ME 646: Locomotor Mechanics and Design/Control of Wearable Robotic Systems
(Mechanics and Control of Human Movement)
Professor Rouse, University of Michigan, Winter 2019

Instructor: Professor Elliott Rouse, 2424 GG Brown, email: ejrouse@umich.edu. Office hours: Monday / Wednesday, 9:30 – 11:00 (2424 GGB).

Course Time: Tuesday / Thursday, 3:00 – 4:30 pm. **Room:** 1005 Dow.

GSI: Alejandro Azocar, email: afazocar@umich.edu. Office hours: TBD. Room: TBD.

Textbook: No textbook required. Weekly readings from scientific literature will be provided. Optional texts that may be helpful include (most posted to Canvas):

- Winter, David A. *Biomechanics and motor control of human movement*. John Wiley & Sons, 2009
- Pons, José L. *Wearable robots: biomechatronic exoskeletons*. John Wiley & Sons, 2008
- Keesman, Karel J. *System identification: an introduction*. Springer Science & Business Media, 2011
- Aström, Karl Johan, and Richard M. Murray. *Feedback systems: an introduction for scientists and engineers*. Princeton university press, 2010
- Lessard, Charles S. "Signal processing of random physiological signals." *Synthesis Lectures on Biomedical Engineering* 1, no. 1 (2005): 1-232

Course Description: The primary objective of this course is to learn how to analyze, understand, and model human locomotion, as well as develop bio-inspired assistive technologies and assess their impact. We will learn about the human machine—the sensing, acting, and reasoning components of the human neuromusculoskeletal systems, as well as how to replicate this functionality with traditional approaches from robotics, including modeling, machine design, mechatronics, and control.

Homeworks: A brief homework assignment (1-2 questions) will be assigned approximately once per week, covering the relevant theoretical concepts of the corresponding module. Homeworks will be due one week after they are assigned.

Case Studies: Approximately each week, at the conclusion of each module, we will have a 'case-based' discussion session for approximately half the class period. Cases will be fictitious problem descriptions designed to reinforce lecture / journal article content by considering a 'real-world' scenario where the course concepts can be applied. We will post the case one week in advance. For each case, each student will write a ~1-2 page executive summary outlining their solution to the case scenario, including relevant analyses, schematics, and graphs. Guidelines on report format will be provided with the first case. The report is to be turned in <u>before</u> the lecture where the case will be discussed. We will randomly select a subset of the case-reports each week to be evaluated and provide a formal grade and feedback. Expect ~4 of your executive summaries to be evaluated over the term.

Groups of ~3 students will be selected to present their case report each week, consisting of a ~15 minute presentation outlining a case solution and motivating discussion, which they will lead, ~1 time during the semester. Groups will be assigned a presentation / discussion timeslot in the first week of class. Finally, the class participation grade (in part) will assess each student's ability to turn in executive summaries and their interaction during case discussions.

Project: Students will work in teams of 3 – 4 to develop a wearable robot to assist with an ambulation task at a single (or multiple) joint(s) (*e.g.* an ankle exoskeleton for walking assistance). Teams must specify a set of desired joint mechanics and select a motor-transmission / design combination that achieves the desired mechanics while satisfying actuator torque / speed, motor voltage / current, and thermal limitations. Teams must also select sensors to use in their design, and develop and simulate a control architecture to provide the appropriate effort during the selected ambulation task. Each team will write a report (< 10 pages) and create a presentation to be presented during the final week of classes. More details on the project will be distributed in class and posted on Canvas.

Attendance: Attendance is mandatory, and will be assessed in your class participation grade. Lectures will be recorded, but are not a substitute for attending class.

Late assignments: This is an upper-level graduate course, and late assignments will not be accepted. If there are extenuating circumstances, contact the Professor / GSI.

Midterm Exam: Thursday, February 21st
Final Exam: No final exam. Project report will be used in lieu of a final exam.
Honor Code: You may discuss the homeworks, cases, and the final project with each other and with the instructors, but you must write your own solutions / code which reflect your own understanding of the material. Sharing / copying of MATLAB code is prohibited.

Grading Breakdown:

- Homeworks - 20%
- Case Studies - Reports: 15%; Presentation: 10%
- Project - Report: 15%; Presentation: 10%
- Midterm Exam - 20%
- Class Participation - 10%

<u>Module 1: Muscle Mechanics and Actuation</u>

Class 1/10

Topics:

- Course introduction
- Muscle structure
- Excitation-contraction coupling
- SISO model
- Motor units

Reading:

- Zajac, Felix E. "Muscle and tendon Properties models scaling and application to biomechanics and motor." *Critical reviews in biomedical engineering* 17, no. 4 (1989): 359-411.

- Azizi, Emanuel, Elizabeth L. Brainerd, and Thomas J. Roberts. "Variable gearing in pennate muscles." *Proceedings of the National Academy of Sciences* 105.5 (2007): 1745-1750.

Class 1/15

Topics:

- Fiber types
- Force-length / Force-velocity
- Muscle-tendon mechanics
- Hill model
- Short range stiffness

Reading:

- Rack, Peter MH, and D. R. Westbury. "The short range stiffness of active mammalian muscle and its effect on mechanical properties." *The Journal of physiology* 240, no. 2 (1974): 331-350.
- Gasser, Herbert Spencer, and Archibald Vivian Hill. "The dynamics of muscular contraction." *Proc. R. Soc. Lond. B* 96, no. 678 (1924): 398-437.

Case:

- DARPA solicitation case

Module 2: Sensing and Motor Control

Class 1/17

Topics:

- Stretch reflexes (antagonist / synergist pathways)
- Proprioception (GTO / muscle spindle)
- Mechanoreceptors / nociceptors
- Vision sensing and motion sensing

Reading:

- Proske, Uwe, and Simon C. Gandevia. "The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force." *Physiological reviews* 92.4 (2012): 1651-1697.
- Nielsen, Jens Bo, and Thomas Sinkjær. "Afferent feedback in the control of human gait." *Journal of electromyography and kinesiology* 12.3 (2002): 213-217.
- Shepherd, Max K., Alejandro F. Azocar, Matthew J. Major, and Elliott J. Rouse. "Amputee perception of prosthetic ankle stiffness during locomotion." *Journal of neuroengineering and rehabilitation* 15, no. 1 (2018): 99.

Class 1/22 (Make-up or alternate lecturer)

Topics:

- Integration and motion planning

- Equilibrium point vs. Internal models
- Muscle synergies
- Central Pattern Generators

Reading:

- Kuo, Arthur D. "The relative roles of feedforward and feedback in the control of rhythmic movements." *Motor control* 6.2 (2002): 129-145.
- Wolpert, Daniel M., Zoubin Ghahramani, and Michael I. Jordan. "An internal model for sensorimotor integration." *Science* 269.5232 (1995): 1880-1882.
- Ting, Lena H., and J. Lucas McKay. "Neuromechanics of muscle synergies for posture and movement." *Current opinion in neurobiology* 17.6 (2007): 622-628.

Case: TBD muscle case

Class 1/24: Cancelled

Module 3: Walking Models

Class 1/29

Topics:

- Compass gait
- Spring-loaded inverted pendulum (SLIP)
- Collisions

Reading:

- Garcia, Mariano, Anindya Chatterjee, Andy Ruina, and Michael Coleman. "The simplest walking model: stability, complexity, and scaling." *Journal of biomechanical engineering* 120, no. 2 (1998): 281-288.
- Kuo, Arthur D. "Energetics of actively powered locomotion using the simplest walking model." *Journal of biomechanical engineering* 124.1 (2002): 113-120.
- Geyer, Hartmut, Andre Seyfarth, and Reinhard Blickhan. "Compliant leg behaviour explains basic dynamics of walking and running." *Proceedings of the Royal Society B: Biological Sciences* 273.1603 (2006): 2861-2867.

Class 1/31

Topics:

- Reflex-based neuromuscular model
- Ground reference points (ZMP, COP, FRI)

Reading:

- Geyer, Hartmut, and Hugh Herr. "A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities." *IEEE Transactions on neural systems and rehabilitation engineering* 18.3 (2010): 263-273.

- Popovic, Marko B., Ambarish Goswami, and Hugh Herr. "Ground reference points in legged locomotion: Definitions, biological trajectories and control implications." *The International Journal of Robotics Research* 24.12 (2005): 1013-1032.

Case: Exoskeleton afferent signals

Module 4: System Identification

Class 2/5

Topics:

- Models - time and frequency domain
- IRFs and frequency response
- Static ID
- Relationships between muscle / joint properties and impedance

Reading:

- Kearney, Robert E., and Ian W. Hunter. "System identification of human joint dynamics." *Critical reviews in biomedical engineering* 18.1 (1990): 55-87.

Class 2/7

Topics:

- Time-varying ID
- Impedance during locomotion
- Relation to human motor control

Reading:

- Rouse, Elliott J., Levi J. Hargrove, Eric J. Perreault, and Todd A. Kuiken. "Estimation of human ankle impedance during the stance phase of walking." *IEEE Trans. Neural Syst. Rehabil. Eng* 22, no. 4 (2014): 870-878.
- Lee, Hyunglae, and Neville Hogan. "Time-varying ankle mechanical impedance during human locomotion." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 23.5 (2015): 755-764.

Case: TBD walking models

Module 5: Brushed/Brushless Electric Motors

Class 2/12

Topics:

- Shift into robot design-control
- Brief overview of circuit elements / analysis
- Brushed motor model
- Current or position feedback control

Reading:

- Rouse, Elliott J., Luke M. Mooney, and Hugh M. Herr. "Clutchable series-elastic actuator: Implications for prosthetic knee design." *The International Journal of Robotics Research* 33.13 (2014): 1611-1625.

Class 2/14

Topics:

- Brushed vs. brushless motors
- Sensorless vs sensorized commutation
- Brushless drive architecture
- Trapezoidal, sinusoidal and FOC commutation

Reading:

- Sensinger, Jonathon W., Stephen D. Clark, and Jack F. Schorsch. "Exterior vs. interior rotors in robotic brushless motors." *Robotics and Automation (ICRA), 2011 IEEE International Conference on*. IEEE, 2011.
- Texas Instruments, Field Oriented Control of 3-phase AC-Motors (pages 1-8)

Class 2/19

Topics:

- Thermal physics / governing equations
- Thermal time constant and resistance

Reading:

- Lenzi, Tommaso, Marco Cempini, Levi Hargrove, and Todd Kuiken. "Design, development, and testing of a lightweight hybrid robotic knee prosthesis." *The International Journal of Robotics Research* 37, no. 8 (2018): 953-976.

Case: Actuator system ID

<u>Midterm Exam: Thursday 2/21</u>

<u>Module 6: Transmissions & Design</u>

Class 2/26

Topics:

- Power transmission
- Transmission elements
- Bearings

Reading:

- Mooney, Luke M., Elliott J. Rouse, and Hugh M. Herr. "Autonomous exoskeleton reduces metabolic cost of human walking during load carriage." *Journal of neuroengineering and rehabilitation* 11.1 (2014): 80.

- Collins, Steven H., M. Bruce Wiggin, and Gregory S. Sawicki. "Reducing the energy cost of human walking using an unpowered exoskeleton." *Nature* 522.7555 (2015): 212.
- Shepherd, Maxwell, and Elliott Rouse. "Design and validation of a torque-controllable knee exoskeleton for sit-to-stand assistance." *IEEE ASME Trans. Mechatron* (2017): 1-1.

Class 2/28

Topics:

- Material properties
- Manufacturing (additive / subtractive)

Reading:

- Sengeh, D.M., Moerman, K.M., Petron, A. and Herr, H., 2016. Multi-material 3-D viscoelastic model of a transtibial residuum from in-vivo indentation and MRI data. *Journal of the mechanical behavior of biomedical materials*, *59*, pp.379-392.
- Olesnavage, Kathryn M., Victor Prost, William Brett Johnson, and Amos G. Winter. "Passive prosthetic foot shape and size optimization using lower leg trajectory error." *Journal of Mechanical Design* 140, no. 10 (2018): 102302.

Case: TBD Motors

Class 3/5: No Class - Spring Break

Class 3/7: No Class - Spring Break

Module 7: Series Elastic Actuators

Class 3/12

Topics:

- Theory
- SEA motor model

Reading:

- Pratt, Gill A., and Matthew M. Williamson. "Series elastic actuators." *Intelligent Robots and Systems 95.'Human Robot Interaction and Cooperative Robots', Proceedings. 1995 IEEE/RSJ International Conference on.* Vol. 1. IEEE, 1995.
- Paluska, Daniel, and Hugh Herr. "The effect of series elasticity on actuator power and work output: Implications for robotic and prosthetic joint design." *Robotics and Autonomous Systems* 54.8 (2006): 667-673.
- Vallery, Heike, Jan Veneman, Edwin Van Asseldonk, Ralf Ekkelenkamp, Martin Buss, and Herman Van Der Kooij. "Compliant actuation of rehabilitation robots." *IEEE Robotics & Automation Magazine* 15, no. 3 (2008).

Class 3/14: Group project working time - catch up lecture if needed

Reading:

- None.

Case: Cascading inefficiencies

Module 8: Sensors

Class 3/19

Topics:

- Encoders
- Load cells
- IMUs

Reading:

- Pons, José L. *Wearable robots: biomechatronic exoskeletons*. John Wiley & Sons, 2008 - Chapter 6

Class 3/21

Topics:

- EMG
- DAQ
- Sampling

Reading:

- None

Case: TBD SEAs

Module 9: Control

Class 3/26

Topics:

- Overview of control
- Low level control / feedback systems

Reading:

- Tucker, Michael R., Jeremy Olivier, Anna Pagel, Hannes Bleuler, Mohamed Bouri, Olivier Lambercy, José del R Millán, Robert Riener, Heike Vallery, and Roger Gassert. "Control strategies for active lower extremity prosthetics and orthotics: a review." *Journal of neuroengineering and rehabilitation* 12, no. 1 (2015): 1.
- Hogan, Neville. "Impedance control: An approach to manipulation: Part II—Implementation." *Journal of dynamic systems, measurement, and control* 107.1 (1985): 8-16.
- Gordon, Keith E., and Daniel P. Ferris. "Learning to walk with a robotic ankle exoskeleton." *Journal of biomechanics* 40.12 (2007): 2636-2644.

Class 3/28

Topics:

- Mid-level control

Reading:

- Zhang, Juanjuan, Pieter Fiers, Kirby A. Witte, Rachel W. Jackson, Katherine L. Poggensee, Christopher G. Atkeson, and Steven H. Collins. "Human-in-the-loop optimization of exoskeleton assistance during walking." *Science* 356, no. 6344 (2017): 1280-1284.
- Ding, Ye, Myunghee Kim, Scott Kuindersma, and Conor J. Walsh. "Human-in-the-loop optimization of hip assistance with a soft exosuit during walking." *Science Robotics* 3, no. 15 (2018): eaar5438.
- Quintero, David, Dario J. Villarreal, Daniel J. Lambert, Susan Kapp, and Robert D. Gregg. "Continuous-Phase Control of a Powered Knee–Ankle Prosthesis: Amputee Experiments Across Speeds and Inclines." *IEEE Transactions on Robotics* 34, no. 3 (2018): 686-701.

Class 4/2

Topics:

- High-level control
- State machines
- Machine learning approaches
- Signal processing / feature reduction

Reading:

- Huang, He, Todd A. Kuiken, and Robert D. Lipschutz. "A strategy for identifying locomotion modes using surface electromyography." *IEEE Transactions on Biomedical Engineering* 56.1 (2009): 65-73.
- Hargrove, Levi J., Ann M. Simon, Aaron J. Young, Robert D. Lipschutz, Suzanne B. Finucane, Douglas G. Smith, and Todd A. Kuiken. "Robotic leg control with EMG decoding in an amputee with nerve transfers." *New England Journal of Medicine* 369, no. 13 (2013): 1237-1242.
- Banala, Sai K., Seok Hun Kim, Sunil K. Agrawal, and John P. Scholz. "Robot assisted gait training with active leg exoskeleton (ALEX)." *IEEE transactions on neural systems and rehabilitation engineering* 17, no. 1 (2009): 2-8.

Case: TBD sensors

Module 10: Technology Evaluation

Class 4/4

Topics:

- Motion capture

- Force plates
- Metabolic cost
- Augmentation factor

Reading:

- Selinger, Jessica C., Shawn M. O'Connor, Jeremy D. Wong, and J. Maxwell Donelan. "Humans can continuously optimize energetic cost during walking." *Current Biology* 25, no. 18 (2015): 2452-2456.
- Ferris, Daniel P., Gregory S. Sawicki, and Monica A. Daley. "A physiologist's perspective on robotic exoskeletons for human locomotion." *International Journal of Humanoid Robotics* 4.03 (2007): 507-528.

Class 4/9: Possible group project work day

Reading:

- Seethapathi, Nidhi, and Manoj Srinivasan. "The metabolic cost of changing walking speeds is significant, implies lower optimal speeds for shorter distances, and increases daily energy estimates." *Biology letters* 11, no. 9 (2015): 20150486.

Case: TBD Control

Class 4/11: Catch up / review

Class 4/16: Catch up / review

Class 4/18: Group presentations

Class 4/23: Group presentations