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A Mechanics of Materials Outreach Activity: Reconstructing the Human Body: Biomaterials and Biomimicry

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My research focus is in mechanics, materials and tribology. This work utilizes mechanical engineering fundamentals, multi-scale experimental techniques, and computational modeling to develop, characterize and study high performance materials for tribological (friction and wear), structural, and biomedical applications. I am also involved with advising and outreach. I am a founding member of the Advisory Committee for the WiSE Women of Color in STEM Program. I have also participated in college level outreach programs; specifically developing a hands-on activity to introduce students to the fundamental material science, mechanics and biomedical engineering through the concept of biomimicry.

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A Mechanics of Materials Outreach Activity: Reconstructing the Human Body: Biomaterials and Biomimicry

Abstract

In order to engage and stimulate students, an outreach activity needs to integrate exciting subject material with hand-on laboratory experiments. Biomimetics is when complex problems are solved by imitating systems and elements found in nature. One of the largest areas of biomimetic inspiration is the human body. From this concept, students were asked to perform a hands-on activity to introduce them to the fundamental material science and mechanics through the concept of biomimicry. Student groups were tasked with designing a muscle replacement for a distal bicep fracture. The scaffold needed to mimic the mechanical properties of the natural tissue in the direction of highest applied force. Then to assess the viability of their designs, each groups scaffold was tested in tension. This engaging activity interconnects several mechanical concepts and provides a link between material science, mechanics and biomedical engineering.

Introduction

Future generations of scientists and engineers will need to be inspired through interesting experiences and activities that link the natural world with scientific theory. Specifically, high school students or incoming college freshmen learn better when they have direct links between their physical world and theory. The field of biomimicry can be an inspiring introduction, and can be a clear illustration of how materials play a role in the world around them. It makes engineering both approachable and relevant. The science classes that high school students, college freshman and sophomores take typically present collections of theories and laws using techniques that do not foster creativity, experimentation and curiosity. As a result, students increasingly fail to pursue careers in Science Technology Engineering and Mathematics (STEM). For the past 10 years the number of high school seniors who plan on entering an engineering career has dropped more than 35%.[1] Additionally, attrition rates of engineering disciplines have been as high as 50%,[2] and minority students have been shown to receive less than 8% of all bachelor degrees awarded in engineering fields, respectively.[3] Consequently, it is imperative that universities stimulate and foster curiosity early on in a student’s academic career. Early exposure to hands-on laboratory experiments has been shown to increase student retention by engaging students, promoting discussions, and forming connections between observations and learned engineering concepts.[4] This paper describes an activity that can be performed with groups of students ranging from high school seniors to incoming college freshman or sophomores. The objective of the outreach activity is to give students an introduction to fundamental material science, mechanics and biomedical engineering concepts while encouraging imagination, inquiry and excitement.

Activity Overview

The premise of the activity is to expose the students to concepts of mechanical testing and biomaterials through the area of biomimetics. Namely, solving complex problems by imitating systems and elements in nature.[5] Initially, students are shown how nature is one of the smartest engineers around, with animals, plants, and our bodies adapting and evolving to survive and prosper. Therefore it is natural for scientists to look to the natural world to solve problems. Students can be given an immediate recognizable real-world connection by discussing prime examples of biomimicry, such as the invention of Velcro,[6] the design of racing swim suites and wet suites from sharkskin[7] and design of HVAC systems based on African termite dens.[8] Due to the complexity of biological systems, biomimetics is applied in many fields. Specifically, one of the largest areas of biomimetic inspiration is the human body. There is an increasing need for treatments of variety of human body injuries including orthopedic, neurological, musculoskeletal and dental. Scientists and engineers work to develop synthetic materials that mimic human body to better treat injury such as renew lost function,[9] time efficient wound healing,[10] or to repair non-healable tissues.[11] This type of introduction[a] provides a smooth segue to introduce the project concept; namely, designing a material “implant” for Distal Bicep Fracture in Athletes.[b] Giving the students a contextual project with relatable and recognizable applications helps ignite student interest and maintain engagement.

Background for the design project is that approximately 5.2 million sports injuries occur every year which leads to yearly spending of $1.83 billion dollars on athletic injuries.[12] Five percent of these injuries occur in the wrist or forearm, meaning that annually $91.5 million dollars is spent repairing and rehabilitating forearm injuries. One of the most prominent forearm injuries is a distal bicep rupture. This occurs when the tendon that attaches the biceps muscle to the elbow is torn from its insertion in the bone (Figure 1). This injury occurs mainly in athletics that involve instantaneous flexion and extension forces applied to the arm.[13] Along with a bicep tear, the supporting muscles around the joint (such as the brachialis, the brachioradialis and the triceps) can also rupture. This can happen when an object is quickly thrown or hit, or an attempt is made to suddenly catch or hit an object, such as in the sports of lacrosse or tennis. Women athletes are especially affected by this injury. Women tennis and lacrosse players tend to have the same body shape and use their muscles in similar ways. Lacrosse and tennis players vary between a mesomorphic and endomorphic body types; which means that the women are typically tall and muscular with slim, yet powerful fast twitch muscle fibers.[14] It is usually the occurrence of these fast motions within their sport that results in injury of the forearm muscles. After some background on the problem, it is recommended that the biology of the muscle be discussed, with a focus on explaining that tendons carry tensile forces from muscle to bone, with the collagen fibrils contained within tendons accounting for the mechanical resistance to tension.[15] Finally,

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[a] See example introduction presentation in the supporting information (S1).
[b] If the activity is used for women outreach purposes the project can be shifted to create an implant for female athletes.

depending on the group of students, the presenter can give a review of stress, strain and material properties.

The objective of this hands-on activity is twofold. First, using the given materials and their intrinsic knowledge of forces and materials, student groups design a muscle replacement for a distal bicep fracture. Second, a tensile analysis is performed on the "implant" in order to determine the viability of the design. The activity requires nominally 45 – 90 minutes depending on the number of students in the class, which will affect the number of samples that need to be tested in tension.

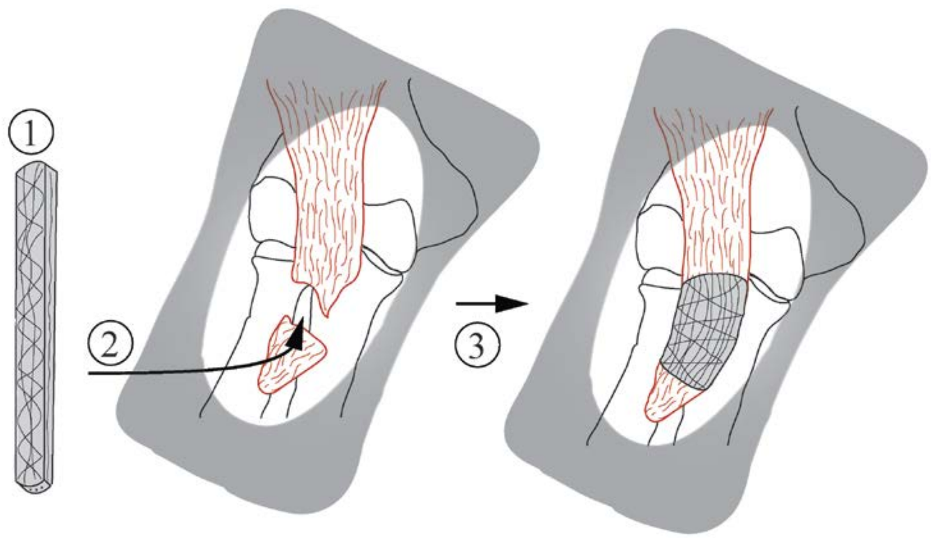

Figure 1: Schematic overview of design project showing (1) replacement scaffold implanted into (2) a distal bicep rupture in order to (3) repair the injury.

Materials Preparation

Instructor Materials

The activity can be performed with several common place items, along with an oven (or toaster oven), custom made molds[c] (Figure 2), and one mechanical testing apparatus. The activity to date has been performed with an MTS Sintech 2/G Tensile Tester (MTS, Eden Prairie, MN). Students should be nominally separated into teams of no more than 4 (2-3 students per group is ideal).

[c] See engineering drawings of molds available in supporting information (S2).

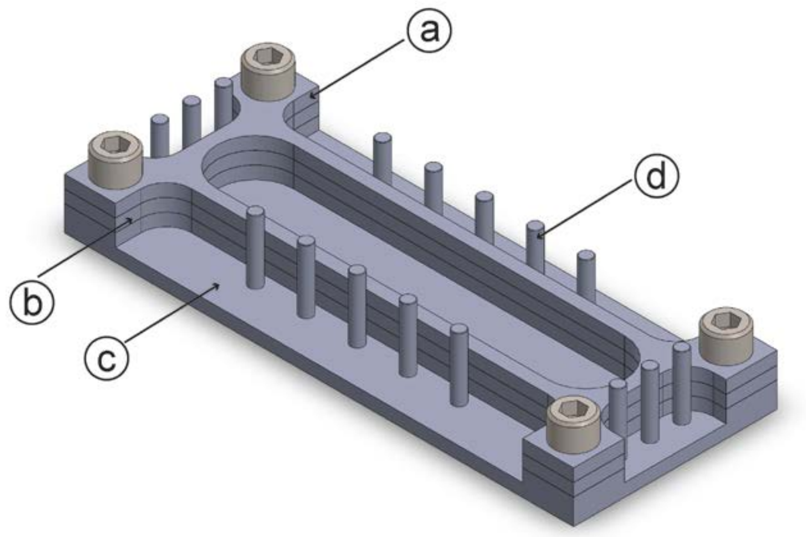

Figure 2: Drawing of scaffold mold showing (a) the top and (b) middle mold plates which separate the fiber layers, along with (c) the bottom holder and (d) pins that are used to string the fibers.

Student Materials

Each student team is given the following items:

- laboratory gloves
- 36'' of fiber (fishing wire) (x2)
- 1 plastic weigh-boat with 15 g of polymer binder (PDMS)[d]
- Aluminum scaffold mold
- razor blade
- set of calipers/ruler
- Allen (Hex) wrench

Activity Execution

After initial introduction, the students can begin the activity. For initial assessment, an introductory quiz can be given to evaluate student comprehension of fundamental mechanical and materials concepts.[e] The procedure is detailed in steps in the worksheet in supporting information. A brief overview is given here. Initially the students are asked to weave two fiber layers in any pattern they choose, making sure that they record the weave directions for post-test analysis. After stringing the fiber strands, the top of the mold is secured on and the polymer

[d] Prior to activity, the instructors should measure out and mix together the PDMS material in a plastic weigh-boat. For the molds shown (Figure 2), 15 g with a 15% binder ratio gave optimal samples.
[e] See the worksheet available in supporting information (S3).

binder is poured into the mold. The scaffolds are then placed in an oven. It takes roughly twenty minutes for the binder to harden and five minutes for the molds to cool. A picture of a final sample can be seen in Figure 3(a).

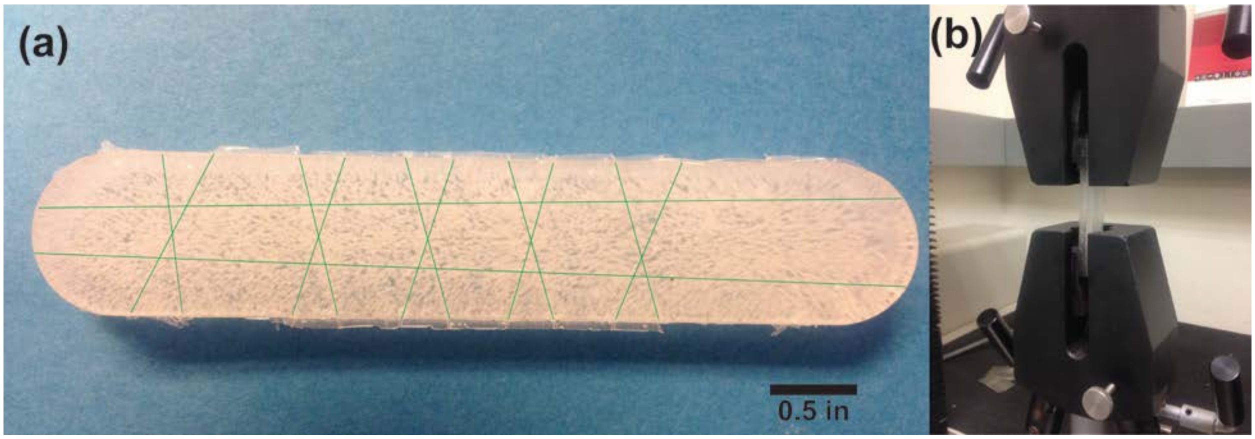

Figure 3: (a) Example of finalized scaffold with the embedded fibers highlighted in green. (b) Tension test set up with scaffold positioned in machine

Once the samples are cooled and removed from the molds, students take pre-measurements prior to performing a tensile test on their “implant”. Students measure and record the width, thickness and gage length of the specimens. The purpose of a tensile test is to measure the stress-strain response of a material. This is accomplished by subjecting a rod of material to increasing axial elongation until it breaks. A picture of the mold in the experimental setup can be seen in Figure 3(b). The result of such test is usually reported in the form of a force-displacement diagram. The curve is plotted with the force (stress) in the vertical axis and the displacement (strain) in the horizontal axis. After learning about a stress-strain curve, along with knowledge of anisotropic materials, the students are asked to draw a predictive sketch of how they think their “implants” stress-stain profile will look and to discuss within their group why the “implant” had that type of material response. During tensile testing, the students record the maximum force the sample could hold.

After testing, the students are asked to calculate the maximum stress and strain seen by the sample and to draw the shape of the actual load-displacement graph. Finally, students are asked to reflect on their scaffold design. After a discussion on mechanics and the importance of fiber direction, students are asked how they would change their design to better mimic the structure and function of the distal bicep. Finally students are asked to sketch a representative pattern of a scaffold design to be strong in shear, and to discuss within their group why this would result in the desired the material response.

Discussion & Student Outcomes

The described activity can be tailored toward different educational levels. This activity was performed successfully with 32 rising eighth grade girls as well as 25 incoming freshmen college students, both male and female. The instructors provided worksheets to allow participants to present their hypotheses tabulate their observations and express their understanding in their own words throughout the experiment. The efficacy of the activity was determined through the results obtained from the worksheet questionnaire and a survey. The results can be utilized to modify and strengthen the activity for future use.

From the results of the questionnaire, three major conclusions were drawn; (1) students had difficulty making predictions material response of the scaffold; however (2) they were able to grasp the overall concept of biomimicry and directional strengthening of a material. Finally (3) students found the activity exciting, engaging and inspirational. As expected, students performed well in the initial "quiz," with 100% of students answering the questions correctly when they performed the activity in one class session. Prior to creating the scaffolds and testing, student were asked to draw their weave patterns on the worksheet as well as predict the force-displacement response curve of their material. Students had the most difficulty sketching a predictive curve of the force-displacement response of their scaffolds. The majority of students (42%) sketched a linear load-displacement profile discerning that the material would behave in a purely elastic manner before some sort of abrupt failure occurred. Fewer students correctly identified the scaffold as behaving in non-linear manner (33%). However, no student correctly identified the initial hyper-elastic toe region that occurs due to elongation and unraveling of the polymer chains. The final quarter of the students sketched a force-displacement graph that made no physiological sense.

We investigated what percent of students that initially designed their scaffolds with fibers oriented in the vertical direction for strength in tension (which would signify the mimicking of an actual bicep muscle). Overall, student patterns were random, with 58% having a combination with the majority of the fibers running horizontally. This could be a result of the scaffold mold, as there were more pins for stringing the fibers in the horizontal direction versus the vertical direction. The students who oriented in primarily the vertical direction articulated that they made this decision because of biomimicry. Of the 42% that oriented vertically, all of them responded in the reflection section about their design mimicking the natural structure of a bicep tissue. After performing the tension test on their scaffolds, students were asked to reflect on their design. They were asked what they would change about their design to better mimic the structure and function of the distal bicep. Overwhelmingly 83% of students responded with the understanding that the fibers needed to be oriented in a more vertical pattern. Only 17% of the student did not grasp the concept.

The final reflection question asked the student to sketch the weave patterns to design a scaffold that needed to be strong against shear forces, with the expectation that students would transfer the knowledge about vertical weave resulting in strength in tension to horizontal weave being resistive of shear forces. This question can be put in the context to relate to another tissue scaffold if desired (such as design of an articular cartilage replacement). The majority of students (58%) could transfer the concept, with their sketches having fibers oriented majorly in the horizontal direction but 42% did not make the desired connection.

A final evaluation of the activity was given to the students, rating the popularity of the activity. Of the collected responses, 14% of students responded that the activity was excellent, 41% rated the activity very good, and 46% rated the activity good, with no one commenting that the activity needs improvement. Students commented that the activity was engaging and inspirational toward pursuing careers in the biomedical engineering field. The activity can be varied based on testing configuration desired or available; namely, changing the context of the design to either compression or shear testing is reasonable.

There are a few limiting factors which affect the activity. The first major concern is the number of students that perform the activity. Increasing the number of students leads to an increase in instructional materials; the most costly and time consuming being the need to create more scaffolds. Increasing the number of "implants" in the ovens might also result in needing a higher curing time, which would increase the total activity time, but this depends on the type of oven being used to cure the specimens. For a small toaster oven, a nominal number of molds per over is five. Over five molds leads to a longer curing time for the specimens. If student number is increased, but number of molds is held constant, then there is a decrease in the hands-on experience per student. The ideal maximum student number per group for this activity is three. With three students, each student can participate in a major part of creating the scaffold. For example, two students can each string a layer of fiber, and another student can pour the binder. With a group larger than three students, there becomes less opportunity for each student to participate in the hands-on making of the implant.

The students appreciated the hands-on aspect of the experiment. They enjoyed being able to weave the fiber design, pour the binder material, and then test the final product. Working together in small groups encouraged the students to discuss the predictions and results. Predictions helped to correct student's preconceived misconceptions of topics, such as force versus stress. Furthermore, comments from the final questionnaire indicated that students were engage throughout the activity. From the student's discussions and the questionnaire, it was evident that the mechanical and biomedical concepts of biomimicry, material properties and mechanics were successfully tied into a demonstration based activity.

Safety and Hazards

Comprehensive safety standards should be practiced during the activity. It is recommended that laboratory gloves be worn during the part of the activity where the students pour the binder into the mold. Caution must be taken when handling the PDMS to avoid clothing and skin contact. It is also recommended to have the leader of the activity (or aids) put the molds into and remove the molds from the oven(s) with oven mitts. This mitigates the risk of burn injury. A knowledgeable operator is required to be on hand to facilitate the tensile testing, giving the options of permitting the students to set-up and perform the test or have the operator perform all of the tensile testing while the students watch. Finally, care should be taken during clean-up so that the razor blades are properly disposed of or are cleaned and safely repackaged for additional use.

Acknowledgements

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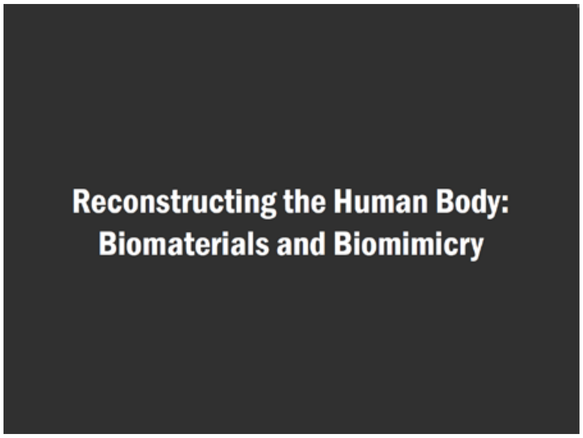
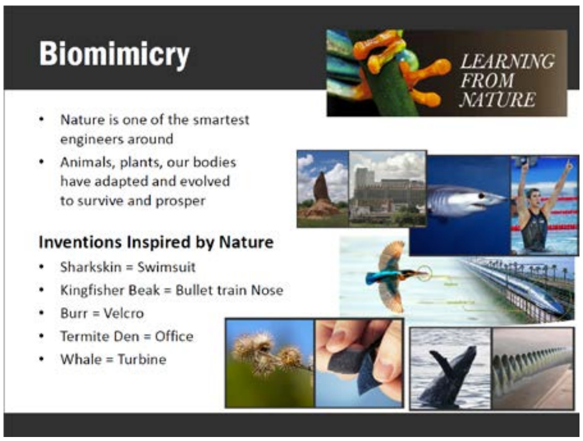
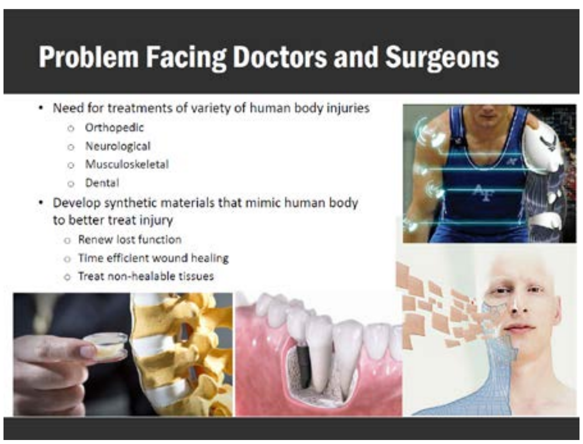
Supplemental Information

S1: Example Slides to set up activity







Design Project

Distal Bicep Fracture in Female Athletes

- 5.2 million sports injuries occur every year which leads to yearly spending of $1.83 billion on athletic injuries
  [Sports Injuries Report 2004]
- 5 % of these injuries (250,000) occur in the wrist or forearm
- Most prominent forearm injuries is a distal bicep rupture
- Women athletes mainly affected
  - Lacrosse
  - Tennis
  - Softball

What is the primary load this muscle experiences?

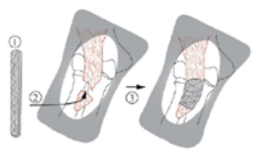
Design Project

Objective

- Design a tissue scaffold for repair of a distal bicep rupture
- Tissue scaffold that is strong in **TENSION**

Materials

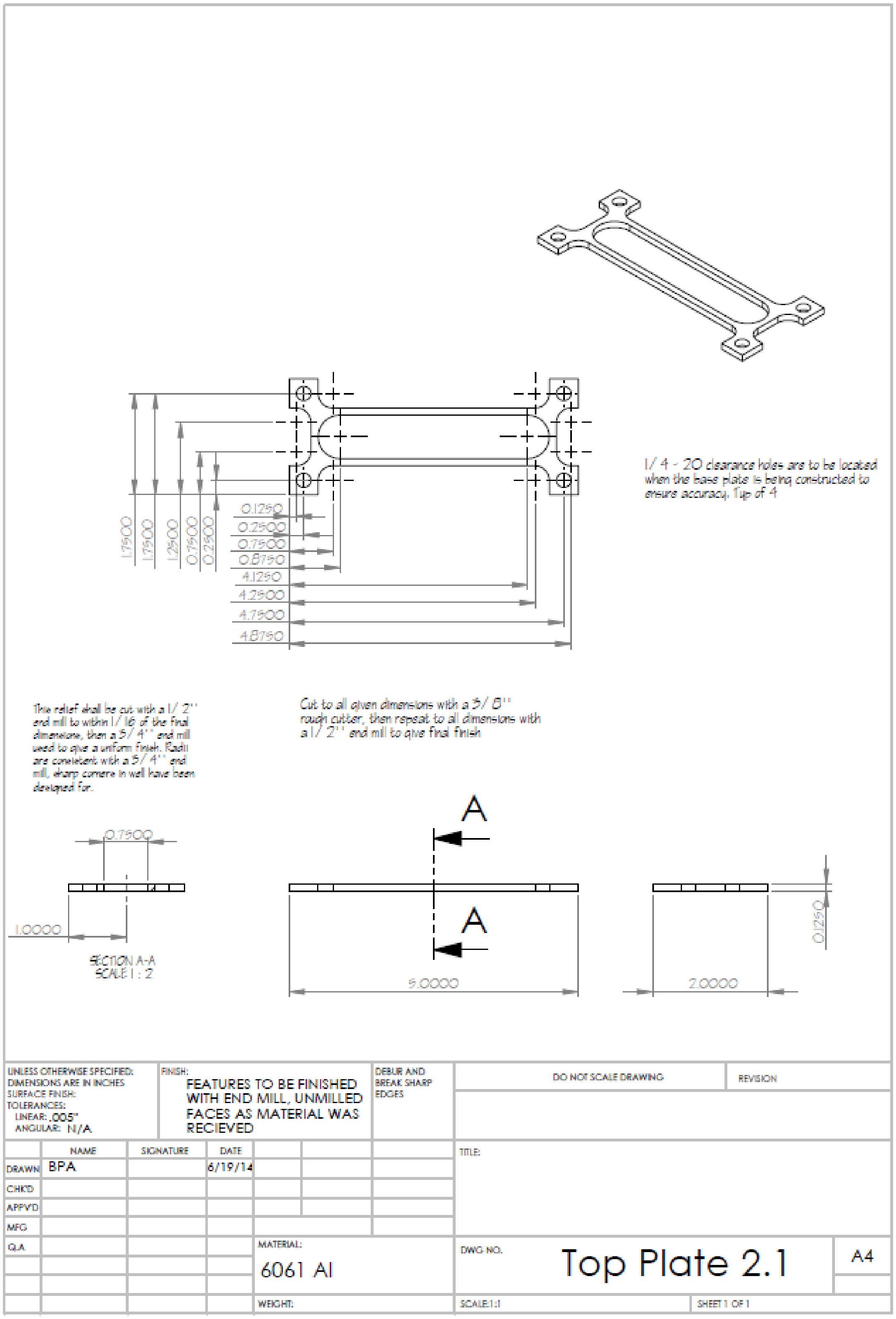
- 36" length of fiber (2x)
- Binder Material
- Scaffold Mold

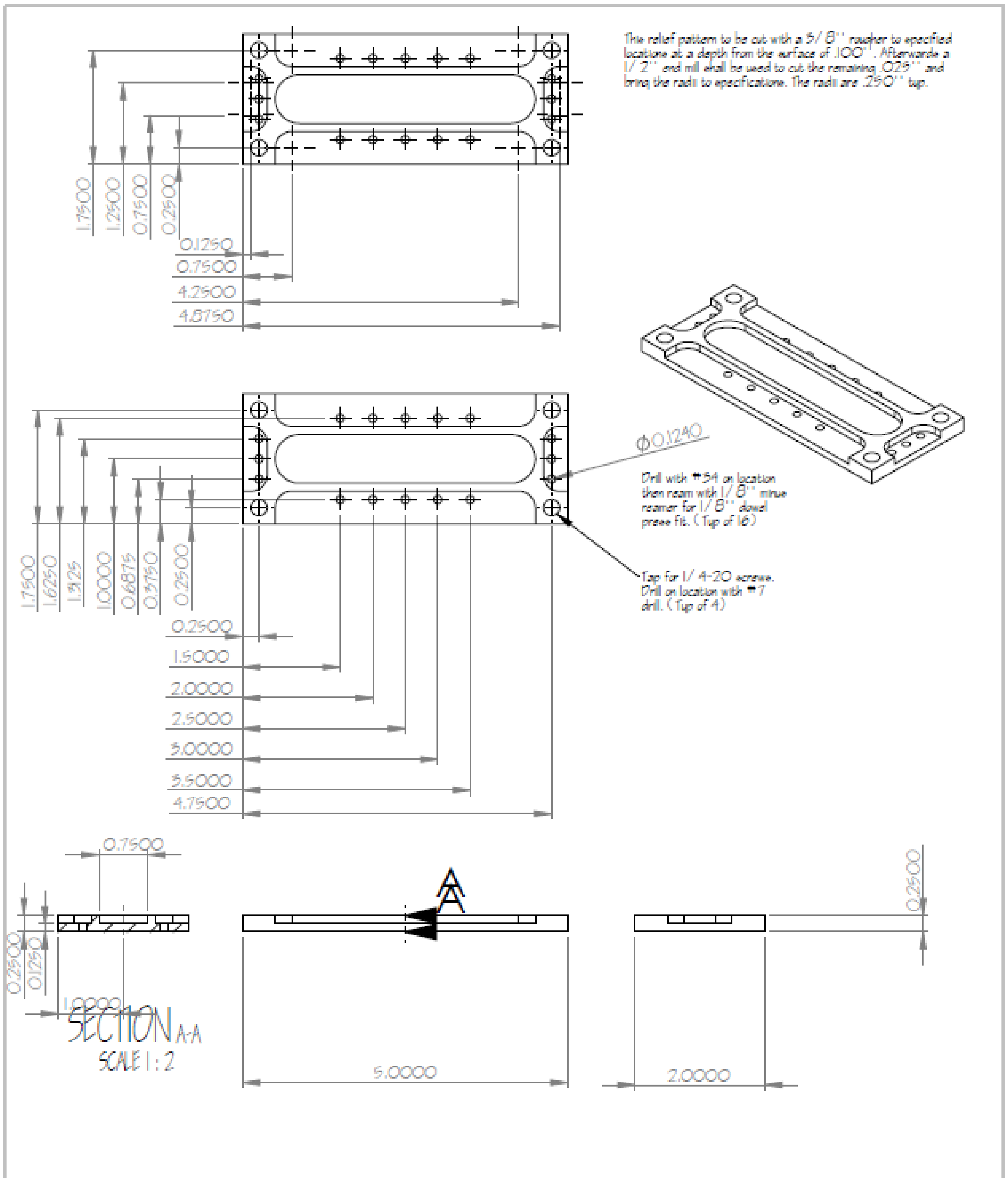


General Procedure

- String the fiber around the pins in any desired pattern
- Pour binder material into the molds
- Put all scaffolds in the oven to cure (30 minutes)

S2: Engineering Drawings of "implant" molds





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: TOLERANCES: LINEAR: .005" ANGULAR: N/A	FINISH: MACHINE ALL OVER	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING — REVISION 2

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S3: Example of activity worksheet

Reconstructing the Human Body: Biomaterials and Biomimicry

Biomimetic Engineering Scaffolds – Background

Remember that engineers design materials to mimic the muscles and tissues of the body. Reinforcing a polymer material with fibers is an efficient way of giving the polymer strength in a very specific desired direction. Today you will be performing an experiment to design a tissue implant that needs to have **strength in tension**.

A quick quiz to see if you remember your engineering definitions ☺

1. A **homogeneous material** is one that is made of

   (a) all the same kind of material

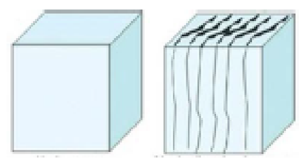
   (b) simple materials

   (c) different kinds of material

2. A structure that is Anisotropic has

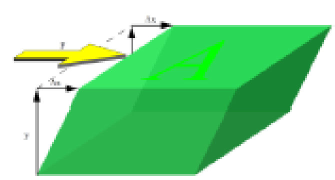
   (a) same properties in all directions

   (b) different properties in varying directions

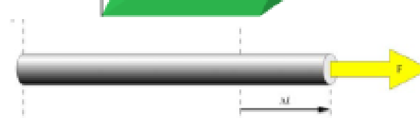


3. Draw a line from the mechanical property test to the corresponding picture:

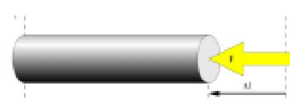
Tension



Compression



Shear



Creating Anisotropic Scaffolds – Experiment

1. Set Up. Each team should have the following:

- laboratory gloves
- 36" of fiber (fishing wire) (x2)
- 1 plastic weighboat with 15 g of polymer binder (PDMS)
- Aluminum scaffold mold
- razor blade
- set of calipers/ruler
- Allen (Hex) wrench

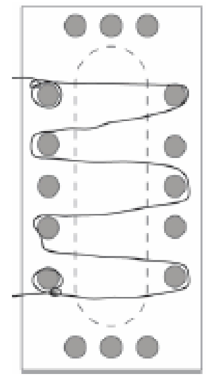
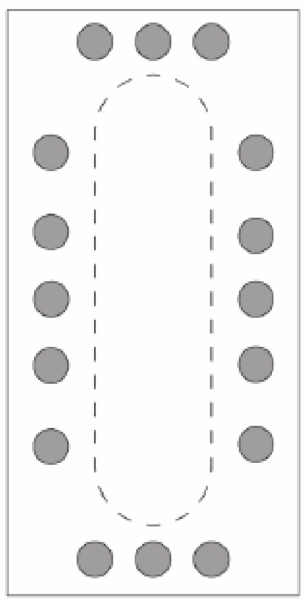


Figure: Representative sketch of mold with string.

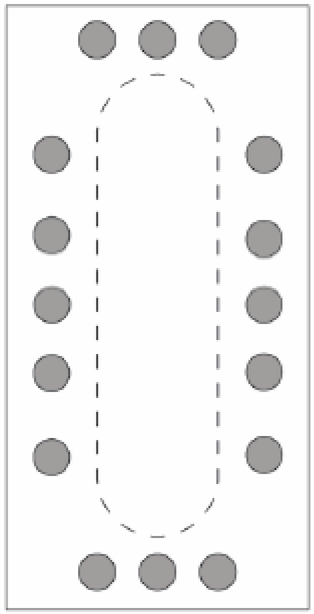
2. Create Scaffolds. The procedure is detailed in steps. If you have questions, ask one of the instructors.

1. Take the fiber and fasten it to whichever pin you would like to start at (tie a small knot)
2. Have one partner hold the beginning knot and the mold while the other partner weaves any pattern they like through the pins (see Figure). Draw a representative sketch of your patterns below.



First Pattern

3. Place the next mold on top of the string. Repeat procedure with the partners switching places. Draw a representative sketch of your pattern below.



Second Pattern

4. After stringing the second fiber strand, place the top piece on and secure down with the 4 outside bolts with Allen wrench. Have an instructor check the tightness.
5. After the mold is secure, pour in the polymer binder (located in the plastic weighboat) into the mold.
6. Raise your hand and an instructor will come over and take your mold to the oven for curing.

*It will take roughly 20 minutes for the scaffold to harden and 5 minutes for the molds to cool.

3. Sample Removal.

1. Using the Allen Wrench, remove the 4 bolts (see Figure).
2. Remove top mold cover.
3. Take the razor blade and cut around the sample to separate the excess string that is still connected to the pins.
4. Remove middle mold spacer.
5. Take the razor blade and cut around the sample to separate the excess string that is still connected to the pins.
6. Remove sample from mold.
7. (If necessary) use scissors to cut excess string and PDMS from around sample edges.

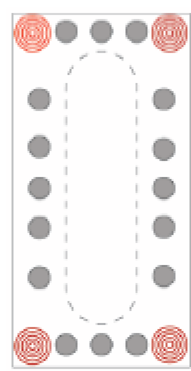
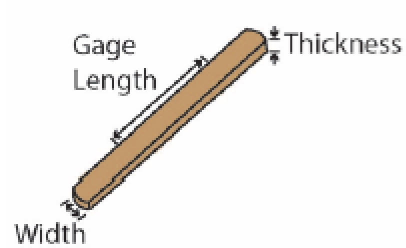


Figure: Red circles show bolt lock/unlick positions.

4. Measurements before tension testing.

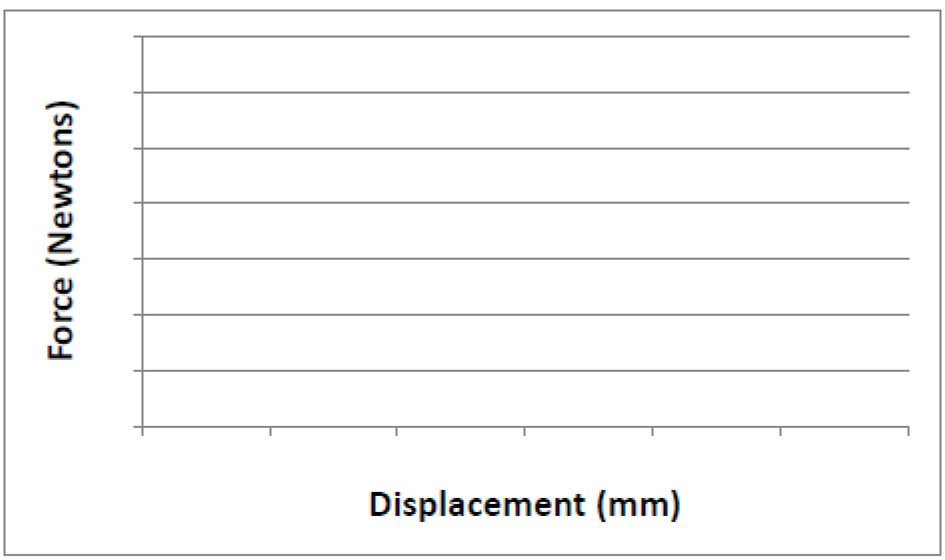
1. Measure the width, thickness and gage length of the specimens. Record your measurements here:



Width: ________mm Thickness: ________mm Gage Length: ________mm

Recall that the purpose of a tension test is to measure the stress-strain response of a material. This is accomplished by subjecting a rod of material to increasing axial elongation until it breaks. The result of such test is usually reported in the form of a Force-Displacement diagram. The curve is usually plotted with the force (stress) in the vertical axis and the displacement (strain) in the horizontal axis.

After learning about a stress-strain curve, along with your knowledge of fiber reinforced materials, draw a predictive sketch of how you think your materials stress stain profile will look?



Discuss with your partner why the material would respond this way?

5. Record measurements during tension testing.

- Note the maximum force that your sample could hold.

Max Force: _______ Newton

6. Calculate Maximum Stress.

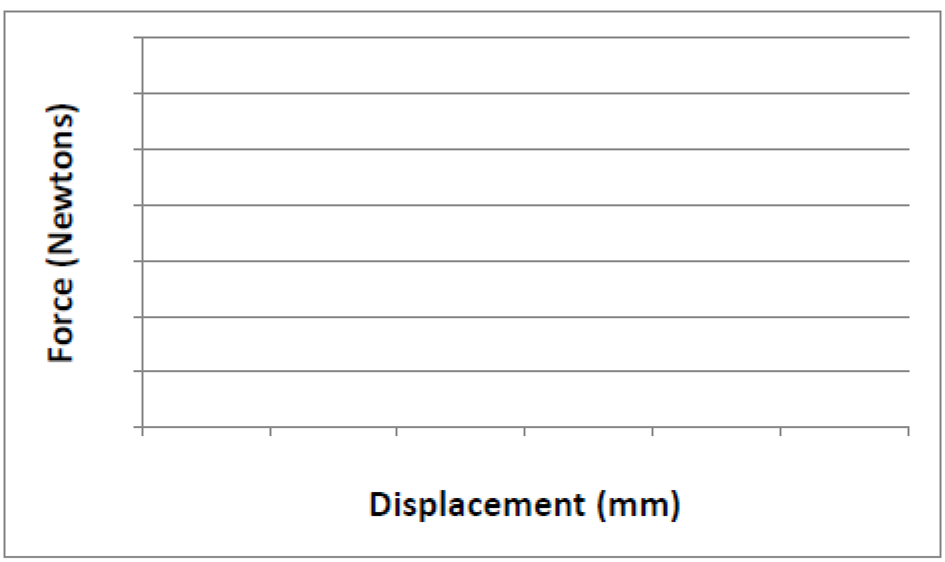
- Recall the formula for calculating stress: $Stress = \frac{Force}{Area}$
- Calculate the area of your sample using the measurements you took before testing

$$\text{Area} = \text{Width} \times \text{Thickness} = \underline{\qquad\qquad} \text{mm}^2$$

$$\text{Maximum Stress} = \frac{\text{Maximum Force}}{\text{Area}} = \underline{\qquad\qquad} \text{N/mm}^2$$

$$\text{Maximum Strain} = \frac{\text{change in length}}{\text{original (gage) length}} = \underline{\qquad\qquad} \text{mm/mm}$$

Draw what your actual load-displacement graph looked like:

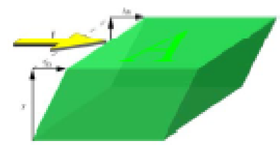


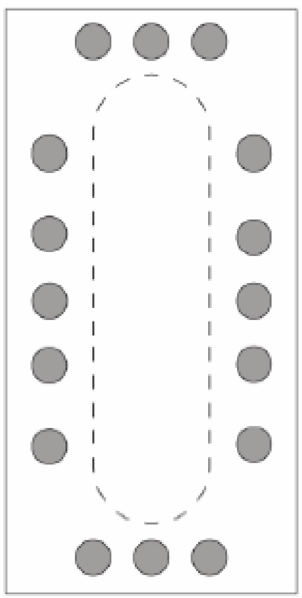
Discuss with your partner why the material would respond this way?

7. Reflection of Design

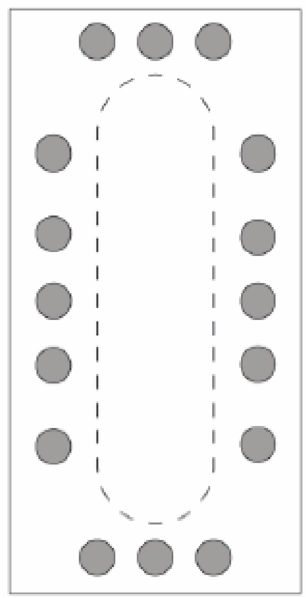
1. After hearing more about fiber reinforced polymers scaffolds and the importance of fiber direction, how would you change your design to better mimic the structure and function of the distal bicep?

2. How would you design a scaffold that needs to be strong in **SHEAR**? Draw a representative sketch of the pattern below and discuss with your partner why this would result in the desired the material response?





First Pattern



Second Pattern

3. Go over to the computers and use what you have learned about how to calculate stress and strain and plot a stress-strain curve from your load-displacement data. How does it compare to the raw data? What changed?