INNOVERSE EXPO 2025

Improving the design of pneumatic muscles: Simulation and analysis of the dynamic behavior of the system

Niki Abtahi

Parsa AhmadpourRahiminejad

Baran Derakhshandeh Daryasari

Sarina Nosrati

Ramiya Rahjou

Supervisor : Mohammad Arjmand

Valeh Cultural and Educational Institute

Iranian Youth Science and Technology Center (IYSTC)

Improving the design of pneumatic muscles: Simulation and analysis of the dynamic behavior of the system using a balloon

1) Abtahi Niki, Valeh educational and cultural institute, 12th grade, Tehran, Iran nikabt2007@gmail.com
2) AhmadpourRahiminejad Parsa , Valeh educational and cultural institute, 8th grade, Tehran, Iran pajohesh.dept@valeh.ir
3) Derakhshandeh Daryasari Baran , Valeh educational and cultural institute, 10th grade, Tehran, Iran pajohesh.dept@valeh.ir
4) Nosrati Sarina , Valeh educational and cultural institute, 12th grade, Tehran, Iran sarina.n1386@gmail.com
5) Rahjou Ramiya , Valeh educational and cultural institute, 11th grade, Tehran, Iran ramiarahjoo@gmail.com
Supervisor : Arjmand Mohammad , The director of the department of creativity ,research and skills training of Valeh institute, pajohesh.dept@valeh.ir

1.Abstract

This work presents the concept of a low-cost, light, and wearable pneumatic muscle to replace conventional artificial muscles such as Festo and McKibben actuators. The muscle can be used in soft robotics (e.g., pneumatic network actuators), rehabilitation robots, and compliant mechanical systems like robotic grippers and compliant mechanisms.The actuator consists of a latex balloon as the hyperelastic core due to the high reversibility and elasticity, and a polyethylene mesh as the outer framework to govern the contraction. The material of the mesh, mesh-to-balloon length ratio, nozzle angle, and air pressure were some of the parameters investigated to improve performance.Control was achieved with a 2-position 5-way pneumatic valve, cycle actuation timer, and pressure regulator to allow even input. Experimental trials found increased magnitude of contraction with higher air pressure but also with more internal stress. Motion quality varied with nozzle angle, with 0° configuration yielding most effective expansion. Increased loads reduced contraction, showing isotonic resistance. Polyethylene mesh was more efficient than foam and polyester with greater response speed and energy restitution.This muscle design conforms to the UN Sustainable Development Goals (SDGs): Goal 3 (Good Health and Well-being) by affordable prosthetics, Goal 4 (Quality Education) through education-based applications in robotics, and Goal 9 (Industry, Innovation and Infrastructure) through soft robotic innovation promotion. The total cost is approximately 10 times lower compared to traditional pneumatic actuators, making it a highly promising answer for research and practical purposes.

.Keywords: elasticity/ stress and strain/ pressure jump across the membrane /muscle efficiency /muscle dynamics

2.Introduction

2.1.Problem review

Projected in the World Report on Disability released jointly by the World Health Organization (WHO) and the World Bank in 2011, over 1 billion people live with disability, and nearly 200 million suffer from severe functional limitation. There has been a 10% increase since 1970. The projections suggest that there will be a need for at least one assistive product by more than 2 billion people worldwide in order to enable activities of daily living by 2030. In spite of the growing need, existing assistive technology—especially artificial muscles and motion-supporting systems—tends to be costly, heavy, or unavailable in low-resource environments. The pneumatic muscle, which reproduces the contraction dynamics of natural muscles through compressed air, provides a low-cost, lightweight alternative with significant promise. Optimal design, responsiveness, and dynamic performance under changing load and pressure conditions remain to be addressed. This project introduces a novel solution by improving the design of pneumatic muscles through accurate simulation and analysis of their dynamic behavior. Our goal is to develop more efficient, durable, and accessible actuators that can be used in prosthetics, rehabilitation devices, and assistive robotics.

2.2. History

The history of pneumatic muscles dates back to the 1950s, when the idea of creating artificial muscles was first proposed. In the 1960s, Joseph L. McKibben built a muscle that had been theorized the previous decade, and named it the McKibben muscle. This muscle consists of a cylindrical elastic cushion placed inside a woven mesh. When air is applied to it, the elastic cushion expands radially and the mesh contracts, making it function similarly to a natural muscle. In the 1970s and 1980s, McKibben muscles moved towards commercialization and use in medical prosthetics and the robotics industry. In the 1990s, companies such as Festo and Shadow Robotics began refining and commercializing McKibben muscles. Since the 2000s, pneumatic muscles have been popular in soft robotics, rehabilitation devices, and haptic interfaces. A more advanced version of the McKibben muscle is the Festo Fluidic Muscle, which is widely used in robotics.

Figure 1 – pneumatic muscle development

2.3. Research purpose and hypothesis

Most current pneumatic muscle systems are afflicted with asymmetrical pressure distribution because the elastic cushion inside is not shaped uniformly. Such non-uniform pressure has a tendency to cause some localized zones of the cushion to proportionally grow unevenly, resulting in asymmetric contraction. Overall efficiency of the actuator is negatively affected. In addition, the mesh fabric commonly employed in such muscles typically has very low elasticity that constrains range of contraction and prevents the muscle from being restored fully to its original shape upon deflation. Such limited elasticity also reduces long-term system performance and responsiveness. To mitigate these limitations, this paper formulates a new design and model for pneumatic muscles. The main hypothesis is to replace the traditional air-filled cushion with a hyperelastic spherical material that will distribute pressure more evenly and improve the resiliency of the muscle with cyclic contraction–relaxation. Furthermore, replacing the existing woven mesh with a more flexible and recovery-friendly polyester-based mesh would reduce response time and optimize the mechanical performance of the muscle.The new design has clear implications for individuals with upper or lower limb impairment. Through increased efficiency, responsiveness, and comfort of pneumatic muscles, the system can significantly increase users' mobility, daily functioning, and quality of life.

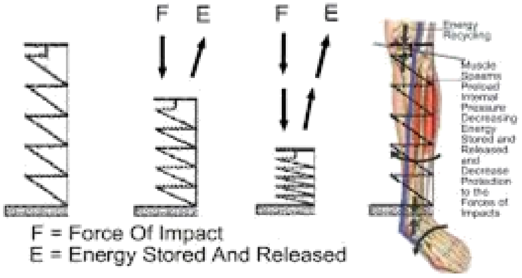
2.4.Theory

Elasticity is used to describe the resiliency of pneumatic muscles. Hooke's law is used to calculate the resiliency of a constructed muscle. By that parameters such as balloon volume, balloon wall thickness and mess material can be extracted.

Formula 1 – hook's law formula

$$F = \pi E(r^{2}_{r_0} - r^{2}_{i})(\lambda 1 - 1)$$

Figure 2 – hook's law in muscles



When air is pumped into a balloon, it creates a movement in the balloon that is explained using Bernoulli's principle. Amount of air and the velocity of air are the related parameters to this theory.

Formula 2 – Bernoulli's principal calculation formula

$$\frac{1}{2}u^2 + \frac{P}{\rho} + gz = c$$

Figure 3 – air movement in ballon calculation formula

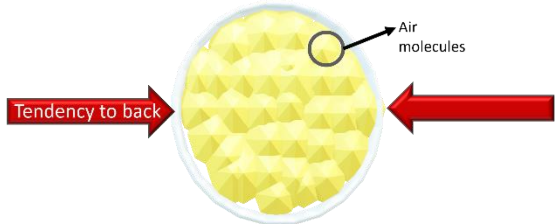
Balloon is a hyperelastic material. These materials are also known as Mani Rivlin and have high resilience properties and are therefore a suitable option for replacing elastic cushions. The resilience of these materials is described by the wall pressure formula. A higher jump pressure in the wall will cause a higher reversibility that will speed up the contraction cycle in the muscle.

Formula 3 – Dependance of the pressure jump across the membrane

$$[P_B](r)=2S_1 \frac{d_1}{r_1}\left(\frac{r_0}{r} - \left(\frac{r_0}{r}\right)^7\right)\left(1 - \frac{S_1}{S_{-1}}\left(\frac{r}{r_0}\right)^2\right)$$

d_0 and r_0 are the thickness and the radius of the balloon, respectively, before inflation, and s_1 and $s\_\ (-1)$ are the two constants of a Mooney–Rivlin material.

Figure 4 – Dependance of the pressure jump across the membrane



When air enters a balloon (air cushion), its wall is compressed from the inside and stretched from the outside, which is explained and studied by tensile stress. There is also a decrease in the height of the balloon and an increase in its width, which is studied and explained by the Poisson ratio. When the stress and strain are higher in the balloon the contraction force and in result, the efficiency will increase. The length of net parameter is related to this theory.

Formula 4 – Poisson ratio calculation formula

$$\mathcal{V} = -\frac{d\varepsilon_{trans}}{d\varepsilon_{axial}}$$

Formula 5 – tensile stress for ballon calculation formula

$$\sigma = \frac{P.\,r}{2t}$$

Formula 6 – tensile stress for net calculation formula

$$\sigma = \frac{p.\,2\pi rL}{N.\,A_f.\sin(\theta)}$$

Muscle contractions in the wall of the balloon create waves that are effective in the overall efficiency of the muscle and the stability of the contraction. That is calculated by wave propagation.

Formula 7 – tensile stress for net calculation formula

$$\rho = \frac{\partial^2 u}{\partial t^2} + (2\mu + \lambda)\frac{1}{r}\frac{\partial \varepsilon}{\partial r}$$

Due to the entry of air, a change occurs in the wall of the balloon, which causes energy consumption.

Formula 8-muscle bending changes calculation formula = Helfrich

$$E_{bend} = \int \left(\frac{1}{2}k_b(c_1 + c_2 - c_3)^2 k_b - c_1 c_2\right) da$$

Formula 9- muscle area deformation calculation formula

$$E_a = \frac{k_a}{2} \int \left(\frac{\Delta_a}{a_0}\right)^2 da$$

Formula 10 _muscle thickness change calculation formula

$$E_{Thickness} = \frac{k_t}{2} \int_{r_1}^{r_2} \left(\frac{w(r) - w_0}{w_0}\right)^2 da$$

Properties of muscle include calculating efficiency and function of muscle. With the help of energy consumption and muscle work formulas, the efficiency formula is obtained and calculated.

Formula 11- energy consumption calculation formula

$$PdV \int = E$$

Formula 12- muscle work calculation formula

$$\Delta x \,.\, F_{ce} = W$$

$$\Downarrow$$

Formula 13- muscle efficiency calculation formula

$$\frac{W_{useful}}{E_{input}} = \eta$$

Calculating spring parameters and resentence

The muscle is modeled with a spring and with formulas, the spring constant, resistance and contraction force can be checked.

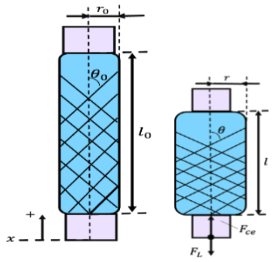
Formula 14 – spring parameters calculation formula

$$s_i P^i \sum_{i=0}^{n} = S(P)$$

Formula 15 – muscle resentence calculation formula

$$d_i P^i \sum_{i=0}^{n} = D(P)$$

Figure 5-Calculating spring parameters and resentence



Muscle dynamics

With the following formula, the relationship between muscle resistance and contraction force can be obtained.

Formula 16 – equation of muscle motion calculation

$$F_L - F_{ce} = S_x + D_{\dot{x}} + M_{\ddot{x}}$$

M is muscle mass , D is resistance coefficient , S is spring constant , F_L ad F_ce are foreign force and contraction force

With the following formula, you can compare the ratio of longitudinal and transverse muscle changes with internal pressure.

Formula 17- equation of muscle motion calculation formula

$$\pi r_0^2 P[a(1 - \epsilon)^2 - b] = F_{ce}$$

r_0 and P are initial radius and initial pressure , (a,b) are mesh angle , ϵ is ratio of initial and current length

Time-Dependent Pressure Dynamics

Air pressure inside the muscle changes over time due to valve dynamics, air compressibility, and internal volume changes.

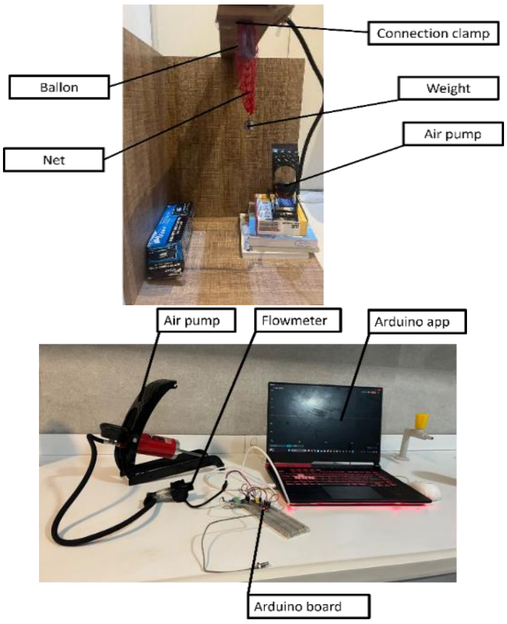
Formula 18- muscle time dependent pressure dynamics calculation formula

$$P(t) = \frac{\dot{Q}_{in} - Q_{out}}{v(t)}$$

3.Material and method

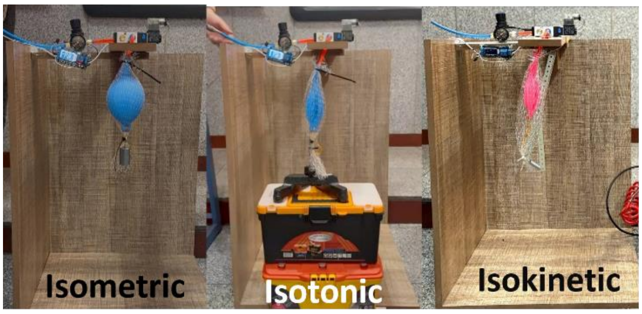
This pneumatic muscle design began with a series of basic experiments using a plain air compressor, balloon, and mesh netting. Some volumes of air and air flow rates were tested to a hyperelastic inner bladder, various tests were conducted while varying the size and wall thickness of the balloons. These tests were conducted to figure out the most suitable type that would display high elasticity along with long-term viability under repeated inflation cycles. Simultaneously, different net materials like polyethylene, polyester, and other elastic materials were experimented with to determine their elastic characteristics and structural performance. The objective was to select a mesh that is capable of providing the necessary external constraint with smooth and uniform contraction. Additional experiments were performed using nets of various lengths to explore stress distribution along the muscle body and to obtain symmetric and effective contraction. This iterative process of material selection and performance test was the foundation from which a feasible, inexpensive, and efficient pneumatic muscle prototype could be built.

Figure 6– first setup design



- To achieve high precision in testing, the applied air pressure was precisely controlled with a pressure regulator, and the cycle of the contraction time was controlled by a solenoid valve connected to a programmable timer.
- The purpose of this experimental setup was to analyze the impact of various parameters on the new pneumatic muscle design's performance, in an effort to establish optimum operating conditions. The setup was also designed to test the muscle's capability to perform all three muscle contractions of biological muscles: concentric, eccentric, and isometric.
- All the experiments were recorded on a high-definition camera at 240 frames per second(HD 240 FPS) to capture detailed motion analysis and to allow accurate data collection.

Figure 7 – different muscle contraction setup design



3-2- Experimental details

Test 1: The amount of air in the balloon

The amount of air inside the balloon effects the jump pressure and stress and strain. 3 tests were conducted for this parameter:

1-In18cm^3, the desired contraction does not occur and the efficiency is low.

2-In54cm^3, the stretch is excessive.

3-In36cm^3, we have the best condition.

Table1- Investigating the effect of amount of air on muscle properties data

Weight (g)	$18cm^3$	$36cm^3$	$54cm^3$
Net angle (°)	61.9	73.5	55.4
Curve slope(°)	1.93	2.80	1.50
Tensile stress (net)	0.07	0.105	0.21
Tensile stress (ballon)	0.036	0.035	0.80
Poisson ratio	0.01	0.16	0.33
Thickness change (μm)	0.61	0.76	0.81
Area deformation	3.98	4.90	6.22
Hooke's law(ballon)(N)	43.29	44.92	106.76
Hooke's law (net)(N)	106.76	110.89	98.54
Jump pressure (pa)	170.00	187.00	215.00

Test 2: The speed of air inserting the balloon

The speed of air is effective on Bernoulli's principle. When the speed is low, the air is spread more inside the balloon, but when the speed increases, the air is concentrated in 1 point that would make the lower speed(3.6 m/s) the best condition.

Table 2- Investigating the effect of air inserting speed on muscle properties data

Speed ($\frac{cm}{s}$)	7.2	3.6
Net angle (°)	50.22	73.5
Curve slope(°)	1.93	2.80
Tensile stress (net)	0.0531	0.105
Tensile stress (ballon)	0.017	0.035
Poisson ratio	0.02	0.16
Thickness change (μm)	0.71	0.76
Area deformation	4.99	4.90
Hooke's law (ballon)(N)	60.49	44.92
Hooke's law (net)(N)	150.49	110.89
Jump pressure (pa)	108.00	187.00

Test 3: Nazel angle

Nazel angle is effective in pressure distribution in the balloon. 3 tests were conducted in which the 0 degrees was the best condition due to the uniform pressure distribution.

Table 3- Investigating the Nazel angle on muscle properties data

Nazel angel (°)	20-R	20_l	0	45_R	45_L
Net angle (°)	80		73.5	87	
Curve slope(°)	2.36	1.6	2.80	1.55	1.84
Tensile stress (net)	0.06	0.09	0.105	0.03	0.02
Tensile stress (ballon)	1.21	1.27	0.035	0.6	0.01
Poisson ratio	0.96	0.56	0.16	1.25	0.98
Thickness change ($\frac{J}{\mu m^2}$)	4.98	3.07	0.76	3.02	2.03
Area deformation	2.56	1.56	4.90	3.56	2.98
Hooke's law (ballon)(N)	246.38	160.38	44.92	515.98	293.98
Hooke's law (net)(N)	614.48	399.48	110.89	1288.44	733.48
Jump pressure (pa)	225	581	187.00	304.00	763.00

Test 4:- amount of weight

By testing the amount of weight, it can be shown that the muscle is capable of lifting light and heavy weights.3 tests were conducted for this parameter.

The best condition is 100g weight due to the lower elongation (the 50g was too light) But the muscle was able to lift up 200g too.

Table4 – Investigating the effect of amount of weight on muscle properties data

Weight (g)	50g	100g	200g
Net angle (°)	66.6	73.5	85.7
Curve slope(°)	1.93	2.80	9.31
Tensile stress (net)	0.0531	0.105	0.239
Tensile stress (ballon)	0.017	0.035	0.80
Poisson ratio	0.02	0.16	0.23
Thickness change (μm)	0.71	0.76	0.82
Area deformation	4.99	4.90	4.46
Hooke's law (ballon)(N)	60.49	44.92	40.59
Hooke's law (net)(N)	150.49	110.89	98.54
Jump pressure (pa)	285.00	187.00	604.00

Test 5: length of net

The length of net effects the stress and strain.3 tests were conducted for this parameter:

1- At 15 cm, the net was too short and did not allow the desired contraction, in other words, it restricted the balloon.

2- At 35 cm, the net was too long, letting the balloon to move freely and to become too unrestricted, when it should have some limits.

3-At 25cm, the length gave a net to balloon ration of 5 to 1, the best condition.

Table 5- Investigating the effect of length of net on muscle properties data

Length (cm)	15 cm	25 cm	35 cm
Net angle (°)	57.6	73.5	49.1
Curve slope(°)	1.5	2.80	0.2
Tensile stress (net)	0.07	0.105	0.07
Tensile stress (ballon)	0.07	0.035	0.07
Poisson ratio	0.01	0.16	0.23
Thickness change ($\frac{J}{\mu m^2}$)	0.56	0.76	0.70
Area deformation	2.03	4.90	2.16
Hooke's law (ballon)(N)	22.5	44.92	21.15
Hooke's law (net)(N)	53.65	110.89	53.65
Jump pressure (pa)	108.00	187.00	617.00

Test 6: Elasticity and flexibility of net

Choosing a muscle net with higher elasticity makes the muscle more flexible and resilient; that would make the muscle contraction and relaxation easier.

In the tests, 3 types of net, poly ester, poly ethylene and foam, were used. The best condition was poly ethylene, due to its higher elasticity compared to foam, witch tore during the test because of its low elasticity that couldn't withstand the force of the balloon's contraction, and poly ester.

Table 6- Investigating the elasticity and flexibility of net on muscle properties data

Net's material	Foam	Poly ethylene	Poly ester
Net angle (°)	82.2	73.5	14.2
Curve slope(°)	1.76	2.80	5.00
Tensile stress (net)	0.07	0.105	0.07
Tensile stress (ballon)	0.03	0.035	0.04
Poisson ratio	0.52	0.16	1.90
Thickness change ($\frac{J}{\mu m^2}$)	0.12	0.76	0.01
Area deformation	4.70	4.90	4.66
Hooke's law (ballon)(N)	38.24	44.92	42.34
Hooke's law (net)(N)	94.14	110.89	104.39
Jump pressure (pa)	1.78	187.00	857.00

Test 7: Pressure exerted by the balloon wall

The elasticity of the air cushion in the muscle affects the pressure exerted by it. As a result, it affects the rate of muscle contraction.

3 tests were conducted for this experiment in which the 11 inches was the best condition due to the higher efficiency with less air volume.

Table 7- Investigating the Pressure exerted by the balloon wall on muscle properties data

Ballon size (")	5	11	16
Net angle (°)	51.0	73.5	35.8
Curve slope(°)	5.0	2.80	0.87
Tensile stress (net)	0.14	0.105	0.07
Tensile stress (ballon)	0.02	0.035	0.01
Poisson ratio	0.15	0.16	1.54
Thickness change ($\frac{J}{\mu m^2}$)	0.70	0.76	0.01
Area deformation	5.17	4.90	4.00
Hooke's law (ballon)(N)	42.40	44.92	33.98
Hooke's law (net)(N)	104.53	110.89	83.49
Jump pressure (pa)	557.00	187.00	197.00

Test 8: Balloon wall thickness

The wall thickness test is to determine the best thickness for the muscle fiber wall, which affects elasticity and jump pressure that are directly related to each other. In 20μ test, the elasticity is excessive and as a result, the jump pressure is highly increased and due to that, the balloon does not inflate at all. 10μ was the best condition in this parameter

Table 8- Investigating the effect of balloon wall thickness on muscle properties data

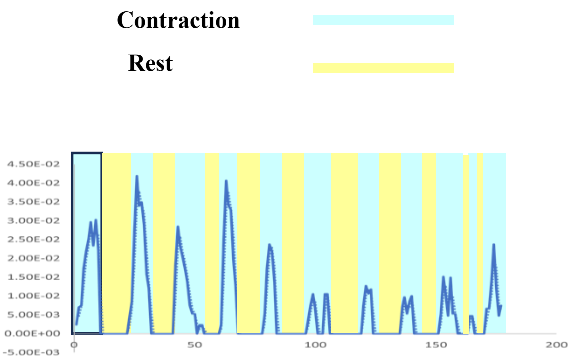
Wall thickness (μm)	**20**	**10**
Net angle (°)	**Doesn't happen**	73.5
Curve slpe(°)		2.80
Tensile stress (net)		0.105
Tensile stress (ballon)		0.035
Poisson ratio		0.16
Thickness change ($\frac{J}{\mu m^2}$)		0.76
Area deformation		4.90
Bending energy (J)		9.00
Hooke's law (ballon)(N)		44.92
Hooke's law (net)(N)		110.89
Jump pressure (pa)		187.00

4. Results & Discussion

Analysis guide:

The diagram below shows muscle's contraction and relaxation. The peak part of the graph shows the contraction and the zero part of the graph shows the relaxation of the muscle.

Chart 1- muscle's contraction & relaxation



For better analysis and to show muscle contraction, FFT was calculated to determine the peak point of the graph. Due to the wall wave, the balloon creates noise in the system, which is removed from the system using FFT and a clearer analysis of the graphs and motion peaks is obtained.

Formula 19 - FFT magnitude

$$X_k = \frac{1}{N}\sum_{n=0}^{N-1} p_n e^{\frac{i2\pi nk}{N}}$$

Chart 2- FFT magnitude velocity plot

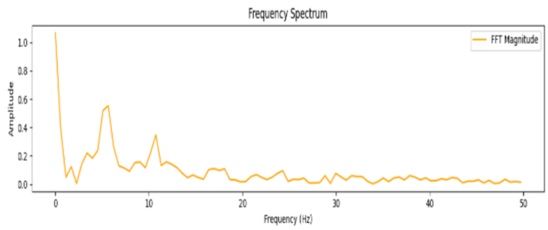
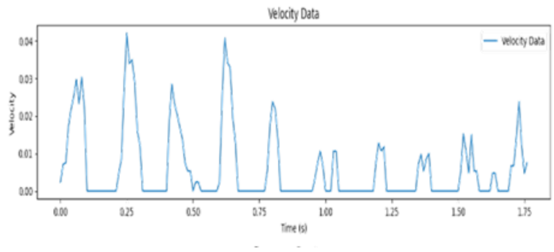


Chart3- Velocity data plot



Error calculating:

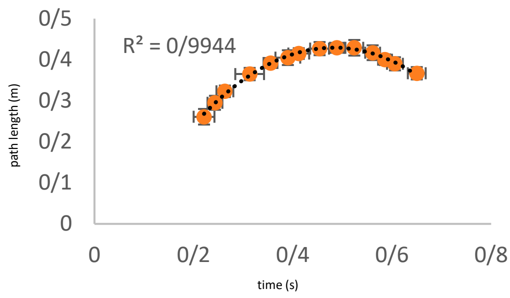
An equation was considered to calculate the amount of test error.

Formula 20 _ error calculating

$$\Delta Q = \sqrt{\left(\frac{\partial Q}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial Q}{\partial x_2}\Delta x_2\right)^2 + \cdots}$$

Error = ± 0.01

Chart 4- error calculating plot



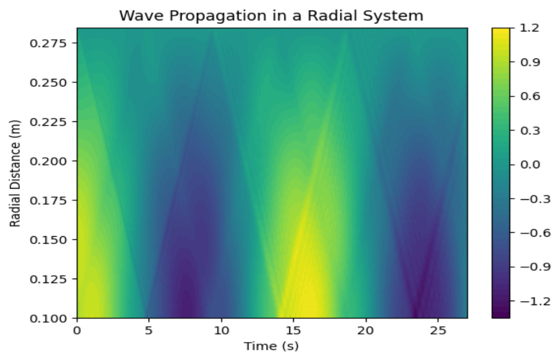
Analysis 1: Investigating the effect of amount of air on muscle properties*(charts)*

Velocity and acceleration graph: It can be seen in velocity and accelerations graphs that as the volume of air inside the balloon increases, the speed of muscle movement decreases, but due to the density of the air and the capacity of the balloon, a balloon that is filled with 36 cm^3 of air experiences a higher peak**.**

Displacement diagram: This diagram shows that a large volume of air experiences a lower peak due to the compression of the air inside the balloon, but displacement decreases as the air increases.

- In this study, chromatic plots were utilized to visualize the distribution of key physical parameters such as internal pressure, deformation, and stress across the structure of the pneumatic muscle during dynamic simulations. These plots use color gradients to represent the magnitude of each parameter, allowing for immediate identification of non-uniformities or critical stress zones. Regions with higher values are typically shown in warm colors (e.g., red, orange), while lower values appear in cooler tones (e.g., blue, green). This visual approach enables a more intuitive assessment of the system's performance under varying load conditions, and plays a vital role in optimizing the design by highlighting structural weaknesses and areas requiring refinement.

Chromatic chart 1-Wave propagation in a radial system



18 cm^3 air amount chromatic wave plot analysis:

Wave Characteristics: Localized patterns with gradual, smooth transitions.

Amplitude: Ranges from -4.445 to 4.445, indicating lower energy dissipation.

Radial Distance: Spans from 0.204m to 0.291m.

Interpretation: The system is less constrained, allowing more fluid wave motion. Reduced stiffness or damping is evident in significant wave propagation.

36 cm^3 air amount chromatic wave plot analysis:

Wave Characteristics: Sharper waves with well-defined peaks and troughs, indicating higher frequencies.

Amplitude: Slightly larger, ranging from -1.44 to 1.08, suggesting more energetic motion.

Radial Distance: Narrower, spanning 0.1 m to 0.18 m, reflecting increased constraints.

Interpretation: The system balances flexibility and tension, leading to higher frequencies and moderate wave energy.

54 cm^3 air amount chromatic wave plot analysis:

Wave Characteristics: Localized patterns with gradual, smooth transitions.

Amplitude: Ranges from -4.445 to 4.445, indicating lower energy dissipation.

Radial Distance: Spans from 0.204m to 0.291m.

Interpretation: The system is less constrained, allowing more fluid wave motion. Reduced stiffness or damping is evident in significant wave propagation.

Analysis 2: Investigating the effect of air inserting velocity on muscle properties (charts)

Velocity and acceleration diagram: It is observed in the velocity and acceleration diagrams that as the speed of the incoming air increases, the speed and acceleration of the muscle movement decreases and it is also observed that the balloon with a lower incoming air speed experiences a higher peak.

Displacement diagram: As the speed of the incoming air increases, less displacement occurs and also the lower peak belongs to the muscle to which the air entered at a higher speed.

Low velocity air inserting chromatic wave plot analysis:

Wave Characteristics: Sharper waves with well-defined peaks and troughs, indicating higher frequencies.

Amplitude: Slightly larger, ranging from -1.44 to 1.08, suggesting more energetic motion.

Radial Distance: Narrower, spanning 0.1 m to 0.18 m, reflecting increased constraints.

Interpretation: The system balances flexibility and tension, leading to higher frequencies and moderate wave energy.

High velocity air inserting chromatic wave plot analysis:

Wave Characteristics: Localized patterns with gradual, smooth transitions.

Amplitude: Ranges from -4.445 to 4.445, indicating lower energy dissipation.

Radial Distance: Spans from 0.204m to 0.291m.

Interpretation: The system is less constrained, allowing more fluid wave motion. Reduced stiffness or damping is evident in significant wave propagation.

Analysis 3: Investigating the effect of nazel angle on muscle properties

Velocity and acceleration diagram: It can be seen in the velocity and acceleration diagrams that increasing the nozzle angle increases the speed and acceleration of muscle movement.

Displacement diagram: Increasing the nozzle angle results in less displacement.

20 degrees nazel angle chromatic wave plot analysis:

Wave Characteristics: Data shows longer wavelengths with smoother, widely spaced wavefronts.

Amplitude: Moderate, ranging from -1.2 to 1.2, indicating balanced energy distribution.

Radial Distance: Larger range, spanning from 0.1 m to 0.26 m, suggesting a less constrained system.

Interpretation: The system allows for slower propagation and broader wave motion, likely due to lower stiffness or damping.

0 degrees nazel angle chromatic wave plot analysis:

Wave Characteristics: Sharper waves with well-defined peaks and troughs, indicating higher frequencies.

Amplitude: Slightly larger, ranging from -1.44 to 1.08, suggesting more energetic motion.

Radial Distance: Narrower, spanning 0.1 m to 0.18 m, reflecting increased constraints.

Interpretation: The system balances flexibility and tension, leading to higher frequencies and moderate wave energy.

45 degrees nazel angle chromatic wave plot analysis:

Wave Characteristics: Longer wavelengths with smoother, widely spaced wavefronts.

Amplitude: Moderate, ranging from -1.25 to 1.00, indicating balanced energy distribution.

Radial Distance: Larger range, spanning from 0.10 m to 0.35 m, suggesting a less constrained system.

Interpretation: The system allows for slower propagation and broader wave motion, likely due to lower stiffness or damping.

Analysis 4: Investigating the effect of amount of weight on muscle properties

Velocity and acceleration diagram: In the velocity and acceleration diagrams, it is observed that with increasing mass of the system, the velocity and acceleration of the muscle movement increases up to 100 grams of weight, but then decreases.

Displacement diagram: With increasing mass of the system, the displacement of the muscle decreases.

50 g weight chromatic wave plot analysis:

Wave Characteristics: Smooth waves with broader wavefronts and lower frequencies.

Amplitude: Moderate, ranging from approximately -1 to 1, indicating low energy dissipation.

Radial Distance: Extensive, spanning 0.1 m to 0.35 m, with minimal confinement.

Interpretation: The system exhibits high flexibility and low internal resistance at this weight.

Wave Characteristics: Sharper waves with well-defined peaks and troughs, indicating higher frequencies.

Amplitude: Slightly larger, ranging from -1.44 to 1.08, suggesting more energetic motion.

Radial Distance: Narrower, spanning 0.1 m to 0.18 m, reflecting increased constraints.

Interpretation: The system balances flexibility and tension, leading to higher frequencies and moderate wave energy.

200g weight chromatic wave plot analysis:

Wave Characteristics: Highly localized waves with steep, well-defined fronts.

Amplitude: Significantly lower, ranging from -0.0006 to 0.0006, indicating high energy dissipation.

Radial Distance: Smallest, spanning 0.1 m to 0.2 m, due to considerable tension or damping.

Interpretation: The system is highly constrained, with increased stiffness or damping suppressing wave motion.

Analysis 5: Investigating the effect of length of net on muscle properties

Velocity and acceleration diagram: In the velocity and acceleration diagrams, it is observed that the increase in the length of the net has a range when the ratio of the length of the net to the balloon is 3 to 1 to a ratio of 4 to 1, the speed and acceleration trend is increasing and then there is a decreasing trend.

Displacement diagram: The increase in the length of the net has a range when the ratio of the length of the net to the balloon is 3 to 1 to a ratio of 4 to 1, the speed and acceleration trend is increasing and then there is a decreasing trend. Also, the artificial muscle with a net length of 25 cm experiences a higher peak.

- The range should be a ratio of 1 to 5.

15 cm net length chromatic wave plot analysis :

Wave Characteristics: Shorter wavelengths with densely packed, rapid oscillations.

Amplitude: Higher, ranging from -1.5 to 1.5, reflecting greater energy in the system.

Radial Distance: Smaller range, spanning 0.1 m to 0.22 m, indicating a more constrained system.

Interpretation: The system is highly constrained, with increased stiffness or boundary effects leading to faster wave propagation and higher frequency.

25 cm net length chromatic wave plot analysis:

Wave Characteristics: Sharper waves with well-defined peaks and troughs, indicating higher frequencies.

Amplitude: Slightly larger, ranging from -1.44 to 1.08, suggesting more energetic motion.

Radial Distance: Narrower, spanning 0.1 m to 0.18 m, reflecting increased constraints.

Interpretation: The system balances flexibility and tension, leading to higher frequencies and moderate wave energy.

35 cm net length chromatic wave net plot:

Wave Characteristics: Longer wavelengths with smoother, widely spaced wavefronts.

Amplitude: Moderate, ranging from -1.2 to 1.2, indicating balanced energy distribution.

Radial Distance: Larger range, spanning 0.1 m to 0.26 m, suggesting a less constrained system.

Interpretation: The system allows for slower propagation and broader wave motion, likely due to lower stiffness or damping.

Analysis 6: Investigating the effect material of net on muscle properties

Velocity and acceleration diagram: It can be seen in the velocity and acceleration diagrams that as the elasticity of the mesh increases, the velocity and acceleration of the muscle movement also increase.

Displacement diagram: Increasing the elasticity of the mesh increases the peak of the muscle movement.

Foam net chromatic wave plot analysis:

Wave Characteristics: Data shows longer wavelengths with smoother, widely spaced wave fronts.

Amplitude: Moderate, ranging from -1.2 to 1.2, indicating balanced energy distribution.

Radial Distance: Larger range, spanning from 0.1 m to 0.26 m, suggesting a less constrained system.

Interpretation: The system allows for slower propagation and broader wave motion, likely due to lower stiffness or damping.

Poly ethylene net chromatic wave plot analysis:

Wave Characteristics: Sharper waves with well-defined peaks and troughs, indicating higher frequencies.

Amplitude: Slightly larger, ranging from -1.44 to 1.08, suggesting more energetic motion.

Radial Distance: Narrower, spanning 0.1 m to 0.18 m, reflecting increased constraints.

Interpretation: The system balances flexibility and tension, leading to higher frequencies and moderate wave energy.

Poly ester net chromatic wave plot analysis:

Wave Characteristics: Longer wavelengths with smoother, widely spaced wavefronts.

Amplitude: Moderate, ranging from -1.25 to 1.00, indicating balanced energy distribution.

Radial Distance: Larger range, spanning from 0.10 m to 0.35 m, suggesting a less constrained system.

Interpretation: The system allows for slower propagation and broader wave motion, likely due to lower stiffness or damping.

Analysis 7: Investigating the effect of size of balloon on muscle properties

6” ballon size chromatic wave plot analysis:

Wave Characteristics: Longer, smoother wavefronts, indicating slower propagation and lower stiffness.

Amplitude: Similar range (-1.44 to 1.08) with smoother energy distribution.

Radial Distance: Larger range (0.10 m to 0.20 m), reflecting a less constrained system.

Interpretation: A more elastic system with broader wave motion and lower damping.

11” ballon size chromatic wave plot analysis:

Wave Characteristics: Sharper waves with well-defined peaks and troughs, indicating higher frequencies.

Amplitude: Slightly larger, ranging from -1.44 to 1.08, suggesting more energetic motion.

Radial Distance: Narrower, spanning 0.1 m to 0.18 m, reflecting increased constraints.

Interpretation: The system balances flexibility and tension, leading to higher frequencies and moderate wave energy

16” ballon size chromatic wave plot analysis:

Wave Characteristics: Moderate wavelength with sharper, closely spaced wavefronts, indicating faster propagation and higher stiffness.

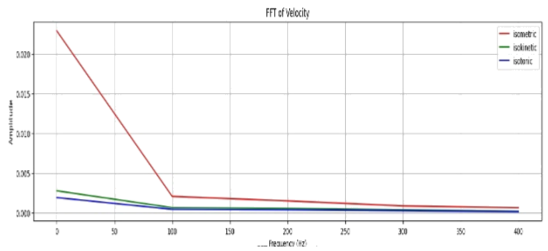
Amplitude: Balanced energy with a range of -1.44 to 1.08, showing efficient energy transmission.

Radial Distance: Limited range (0.10 m to 0.18 m), suggesting a more constrained system.

Interpretation: A stiffer system with quicker wave propagation and strong reflections.

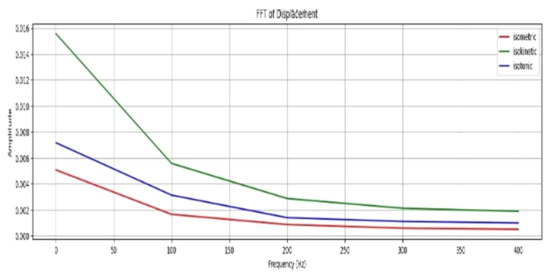
Velocity and displacement comparison in 3 types of contraction:

Chart 5 –FFT velocity plot for different contractions



According to the chart above, it can be seen that the velocity in isometric is higher than the other two, likely due to the unconstrained muscle structure that would allow smoother and faster movement for the muscle.

Figure 6 –FFT displacement plot for different contractions



The scaffolds in the isokinetic muscle setup are likely the reason of the higher displacement in this setup, due to the extra force they exert on the muscle.

3-2- Results

Parameter air inserting amount: The relation between pressure in balloon wall (amount of air) and function of muscle.

It could be seen that by increasing the volume of air the pressure dependence on wall would be increase too.

So, contractile force (N) has negative relationship, work done (J) and efficiency has positive relationship.

Parameter air inserting velocity: The relation between the air inserting velocity and function of muscle.

It could be seen that by increasing the velocity of air the pressure dependence on wall would be decrease.

So, contractile force (N) has positive relationship, work done (J) and efficiency has positive relationship, too.

Parameter nazel angle: The relation between the Nazel angle and function of muscle.

It could be seen that by increasing the nazel angle the pressure dependence on wall would be increase too.

So, contractile force (N) has negative relationship, work done (J) and efficiency has positive relationship.

Parameter over load weight: The relation between the amount of weight and function of muscle.

It could be seen that by increasing the system weight up to 100 g the pressure dependence on wall would be decrease but after it, it would be increase .

So, contractile force (N) has negative relationship, work done (J) and efficiency has positive relationship .

Parameter net length: The relation between the length of net and function of muscle.

It could be seen that by increasing the net length up to 25cm the pressure dependence on wall would be decrease but after it, it would be increase.

So, contractile force (N) has negative relationship, work done (J) and efficiency has positive relationship.

Parameter net material: The relation between the material of net and function of muscle.

It could be seen that by increasing the elasticity of the net the pressure dependence on wall would be increase too.

So, contractile force (N) has negative relationship, work done (J) and efficiency has positive relationship.

Parameter balloon size: The relation between the balloon size and function of muscle.

It could be seen that by increasing the elasticity of the net the pressure dependence on wall would be increase too.

So , contractile force (N) has negative relationship, work done (J) and efficiency has positive relationship .

5. Conclusion

5-1- Checking the correctness and incorrectness of the hypotheses:

The parameters that had the same value in the hypothesis and the result include the following parameters:

1. The amount of air, which is the best amount is 36 cm^3.
2. Nazel angle, the best value of which is zero degrees.
3. The amount of weight that is best is 100 grams.
4. The length of the net, which is the best, is 25 cm.
5. The size of the balloon is 11 inches.
6. The thickness of the wall, which is 10 mm.

The parameters that had a different value in the hypothesis and the result include the following parameters:

1. The speed of air inserting: the best condition in the hypothesis is 7.2$^{m}/_{s}$, but as a result of the tests, it was recorded as 3.6$^{m}/_{s}$.
2. Net material: the best condition is polyester in the hypothesis, but as a result of the tests, poly ethylene was registered.

The hypothesis of the test was that in all tests (air amount, air inserting speed, Nazel angle, weight size, net length, net material, balloon size, wall thickness), with the increase of each parameter, the muscle contraction decreases, but the efficiency and work of the muscle increases. This hypothesis was correct in 7 of the tests, but it was wrong in the air inserting speed test. In this test, the contraction force has an inverse relationship with the speed value.

5-2- Consequence

Elasticity is defined as proteins that proteins and power increase but pressure and contraction decreases.

Inside pressure is defined as ATP that ATP, pressure and power increase but the contraction decreases.

Inside pressure is defined as fiber muscle that fiber of muscle, pressure, contraction and power increase.

Best muscle condition:

The best condition of muscle have specified based on parameters.

Table 9- best muscle condition

Parameter	Best condition
Air amount	$36cm^3$
Air inserting speed	$3.6\ ^{m}/_{s}$
Nazel angle	0 °
Weight amount	100 g
Net length	25 cm
Net material	Poly ester
Balloon size	11”
Wall thickness	10μ

5-3- Comparison the price of pneumatic muscles and the project muscle

For building this muscle, an air compressor (20-35 $), an air regulator (10-13$), a pneumatic solenoid valve (13-15$), a digital timer (6-9$), a latex balloon, (0.5-1$), 12v adaptor (7-9$), 2 scaffolds (6-7$) and some fittings (8-10$) were used. By considering the building process cost (14-22$) this project is 84.5-121 dollars. Which is 2-4 times cheaper than Festo muscles (220-388$).

5-4- Comparison of the SWOT of pneumatic muscles and the project muscle

The **Strengths** of pneumatic muscles are accuracy in force and pressure control and being repairable. The strengths of the project muscle are having higher elasticity, lower price, lower weight and uniform pressure distribution.

The **Weaknesses** of pneumatic muscles are the need for compresses air supply, having higher price and higher weight. The weaknesses of the project muscle are being sensitive to environmental changes and the need to be completely replaced if it is damaged.

The **Opportunities** of pneumatic muscles include medical use, robotic use, automation use and capable for hard tasks. The opportunities of the project muscle includes experimental and educational use, using in simple prostheses for patients, more eco-friendly, combining with other materials for better outcomes and potential for development in future research .

The **Threat** of pneumatic muscles are high pressure safety risk. The threats of the project muscle includes competition with pneumatic muscles and low resistance to impact and wear.

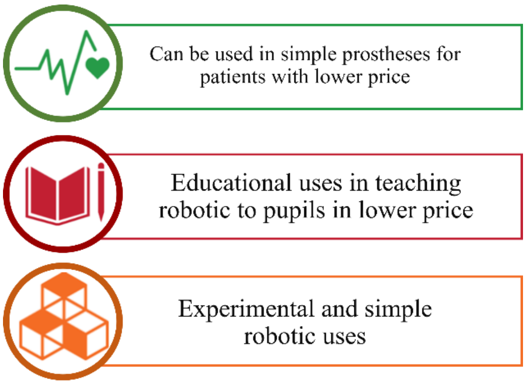
SWOT strategies:

Strengths and opportunities that cover the project’s weaknesses and threats:

1. Less durable - covered with the low cost and accessible materials
2. Not suitable for long-term/industrial use – covered with simple construction and the potential of further research and upgrades
3. Performance inconsistency or breakage – covered by low costs and the potential of further research and upgrades
4. competition with pneumatic muscles – covered by the higher efficiency and elasticity, lower price and weight and potential for development in future research

5-5- UN SDG

This project support this parts in UN SDG.



5-6- LCA comparison

According to the LCA analysis of this project and the pneumatic muscles, the energy consumption in this project is lower than regular pneumatic muscles due to the higher efficiency. The life cycle in this project is shorter than pneumatic muscles, but it can be fixed by changing the air cushion material into something more resistance-to-damage, like RTV (room temperature vulcanizing) silicon or cathedral balloons, in future researches. In recycling, both sides are using some non-recyclable materials, but the environmental effects of this project is way lower than the pneumatic muscles due to the more simple materials and low energy consumption. In general, this project has achieved better results in this comparison and could have better chances in the industry cycle.

5-7- Out look

This project is a wiser choice to be used in soft robotics, robotic factory arms and simple prosthesis than previous pneumatic muscles due to the higher efficiency, less cost and also, being more eco-friendly, due to its less energy consumption. Since this project is at student level further research is needed to reach the commercial level. Using a more resistance-to-damage material to replace the balloon, like RTV (room temperature vulcanizing) silicon or cathedral balloons, some weaknesses of this project will be fixed and the scope of its usage will get wider. By extensive advertising and finding a sponsor, this project can beat the other brands and take their place in this industry.

6. Acknowledgement

Thanks to the Innoverse Invention & Innovation Expo team and staff.
Thanks to Mr. Ali Valeh, the manager of Valeh educational and cultural Institute.
Thanks to Mahdi Rashidi Jahan, the head of the Iranian young science and technology center (IYSTC)
Special thanks to Mr. Mohammad Arjmand, the team's supervisor, the director of the department of creativity, research and skills training of Valeh institute.

7. References

For Contents:

1. B. Kalita, A. Leonessa, and S. K. Dwivedy. A review on the development of pneumatic artificial muscle actuators: Force model and application. Actuators 11, 10, 288 (2022)

2. B. Kalita and S. K. Dwivedy. Nonlinear dynamic response of pneumatic artificial muscle: A theoretical and experimental study. Int. J. NonLin. Mech. 125, 103544 (2020)

3. George Andrikopoulos, George Nikolakopoulos, Stamatis Manesis, Pneumatic artificial muscles: A switching Model Predictive Control approach,Control Engineering Practice,Volume 21, Issue 12,2013,Pages 1653-1664

4. I. M. Petre. Studies regarding the use of pneumatic muscles in Precise Positioning Systems. Appl. Sci. 11, 21, 9855 (2021)

5. Ingo muller , inflating ballon , 2002

6. Kalita, B.; Leonessa, A.; Dwivedy, S.K. A Review on the Development of Pneumatic Artificial Muscle Actuators: Force Model and Application. Actuators 2022, 11, 288.

7. Kotkas, L.; Zhurkin, N.; Donskoy, A.; Zharkovskij, A. Design and Mathematical Modeling of a Pneumatic Artificial Muscle-Actuated System for Industrial Manipulators. Machines 2022, 10, 885.

8. W. S. W. A. Najmuddin and M. T. Mustaffa. A study on contraction of pneumatic artificial muscle (PAM) for load-lifting. J. Phys.: Conf. Ser. 908, 012036 (2017)

9. : Zabihollah, S.; Moezi, S.A.; Sedaghati, R. Design Optimization of a Miniaturized Pneumatic Artificial Muscle and Experimental Validation. Actuators 2023, 12, 221.

For muscle’s cost:

1. https://www.amazon.com/Powools-Inflator-Portable-Compressor-Motorcycle/dp/B0DDTBGF1G/ref=mp_s_a_1_20?crid=3G4W80OYFZ0UI&dib=eyJ2IjoiMSJ9.7VC4Mw-VHF40HxECTxSzrNvJZFhIk9wvSIZhuk1MDNs9Z4NMMkRtx25cBL8IZyYDxHLJVqwpYH465dNTmKqGClVgUbyKGFvJeg0sSKoLu0O2Wmb-L37Vtw5ERHxQJOwEMOc6gOQrq-uSoXz-PoS2OTpMyMu8ipjB4T0H7lwHlBfZs6tO0K3u6uh2wo7UXlgINihQN8vgPF92HUR2aW3iwQ.b9_PMqaZgLdNSsK_IOCi7BYFJDnExaOKHJ6_2auus24&dib_tag=se&keywords=compressor+air+compressor&qid=1754472382&sprefix=%2Caps%2C1165&sr=8-20&xpid=yYfUXUVWlljcS
2. https://www.amazon.com/Regulator-Compressor-Precision-Compressed-AR2000-02/dp/B0DQPLYJ1X/ref=mp_s_a_1_24?crid=2AO4LAIZ5VKCP&dib=eyJ2IjoiMIj9.YcTCLF1DsII7vJMniiauavdul0gDYgDY3OWdzBbQQSeL2ij7T7iRjOWlP9S4VO0tQslccpGDTWS_Qx8S5eq_QKmiviQKmiviiCuzxBATZaC_vGgqy_fTCbIDEf_y-ubOqq-sKsbVfqc8sAFg11QJNMm3wV60B8FLaFL0t_hbn7kwoPDb92d0IJ1qgYdpJSD-I0fcAvoeET5G_8Yo2WoIsg.6GCU9baJXlbaJXlAzc4GorMwGi2JuIyYK3GBxfTbG30&dib_tag=se&keywords=air+regulator&qid=1754472523&sprefix=air+regulato%2Caps%2C479&sr=8-24&xpid=7P_KVBWcIp_kX
3. https://www.amazon.com/EBEIZZI-Pneumatic-Solenoid-Pilot-Operated-Connection/dp/B0F3CYVTDR/ref=mp_s_a_1_14?cr

id=3BEG704LGGXTP&dib=eyJ2IjoiMSJ9.ckN07ZUNnO19qPgTHDR19eYckK3-ddpnrKtVhKnEjKQlh3IjUvmI0AChU5LIgDF5idgCJqQOaNZXtWJ5kZYQ5zD_NpSNEGyX3OjKmcVN-
4. https://www.amazon.com/XY-LJ02-Display-Digital-Control-Trigger/dp/B0CP77BK4R/ref=mp_s_a_1_8?crid=LFDERUN9W7EV&dib=eyJ2IjoiMSJ9.nRR7z6Io0Dhg0uNEPeJe9oFyHxow6k4cy3SYFW1NsEhUswWRjBBGwuGEVviWqEUl1OOVq1jGN3IDshBl-UcUAUs572Ivq5ZyB5m6uzPh-ogq93VcSl3IoMb74eIAY8jzEN-hjSYSTDaxRFM5-YUpNAxBlIRoUIBhCHyKUacXvtF8cV00VNlDh9giSCvGgs6vLskNazhO3eLvGlPYw5ndIA.MI8JGlQYvmBxKx3vb_8xI0cF71PuNVL9EI8TqeEcQwE&dib_tag=se&keywords=xy-j02+timer+module&qid=1754472737&sprefix=xy+_+j02+%2Caps%2C605&sr=8-8
5. https://www.amazon.com/Oatey-33923-Galvanized-Hanger-Bagged/dp/B000FSVUDS/ref=mp_s_a_1_1?crid=2D9P887YH4Z3R&dib=eyJ2IjoiMSJ9.bZ-nzgZB4weWfznzfbftJTE3H-VP0HXTMu9T2hIOyeojiGhz7_BQR-3xPZY4ud1zIs62ViMBKznYYtVORJ07Qyii5-CnuS3b1uerNyCEc7FZfg9e_7wkq_vn-MeNSWfa6tnReavYi5Kojnwj8y4IFfv3mBijRt0xzQcZMyRYpIgovksGM9rSdbLEf7dniAFA_xHWjWUKMSQfiDyV2H_EhA.I0MY829_EY6L5r3uqz3yXlIdl4If4kcbqKcou3vQQFI&dib_tag=se&keywords=perforated+metal+strip&qid=1754473260&sprefix=perforated+metal%2Caps%2C612&sr=8-1
6. https://www.amazon.com/Adapter-100-240V-Transformer-Charger-Security/dp/B091XSVV1Y/ref=mp_s_a_1_3?crid=1CML9ME5JTC77&dib=eyJ2IjoiMSJ9.YIvI5IqcVGPDiQooGl3t2EtBIMxcEZreFVAriy0PerOn_w4yZ5fhqJHyarBAXgsPjywpkpSzZGvRlilJou-l8TQx61ZErLid_vCHrq3wLYJzuUh5aTOo0nmQfry2AXVwP
7. https://www.amazon.com/Pneumatic-Connector-Connect-fittings-Straight/dp/B0D14HL2LR/ref=mp_s_a_1_28?crid=LOM52AL3GFPZ&dib=eyJ2IjoiMSJ9.euJwL3-PA2PsJNlyywh-PPUcpcde-F6DxMaquEzzoJcSXsCKakMDtR49uhPXqqiMMG0u-nXUYzh_5k_l8AyQuTP4yCkZ2exLzJdKJ8AQhCcjwXPvAqCHob-BlkyKiTxo4Gl5CwmSz8QqjVT322c2GOsp8cSO9iR0DzFJHNQz_pxLzjfBHhm25oxc-96E5WPhNwQ1nO6mODqJXyp4RtLVMQ.cEy6Tb2RMAFC386GFv1ArGeUcarnCjFfgqfi5VRP1d4&dib_tag=se&keywords=fittings+1%2F4&qid=1754473844&sprefix=fittings%2Caps%2C1454&sr=8-28&xpid=jADnYvxXuQlxW