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A Study on the Influence of the Pressure upon the Pneumatic Muscle Forces

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Abstract
The paper presents an experimental study regarding the evolution of the forces developed by a pneumatic muscle under the action of pressure. Pneumatic muscles are consisted by an elastic membrane covered with a braided structure and they act as a spring, shortening its length and increasing its diameter, under the action of compressed air. The aim of the paper is to identify the regression that corresponds to the evolution of the force developed by the pneumatic muscle in relation to the compressed air pressure. The analysis of the obtained results also highlighted the correlation between pressure and force. The measured force was then compared with the force provided by the manufacturer and some conclusions were drawn, which highlight the real possibilities of the pneumatic muscle.

Keywords
pneumatic muscle, the least squares method, correlations, force, pressure

1. Introduction

Pneumatic muscles are novel actuators, constructed by an elastic membrane covered with a braided shell according to helical weaving. The braided sleeves act to constrain the expansion for maintaining the cylindrical shape. They are acting as a spring, decreasing their length and expanding their diameter, when internal pressure is applied.

Advantages like smooth movement, higher power-to-weight ratio, smooth speed adjustment [1], and longer operating life (50 million cycles for FESTO pneumatic muscles) [2], make pneumatic muscle useful in various applications. Some examples of pneumatic muscle applications are: industrial manipulators [3], robotic arms [4, 5] and assistive devices [6, 7, 8].

Some disadvantages of using pneumatic muscles can be mentioned: the force which can be applied is only tensile in nature; its total displacement is only about 20% to 30% of its initial length; friction between the braided mesh and the tube leads to a substantial hysteresis in the force-length characteristics; rubber deformation will lower the force output of this type of muscle up to 60% [9].

The aim of the presented research is to obtain some real information about the maximum forces developed by a FESTO origin pneumatic muscle, in order to establish the possibility of using it as an actuator for a human leg assistive device. The method used proposed the applying of different pressures to the pneumatic muscle and recording the maximum forces. The evolution of the measured forces is analyzed and a comparison to the values provided by the manufacturer is made. Some mathematical expressions can be developed for describing the correlation between contraction of the pneumatic muscle and the developed force.

2. Materials and Methods

2.1. Experimental stand

For the purpose of determining the evolution of the developed forces by a pneumatic muscle in relation to pressure an experimental stand was used, as seen in Figure 1. It consists of a FESTO origin pneumatic muscle of 750 mm length and 20 mm diameter. It is fixed at one side and, at the free end of the muscle, a pulley system is mounted, which performs the horizontally movement of the slider. Other components of the experimental stand are: compressed air preparation group, 3/2 distributor with retention (hold button), pressure regulator with manometer, transducers for determining the pressure, flow rate and force.

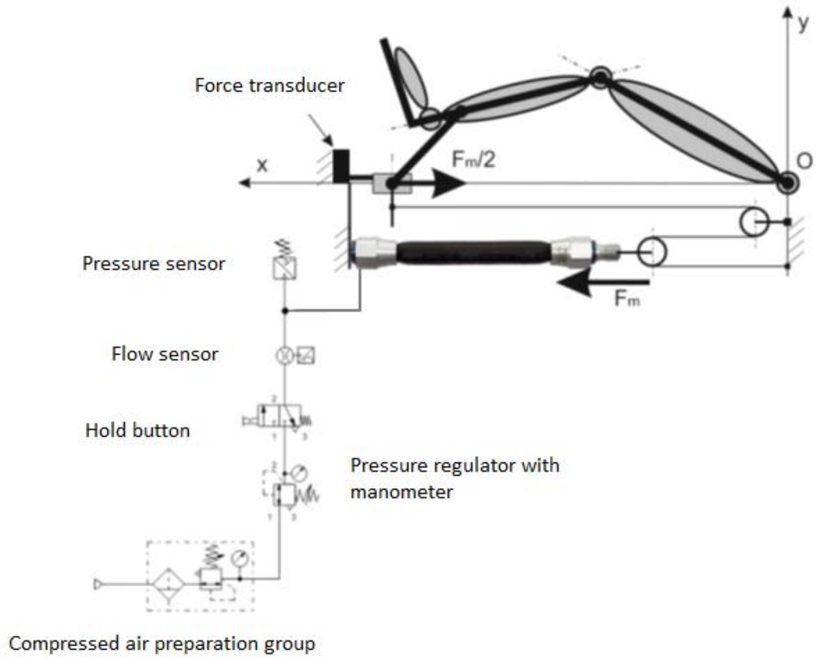

Fig. 1. Experimental stand

2.2. Methods

By means of the pressure regulator with manometer the compressed air pressure level supplied by its preparation unit is set. The hold button (3/2 distributor with retention) is actioned in order to load the pneumatic muscle. The measurement of the flow and pressure of the compressed air is carried out by means of the analogue flow sensor, positioned after the retainer button, and, respectively, with the pressure transducer, positioned close to the muscle supply connection. The stand also contains a force transducer, used to determine the maximum value of the developed by the pneumatic muscle.

The force developed by the pneumatic muscle is denoted by F_m. At the slider, due to the multiplier effect of the mobile pulley system, the size of the force, measured with the help of the transducer, becomes $F_m/2$.

3. Results and Discussion

The values obtained in the experimental determination are presented in Table 1.

Table 1. The correspondence between Pressure p and Measured Force F_m

Pressure [bar]	$F_m/2$ [N]	F_m [N]	Pressure [bar]	$F_m/2$ [N]	F_m [N]
2.7	61	122	4.4	179.94	359.88
2.8	68.99	137.98	4.5	185.88	371.76
2.9	74.92	149.84	4.6	190.89	381.78
3	83.93	167.86	4.7	200.92	401.84
3.1	89.97	179.94	4.8	204.91	409.82
3.2	97.95	195.9	4.9	209.93	419.86
3.3	104.91	209.82	5	218.94	437.88
3.4	113.15	226.3	5.1	224.87	449.74
3.5	120.98	241.96	5.2	228.86	457.72
3.6	127.94	255.88	5.3	236.85	473.7
3.7	135.93	271.86	5.4	237.87	475.74

3.8	138.89	277.78	5.5	241.86	483.72
3.9	147.925	295.85	5.6	248.93	497.86
4	155.89	311.78	5.7	255.89	511.78
4.1	159.88	319.76	5.8	259.88	519.76
4.2	164.89	329.78	5.9	264.89	529.78
4.3	174.92	349.84	6	273.9	547.8

To identify the function that describes the evolution of forces in relation to pressure, the least squares method was used. This minimizes the squares of the deviations between the given values and the calculated values, using the identified function.

The least squares method involves maximizing the similarity, the degree of resemblance of theoretical values to real values, so minimizing errors.

Table 2. The least squares method calculated values

p [bar](X_i)	F_m [N] (Y_i)	$X_i - \bar{X}$	$Y_i - \bar{Y}$	$(X_i - \bar{X}) \cdot (Y_i - \bar{Y})$	$(X_i - \bar{X})^2$
2.7	122	-1.65	-224.31	370.112	2.723
2.8	137.98	-1.55	-208.33	322.912	2.403
2.9	149.84	-1.45	-196.47	284.882	2.103
3	167.86	-1.35	-178.45	240.908	1.823
3.1	179.94	-1.25	-166.37	207.963	1.563
3.2	195.9	-1.15	-150.41	172.972	1.323
3.3	209.82	-1.05	-136.49	143.315	1.103
3.4	226.3	-0.95	-120.01	114.010	0.903
3.5	241.96	-0.85	-104.35	88.698	0.722
3.6	255.88	-0.75	-90.43	67.823	0.562
3.7	271.86	-0.65	-74.45	48.393	0.422
3.8	277.78	-0.55	-68.53	37.692	0.303
3.9	295.85	-0.45	-50.46	22.707	0.203
4	311.78	-0.35	-34.53	12.086	0.123
4.1	319.76	-0.25	-26.55	6.638	0.063
4.2	329.78	-0.15	-16.53	2.480	0.022
4.3	349.84	-0.05	3.53	-0.176	0.002
4.4	359.88	0.05	13.57	0.679	0.003
4.5	371.76	0.15	25.45	3.818	0.023
4.6	381.78	0.25	35.47	8.867	0.063
4.7	401.84	0.35	55.53	19.436	0.123
4.8	409.82	0.45	63.51	28.580	0.203
4.9	419.86	0.55	73.55	40.453	0.303
5	437.88	0.65	91.57	59.521	0.423
5.1	449.74	0.75	103.43	77.573	0.563
5.2	457.72	0.85	111.41	94.699	0.723
5.3	473.7	0.95	127.39	121.021	0.903
5.4	475.74	1.05	129.43	135.902	1.103
5.5	483.72	1.15	137.41	158.022	1.323
5.6	497.86	1.25	151.55	189.438	1.563
5.7	511.78	1.35	165.47	223.385	1.823
5.8	519.76	1.45	173.45	251.503	2.103
5.9	529.78	1.55	183.47	284.379	2.403
6	547.8	1.65	201.49	332.459	2.723
			Σ	4173.135	32.725

Table 2 presents the least squares method used to develop the evolution of the pneumatic muscle forces, measured when different pressures are applied. The simple linear regression is used to find the relationship between the force and pressure. The dependent variable is the measured force (F_m), noted with Yi and the independent variable is the pressure (X_i). The means of the determined values are: $\bar{X} = 4.35$ and $\bar{Y} = 346.31$. The linear relationship between the variables (1) is defined as follows:

$$\hat{Y} = aX + b \tag{1}$$

Using the data calculated in Table 2, the values of coefficients (a and b) are determined.

$$a = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^{n}(X_i - \bar{X})^2} = 127.52$$

$$b = \bar{Y} - a \cdot \bar{X} = -208.41$$

The obtained linear regression is:

$$\hat{Y} = 127.52X - 208.41 \tag{2}$$

So, the relationship between the measured force and pressure is:

$$F_m = 127.52 \cdot p - 208.41 \tag{3}$$

In order to establish if a function is suitable as a pattern, the correlation ratio and determination ratio must be calculated. Table 3 presents the method of calculation of the correlation ratio, for the obtained regression.

Table 3. Method of calculation of the correlation ratio value.

p [bar](X_i)	F_m [N] (Y_i)	$\hat{Y}$	$(Y_i - \hat{Y})^2$	$(Y_i - \bar{Y})^2$
2.7	122	135.894	193.043	50314.98
2.8	137.98	148.646	113.764	43401.39
2.9	149.84	161.398	133.587	38600.46
3	167.86	174.150	39.564	31844.4
3.1	179.94	186.902	48.469	27678.98
3.2	195.9	199.654	14.093	22623.17
3.3	209.82	212.406	6.687	18629.52
3.4	226.3	225.158	1.304	14402.4
3.5	241.96	237.910	16.403	10888.92
3.6	255.88	250.662	27.228	8177.585
3.7	271.86	263.414	71.335	5542.803
3.8	277.78	276.166	2.605	4696.361
3.9	295.85	288.918	48.053	2546.212
4	311.78	301.670	102.212	1192.321
4.1	319.76	314.422	28.494	704.9025
4.2	329.78	327.174	6.791	273.2409
4.3	349.84	339.926	98.287	12.4609
4.4	359.88	352.678	51.869	184.1449
4.5	371.76	365.430	40.069	647.7025
4.6	381.78	378.182	12.946	1258.121
4.7	401.84	390.934	118.941	3083.581
4.8	409.82	403.686	37.626	4033.52
4.9	419.86	416.438	11.710	5409.603
5	437.88	429.190	75.516	8385.065
5.1	449.74	441.942	60.809	10697.76
5.2	457.72	454.694	9.157	12412.19

5.3	473.7	467.446	39.113	16228.21
5.4	475.74	480.198	19.874	16752.12
5.5	483.72	492.950	85.193	18881.51
5.6	497.86	505.702	61.497	22967.4
5.7	511.78	518.454	44.542	27380.32
5.8	519.76	531.206	131.011	30084.9
5.9	529.78	543.958	201.016	33661.24
6	547.8	556.710	79.388	40598.22
		Σ	2032.194	534195.7

A function is suitable as a pattern if correlation ratio R value is close to 1. The best model is considered the one with a high correlation ratio, between 0.8 and 0.9. The determination ratio R^2 offers a percentage interpretation of the obtained regression for the experimental data.

$$R = \sqrt{1 - \frac{\sum_{i=1}^{n}(Y_i - \hat{Y})^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} = 0.9980$$

$$R^2 = 0.9961$$

The correlation ratio can take values between 0 and 1. By how much the ratio value is closer to 1 the correlation link is stronger and vice versa. The obtained result ($R = 0.9980, R^2 = 0.9961$) showed that the connection between the analysed variables (F_m and pressure) is strong.

Based on the experimental results, a statistic validation of the regression is made, using SPSS software. Table 4 presents the descriptive statistics of the measured data. The number of records is 34 (N = 34).

Table 4. Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
p	34	2.7	6	4.350	0.9958
F_m	34	122	547.8	346.3103	127.23109

Linear Regression was applied to the data, in order to find the relationship between the measured force and the pressure. Table 5 contains information regarding the correlation and determination ratio, as well as standard error of estimation. The coefficient of determination R Square ($R^2 = 0.996$) expresses what percentage of the variance of the dependent variable is explained by the equation of regression.

Table 5. Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.998[a]	0.996	0.996	7.96906

a. Predictors: Pressure (Constant); b. Dependent Variable: F_m

The validity of the model was tested and the results are shown in Table 6. Fisher ratio (F = 8379.737) indicates that the influence of regression is much higher compared to the residual influence. Sig. value is below 0.05 means that the regression model is statistically valid.

Table 7 contains information on coefficients: column B - the value of the coefficient, Std. Error - standard error of the coefficient, Beta - the value of the standardized coefficient (shows how many standard deviations Y changes if X changes with a standard deviation), t - statistic of significance test of the coefficient, Sig. - critical probability of the test. Therefore, a coefficient is significant (different from zero in the regression equation) if Sig < 0.05.

Table 6. ANOVA[a]

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	532163.531	0.996	0.996	8379.737	0.000[b]
Residual	2032.192	32	63.506		
Total	534195.723	33			

a. Dependent Variable: F_m; b. Predictors: Pressure (Constant)

For the measured values the simple regression equation is $F_m = 127.521 \cdot p - 208.407$, all coefficients being statistically significant.

Table 7. Coefficients[a]

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-208.407	6.212		-33.549	0.000
p	127.521	1.393	0.998	91.541	0.000

a. Dependent Variable: F_m

There is a very strong correlation between the pressure and the measured force, as seen in Table 8. Pearson correlation measures the association between two quantitative variables and can range from +1 to -1. The extreme values indicate a perfect relationship (positive for +1 and negative for -1), while a value of 0 means that there is no correlation between the variables. For the analyzed data, the Pearson coefficient is 0.998, indicating a very strong correlation between variables.

Table 8. Correlations

		F_m
Pressure	Pearson Correlation	0.998**
	Sig.	0.000
	N	34

**Correlation is significant at the 0.01 level (2-tailed).

The graphical representation of the evolution of the pneumatic muscle forces, for different pressures applied are shown in Figure 2. The values of the forces obtained by measurement are represented by points, and the solid line shows the linear regression.

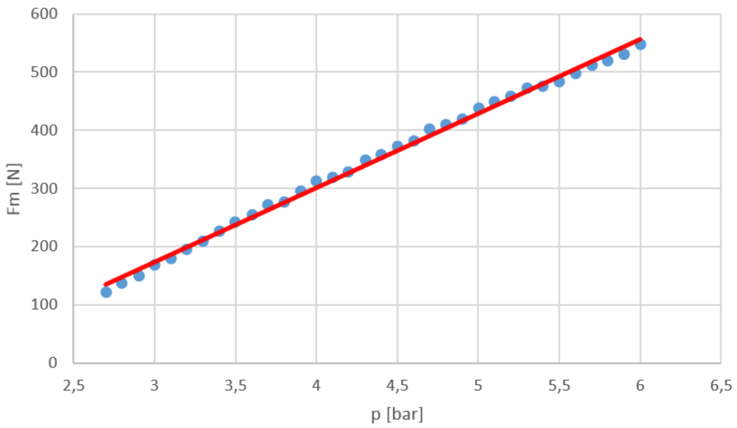

Fig. 2. The evolution of the forces versus pressure

A comparison between the technical data provided by the pneumatic muscle manufacturer (FESTO Ag & Co) and the experimental results obtained on the equipment is presented below. The theoretical forces developed by the chosen pneumatic muscle, corresponding to the compressed air pressure, were selected from the technical data. The results are shown in Table 8.

Table 8. Correspondence between the theoretical force developed by pneumatic muscle and pressure

Pressure [bar]	Theoretical force [N]	Pressure [bar]	Theoretical force [N]
2.7	4.8	4.4	178.6
2.8	15.1	4.5	188.6
2.9	25.5	4.6	198.7
3	35.8	4.7	208.8
3.1	46.1	4.8	218.8
3.2	56.4	4.9	228.8
3.3	66.6	5	238.8
3.4	76.9	5.1	248.8
3.5	87.1	5.2	258.8
3.6	97.3	5.3	268.8
3.7	107.5	5.4	278.7
3.8	117.7	5.5	288.7
3.9	127.9	5.6	298.6
4	138.1	5.7	308.5
4.1	148.2	5.8	318.4
4.2	158.3	5.9	328.3
4.3	168.5	6	338.2

Figure 3 presents the evolution of the measured forces and those provided by the manufacturer, in relation to the pressure. It is observed that the measured forces are superior to the theoretical ones, provided by the FESTO Company. This difference implies that the pneumatic muscle has superior performance to the stated theoretical ones, the company taking a safety margin when establishing the technical specifications.

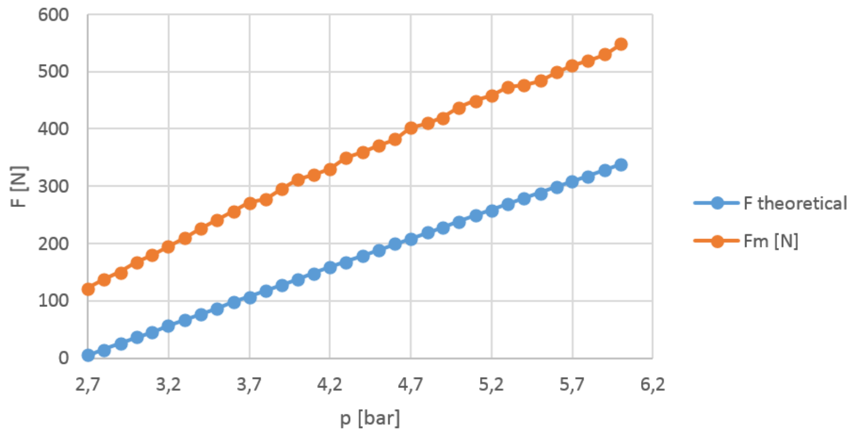

Fig. 3. $F_m = f_1(p)$; $F_{theoretical} = f_2(p)$

4. Conclusions

The aim of the experiments presented in this paper was to obtain some real information about the forces developed by a FESTO origin pneumatic muscle, in order to establish the possibility of using it as an actuator for a human leg assistive device. The forces developed by the muscle are increasing as the different amount of pressure applied increases. There is a direct correlation between the pressure and measured force.

Based on the obtained results, it was made an analysis and identified the linear regression equation for the data, by means of least squares method. The statistical validation was made, using SPSS Software.

The comparison between the measured forces and the values provided by the manufacturer highlighted that the pneumatic muscle has superior performance to the stated theoretical ones, the company taking a safety margin when establishing the technical specifications.

The obtained results gave a concrete and effective description to understand the real possibilities of the pneumatic muscle.

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