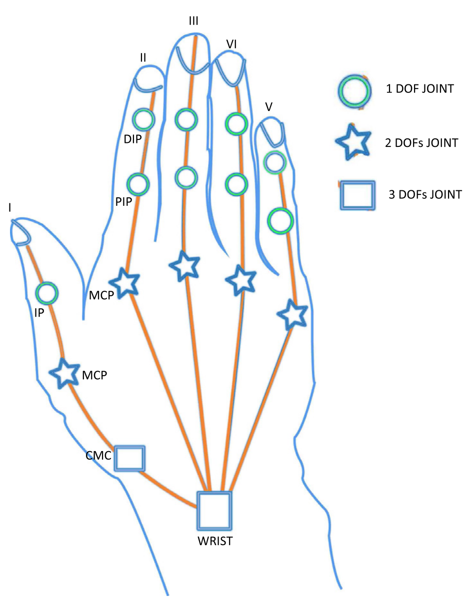


Fig. 3. Human hand link structure.

If the wall thickness is made asymmetric, the tube actuator under internal pressure will curve in the direction of the side having greater thickness as the expansion of the thinner side (outside radius) will be more than thicker side (inside radius) as shown in Fig. 2. This effect is due to the dual effect of an unequal expansion or in other words differential expansion of the tube actuator at various points and the end moment induced due to asymmetry of cross section.

Bellows can be used to form finger joints similar to the interphalangeal joints in human hand. In the case of human hand, except thumb which has a single interphalangeal (IP), metacarpophalangeal (MCP) and carpometacarpal (CMC) joints, other 4 fingers have 2 IP and 1 MCP joints to provide 25 DOFs as shown in Fig. 3 [38].

3. Basic characteristics of ABFPA

Bellows can be made asymmetric in cross section either with circular bellow or semicircular bellow. The static characteristics of

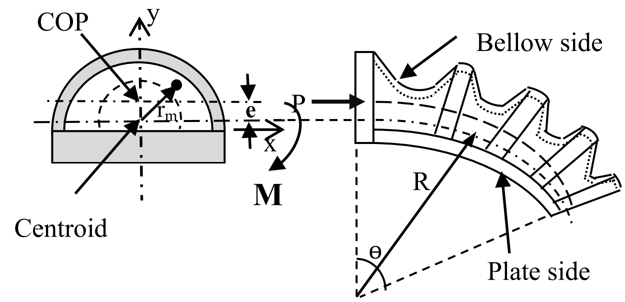


Fig. 4. Bending of tapered ABFPA subjected to internal pressure.

the bellow actuator are explained in [39]. However, a brief mention of the same is given below along with dynamic characteristics of the bellow actuator. These approximate equations are obtained by linear analysis based on the theory of infinitesimal elastic deformation.

3.1. Static characteristics

When fluid pressure P is applied with the free end closed, the ABFPA bends due to the combined effect of an end moment which develops at the free end due to eccentricity and also due to differential expansion of the top and bottom fibers. The force generated due to pressure P is given by $F = P \cdot A$, where A is the average internal cavity's cross sectional area. Since the cut-section is not axis-symmetrical, its centroid is slightly shifted from the center of pressure (COP) by a small distance 'e'.

Radius of curvature at any pressure is $R = EI/M$.
where M is the moment acting at the free end, E is the Young's modulus and I is the second moment of area.

The moment due to eccentricity of the actuator is $M_e = Fe$. where e is the eccentricity. Fig. 4 shows bending of asymmetric flexible semicircular tapered bellow actuator subjected to internal pressure.

The deflection of the actuator is due to differential expansion and the moment created due to the eccentricity of the geometry [20,21]. From the beam theory, the vertical deflection δ at the tip of the bellow and the angular deflection θ_1 is given in terms of M as

$$\delta = \frac{FL^3}{3EI_x} = \frac{ML^3}{3EeI_x} \tag{1}$$

$$\theta_1 = \frac{ML^2}{3EeI_x} \tag{2}$$

where I_x is the second moment of area of the cross section of asymmetric bellow and L is the length of the bellow actuator.

The angular deflection due to differential expansion of the bellow and plate side of the actuator is given by

$$\theta_2 = \frac{\delta_d}{r_m} \tag{3}$$

where δ_d is the amount of differential expansion and r_m is the average radius of the bellow actuator.

The total angular deflection of the asymmetric bellow actuator due to bending is obtained by adding (2) and (3) and is given by

$$\theta = \theta_1 + \theta_2 = \frac{ML^2}{3EeI_x} + \frac{\delta_d}{r_m} \tag{4}$$

The total moment due to internal pressure P is obtained by

$$M = Fe + \frac{F_{\max} r_m}{2} \tag{5}$$

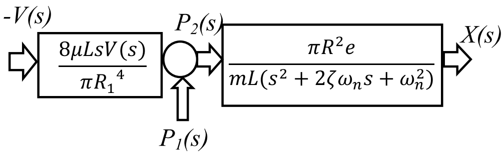


Fig. 5. Block diagram of the transfer function.

where $F_{\max}$ is the maximum force at the top of the bellow where it is subjected to maximum deflection.

3.2. Dynamic characteristics

The dynamic characteristics of the ABFPA can be determined by analyzing the movement of the actuator tip subjected to varying fluid pressure. The basic hypothesis is to treat the actuator as a cantilever beam which is a single spring mass damper system.

The dynamic equation of the actuator subjected to fluid pressure is

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \tag{6}$$

where $F(t)$ is the force acting at the free-end of the actuator transverse to the centroidal axis and causes the deflection $x(t)$.

Eq. (6) can be written as

$$\left(s^2 + \frac{c}{m}s + \frac{k}{m}\right)X(s) = \frac{F(s)}{m} \tag{7}$$

$$(s^2 + 2\zeta\omega_n s + \omega_n^2)X(s) = \frac{P_2(s)Ae}{mL} \tag{8}$$

where, ζ is the damping ratio, $P_2(s)$ is the internal pressure, A is the internal area, e is the eccentricity, m is the mass of the actuator, L is the length and ω_n is the natural frequency of the actuator.

$$\text{where,}\ \ \omega_n = \sqrt{\frac{k_{eq}}{m_{eq}}} = \sqrt{\frac{3EI}{l^3\left\{\left(\frac{F}{g}\right) + 0.23m\right\}}} \tag{9}$$

$$\text{and } F = \frac{P_2Ae}{L} \tag{10}$$

The transfer function for the bending dynamics of the ABFPA can be written as

$$G(s) = \frac{X(s)}{P_2(s)} = \frac{\pi R^2 e}{mL(s^2 + 2\zeta\omega_n s + \omega_n^2)} \tag{11}$$

where R is the effective internal radius of the ABFPA,

Considering laminar flow between the flow control valve and the ABFPA, using Hagen–Poiseuille equation,

$$P_1(s) = P_2(s) + \frac{8\mu LsV(s)}{\pi R_1^4} \tag{12}$$

where $P_1(s)$ is the input pressure at the flow-control valve, μ is the dynamic viscosity, $V(s)$ is the volume flow rate and R_1 is the internal radius of the tubing.

The block diagram of the transfer function with $X(s)$ as the output and $P_1(s)$ and $V(s)$ as inputs is shown in Fig. 5.

Comparing Eq. (11) with the canonical form,

$$\frac{C(s)}{R(s)} = \frac{K\omega_n^2}{(s^2 + 2\zeta\omega_n s + \omega_n^2)} \tag{13}$$

we can write, system gain,

$$K = \frac{\pi R^2 eL^2\left\{\left(\frac{F}{g}\right) + 0.23m\right\}}{3mEI} \tag{14}$$

Characteristic time period, τ is

$$\tau = \frac{1}{\omega_n} = \sqrt{\frac{L^3\left\{\left(\frac{F}{g}\right) + 0.23m\right\}}{3EI}} \tag{15}$$

Damping ratio ζ is given by

$$\zeta = \frac{c}{m} \tag{16}$$

where c is the damping coefficient.

The damped frequency for under-damped system is given by

$$\omega_d = \omega_n\sqrt{1-\zeta^2} = \frac{\sqrt{1-\zeta^2}}{\tau} \tag{17}$$

Some of the characteristic terms are

$$\text{Peak time,}\ \ t_p = \frac{\pi}{\omega_d} \tag{18}$$

$$\text{Settling time,}\ \ t_s = 4\tau \tag{19}$$

$$\text{Rise time,}\ \ t_r = \frac{\pi - \varphi}{\omega_d} \tag{20}$$

By experiments, the peak time and the settling time can be found out which can be used to determine the damping ratio and the damping coefficient.

For a unit step input of pressure P_2, the deflection $x(t)$, of the tip of the actuator is given by

$$x(t) = \frac{\pi R^2 eP_2}{\omega_n^2 mL}\left[1 - \frac{e^{-\zeta\omega_n t}}{\sqrt{1-\zeta^2}}\sin\{\omega_n\left(\sqrt{1-\zeta^2}\right)t + \phi\}\right] \tag{21}$$

$$\phi = \tan^{-1}\left(\frac{\sqrt{1-\zeta^2}}{\zeta}\right) \tag{22}$$

where ϕ is the phase angle

4. Design and manufacturing of ABFPA

The design of the ABFPA made of rubber is almost semicircular in shape such that, on one half it has a bellow profile and on the other side it is flat. The asymmetric bellow design gives maximum deflection compared to normal symmetric designs up to certain value of eccentricity and withstands high pressures. The shape of the bellow profile also affects on the deflection of the actuator [39]. To decide on an optimum design for a particular shape useful for easy manufacturing, FE analysis is carried out using Abaqus 6.13. Hyper elastic tetrahedron elements are used for rubber structures on wall of the actuator. Applied pneumatic pressures are given as incremental pressure load in the software, which always acts in the nominal direction on the rubber walls of the actuator. In the FEM analysis, the Mooney–Rivlin model is used for approximating the characteristics of nitrile rubber. The coefficients are identified through the experimental results of plane strain tension tests of nitrile rubber.

4.1. Effect of eccentricity on bending of ABFPA

Eccentricity plays a major role in the bending of the bellow. Fig. 6 shows the variation of bending angle with respect to eccentricity for the square corrugated, straight triangular corrugated and taper triangular corrugated ABFPA's at 5 bar pressure.

It is clearly seen that bending angle increases with increase in eccentricity, till a certain point, and then it decreases. This trend is followed by three of the bellow designs. There exists a certain value of optimum eccentricity for each model at a fixed pressure

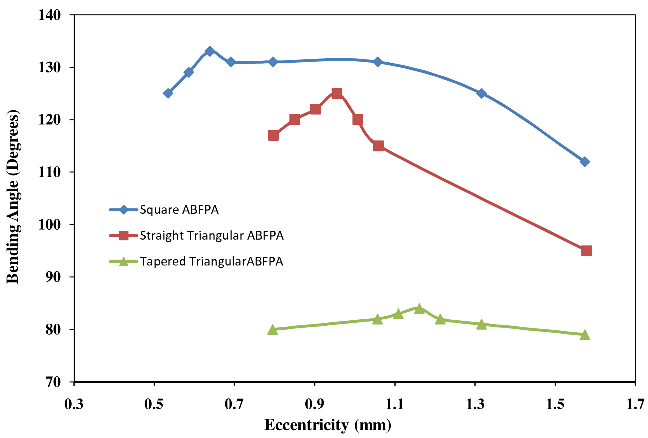


Fig. 6. Effect of eccentricity on the bending angle of various ABFPAs.

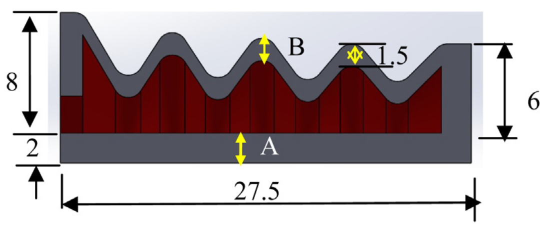


Fig. 7. Cross section of tapered triangular ABFPA showing *A* and *B* parameters (all dimensions are in mm).

Table 1
Eccentricity and bending angles of three types of rubber ABFPA's.

Type of ABFPA's	Eccentricity (mm)	Bending angle (degree)
Square	0.638	133
Straight triangular	0.955	125
Tapered triangular	1.161	87

for which the bending angle is maximum. The optimum values of eccentricity for the three types of bellow are given in Table 1.

It is clearly inferred that bending angle is less for a bellow with eccentricity above or below the optimum eccentricity value shown in Table 1.

4.2. Selection of bellow shape

The triangular tapered bellow with rounded tip was selected to make the manufacturing process easier and to prevent air leakage from repeated use. The advantage is that the bellow is made in a single piece instead of two pieces as in the case of square or straight triangular shaped bellows. To find the optimum design, different models by varying parameter *A* and keeping *B* constant are created for analysis which are responsible for the eccentric actuation. *A* and *B* represent the thickness of flat side and bellow side of the actuator respectively as shown in Fig. 7.

As shown in the Table 2, models 1 to model 4 with different values of parameters are considered for analysis.

The bending angle for different models having different bottom thicknesses and constant top thickness is plotted as shown in Fig. 8. Length of the tapered actuator in all the models are 27.5 mm and radius varies from 8 to 6 mm from bigger to smaller end.

To select the best tapered ABFPA (the actuator providing maximum bending angle), analysis is carried out and the results are plotted. From the analysis, it is observed that the best combination of top and bottom thickness is 1.5 mm and 2 mm respectively for model 2. The bending angle for this combination of top and bottom

Table 2
Parameters of tapered triangular rubber ABFPA.

	A [mm]	*B* [mm]
Model 1	1.5	1.5
Model 2	2.0	1.5
Model 3	2.5	1.5
Model 4	3.0	1.5

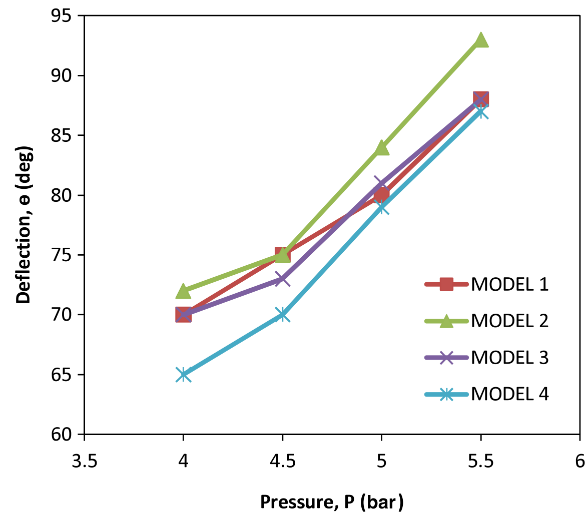


Fig. 8. Pressure vs bending angles of different models of tapered triangular rubber ABFPA.

Table 3
Material properties of nitrile rubber.

	Properties	Values
1	Appearance	Black color
2	Density	1300 kg/m^3
3	Shore hardness	65
4	Elastic modulus	3 MPa
5	Tensile strength	4 MPa
6	Elongation at break	475%

thickness is 87° at 5 bar pressure. Since the stress concentration at the surface of bellow at 5.5 bar is maximum, 5 bar is taken as the maximum operating pressure and the corresponding value of bending angle is 87°.

4.3. Analysis of ABFPA with tapered triangular corrugations

To simplify the manufacturing process and design a single mold bellow, the corrugations are made tapered triangular as shown in Fig. 9 along with the manufactured bellow actuator showing a deflection of about 90° subjected to an internal pressure of 5 bar. To make the core pin removal easier, the internal and external corrugations are tapered. This may reduce bending angle but the life of the actuator increases compared to straight triangular and square shaped bellow actuator. Due to the taper towards the end of the bellow, the core pin can be easily removed from the bellow. Hence, the taper model can be manufactured in a single piece mold. This model has a top thickness of 1.5 mm and base thickness of 2 mm. Length has been reduced to 27.5 mm. This taper model gives a bending angle of 87° for a pressure of 5 bar as shown in Fig. 10.

Table 3 shows the material properties of the nitrile rubber used in analysis and manufacturing.

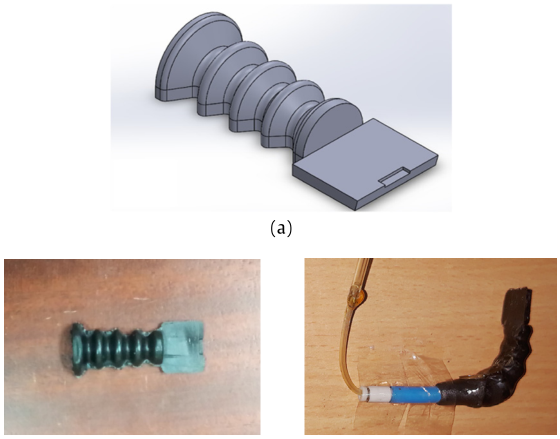


Fig. 9. Tapered triangular nitrile rubber ABFPA (a) 3D model (b) Manufactured bellow actuator (c) Deflection of the actuator subjected to internal pressure.

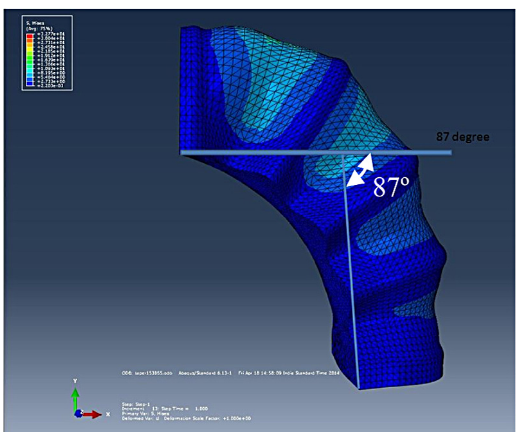


Fig. 10. Finite element analysis of tapered triangular ABFPA at 5 bar pressure using Abaqus software.

4.4. Simulation of a finger

The two triangular ABFPA are connected together to form a two jointed finger as shown in Fig. 11 along with FE analysis using Abaqus software and the bending of actual fabricated finger.

The two ABFPA's are separated by a flat plate of about 13 mm length and joined by the adhesive. The tip of the finger is initially bent to an angle of 15°. The bending occurs in 2D as shown in Fig. 11. However, if provision is made for rotating the fingers or wrist joint, the hand can be oriented in any direction achieving 3D manipulation of the object. The combined bending of both ABFPA's and the fixed bending angles at the tip gives the finger a bending angle of about 165° at 5 bar pressure. Pressure is applied separately to each bellow using pneumatic polyurethane tubes of 2 mm diameter.

4.5. Tensile testing of ABFPA material

Material properties such as tensile strength at break, elongation at break and stress values are determined by tensile testing of the nitrile rubber using universal testing machine (UTM). Fig. 12 shows the comparative graphs of a typical nitrile rubber material with and without reinforcement. Nylon fiber is reinforced with rubber to improve the properties.

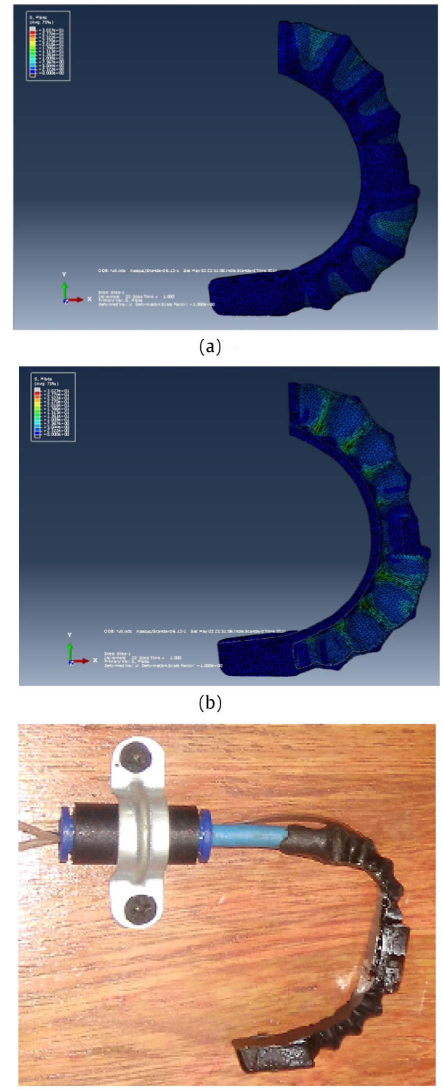


Fig. 11. Bending simulation of a finger (a) outside view (b) cross sectional view (c) fabricated finger using two ABFPA's.

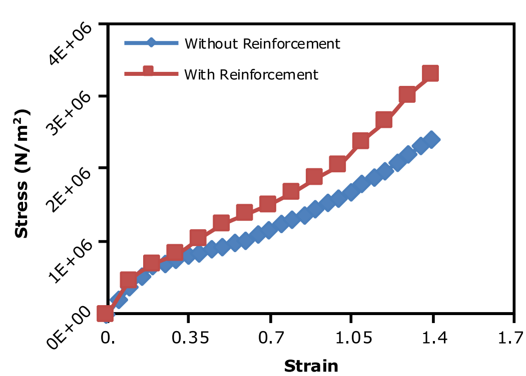
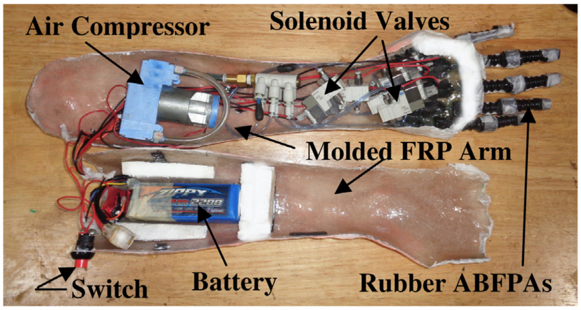


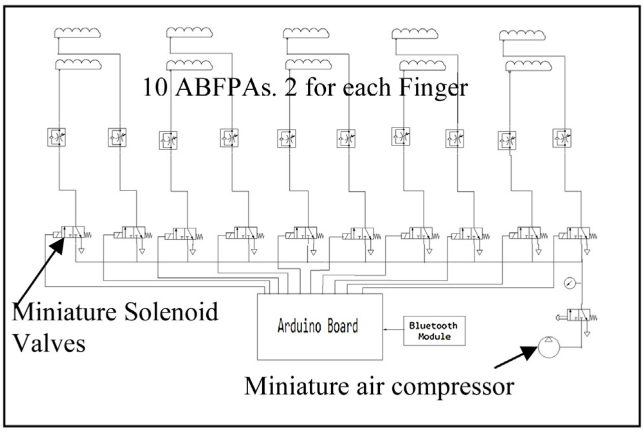
Fig. 12. Stress vs strain graph for nitrile rubber material.

5. Multi-fingered soft robotic hand

The fingers of the present Robotic hand is designed using 10 ABFPAs providing 10 DOF. The ABFPA acts as a bending joint in the finger that helps in flexion and rotation of the finger. Each of the inter-phalangeal and metacarpo-phalangeal joints contain single



(a)



(b)

Fig. 13. Exploded view of a (a) rubber ABFPAs multi-fingered hand showing various components (b) Pneumatic control system.

asymmetric bellow actuator and thus providing 2 DOF for each finger. The micro-controller, solenoid valves, mini-compressor or pump and battery are provided in the arm. The mini-compressor or pump and battery can be mounted separately or tied to a belt of the patient to reduce the weight of the arm. The design requirement of the hand is to have an independent motion of the finger with a total of 10 DOF for the whole hand and it should lift a minimum weight of 200 g at 5 bar pressure without using any reinforcement material during manufacturing of the actuator. Fig. 13(a) shows an exploded view of the multi-fingered hand made of rubber ABFPAs showing various components and Fig. 13(b) shows pneumatic control block diagram.

The whole setup is confined in the arm extending from the hand. A miniaturized compressor supplies the air and passes it onto the solenoid valves. A 12 V battery is provided in the arm which provides power to run the DC motor of the compressor. An Arduino nano board is used for controlling miniature solenoid valves.

Using an android mobile app, we can control the general purpose input and output (GPIO) pins of an Arduino through Bluetooth. By pressing a button in the mobile app, a control signal is generated from the microcontroller that controls the solenoid valve. The solenoid valves driven by a transistor provide a 10 way supply of regulated air pressure to each of the actuator. This system allows each of the actuator to be operated individually and the whole hand can perform a variety of grasps that can be programmed into the IC. To demonstrate the working principle of the hand, a simple linear forward control model is used for the valve opening time to achieve a desired pressure, corresponding to a desired grasping force required to lift a particular object. Thus an underactuated multi-fingered hand is designed using a single motor compressor system as against many motors normally provided in commercial hands to get many degrees of freedom.

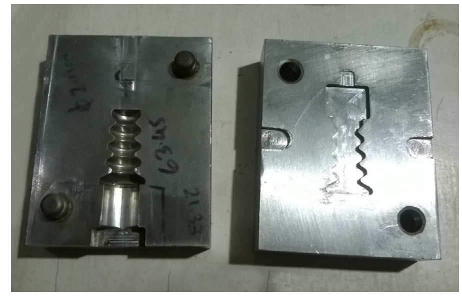


Fig. 14. Molds used to manufacture tapered triangular ABFPA of length 27.5 mm.

6. Experiments

Nature has provided plants and animals with gripping organs. Some plants have special devices for support or holding and the significant ones are tendrils, hooks, aerial roots and tentacles. The prehensile tail in chameleon and monkeys help in holding the support. Inspired by the natural grippers, experiments are conducted using various materials, rubber, plastic, neoprene etc. Properly designed components would be desirable for industrial and prosthetic application as positional accuracy, reliability and stability are essential requirements for any field application.

6.1. Manufacturing of tapered triangular ABFPA

The hand is manufactured by joining the ABFPAs to form the five fingers which are then fixed to the palm portion of the hand. Various types of ABFPAs are manufactured using different materials and experimented to arrive at a particular design for easy manufacturing and to provide better performance. Hence tapered triangular ABFPA is chosen for manufacturing of the hand. To make the core pin removal easier, the internal and external corrugations were tapered and accordingly the mold is prepared as shown in Fig. 14.

The length of the ABFPA is reduced 27.5 mm. This taper model gives a bending angle of 87° for a pressure of 5 bar.

6.2. Prototype of fabricated hand

A multi-fingered hand has been fabricated using rubber ABFPA as shown in Fig. 15. The two rubber ABFPAs are separated by a flat plate of about 13 mm length and joined by the adhesive. Pressure is applied separately to each bellow actuator using pneumatic polyurethane tubes of 2 mm diameter. The assembled fingers can be made easily interchangeable and also replaceable. The palm and arm of the hand are made of FRP material to reduce the weight. All the components including the pneumatic valves, mini diaphragm type air compressor and the battery are placed inside the arm. The hand may be covered with surgical gloves for aesthetic look or to prevent any damage caused to either the fingers or object while picking soft objects. The total weight of the hand is about 950 g. However, about 500 g of weight can be reduced if both the battery and the mini compressor are removed from the arm of the hand and mounted separately.

Fig. 16(a)–(f) show some of the grasps obtained using the manufactured multi-fingered hand.

7. Results and discussion

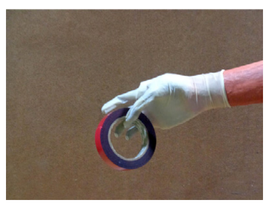
The ABFPAs are made of nitrile rubber which are elastic in nature and exhibits nonlinear properties. Some of the parameters which affect the bending of the ABFPA are material composition, shape, eccentricity etc. which are discussed earlier.

Fig. 15. Multi-fingered hand prototype made of rubber ABFPA.

(a) Cylindrical grasp.

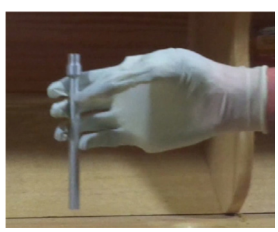
(b) Tripod grasp.

(c) Precision grasp.



(d) Pinch grasp.

(e) Power grasp.



(f) Prismatic grasp.

Fig. 16. Various grasps by hand made of rubber ABFPA.

7.1. *Static bending characteristics of ABFPA*

Fig. 17 shows the static bending characteristic of the rubber ABFPA. The analysis and experimental results are close to each other. The simple characteristic equations are obtained by assuming Young's modulus (E) is constant and the calculated characteristics are compared with experimental data taken from a tapered bellow actuator. As the pressure increases, the angular deflection of the tube actuator increases. However the radius of curvature decreases.

7.2. *Weight carrying capacity*

Consider an object being held by a five fingered pneumatic hand. Each finger is made of two ABFPA bellow actuators.

Assuming an actuator as a simple cantilever beam with force acting at free end which is given by

$$F = \frac{M}{L} = \frac{PAe}{L} \tag{23}$$

The frictional force is

$$F_f = \mu F = \frac{\mu PAe}{L} \tag{24}$$

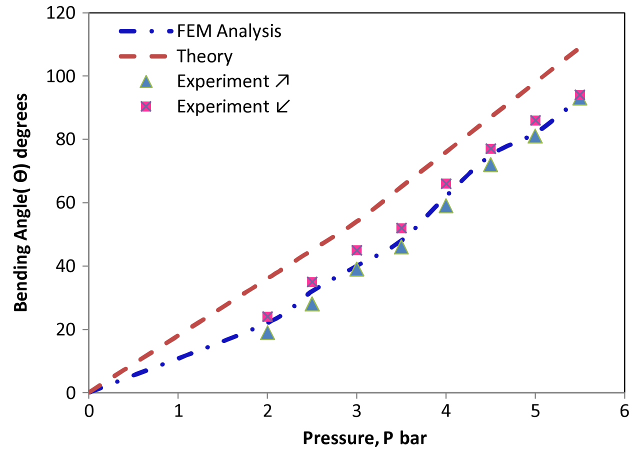


Fig. 17. The static bending characteristics of rubber ABFPA.

(a)

(b)

Fig. 18. Experiment of lifting water bottle by multi-fingered hand without slipping at 5 bar (a) without water (b) with 220 g of water.

The weight carrying capacity is given by

$$W = \frac{n\mu PAe}{L} \tag{25}$$

where n is the number of fingers, μ is the coefficient of friction, P is the pressure applied to the object, L is the length of the actuator, A is the inner cross sectional area of the bellow tip and e is the eccentricity of the bellow actuator.

Fig. 18 shows the lifting of water bottle by the hand. The manufactured hand can carry a payload of about 220 g at 5 bar pressure without slipping. The strength and weight carrying capacity of the hand can be increased by providing thin steel wire or fiber reinforcement at the thicker side of the rubber bellow actuator.

Fig. 19 shows weight carrying capacity of the hand made of rubber ABFPAs at various pressures. Various light weight objects such as bottle, ball, egg, fruit etc. can be lifted by the manufactured hand.

7.3. *Force generated by the actuator*

The maximum force generated by the actuator is measured by a load cell. To detect the force, one end of the actuator is fixed and the deflecting end is touching the load cell. The load cell is set up to measure the force from the tip of the actuator. Fig. 20 shows the experimental and theoretical force curves of the actuator subjected to various internal air pressures. The pressure range is from 0 to 5 bar. The force characteristics are non-linear. The maximum measured force is 0.46 N for rubber at 5 bar pressure.

7.4. *Dynamic experiment*

Fig. 21 shows experimental results from a typical step response curves for the two different sizes of ABFPAs at 3 bar pressure. The

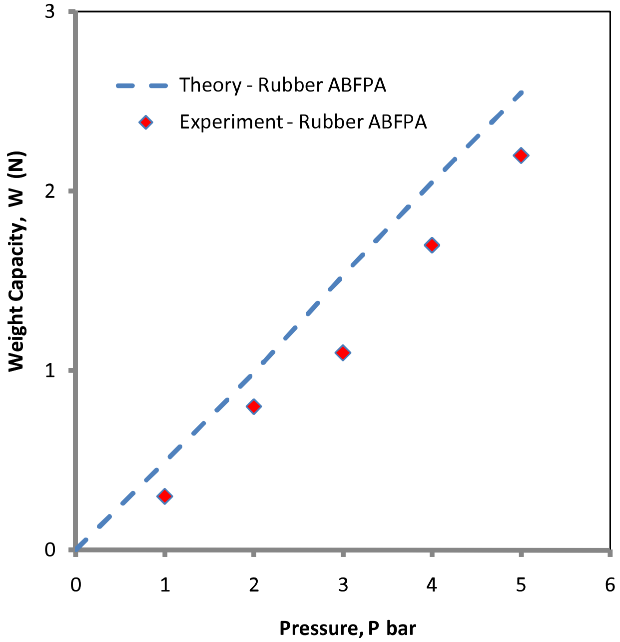


Fig. 19. Weight carrying capacity of hand made of rubber ABFPA subjected to varying internal pressure.

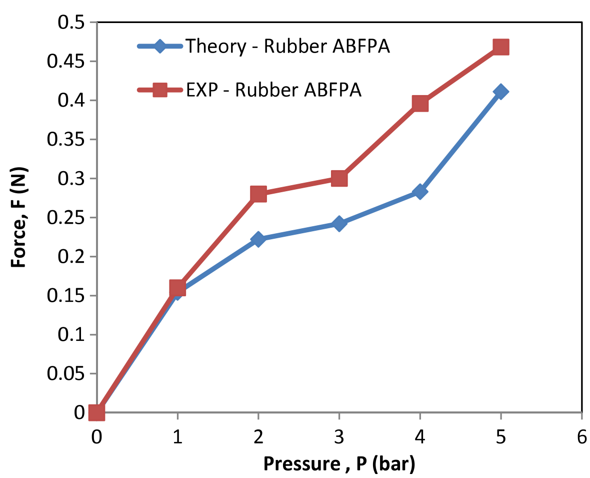


Fig. 20. Force generated by the rubber ABFPA.

movement of the ABFPA tip is measured with a CCD camera using a small LED attached to the tip of the ABFPA.

Fig. 21(a) shows a satisfactory response of the smaller ABFPA-I used in the fabrication of the hand, where the fundamental frequency of the ABFPA is high. In Fig. 21(b), the fundamental frequency of the bigger size ABFPA-II is low and the response becomes unsteady. In general, the force density of the ABFPA is inversely proportional to its size.

Fig. 22 shows a theoretical step response for rubber ABFPA-I and ABFPA-II respectively. There exists a deviation in the theoretical response characteristics obtained by Eqs. (18) to (20) as compared to experimental data. Comparing Figs. 21 and 22, the major difference is in the settling time of the vibration which is about one second as seen in Fig. 22. The deviation may be due to an assumption of simple transfer function of one degree of freedom, which clearly stands for a simple approximation to real conditions. The details of the two ABFPAs along with experimental and theoretical step response characteristics are shown in Table 4.

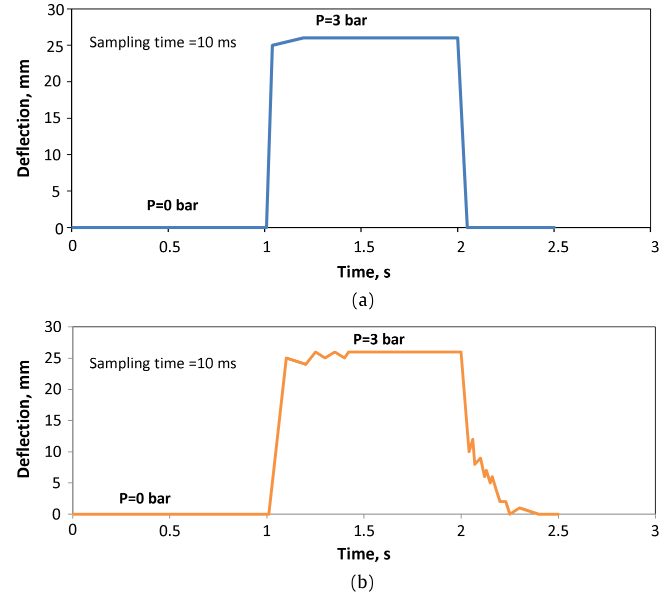


Fig. 21. Experimental step response for rubber actuator (a) ABFPA-I and (b) ABFPA-II.

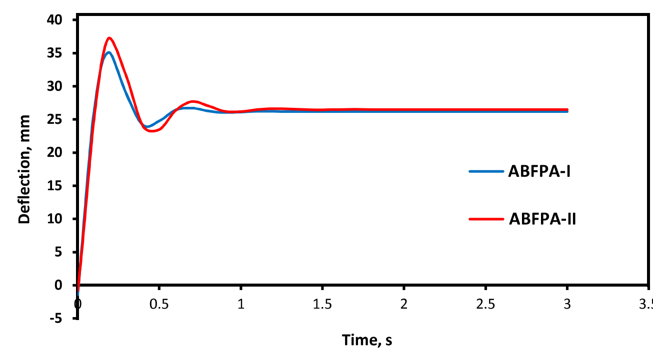


Fig. 22. Theoretical step response for ABFPA-1 and ABFPA-II.

Table 4
Details of two ABFPAs and its experimental and theoretical step response characteristics.

Characteristics	ABFPA-I	ABFPA-II
Design characteristics		
Max diameter (mm)	16	20
Min diameter (mm)	12	16
Length (mm)	27.5	47
Bellow thickness (mm)	1.5	1.5
Bottom plate thickness (mm)	2.0	2.0
Inner diameter of tube (mm)	1.2	1.2
Experimental step response characteristics		
Peak time, T_p (s)	0.20	0.24
Settling time, T_s (s)	0.29	0.42
Rise time, T_r (s)	0.03	0.15
Theoretical step response characteristics		
Peak time, T_p(s)	0.24	0.25
Settling time, T_s (s)	0.28	0.30
Rise time, T_r (s)	0.1	0.12

7.5. Characteristics and functionality

Since the fingers are fabricated using nitrile rubber material without fiber reinforcement, each finger weighs less than 15 g. This makes possible to reduce the mass of a new multi-fingered hand to less than 40% of the mass of a conventional prosthetic hand [40] without considering the mass of the fore arm. The total mass of the full prosthetic arm including mini compressor, valves and battery is just about half the mass of the conventional prosthetic hand [40]. However the conventional hand carries weights up to 6 kg as compared to the current hand which carries up to 220 g. With proper reinforcement to the rubber actuator or using asymmetric flexible metal bellow actuators with higher pressures the current hand can be made to lift heavier objects. It is able to grasp various types of objects of different shapes and sizes and the bending of fingers is close to the human hand. One of the design features of this hand is that the fingers are made with 2 independent DOF whereas the general soft hand has one degree of freedom in one finger. There is a limitation in functionality of the hand if the fingers have only one degree of freedom and hence cannot adapt to the shape of an object. This causes more force required for 1 DOF fingers to hold the object stable. The time for a complete flexion and extension of fingers is less than 100 ms. Therefore it is possible to open and close the hand with a frequency of about 10 Hz. This is 5 to 8 times faster than conventional prostheses as the complete flexion and extension takes 0.5 s [40] to 0.8 s [41]. All the fingers are made of same design and can be easily interchangeable and inserted into the slot made in the palm of the hand which can be easily replaced whenever required. As the construction of the hand is very soft, the risk of accidents in direct interaction with humans can be minimized. This enables the development of a light weight prosthetic hand with high functionality compared to the commercially available hands.

8. Conclusions

A single chamber asymmetric rubber bellow flexible pneumatic actuator (ABFPA) has been designed and manufactured for the construction of a novel underactuated multi-fingered soft robotic hand for prosthetic application. Several actuator designs are compared and validated experimentally. Analysis in Abaqus software resulted in optimized design of the actuator. In the present work, two ABFPA are used in each finger to make a prototype thus achieving 2 DOF finger as compared to 1 DOF fingers generally provided in a soft hand. The basic characteristics of the ABFPAs have been analyzed theoretically and experimentally. The statics and dynamics can be predicted easily and the ABFPAs are designed efficiently. The dynamic modeling will offer an insight into the dynamic system, as it constitutes a fundamental step to understand how to design a soft robotic device.

It is found that the effect of shape and eccentricity of the ABFPA plays an important role in the bending of the actuator and the deflection of ABFPA is influenced by the eccentricity up to a certain extent. A tapered triangular ABFPA is designed and fabricated by a single mold to prevent leakage of air due to joining of the bellow parts as in the case of square bellow actuators. The tapered triangular rubber ABFPA gives a bending angle of about 90° subjected to an internal pressure of 5 bar which is close to the results obtained by FEM analysis.

The rubber ABFPA hand can carry a payload more than its own weight provided the battery and the mini compressor are mounted separately on the human body. This will reduce the weight of the hand drastically. The multi-fingered hand is able to grasp various types of objects of different shapes and sizes and the bending of fingers is close to the human hand. The hand constructed with this kind of bellow joint will have advantages of low price, simple structure, lighter and good flexibility. The total mass of the full prosthetic arm is just about half the mass of the conventional motorized prosthetic arm. It is possible to open and close the hand with a speed of 5 to 8 times faster than conventional prostheses. The entire hand including the arm can be built within few days using materials worth less than US$ 800.

A single chamber ABFPA gives bending performance better than the symmetric actuators of two or more chambers. The FMA actuator can be bent in any of the three directions by controlling the pressure in the three chambers. In the case of AFPA or ABFPA, by rotating the actuator itself, it can be bent in any direction and thus avoiding more control devices. Also the effect of instability while gripping when the pressure of the working fluid reaches a critical limit as in the case of symmetric FPAs or FMA's are avoided. Although the fiber reinforced hand with or without embedded sensors can carry higher payload, the square shaped tubular finger design is comparatively complex and larger in size than that of present hand. However, by changing the material properties of nitrile rubber with proper reinforcement, the present hand can also be made to lift heavier payload.

In future, a tactile sensor can be incorporated at the tip of the fingers to measure a contact force and a suitable feedback control system can be developed to make the hand very stable for grasping and handling various objects. Instead of rubber actuators, flexible metal actuators can also be used to develop the hand to lift heavy objects. The present work has proved beyond any reasonable doubt that a multi-fingered hand can be developed for prosthetic or robotic application. This type of hand may be most suited for 'Dynamic' application wherein two fingers of the hand could do operations such as tightening the screw or nut while carrying out gripping action using other fingers in the hand. The present work has paved the way for extensive research on this new principle as it holds out the true potential for innumerable and very interesting application in various areas such as service robotics, orthotics and human–robot interaction.

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