LESSON PLAN:
Understanding mechanical properties to improve current knee injury treatments

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Intended Audience: Upper middle school or high school students. They should have a basic knowledge of the human body and be able to comprehend that objects made from different materials have different properties.

Duration: 40 min

Background Information:

The body is made up of different types of tissue that perform different functions. Musculoskeletal soft tissues (cartilage, tendons, etc.) guide and stabilize our joints during movement. Unfortunately, they are often injured, leading to altered structure, loss of function, and pain. In fact, some of the fastest rising injury rates are in children and teens. Therefore, it is important that we understand how these tissues work, how they grow, and how we can design better replacements for injured tissues.

Human growth occurs at many different scales simultaneously within the body. While children grow and become taller, their individual tissues are also increasing in size. For example, an arm growing over the course of childhood involves not only bone growth, but also growth of skin, muscle, fat tissue, connective tissue… all components that make up the arm also grow. These changes include length and weight increases, however there can also be changes to the shape or structure of tissues over time. These changes can be dictated by outside environmental factors, or mechanical, biological, and chemical stimuli in the part of the body surrounding the tissue (also called the tissue environment). While these changes naturally occur during healthy growth and are responsible for the development of normal adult tissues, unexpected changes in the outside or tissue environment can lead to unhealthy tissue growth and long-term issues including misshapen or abnormally-sized tissues.

One way to understand tissue function is through its mechanical properties. For the knee, the most relevant properties are compression and tension. Compression describes how a material deforms when a force is applied to it (IE when it is "squished"). Tension describes how a material acts when it is stretched (IE tension is applied). Some materials are isotropic, meaning they deform the same way regardless of the compression or tension force, and some are anisotropic, which means that they will deform in different ways based on the type and direction of compression or tension. The cartilage in your knee, which serves to keep your femur (thigh bone) and tibia (shin bone) from rubbing against each other is anisotropic because during normal use it is only compressed top to bottom (very rarely is your knee joint compressed side to side during normal use). Another example of an anisotropic tissue is the tendons in your knee, which are designed to stabilize it by stretching or compressing in one direction, much like a rubber band. If you apply force in a different direction, it will react different. Elasticity, or how stretchy or stiff something is, is another key material property of soft tissue. The goal is to develop new treatments from biomimetic materials, meaning those that have similar biological properties to natural tissue and can be implanted in the body, and to do this we must better understand the material properties of existing tissues.

Essential Questions: What are different kinds of tissue in the body, and what roles do they play? What are some things that can affect tissue growth? What are mechanical properties, and how can we relate different properties to different tissues? Does a tissue's function affect its properties? How does a 3D printer work, and how do we hope to use it in the field of medicine in the future?

Objectives: The student will be able to (TSWBAT) understand how growth affects form and function within the human body. TSWBAT to explain how constricting growth of tissues can lead to physical changes later in life, and potentially functional changes. TSWBAT create a model for isotropy and anisotropy, and explain why this information is relevant in the knee. TSWBAT evaluate different materials and judge which would be better suited for different physiological functions, and state why.

Next Generation Science Standards:

MS-LS1-5: Construct a scientific explanation based on evidence for how environmental and genetic factors influence the growth of organisms.

MS-LS1-3: Use argument supported by evidence for how the body is a system of interacting subsystems composed of groups of cells.

MS-ETS1-1: Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution.

MS-ETS1-2: Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.

HS-LS1-2: Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms.

HS-LS4-1: Communicate scientific information that common ancestry and biological evolution are supported by multiple lines of empirical evidence.

HS-ETS1-2: Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering

Recommended Materials:

Material Properties:

- Stress Balls, minimum 1 per pair of students, but 1 per student is ideal (reusable)
  - Note that not all stress balls will work for this activity. We recommend Amazon PN B01HN3RYDC
- Resistance bands of different strengths cut into quarters, one piece per student (reusable):
- Rubber bands: Ideally varying size, but one size is ok too. Minimum 10 per student
- Tongue depressors or Popsicle sticks. Minimum 10 per student.
- Knee model with meniscus & ligaments (The one from Axis Scientific will suffice, or there are many other commercially available options). Alternatively, an image, such as this one can be used: http://www.webmd.com/pain-management/knee-pain/picture-of-the-knee#1).

3D Printing:

- 3D Printer, any model is fine as long as it is open enough to see the object being printed. Alternatively, a video of a 3D printer in action could be shown if a 3D printer is not available. A good video: https://www.makerbot.com/learn/.
- *Optional, if you have a 3D Printer:* 3D Printing file for a simple, small object that can be printed in 3-5 minutes. Here's a possibility: https://www.thingiverse.com/thing:269832 but anything fairly simple should work.
- *Optional, if you have a 3D Printer:* 3D Printing file for a more complicated object, such as the tourist duck found here: https://www.myminifactory.com/object/3dprinteros-tourist-duck-7197?ref=makexyz
- Wikistixx: Enough for each student to have at least 2 feet worth
- [OPTIONAL] Samples of different filament materials used for 3D printing (a 4-6 inch portion is sufficient, though it's recommended to have multiple of each type)

Tissue Growth and Effects of Constraints:

- Zip ties (at least 4 inches long)
- Pop up sponges, 3 per group. Any brand will work as long as they start nearly flat and quickly expand in water. We recommend Amazon PN B008XLGDDQ

    - Before the lesson, tie a zip tie around 1 sponge per group near the middle and cinch it so that it's moderately snug.
- Test tube or graduated cylinder. Diameter depends on sponge size: it should be large enough to accommodate the dry sponge but small enough to constrict the sponge once it's wet/expanded.
- Water
- Scissors/knife sharp enough to cut the zip ties.
- Printouts of images or a monitor to display them (images are in supplement 1)

Introduction and Knee Anatomy Overview (5 minutes):
First give students a brief overview of the knee anatomy using the knee model or image. Introduce students to the meniscus, Anterior Cruciate Ligament (ACL), Posterior Cruciate Ligament (PCL), Lateral Collateral Ligament (LCL) and Medial Collateral Ligament (MCL). Point out that the meniscus is actually two separate pieces of tissue: the lateral meniscus and medial meniscus. Explain the functions of the various parts: the meniscus and cartilage act to reduce friction between the femur and the tibia, and the four ligaments act to stabilize the knee through various types of motion. Ask students which types of movements they think are more likely to result in injury (example: walking, running, jumping, darting sideways, etc). Explain that one area of study is to better understand how these tissues affect the knee's movement and learn about different types of injury that can affect the knee. We want to use this information to design better surgical options for knee injuries, including designing better scaffolds for use in tissue grafts. We use pigs in our research because their hind limb is very similar to the human knee.

Activity 1: Mechanical Properties (10 minutes):
Introduce students to mechanical properties using several hands-on, inquiry-based activities. Have each student stretch a resistance band and characterize how difficult it is to stretch. Have them trade with someone who has a different color band (note: different colors have different stiffness properties) and try again. This activity demonstrates that the strength of a material isn't just due to its size, but also due to its material properties, and this is called an intrinsic property. Now ask the students to squeeze the stress balls (note: all colors have the same resistance). What happens when you squeeze it? What if you rotate it then try again? Does it compress (squeeze) the same way or does it bulge differently based on orientation? Students should realize that no matter which orientation you squeeze them, the ball compresses the same way. This is an example an isotropic material: regardless of the orientation in which you compress it, it deforms in in the same way. Anisotropy is when a material compresses differently based on the orientation that force is applied. To mimic this, have the students use the rubber bands and Popsicle sticks to apply constraints to the stress ball. Can they make it so that if force is applied in one direction, the ball with deform but when applied in a different direction, it does not? (Hint: Try using the sticks as reinforcement or restricting the ball with numerous rubber bands. Do you get different results by using multiple rubber bands or Popsicle sticks in the same orientation/stacked together? How about different orientations?).

Activity 2: 3D Printing (15 minutes):
If students are not familiar with 3D printers, explain that they are used to construct three dimensional objects from plastic filament. There are several techniques that fall under the '3D printing' umbrella term, including different laser-based and extrusion-based techniques, but extrusion-based is what most people are familiar with and what we will use during this lesson. Point out key parts of the printer, including the filament spool and the extruder head. If you don't have access to a 3D printer, show the video (though the video may be useful even if you do have access). The filament is like a long string of plastic that is melted to make it pliable, then the extruder head deposits it onto the base in the pattern indicated by the software. Using this method, it "builds" an object one layer at a time, until you have a 3 dimensional object. Although it can reliably create complex shapes, which is advantageous for creating new tissues, the downside to a 3D printer is that it's slow and has limited resolution. In the case of most common 3D printers this is around 1/10 of a mm. Unfortunately, this is larger than a cell, which is more on the order of

1/100 of a mm, and is an area of ongoing development in 3D biological printing. We hope to eventually use the 3D printer to create parts from biologically compatible plastics with similar material properties to replace damaged tissues in the body. [OPTIONAL ACTIVITY] Show the students the different types of printer filament. Pass them around and ask the student about the material properties of the different types. Is one stiffer than the others? Is one more flexible, compressible, elastic? Which one might be best for a new meniscus? How about new bone?

If a 3D printer is available, explain to the students that they will be racing the 3D printer to create a simple structure, then a more complex one. Start the printer and allow it run through any pre-printing steps (reaching the desired temperature, stage calibration, etc). Give the WikiStix out to students and explain that their goal is to build two things: 1) an easy object (e.g. tiny mug) and 2) a complex object (e.g. a 'tourist duck') and that they're trying to build them faster than the printer can make it. Once the printer is ready, have them begin. Make sure that they don't forget the bottom or the handle on the mug! Typically, the students are able to quickly make a good quality mug faster than the printer, but very few can create a tourist duck as detailed and complete as the one the printer can make. This helps to illustrate how useful 3D printing is for making complex shapes.

Alternate Option: If no 3D printer is available, you can still challenge the students to make a simple object and a more complex one using the WikkiStix. Which one looks more like the intended object (the complex shape or the simple shape)?

Follow up questions: What was one of the hardest aspects of printing? Did they find it limiting to use the thick WikiStix? Could 3D printing be more accurate with thinner filament? What steps would be needed to 3D print things that can be implanted into the human body? Is it plausible to do 3D printing with things other than plastic (aka biological 3D printing with cells or tissue-forming materials?)

Activity 3: Tissue Constraints (10 minutes):
Explain to students that as tissues grow, they can be influenced by their environment. If there is a constraint placed on a tissue, or something that affects its growth, that can affect the tissue shape at adulthood. Have students brainstorm some things that might be constraints that would affect people. Try to keep them on task to actual examples, rather than really out there things that could happen. Some examples include braces/retainers, corrective leg braces, an implanted splint to help a fracture heal, etc. Show them the images in supplement one. Be sure to save the ones with the turtle without the ring for after the one with the ring, to highlight that things don't always spring back when the constraint is removed (and in many cases this is what makes the constraint useful).

Now introduce the sponges. First, show them an unconstrained sponge and then get it wet. It springs out into a normal-shaped sponge. Then show them another dry sponge, and put this one into the tube. Then wet the sponge. Ask students what they think will happen when you remove the sponge from the tube. Show them that even when you remove the sponge, it doesn't quite expand as much as the original sponge (be warned – if you let them sit to long or re-wet the constrained sponge, it will eventually become the same shape as the first one). Then show them the sponge with the zip tie. Have them make predictions. Will the top and bottom expand to be as wide as the first sponge? What will happen to the middle portion? What will happen to the middle portion when you cut off the zip tie? Do the experiment. Show them that due to the constraint, even the parts of the sponge away from the constraints have affected growth (the top and bottom don't get quite as wide as the first sponge). The middle portion barely expands due to the constraint. Once you remove the zip tie, it expands some but not all the way. No matter how long you leave it, as long as you don't re-wet it, an impression will remain from the zip tie. This is an example of how a constraint, even when removed, may have permanent results. Point out that sometimes a constraint can come as a result of injury. One example is when someone has an injury to their knee, such as an ACL tear, the surgical repair could affect further growth.

Supplement 1: Tissue Constraint Images

“Mae West”. Images via http://www.planetexperts.com/meet-the-famous-turtle-with-a-serious-plastic-problem/

"Peanut". Images via https://www.upworthy.com/see-this-turtles-miraculous-recovery-after-getting-caught-in-a-piece-of-litter

Image via Flickr /sea turtle: https://www.flickr.com/photos/sea-turtle/3463746437/in/photolist-6h5B9a-661yde-7KKRJa-6h9LXU-6goQDr

Image via AllDay: http://www.allday.com/these-burmese-women-are-taking-off-their-restrictive-neck-coils-2180791136.html

Image via Wikipedia: By Steve Evans - http://www.flickr.com/photos/babasteve/351227116/, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=1581541