Teaching Force Concepts with Biomechanics

Daniel Christ[1] *Beth Todd*[2]

Abstract – Current trends in prosthetics design include the use of pneumatic artificial muscles. Chemically produced hot gases can be used to power muscle actuators in small volumes allowing for lightweight, small-sized devices. However, the ultimate design still contains basic physical principles of action/reaction, pressure, and work.

A lesson has been developed for middle school science students on the topics of pressure and its capacity to do work. Incorporated into the lesson is an activity for students to design and build pneumatic artificial muscles out of balloons and pipe cleaners. The muscles were then used to actuate elbow joints made from tongue depressors. This paper includes a description of the activity relating it to the topics to be covered in the science class. Results of the lesson were found by observing multiple classrooms with approximately thirty students each and are discussed in terms of both student learning as well as student enthusiasm.

Keywords: Pressure, force, muscle, hands-on activity

INTRODUCTION

Pneumatic Artificial Muscles

Pneumatic artificial muscles (PAMs) are muscle-like actuators that contract under pressure, exerting a pulling force over an external load. The most well-known pneumatic muscle, the McKibben muscle, consists of an inflatable membrane surrounded by a fibrous meshed braid (Fig. 1). As the membrane is inflated with high pressure gas, it expands and pushes against the surrounding fibers. The fibers, attached at both ends of the muscle, do not change their length. Therefore, the two ends of the muscle are pulled together. This type of actuator is first developed as an orthotic power source for use in rehabilitation, leveraging its similar length-load characteristics to the biological muscle [1,2]. Later PAMs have been used to power a variety of robotic systems, mainly those mimicking human limb functions, including robotic arms [3-5], biped walking robots [6,7] and prosthetics [8,9,10].

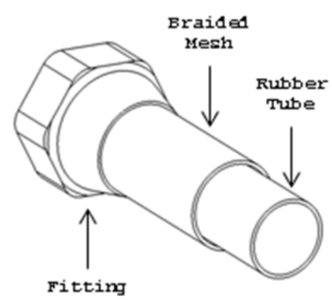

Figure1: McKibben Pneumatic Artificial Muscle Cut-Away

The Chemo-Muscle Actuation System [8,9]

Like all other pneumatic actuators, the PAM relies on traditional pneumatic supplies as sources of high pressure gas. Typical pneumatic supplies either directly store compressed air in high-pressure reservoir tanks or generate compressed air from other energy sources (chemical or electrical) through a compressor. The recently developed Chemo-Muscle Actuation System overcomes the lack of a mobile high pressure gas supply by using a special type of liquid fuel, monopropellant (such as hydrogen peroxide), as an energy-storing media. This type of liquid fuel can be directly converted into high-pressure hot gas through simple catalytic decomposition. This latest step in the development of artificial muscles allows them to be used in mobile applications where their high strength to weight ratio [3] and similarity to biological muscles [1,2] are needed, such as prosthetics and mobile robotics. It also encourages artificial muscles as a future technology that is gaining mainstream understanding and popularity.

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ARTIFICIAL MUSCLE MODULE

Purpose of Pneumatic Artificial Muscle Module

As part of a National Science Foundation GK-12 project, graduate student fellows at The University of Alabama work in conjunction with science and mathematics teachers from Sumter County schools by presenting their research and developing classroom modules to aid in instruction of topics. This particular module was developed in order to help a middle school class better understand the research topic of their graduate fellow; development of a pneumatic artificial muscle prosthetic arm. This module also was intended to help students visualize and understand topics in their course of study such as forces, pressure, machines, biology, chemical reactions and action/reaction. This module was designed to be completed in one (or two) fifty minute class periods.

Pre-Activity Lesson

Before beginning the activity, it is necessary to introduce the students to the idea of artificial muscles and their uses. However, it is likely going to be necessary to reintroduce other topics first so that the students are thinking correctly about the working principles that go into the design of the muscle.

1. Force: A force is a push or a pull that causes:
    a. Stationary objects to move
    b. Moving objects to speed up, slow down or stop
    c. Flexible objects to bend or deform
2. Pressure: Pressure is the force per unit area acting perpendicular to a surface
    a. Pressure in a balloon always pushes outward because the high pressure is inside
    b. Pressure acting on a submarine always acts inward because the high pressure is outside
    c. Units are given in force/area like lb/in^2 or N/m^2
3. Biological Muscles: Biological muscles are contractile elements, meaning they produce a pulling force.
    a. They are found in all types of animals
    b. Muscle cells have filaments that move past each other to change the shape of the cell and create the pulling force
    c. Driven by chemical reactions in the body and signals from the brain
4. Artificial Muscle: Artificial muscles are manmade contractile elements, or actuators, that seek to duplicate or replace the motion and forces of biological muscles
    a. Pneumatic artificial muscles are driven by high pressure gas and are controlled by computers
    b. They are used in industry as a cleaner and stronger replacement for other pneumatic actuators
    c. They are used in robotics for many different applications including human emulation, which means that they are used to build a robot that looks and functions as closely to a human as possible
5. Chemical Reactions: Chemical reactions when a mixture of chemical substances react to form a new set of substances
    a. Some simple examples are
        i. Iron rusting
        ii. Wood burning
    b. In the case of the Chemo-Muscle, Hydrogen peroxide reacts with a catalyst to produce a large volume of gas [8,9]

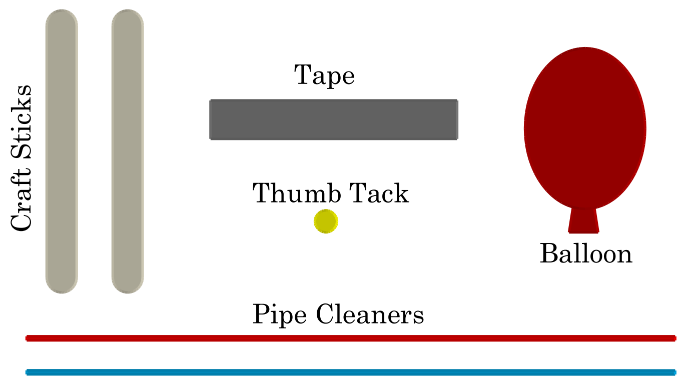
6. Action/Reaction: When an action is performed on an object the object reacts by resisting the action, passing the action on to another object, and/or deforming
    a. Some simple examples
        i. You lean on a wall, the wall pushes back and keeps you from falling over
        ii. You kick a ball, it moves
    b. In the case of a pneumatic artificial muscle or chemo-muscle
        i. A chemical reaction produces high pressure gas
        ii. This pressure inflates the membrane like a balloon
        iii. The balloon pushes against a fiber wrap
        iv. The fibers bend around the balloon and pull at both ends
        v. This pulling force is output to the system
            1. This could be any industrial use such as lifting, opening and closing, etc.
            2. This could also be bending an artificial joint in a prosthetic device

Required Materials (per Student/Group)

2	Pipe Cleaners
2	Popsicle/Craft Sticks
6-10in	Rubber/Electrical Tape
1	Thumb Tack
1	Balloon (Small, Sphere/Pear shape)

Optional materials:

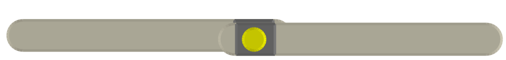
1	Flexible Drinking Straw
1	Spring Scale



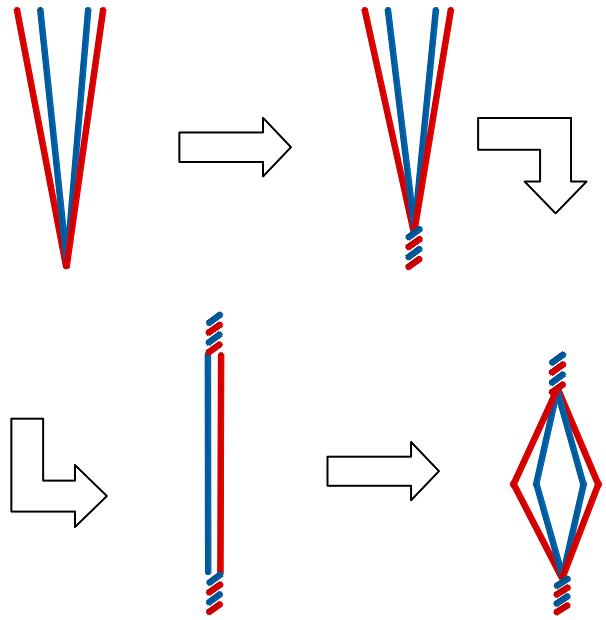
Activity Procedure

1. Wrap one layer of tape around one end of each of the two craft sticks.

2. Carefully push the thumb tack through the now taped ends of the craft sticks one at a time.
    a. Make sure your fingers are not on the other side of the stick as the tack is pushed through!
    b. The joint should rotate freely about the thumb tack pin.

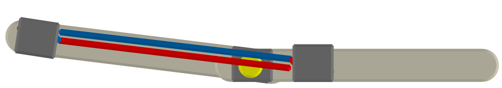


3. Fold each of the pipe cleaners in half.
4. Place the folded ends of the pipe cleaners together one inside the other.
5. Twist the two folded ends together.
    a. Only twist a small section of the two together (<1in).
    b. The four opposite ends should remain free at this point.
6. Together, straighten out the four ends making sure they are fairly even, twist them together tightly (again <1in).
7. Pull apart the four center portions of the pipe cleaners to make a 'cage' shape with both ends twisted.



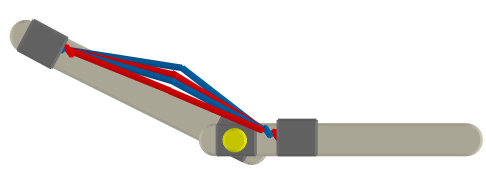
8. Extend elbow joint (attached craft sticks) out to its longest length and stretch out the muscle to its longest length.

9. Attach the pipe cleaner assembly to the joint in two places with tape. For best results attach at the farthest point away from the joint on one stick and as close to the joint as possible on the other.

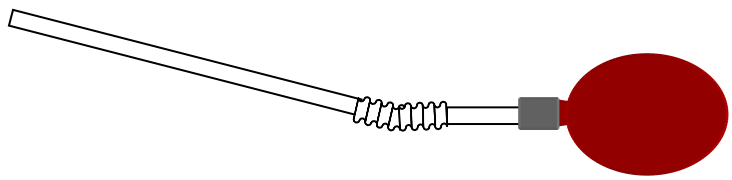


To make the connection between the tape and the muscle stronger, wrap the tape once, tightly around the twisted sections of the muscle before continuing to wrap the tape around the popsicle stick.

10. Pull the 'cage' portion of the muscle towards the inside of the joint (the side which will have the smaller, acute angle). Fan out the 'cage' fibers.

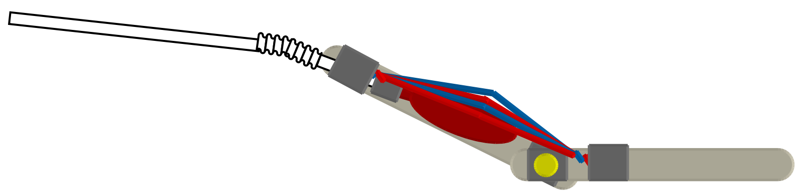


11. (optional) Tape the deflated balloon to the end of the straw so it is air tight.



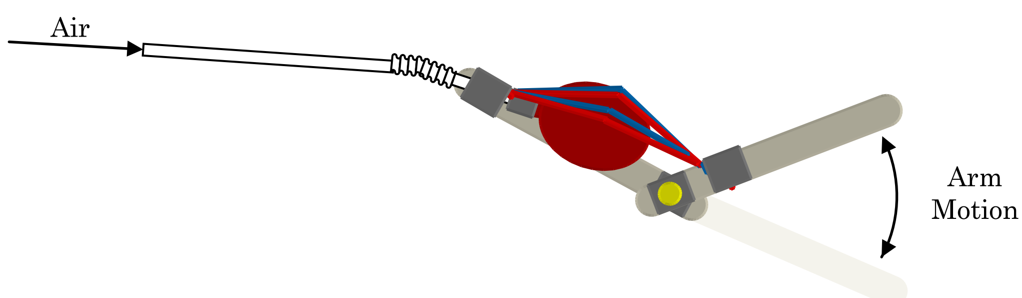
This will allow the person inflating the balloon to be able to see the movement better, but is not necessary. Getting the seal to be air tight may be difficult as well.

12. Stretch out balloon so it inflates easily.
13. Place the deflated balloon between the cage of the pipe cleaners and the popsicle stick.



Tape straw in place if necessary, but make sure not to crush it and block the air flow.

14. Spread 'cage' fibers around balloon so that it does not pop out from in-between the cage and the arm. This may have to be readjusted after slightly inflating the balloon.
15. Inflate the balloon slightly and watch the elbow joint flex!



16. (optional) Use the spring scale to observe the forces output by the muscle/arm.

Handout Version

A one page handout was also developed for distribution to students in the classroom and to other teachers wishing to use the activity with their class. It is included on the following page.

Pneumatic Artificial Muscles Lab

(Activity time aprox. 30min)

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The University of Alabama

NSF GK-12 Grant No. 0742504

Abstract

Current trends in prosthetics design include the use of pneumatic artificial muscles. Chemically produced hot gases can be used to power muscle actuators in small volumes allowing for lightweight, small-sized devices. However, the ultimate design still contains basic physical principles of action/reaction, pressure, and work.

Pneumatic Artificial Muscles (McKibben type) are made up of two main components; an elastic, inflatable membrane and a woven, inelastic fiber mesh. As the membrane is inflated with high pressure gas it expands and pushes against the surrounding fibers. The fibers, attached at both ends of the muscle, do not change their length. Therefore, the two ends of the muscle are pulled together.

Be sure to note to students that this is NOT how biological muscles work, but that these artificial muscles can be used to recreate the same function as biological muscles. (Ex. Robotics, Prosthetics)

Materials (per student/group)

2	Pipe Cleaners
2	Popsicle/Craft Sticks
6-10in	Rubber/Electrical Tape
1	Thumb Tack
1	Balloon (Small, Sphere/Pear shape)

Optional materials

1	Flexible Drinking Straw
1	Spring Scale

Procedure

1. Wrap one layer of tape around one end of each of the two craft sticks
2. Carefully push the thumb tack through the now taped ends of the craft sticks one at a time
   a. Make sure your fingers are not on the other side of the stick as the tack is pushed through!
   b. The joint should rotate freely about the thumb tack pin
3. Fold each of the pipe cleaners in half
4. Place the folded ends of the pipe cleaners together one inside the other
5. Twist the two folded ends together
   a. Only twist a small section of the two together (<1in)
   b. The four opposite ends should remain free at this point
6. Together, straighten out the four ends making sure they are fairly even, twist them together tightly (again <1in)
7. Pull apart the four center portions of the pipe cleaners to make a 'cage' shape with both ends twisted
8. Extend elbow joint (attached craft sticks) out to its longest length
9. Attach the pipe cleaner assembly to the joint in two places with tape. For best results attach at the farthest point away from the joint on one stick and as close to the joint as possible on the other
10. (optional) Tape the deflated balloon to the end of the straw so it is air tight
11. Stretch out balloon so it inflates easily
12. Place the balloon between the cage of the pipe cleaners and the popsicle stick
13. Inflate the balloon slightly and watch the elbow joint flex!
14. (optional) Use the spring scale to observe the forces output by the muscle/arm

Post-Activity Lesson

After completing the activity, refer back to the portions of the activity that related to the topics discussed in the pre-activity lesson. Ask the students questions that allow them to make the connections themselves such as:

1. When you blow into the straw, what causes the balloon to inflate?
    a. (pressure)
2. How does the inflating balloon move the arm?
    a. (the balloon pushes on pipe cleaners which pull on the joint)
3. Is this the same way an artificial muscle works? Did we build an artificial muscle?
    a. (yes)
4. Is this the same way a biological muscle works?
    a. (no, biological muscles use chemical reactions not pressure to cause contraction)

RESULTS

Student Enthusiasm

Students reacted to the activity rather well over all. They enjoyed the hands on, step by step approach to the activity following along intently and asking questions if they were having trouble or did not understand. It was found to be significantly easier for the teacher to build a model along with the students each time rather than having a finished product for them to look at. This allowed the students to visualize and perform each step more easily. After completing the activity, the students were quickly able to recall the pre-activity lessons and apply the concepts and terminology they had previously learned to the models they had built. The students were eager to take their models with them so they could show and explain them to their friends outside the classroom and their families at home.

There was some initial cutting up and inappropriate use of the materials. This was corrected quickly when the students were told that they would not be receiving replacement materials for the ones they misused or broke and that they would then have to write down each step in great detail and draw and color pictures to turn in for a grade rather than turning in their finished models.

Student Learning

The students were actively engaged in learning throughout the activity. The pre-activity lesson was a lot of information and some students lost focus towards the end, but they were easily refocused by being asked to distribute materials. This forced them to think about the task at hand and allowed them to understand the purpose of the materials they were handing out. During the activity, the students asked questions about what each part was for and were excited when they recognized and understood what the part represented and what task it performed. During the post-activity lesson, the students were quick to relate the steps of the activity to the material they had learned. They were able to explain more easily and give better examples of tricky concepts such as force and pressure. They were able to describe each action/reaction that was in play in their models.

A week after the module was done in the classroom, the students were again asked to describe the concepts they had learned from the activity. They were still able to quickly recall the connections they had made with the steps of the activity and the topics of study. They were also happy to report that they had been able to describe these concepts and the models they had built to their parents, siblings and friends.

CONCLUSIONS

After successfully using this module in multiple classes of approximately thirty middle school students it is fair to say that it is a good learning tool that is ready for use in other classrooms. It is a fun activity that helps students learn, understand and retain difficult concepts such as pressure, force, action/reaction, robotics, and prosthetics. This understanding better prepares students for the ever expanding world of science, technology, engineering and mathematics and encourages them to consider careers in STEM fields.

ACKNOWLEDGEMENTS

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