BIOEN 326 2014 LECTURE 1: INTRODUCTION TO THE CLASS AND FORCES AND MOMENTS

Class structure:

<u>Course Policy:</u>

Grading is fully explained on the course homepage and on a document that is linked there. You should read these as they go into much more detail than what I say today.

Briefly, you are graded 40% on homework, 20% on the mid-term and 40% on the final exam. All assignments are given points, which are translated into your final grade on a 4.0 scale, so that 75% is a B, 50% is a C, etc. I thus give 50 points worth of C problems, 25 of B and 25 of A.

Homeworks are due Wednesdays.

Helping vs cheating. Provide coaching, not answers to each other. Tell your peers what information you found important, direct them to the relevant section of the lecture notes, etc. Take your cues from how we provide help in office hours.

What is Biomechanics of Solids and Gels?

Solids are relatively hard materials that respond instantaneously to force with small deformations. **Gels** are mostly liquid, but have significant cross-linking within them that prevent them from flowing like liquids. However, they are often quite soft so that they deform significantly, and often have a **viscoelastic** property that causes them to deform slowly instead of instantly. Together, solids and gels encompass most biomaterials. A **biomaterial** includes living materials, nonliving materials made of biological components, and nonbiological materials that are used for biological and medical applications. So we are studying a wide range of biomaterials – everything except what is covered in your fluids class, Bioen 325.

Biomechanics is the study of how mechanical forces affect biology. There are two main effects of force. Obviously, force can deform objects, and one part of this field and this class is the study of these deformations. However, living materials, unlike almost every other material, can have an additional response to force, which is that it can remodel itself, because mechanical forces are coupled to biochemical reactions.

<u>Statics: How Do External Forces Translate to Internal Stresses</u>?

Regardless of whether we are asking how forces deform a biomaterial or induce a biochemical signal in the biomaterial, we need to first determine the force experienced at particular locations within the biomaterial in question. However, in experiments or engineering applications, force is applied externally, so we need to calculate how the external forces on the object determine the stress (force per unit area) at any location within the object. This requires us to study **statics**, which uses the assumptions of equilibrium and free body diagrams to calculate internal stresses. In particular, you will build on your previous free body diagram skills to utilize internal and externally applied **moments** (with would induce rotation around a point if there were no resistance) in addition to **forces** (which would cause a translation of a point if no resistance).

Mechanics of Materials: How do Biomaterials Deform?

Next, to ask how forces deform materials, we study **mechanics of materials** for solids and gels. That is, when we apply a stress on a material, what is the resulting **strain** (fractional deformation)? Thus, we incorporate knowledge from both statics and mechanics of materials classes, which are common courses in mechanical engineering and materials science curricula. We will learn to evaluate how to calculate deformations for many shapes that are common in bioengineering applications, such as bars, beams, and pressurized cylinders. However, the nonbiological fields often make assumptions to simplify the mathematical analysis of the problems. While these assumptions are justified for most problems in those fields, the biological situation more often violates these assumptions, so we need to learn to deal with additional complexity. Specifically, most text books, including Gere, assume the following:

1) **Small deformations**. We often assume that the geometry is not significantly changing as force is increased. However, biological materials often deform several-fold in their normal functioning range.
2) **Linear elasticity**. We often assume that the ratio of strain to stress (the **Young's modulus**) is constant as stress, or force, increases, but many biological materials are nonlinear.
3) **Isotropic**. We often assume that the Young's modulus is the same in all directions, but many biological materials (such as wood, bones, muscle, artery walls, and electrospun biomaterials) are anisotropic, so that they are stiffer in some directions than others because they are composed of oriented fibers or sheets.
4) **Pure elastic properties**. We often assume that responses are instantaneous, not time-dependent. We also assume responses are reversible, referred to as **elastic**, rather than irreversible, which is referred to as **plastic**. Together, these assumptions mean that the deformation can be calculated from the applied force at this time, without considering the history of how forces were applied in the past. However, many biological materials are visco-elastic, so deformation is time- or rate-dependent.

Thus, in addition to learning to solve problems for linear isotropic materials with small deformations, we need to be aware of when each assumption fails and have additional tools to deal with these situations. To allow time to cover both statics and mechanics of materials in one course and also consider the special properties of biological materials, we are not able to address the same level of complicated problems as you would in pure statics and mechanics of materials classes. Thus, if you take advanced courses that require those topics, you may need additional time and practice to solve some of the problems, but you should have the knowledge base to do so.

Mechanobiology: Influencing Biochemistry

The study of how mechanical forces affect biochemistry is referred to as mechanobiology, and the mechanism by which this occurs is referred to as mechanotransduction. This process is only recently being understood, with bioengineers at the center of many new discoveries, but we are beginning to realize that it is pervasive. That is, many diseases and physiological processes are regulated mechanically. For this class, we will focus on three physiological systems: the muscoluskeletal system and the cardiovascular system. However, there are still significant effects of mechanical forces on cancer and other physiological and disease processes that do not have obvious mechanical functions. In this course, we will learn the molecular basis of mechanotransduction, will have guest lectures provide expert insights on some of these systems, and will apply our knowledge to these problems in some of the homework and exam assignments.

Evaluating Biomechanics Literature.

Many topics covered in this course are still being advanced in research labs around the world. For example, the field of mechanotransduction is in its infancy. In most biological responses, we don't know which molecule converts mechanical force into a biochemical signal, or how it does so. The study of nonlinear materials properties is still young as well, and it has only recently been discovered that some biological materials exhibit a behavior called elastic yielding. Because of this, some of what I teach you is not in the Gere or any other text book, but instead is gleaned from original research articles in my field. I thus think it is important to also teach you how to read these yourselves. Most of you have taken Bioen 215 and know how to research a topic, by finding relevant articles from reliable sources, and properly cite these sources. In this class we will go deeper into how to critically evaluate an original research article. We will ask, not just what are the author's conclusions, but what is their **level of certainty**? The level of certainty will be unique for each conclusion, and is increased by eliminating alternative explanations. We will learn how to identify the author's claimed level of certainty and also to evaluate it ourselves. We will apply this tool on a few original research articles in the field so you can better see the significance of what we are learning in class.

Brief Topics Outline:

In Unit 1 of this course, we stick closely to Gere as we study statics and mechanics of linear elastic materials, but we apply these skills to biological examples at both the nano- and maco-scale. Specifically we cover

- free body diagrams
- linear elasticity
- stress analysis (changing the orientation)
- bars
- beams
- cylinders and spheres

In Unit 2 of this course, we deviate completely from Gere to study topics that are fairly unique to biological materials.

- nonlinear elasticity and its molecular basis
- viscoelasticity
- mechanically active materials (mechanotransduction)
- evaluating biomechanics literature
- integration of all course material.

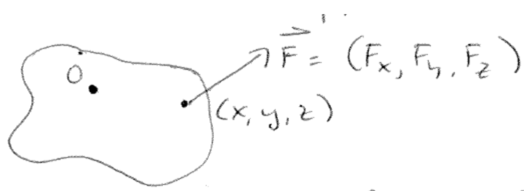
Make sure you read all posted lecture notes and assigned reading!

Finding Forces and Moments

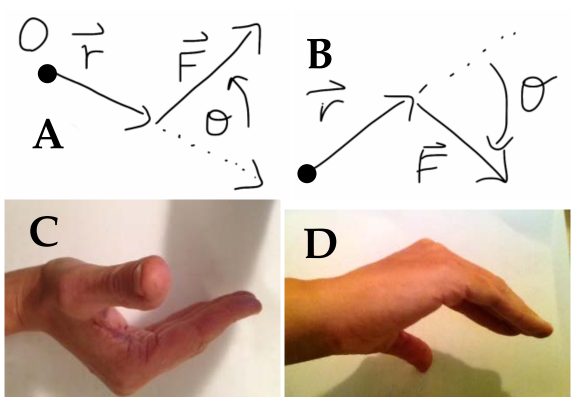
This week we review what you learned in physics class about writing Force-Balance equations, and apply this to biomechanics problems. We need these to calculate the stresses in a structure. Our goal is to calculate the forces and moments applied to a structure given specific forces and moments applied to the structure and given support reactions that arise from places the structure is contacting another object. You have probably learned to do this for forces but not for all aspects involving moments. However, for this course, you will only need to solve problems where all forces lie in a plane.

The following should be already familiar to you.

Forces. A force $\vec{F}$ is a vector applied to a point, as shown below.

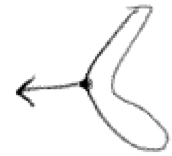


Moments. A force $\vec{F}$ causes a moment at any point O that is not in-line with the force, because such a force would tend to rotate the object around the point O (see panel A above). If $\vec{r}$ is the vector between the point O and the point at which the force is applied, then $\vec{M} = \vec{r} \times \vec{F}$ is the moment. Recall that the cross product is perpendicular to the plane of the two vectors involved. In both examples above, $\vec{r}$ and $\vec{F}$ are in the x-y plane so the moment is along the z-axis (M_z). Specifically, $\vec{r} \times \vec{F} = rFsin\theta \cdot \vec{n}$, where $\vec{n}$ is the unit vector in the positive direction perpendicular to the plane of the two vectors. Thus, the sign of the moment is determined by the sign of $sin\theta$ where θ is the angle from $\vec{r}$ to $\vec{F}$. ($\theta = \theta_F - \theta_r$). In the panel A above, $\theta > 0$ so $sin\theta > 0$, while in panel B, , $\theta < 0$ so $sin\theta < 0$. You may have learned to find the sign of the cross product or moment with the right-hand rule, which has you align the side of your right palm with $\vec{r}$ and your fingers with $\vec{F}$, to see which way your thumb points when you do this. Panels C and D show this rule providing the positive and negative values corresponding to the panels A an B respectively.

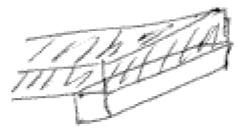


Known forces. Known forces may be concentrated at a point or may be distributed over a region. In the latter case, we can replace the distributed load with a resultant force at a specific point.

- **Concentrated load** is a defined load applied in a defined direction at an idealized point. Examples are a tendon attached to a bone, a microtubule attached to the chromozone at the kineticore, or a weight hanging from a rope attached to a specific point on an object. (Units are N)



- **Linearly distributed load** is a load distributed across the surface along a length of an object, such as a concrete pad lying on a beam. (Units are N/m). If you can define the force density $F_d(x)$ along a distance x, then the linearly distributed load can be idealized as a resultant force $F_R = \int F_d(x)dx$, acting on the x-position of the centroid of a two-dimensional shape that has x as one dimension and $F_d(x)$ as the other. That is, acting on $X_R = \frac{\int xF_d(x)dx}{F_R}$.



- **A surface distributed load** is the same idea, but over a two-dimensional surface. In this case, $F_R = \int\int F_d(x,y)dxdy$, and it is applied at the centroid of the surface, $X_R = \frac{\int\int xF_d(x,y)dxdy}{F_R}$ and $Y_R = \frac{\int\int yF_d(x,y)dxdy}{F_R}$. This time F_d has units N/m2.

- **Body force** is a load distributed over the volume of the whole body, not a surface. For example, consider an object with total mass m, distributed over its bulk. The gravitational force distributed over the body can effectively be replaced by a single force mg, acting on the **center of mass (COM)**. This is the same thing, in three dimensions, and it can be abbreviated $F_R = \int F_d(\vec{r})d\vec{r}$, and F_d has units N/m^3. If the density is constant, then the COM is the centroid of the three-dimensional object.

- **Center of Mass.** Practical steps for calculating the center of mass:
  - If the object is symmetrical in any direction, the COM lies on the axis of symmetry. Therefore, it is in the center of a circle, square or rectangle.
  - See the appendix in your text book for equations for specific shapes.
  - If the object can be described by a discrete number of simple shapes for which you can calculate the COM of each, then the COM can be determined by combining these: $x_{com} = \frac{1}{M}\sum m_i x_i$, and similar for y_{com} and z_{com}, where $M = \sum m_i$ is the combined mass of the system, x_i is the location of the COM of element i , etc.
  - If the object can be described by continuous functions, the COM can be obtained by integration $x_{com} = \frac{1}{M}\int xm(x)dx$, where $m(x)$ is the mass per unit length in the x dimension as a function of x. And similar for y_{com} and z_{com}.