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The Effect of Volume and Pressure On The Force Applied By a Pneumatic Actuator

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Hands-ON Experimental

#6

1 Introduction

Pneumatics is a very useful branch of technology that uses air pressure to accomplish physical motion. It has a wide variety of applications such as robotics, manufacturing, mechanical systems (such as truck air brakes), power tools, and other areas. A useful feature of pneumatics is that it is easily scalable: you can have very small pneumatic actuators moving only inches and running off of low pressures, useful for small part motion, or you can supply a huge actuator with high pressures and have it move massive arms of machinery.

My personal experience with pneumatics is from my robotics team. We have a wide variety of uses for pneumatic actuators. We have some very small ones, like the ones that we use in a gear shifter to change the driving speed and power of our robot, and we've also used some very large ones to lift more than 20 kg of mass.

However, something I have yet to learn about these pneumatic systems is how both the volume and pressure affect the amount of force an actuator can apply. This would be useful as it would allow us to determine which cylinders we would need to use with much less guesswork. That is the subject of my investigation. I want to determine the correlation between volume of a pneumatic actuator and applied force, as well as the correlation between the pressure in a pneumatic actuator and the applied force.

I am fairly certain that as pressure increases force does also. A linear correlation seems logical, given that the definition of pressure is $\frac{force}{area}$ and that the area is staying constant, so force and pressure would be proportional. Volume, however, I am less certain about. There seem to be factors pointing towards the opposite relationship: as volume increases the force would decrease. First off, more volume means more space that needs to be pressurized, which could reduce the effectiveness of the pressure flowing in to the cylinder. Also, depending on which dimension increases, we would see more decreases. If the diameter ("bore") increases we would see the same amount of pressure spread out over a wider area, resulting in less force. If the length ("stroke") increases the force wouldn't change, but the actuator would need to do more work and thus may drain it's pressure before it is able to lift the masses all the way.

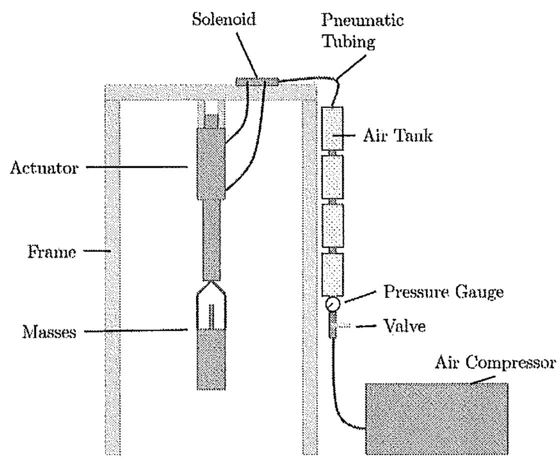

Figure 1: Experiment Setup

2 Methods

2.1 Equipment

The most important part of this experiment is, of course, the actuators themselves. I borrowed a wide variety of sizes from my robotics team. This was the selection of dimensions that I used:

Diameter (Bore) (cm)	**Length (Stroke)** (cm)	**Volume** (cm^3)
1.91	15.24	173.75
1.91	20.32	231.67
1.91	25.40	289.58
1.91	30.48	347.50
5.08	15.24	1235.56
5.08	20.32	1647.41
5.08	40.64	3294.81

Table 1: Pneumatic Actuator Sizes

I also used a large metal frame that I assembled to hang the actuators from. Allowing them to hang freely had the advantage of always facing downwards, meaning that all motion was in the intended direction (straight through the actuator) instead of producing unintended lateral forces (like being forced against the side of the cylinder), as well as making it easier to switch out the actuators between tests.

Attached to the frame was the remainder of the pneumatics system. I had a set of four air tanks linked together in a row. At one end I had a valve and pressure gauge where I could pressurize the system. To do this, I would open the valve, connect a compressor, and release the air into the tanks until I was slightly above the desired pressure. I would then close the system and detach the compressor, then slightly open the valve and slowly release air until I was at the desired pressure. The other end of the tank connected to a tube, and then to a pneumatic solenoid. This is essentially an air "switch" that changes the direction that the air flows: in this case, I used it to change the direction of motion for the actuator by changing the end that the air pressure flowed in to.

The last part of my equipment was the masses. At the base of this was a large 6 kg mass with a handle. This also had a round peg on it to attach more masses. I had multiple of these other 2 kg, 1 kg, and 0.5 kg masses. This would allow me to make any combination of masses in 0.5 kg intervals, an important part of this experiment. I had 4 of these sets of masses. I also made a small hook that allowed me to hang multiple of these masses from a single actuator.

2.2 Procedure

2.2.1 Independent Variable: Pressure

For testing the effect of pressure on the applied force I first needed to choose which actuator to use for the test. I ran three sets of these trials: One using the 347.50 cm^3 actuator, one with the 1235.56 cm^3 actuator, and one with the 1647.41 cm^3 actuator.

For each trial, I would start with the system pressurized at 55.16 kPa (8 PSI). I would then add more mass to the actuator and switch the solenoid to lift the mass. If it was able to be lifted fully, then I would reset the actuator and add more mass. An important note is that if the actuator was able to partially lift the mass but not fully retract, I didn't count it as being lift-able. Essentially, I looked for the largest mass that the actuator could lift entirely. I then repeated this process through the following set of pressures:

PSI	kPa
8	55.16
10	68.95
12	82.74
14	96.53
16	110.32
18	124.11
20	137.90
30	206.84
40	275.79

Table 2: Tested pressures

2.2.2 Independent Variable: Volume

For testing the effect of volume of the applied force I needed to choose which pressure to use. I ran two sets of these trials, one at 137.90 kPa (20 PSI) and one at 206.84 kPa (30 PSI).

For each trial, I would hook up an actuator and pressurize the system to the target pressure. I then would run through a similar process as above, adding masses until it was unable to be lifted. The same criteria as noted above were used. Once I found the highest lift-able mass, I would then switch out and use another actuator and repeat.

2.3 Safety, Ethics, and Environmental Issues

There were no significant ethics or environmental issues in this experiment. There were only two minor safety hazards. The first was working with moderately high pressures. I made sure to use components that were rated for this level of pressure, and I never left the system pressurized unattended. The other safety hazard was the potential for flying parts (mainly the masses). I didn't have a specific way to deal with this safety issue, but I made attempts to mitigate it by removing the masses before resetting the actuator. This was the only time this issue was noticeable, because sometimes the actuator would extend so fast that the weights would fall off.

3 Results and Analysis

3.1 Independent Variable: Pressure

Actuator Volume: 347.5 cm^3	
Pressure (kPa ± 6.9)	**Mass (kg)**
55.15806	0.39 ± 0.005
68.94757	0.89 ± 0.255
82.73708	1.39 ± 0.255
96.5266	1.39 ± 0.255
110.3161	1.89 ± 0.255
124.1056	1.89 ± 0.255
137.8951	2.39 ± 0.255
206.8427	3.89 ± 0.255
275.7903	5.39 ± 0.255

Actuator Volume: 1235.6 cm^3	
Pressure (kPa ± 6.9)	**Mass (kg)**
55.15806	0 ± 0.005
68.94757	1.39 ± 0.255
82.73708	3.39 ± 0.255
96.5266	5.89 ± 0.255
110.3161	7.89 ± 0.255
124.1056	9.50 ± 0.250
137.8951	11.00 ± 0.250
206.8427	20.89 ± 0.255
275.7903	30.39 ± 0.255

Actuator Volume: 1647.4 cm^3	
Pressure (kPa ± 6.9)	**Mass (kg)**
55.15806	2.89 ± 0.255
68.94757	5.39 ± 0.255
82.73708	7.50 ± 0.250
96.5266	9.50 ± 0.250
110.3161	11.00 ± 0.250
124.1056	13.89 ± 0.255
137.8951	15.39 ± 0.255
206.8427	25.39 ± 0.255
275.7903	35.39 ± 0.255

Table 3: Mass vs Pressure Results

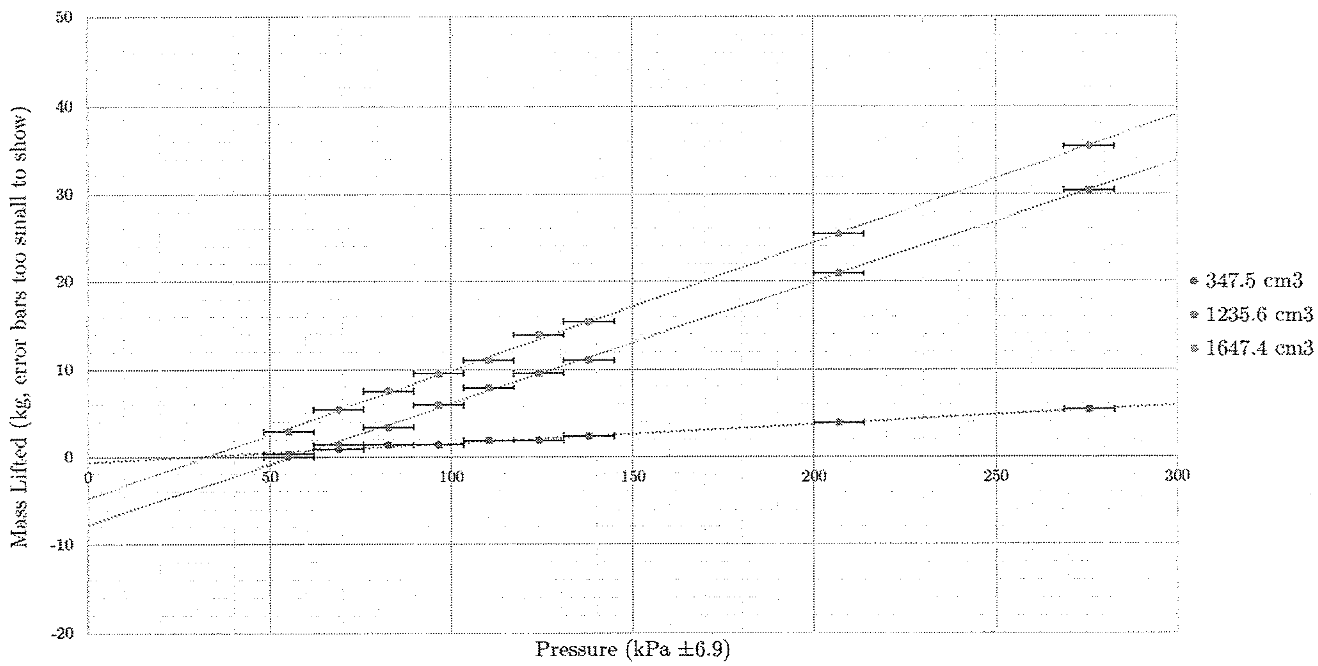

Figure 2: Mass vs Pressure Results (See Table 3)

First, an explanation of a minor point: the variances in the uncertainty were due to some trials using a hook apparatus to hold the masses, while some didn't require them. This hook had a mass of 0.390 kg with an uncertainty of ±0.005 kg, which was then added to the actual lifted mass. There were some odd values in tables 2 and 3 where, at the lowest pressure, the actuator was (or was not) able to lift the hook but no more mass, hence an uncertainty of only ±0.005 kg.

In all of my trials, I saw a distinctly linear trend, although the specific gradients varied based on which actuators I was using in the test. These were the specific equations that I determined:

Volume	**Equation**
347.4999892 cm^3	$M = (0.022 \pm 0.0032 \frac{kg}{kPa})P - 0.6572kg$
1235.555517 cm^3	$M = (0.138 \pm 0.0090 \frac{kg}{kPa})P - 7.7975kg$
1647.407356 cm^3	$M = (0.146 \pm 0.0105 \frac{kg}{kPa})P - 4.7344kg$

Table 4: Determined Equations for Mass vs Pressure

This result makes sense, mainly due to the definition of pressure being force per area. Given that the area stays the same, it makes sense that there is a linear relationship between force and pressure. My theory on why this has a non-zero intercept is that factors like friction and the mass of the actuator rod are not accounted for in these calculations.

As far as error goes, the measurements were much less accurate at the lower masses due to my rather large minimum mass difference of 0.5 kg. The pressure also had a relatively large error (compared to the intervals I was testing) due to the precision of the gauge I was using. Either way these data still produce an almost perfect linear trend, so the error had little effect here.

3.2 Independent Variable: Volume

Pressure: 137.9 kPa

Volume (cm^3)	Mass Lifted (kg)
173.750 ± 15.384	2.0 ± 0.25
231.667 ± 20.211	2.0 ± 0.25
289.583 ± 25.037	2.5 ± 0.25
347.500 ± 29.863	2.0 ± 0.25
1235.556 ± 45.046	11.5 ± 0.25
1647.407 ± 57.917	14.5 ± 0.25
3294.815 ± 109.398	8.5 ± 0.25

Pressure: 206.8 kPa

Volume (cm^3)	Mass Lifted (kg)
173.750 ± 15.384	3.50 ± 0.250
231.667 ± 20.211	3.50 ± 0.250
289.583 ± 25.037	4.00 ± 0.250
347.500 ± 29.863	3.50 ± 0.250
1235.556 ± 45.046	21.89 ± 0.255
1647.407 ± 57.917	24.39 ± 0.255
3294.815 ± 109.398	16.39 ± 0.255

Table 5: Volume vs Pressure Results

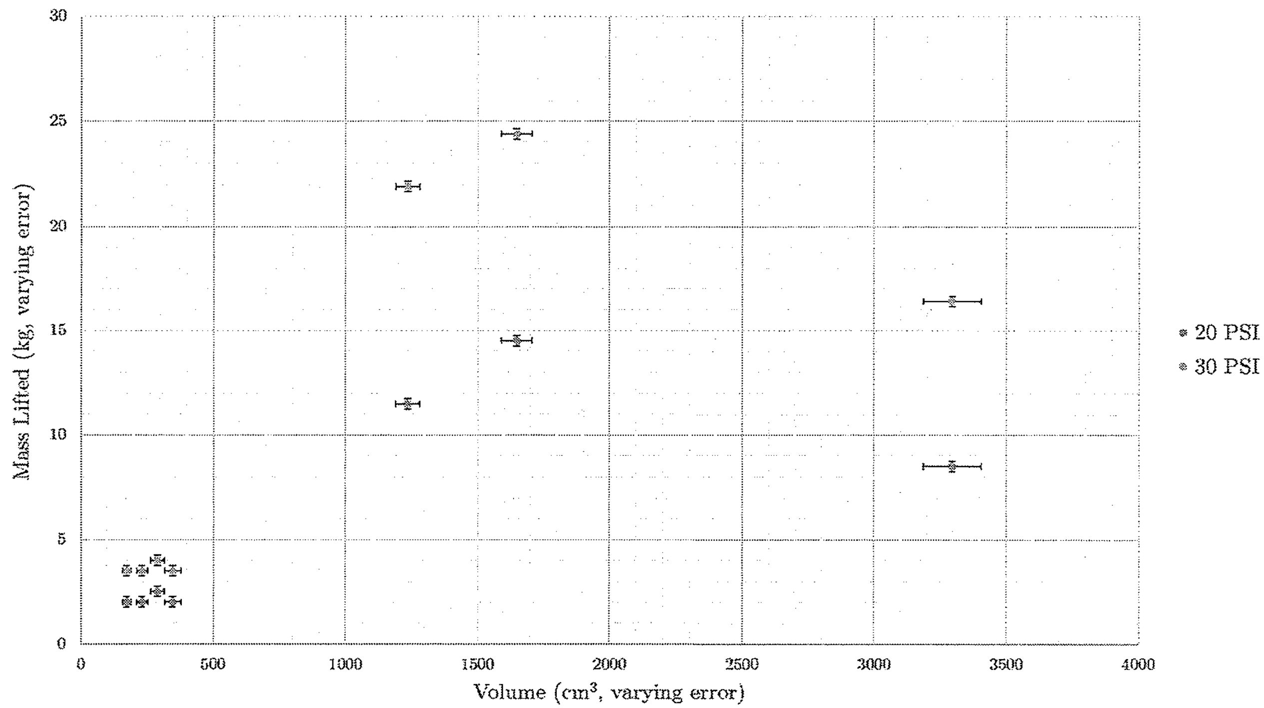

Figure 3: Volume vs Pressure Results (See Table 5)

Oddly enough, there seems to be no correlation between volume and force for a pneumatic actuator. My theory behind this is that because volume consists of two separate variables in this case (actuator diameter and length) this experiment was similar to testing two variables in one, and as such produces erratic results. However, there does seem to be a general positive correlation, it's just that the results are so widespread that I don't believe that volume by itself is the deciding factor here. Even though the error in the volume measurement was somewhat large in the higher range, this still doesn't nearly account for the amount of non-correlation present here.

4 Conclusion and Evaluation

As far as conclusiveness goes this experiment does, in fact, answer the original question. It determined that pressure is linearly related to the applied force, and we also see that volume by itself has no correlation with the applied force (although it's constituent components may be). The linear relationship makes sense due to (as mentioned earlier) the definition of pressure, force per area, as the area is staying constant in this case. For the relationship (or lack of) between volume and pressure, there are multiple factors in why this has no correlation. First, if we look at the definition of pressure again, it's force per area. In this case, the pressure is staying the same, but area would vary with the diameter of the actuator (more surface area to move the actuator rod with). Also, the length of the actuator could have had an effect here due to how the experiment was run: lifting a mass was defined as the actuator fully retracting, but due to how the actuator length varies the distance that the mass has to move also varies, which in turn means more friction, as well as more loss of air/pressure over time. If we look at the ideal gas law, we see that pressure and volume are inversely proportional, but we also see that pressure and the amount in moles are proportional (Nave). In our case, increasing volume also increases the amount of air, which means that there doesn't seem to be a direct relationship between volume and pressure.

This experiment was nice in how it was remarkably simple to execute and had relatively little that could go wrong with it. However, there were two major points that could affect the results of this investigation that I was not aware of until afterwards. First off, I discovered that temperature has an enormous impact on the force the actuators applied: at the same pressures, the results sometimes varied by half of a kilogram (my smallest measurable unit) with only the simple difference of the temperature throughout the day (noon versus 5 PM or so). However, all of my trials were conducted through the same general period of time of approximately half an hour, so inside of a trial this should have relatively little impact. The other, more major point I discovered is that the question may have been better phrased using "initial pressure" instead of just "pressure". This is due to how I set up the pneumatics system. To run the experiment I got the system up to some pressure, then closed the system. However, when I activated the actuator it releases air to allow it to compress, thus lowering the pressure (same volume but less moles of air, as stated in the ideal gas law $PV = nRT$). There are techniques to keep the actuator at a constant pressure, but I did not have access to the necessary equipment at the time of the experiment.

Ultimately, to improve this investigation I would like to investigate the effects of individual dimensions of an actuator on the applied force, and would also like to see if using a constant pressure (instead of initial pressure) has any effect on the results. It would also be interesting to try and find a way to combine these two investigations (either volume or the individual dimensions) to make a more "general" equation, as this would be much more useful for my applications. The main reason I chose to do volume instead of separate dimensions was because of my available sample size: if I ran my experiment by diameter and length I wouldn't have enough different sizes to get a definitive result.

5 Works Cited

Nave, C.R. "Ideal Gas Law." *HyperPhysics.* Georgia State University, n.d. Web. 4 Oct. 2015. <http://hyperphysics.phy-astr.gsu.edu/hbase/kinetic/idegas.html>.