Course: Biomechanics of Movement and Assistive Robotics

Logistics

Instructor: Patrick Slade (slade@seas.harvard.edu)
Teaching staff:
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Meeting time and place: Tuesday/Thursday 11:15am – 12:30pm, SEC 1.413
Patrick's office hours: 15 minutes before and after each lecture, SEC 4.218
TA Office hours: TBD
Text: Biomechanics of Movement: The Science of Sports, Robotics, and Rehabilitation

Learning objectives

- Describe the biological, mechanical, and neurological mechanisms by which muscles produce movement
- Identify and use engineering tools that are used to study movement
- Write and solve equations of motion for simple models of human movement
- Apply biomechanics principles to "real-world" clinical and biomechanical research
- Understand methods to develop effective assistive robotic devices
- Survey state-of-the-art assistive technologies

Description

This course will study the fundamentals of human movement, emphasizing applications in rehabilitation, athletics, and assistive devices. Topics will focus on the biomechanical principles of movement (muscle and tendon properties), experimental data collection techniques (motion capture, wearable sensing, and imaging), simulation with musculoskeletal modeling, and cutting-edge topics in assistive robotics (human-centered design, human-in-the-loop optimization, exoskeletons, etc). A semester-long project will allow students to apply these topics to solve a problem of interest relating to human movement or assisted mobility. Open enrollment to graduate and upper-level undergraduate students.

Prerequisite recommendations

- Math 21b or equivalent linear algebra (matrix addition and multiplication; dot and cross product) and differential equations (solve 1st and 2nd order ODEs)
- CS 50, ES 53, or equivalent introduction to programming

Honor Code

This class will be conducted in the spirit of the Harvard Honor Code.

Coursework

- Homework assignments on biomechanics fundamentals
- OpenSim musculoskeletal simulation assignments
- Midterm exam on biomechanical principles of movement
- Semester-long, open-ended project
    - Project proposal, presentation, paper
- Advanced topic presentation on a cutting-edge paper relating to biomechanics

Grading

35% Homework (homework, OpenSim assignments, and lab participation)
25% Midterm Exam
5% Advanced Topic Presentation
5% Project Proposal
10% Project Presentation
20% Project Paper

Advanced Topic Presentation

Each student will prepare a 5-minute presentation on a research paper from a provided list, or of their own choosing with course staff approval. The goal of the presentation is to summarize the purpose of the study, the main findings, and the most relevant biomechanics findings or methods. The student should prepare a few discussion questions and will lead a class-wide 5-minute discussion following the presentation.

Project

The course will revolve around an open-ended project to investigate a question of interest surrounding biomechanics of movement or assistive devices. The projects will be in small groups of 3 students. These projects will focus on developing the research skills necessary to perform a scientific investigation. Students will explore a solution and provide simple, preliminary results. For example, projects will focus on a topic selected by the students and may simulate human movement or a device, use wearable sensors to evaluate the biomechanics of movement, or develop a simple assistive prototype. Example project questions: how does a runner's gait change through an Achilles injury and the subsequent recovery? Does running downhill backwards reduce knee contact forces (and likely future injuries) in runners? Does increasing torque production (with a simulated assistive device) at the ankles influence fall recovery in the elderly? The project deliverables will consist of an outline (including a literature search and proposed plan), periodic check-ins with Tas, a project presentation (10 minutes), and a project paper (6 pages, including introduction, methods, results, and discussion sections).

Diversity and Inclusion

We would like to create a learning environment that supports a diversity of thoughts, perspectives, and experiences, and honors your identities (including race, gender, sexuality, religion, ability, etc.). We will do our best to support you in this mission, and we look to you to help us create this type of environment. Your suggestions are encouraged and appreciated.

Late Policy and Corrections

Students are allowed a total of 3 late days for the homework and OpenSim assignments. If you feel an exam was graded incorrectly, please return your work to the course staff with a written description of what you believe to be the error. The course staff will review the entire assignment/exam and adjust the score accordingly.

Missing Lecture

Lectures will not be recorded. If you become ill, please stay home and take care, send an email to the course staff and we will send you a video lecture (most but not all of the course has backup video lectures).

Policy for the use of AI

We expect that all work students submit for this course will be their own. In instances when collaborative work is assigned, we expect for the assignment to list all team members who participated. We specifically forbid the use of ChatGPT or any other generative artificial intelligence (AI) tools at all stages of the work process, including preliminary ones. Violations of this policy will be considered academic misconduct. We draw your attention to the fact that different classes at Harvard could implement different AI policies, and it is the student's responsibility to conform to expectations for each course.

Week	Date	Lecture Topic	Readings	Homework
1	9/5	Introduction and Class Overview	Chapter 1	
	9/7	Design of a Tuned Track	Chapter 3	HW 1 out, OpenSim 1 out
2	9/12	Locomotion	Chapter 2	
	9/14	Motion Tracking Techniques	Chapter 7	
3	9/19	**Lab**: Experimental Motion Capture (**LL2.210-03**)		HW 1 due, HW 2 out
	9/21	Muscle Structure and Force Generation	Chapter 4	Project topic, OpenSim1 due
4	9/26	Muscle-tendon Interaction and Mechanics	Chapter 5	OpenSim 2 out
	9/28	**Lab**: Experimental Muscle Models (**LL2.210-03**)		Pre-lab due
5	10/3	Musculoskeletal Geometry	Chapter 6	HW 2 due, Lab-due
	10/5	Neuromuscular System / Muscle Adaptations		
6	10/10	Inverse Kinematics	Chapter 7	OpenSim 2 due, 3 out
	10/12	Inverse Dynamics and Optimization	Chapter 8,9	HW 3 out
7	10/17	**Lab**: Assistive Device Prototyping (**LL1.241**)		Pre-lab, project outline due
	10/19	Assistive Devices		OpenSim 3 due
8	10/24	Midterm review		
	10/26	**Midterm Exam**		Advanced topic assigned
9	10/31	Advanced Biomechanics Techniques	Ch. 10-13	
	11/2	Assistive Devices 2		HW 3 due
10	11/7	Philosophies on Biomechanics and Assistive Tech.		
	11/9	Project Workday / Advanced Topic Presentations		
11	11/14	Advanced Topic Presentations		Paper draft due
	11/16	Advanced Topic Presentations		
Thanksgiving Break				
12	11/28	Advanced Topic Presentations		
	11/30	Student Project Presentations		
13 (Reading week)	12/5	Student Project Presentations		
	12/7	No class		Project papers due
14 (Finals week)	12/12	No class		

Advanced Topics Presentation

Please sign up for a paper to present on an advanced biomechanics or assistive devices topic following the guidelines on Canvas. You will prepare a 5-minute presentation providing an overview of this paper. You will also prepare a few discussion questions and should plan to lead a class-wide 5-minute discussion following the presentation. You will have to trim down or skip over parts of the papers to fit this into 5 minutes, please select what you feel is the most interesting or essential contributions and eliminate any extra material.

Suggested layout for your 5 slides:

1. Introduction
    a. Provide a high-level overview of the research question the paper is proposing to answer and any necessary background information necessary to understand the concepts presented in the paper and necessary for the discussion.
    b. Mention in one sentence what the ultimate result was to prime the listeners expectations, so they are building a roadmap to reach that result during your presentation.
2. Methods
    a. Provide an overview of what scientific study the paper performed. E.g. device development approach, human-subject study, etc.
3. Results
    a. Outline the main research results or scientific findings from the paper.
4. Critique of the study
    a. Add some commentary on the limitations of the study (e.g. they only test on young healthy subjects but propose a device for a patient population or test unnatural conditions), anything you feel may have influenced the results, and general commentary using your critical thinking and biomechanics knowledge.
5. Discussion / Broader Implications
    a. Discuss how the findings from this study may influence future research, may impact societal health, how it relates to topics we've talked about, or other broad consequences of this research.

Notes on reading research papers: When I first read a research paper in a new topic, I start by carefully reading the abstract and title. Then I look somewhat carefully through the figures and figure captions to try and gauge the main idea and results of the paper. I'll then go back through and read the paper in order more carefully if I feel it is relevant (which in this case it is!).

Term Project

Objective of Assignment

This project will give you a chance to deepen your knowledge in an area of biomechanics and assistive devices that interests you. We expect that you will remember what you learn from doing this project long after the class is over. This assignment will get you into the literature where you can see for yourself the results of biomechanics and assistive devices research. This paper may also serve as a springboard for a future independent study or research. The project will help hone your critical reading and writing skills, which are helpful in many endeavors, and it will help you learn how to define a research project. This will also give you experience working on a team project.

Overview of Assignment

Survey the literature on a specific topic in the field of movement biomechanics and assistive devices. Describe the current state-of-the-art and suggest areas that require further research. Then, briefly describe how you would investigate a specific problem yourself.

Some general areas from which you can choose a topic include: sports biomechanics, measurement/development of muscle strength, motion and gait analysis, dynamic simulations of movement, biomechanics of surgical reconstructions, functional neuromuscular stimulation, joint biomechanics, electromyography, assistive robotic devices, computer-assisted surgery, medical imaging, biomedical computation and visualization, computer animation, digital creatures, evolution of gait, or other areas related to biomechanics of movement and assistive devices. From these general areas you should choose a specific topic to investigate. Some topics and paper titles are listed below.

Project Resources

We allow you to define the project broadly. It may incorporate existing datasets, biomechanics simulation, wearable sensors, robotic hardware, etc. This class focuses on the fundamentals of biomechanics and assistive devices, but is not a mechatronics project, so please only select a project that your team already has the technical skills to execute. The active learning lab has many resources available for physical prototyping, please sign up as early in the semester as possible to ensure you have time to complete safety trainings and get access to those materials. There is a limited budget to buy components that are not currently available in the active learning lab, please coordinate with staff if you wish to purchase items. You may use the OpenCap kits for portable motion capture for collecting data for your projects, please coordinate with the course staff if you wish to borrow these systems.

The goal of the research portion of the project is to provide preliminary data to support or refute the hypothesis your project is proposing. This will allow you to apply your biomechanics and assistive device knowledge. It is not necessary to perform a fully finished study ready to be published in a scientific journal. If you enjoy your project and wish to pursue it further after the course, please talk to with the instructor at the end of the term.

Example Titles of Term Papers

Strength of muscles crossing the shoulder, Muscle strength and its development

Effects of bone deformities on muscle moment arms, Adaptation of muscle with immobilization,

Gait analysis for surgical planning: benefits and limitations

Computer assisted knee replacement, Improving balance is elderly individuals

Biomechanics of bicycling: the role of two-joint muscles

The influence of increased muscle stiffness on gait in cerebral palsy

The influence of energy storing prosthetic feet on knee motion in below knee amputee walking

The influence of dynamic coupling on motor planning in the upper limb

The variation of muscle physiologic cross-sectional areas with aging

The role of muscles in providing joint stability, Muscle-tendon adaptation with immobilization

Animation of body motion: from biomechanics to entertainment

Robots that walk and hop, Force-feedback devices: what is needed to fool the CNS?

Optimization techniques for calculating muscle forces

Computer-assisted design of functional neuromuscular stimulation systems

Scaling in musculoskeletal structures, Quantification of spasticity

In vivo imaging of joint kinematics, Three-dimensional models of muscle

Effects of bone lengthening on muscle, molecular motors: the engines of life

Wrist joint replacements: successes and failures

Format of the Paper

The paper (excluding references and figures) ***should not exceed ten, double-spaced pages*.** The paper is short and needs to be extremely well written. A first draft should be written well in advance of the due date so that you have a chance to refine the final product. The instructors will provide feedback on a draft submitted by the date specified in the schedule. The paper should be written in the following form. The paper comprises 25% of your course grade.

TITLE

ABSTRACT (about 150 words)

This is the most important section of any report and should summarize the key points of your paper.

INTRODUCTION: BACKGROUND AND PREVIOUS INVESTIGATIONS (~5-7 pages)

Briefly describe what you will be presenting and why it is important. Relate the anatomical, biological, clinical, or business framework of your topic. (~1-2 pages). Present a review of previous research on

this topic. Do not simply review a number of individual papers, but synthesize what has been done. This section should be in a form such that the current state-of-the-art is easily appreciated. State the shortcomings in our current knowledge, and in a final paragraph or two suggest several areas that require further research. (~4-6 pages)

PROPOSED RESEARCH (~2-4 pages)

From areas suggested at the end of the previous section, state concisely and specifically a particular problem that you propose to address. In broad terms, describe how you might investigate this problem with experiments, computer simulations, or both. Point out the difficulties that you may expect to encounter in this research. State what you believe will be the significance of your proposed research. Provide a realistic timetable for the completion of the work. Include figures that help to illustrate your hypotheses, methods, or experimental design.

CONCLUSION (about 200 words)

Concisely summarize the proposed study's key novelty and how it addresses an open question in the field. Identify future work enabled by this study and/or that could not be addressed within the scope of this work.

REFERENCES

Your paper should primarily reference journal articles. Citations should conform to the style of the *Journal of Biomechanics*. The following sources may be useful. If you are having trouble accessing full-text versions of the articles you find, try accessing them through the Harvard's online library resources.

Lane Library lane.stanford.edu	*Google Scholar*
PLOS One	*Science, Nature*
Science Citation Index	*Developmental Medicine and Child Neurology*
Journal of Biomechanics	*Clinical Orthopaedics and Related Research*
Journal of Biomechanical Eng	*Biological Cybernetics*
Journal of Orthopaedic Research	*Journal of Biomedical Material Research*
Journal of Bone and Joint Surgery	*IEEE Transactions on Biomedical Engineering*

Project Outline and Meetings with Teaching Team

It is our hope that you start working your project going early. The outline will help you get started. It will comprise 5% of your course grade.

Format of Outline

The written outline should include the following three sections.

1. INTRODUCTION & BACKGROUND

   Briefly describe your topic and why it is important.

2. PREVIOUS INVESTIGATIONS

   List several sources that relate to your topic. For each paper, summarize:

   - the goal(s) of the paper
   - how this paper relates to your topic
   - the major conclusions
   - the major shortcomings
   - the next step in this research

3. REFERENCES

   List at least ten references that relate to your topic. This list should conform to the style of the *Journal of Biomechanics*.

This is just an outline, so it can be rough. We just want to make sure that you are on the right track and are finding references that relate to your topic.

Project Presentations

This assignment is intended to teach other students about your project and give you experience clearly articulating your ideas to a group. The presentation will comprise 10% of your course grade.

Format of Oral Presentation

Each student team will give a short, oral presentation on their research topic. Presentations should be a presentation lasting 6-7 minutes followed by 2 minutes of questions from the audience. Your presentation should state the problem you are investigating and what you have found. The intention is to let the class know about your topic and enlighten us with your findings. We will give an example presentation before yours are due. Feel free to be creative. Student teams in the past have given their presentations as a debate or news cast. A team did their presentation on fatigue while holding a fatigue exercise. All of this is fun and good.

Grading Rubric for Term Paper

Section	Criteria	Points
Title	● Clear, concise, descriptive title	___/1
Abstract	● Short introduction/motivation ● Summary of key points	___/2
Introduction	● Highlight the importance of the topic ● Briefly orient readers to the field ● Broadly suggest areas that require further research ● Synthesize the current state of the art to motivate a specific open question/need in the field (e.g., do not simply review)	___/9
Proposed Research	● Concisely state a specific open question/need that will be answered in this study ● Propose methods to answer the specific open question/need (e.g., experiments, simulations) with quantitative support ● Describe methods in enough detail that others could do the work from this proposal ● Provide a realistic timetable to complete this study ● (Optional) Expected results ● Describe limitations and/or expected difficulties	___/9
Conclusion	● Concisely summarize the paper's key novelty and how it answered the open question/need ● Identify future work that could not be addressed within the scope of this work and/or that would be enabled by this study	___/2
Overall	● References used appropriately ● Text is concisely written and proofread for errors	___/2
Total		**___/25**