2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering
Education for 130 Years
ASEE
Paper ID #38094

Board 24: Work in Progress: Teaching Cardiovascular Physiology with Computational Modeling - Insight from a New, Team-Taught Course in Biomedical Engineering

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Work In Progress: Teaching Cardiovascular Physiology with Computational Modeling – Insight from a New, Team-Taught Course in Biomedical Engineering

Introduction

Computational modeling is an increasingly important aspect of biomedical engineering (BME) education. Student exposure to computational modeling and simulation varies in BME departments and institutions. Linsenmeier and Saterbak [1] reported that in 2004 roughly 25% of BME undergraduate programs required courses in computing and 40% required some sort of modeling course. In 2019, over 90% of BME programs incorporate computing in their BME undergraduate and graduate programs. How computing is integrated into the classroom, though, is highly variable. The Fourth BME Education Summit in 2019 concluded that most BME departments use modeling to understand biological systems, but could benefit from using modeling to teach *operating principles of biological systems* [2], i.e. the mechanisms of biology.

Senior undergraduates and new graduate students in BME may have some exposure to cardiovascular physiology but are likely unaware of the complex biomechanical behaviors of cardiac and vascular tissues. For instance, students may know of Poiseuille flow from fluid mechanics, but do not appreciate its clinical application in understanding vasodilator therapy and vascular resistance. Other unique concepts in cardiovascular physiology, e.g., the Frank-Starling mechanism and vascular compliance, are seldom discussed in detail using numerical or quantitative relationships. Computational models addressing these concepts can engage the class through active-learning [3]–[5] and provide a take-home tool for better understanding the link between cardiovascular function in theory and practice. Thus, we developed a course that used computational modeling to explain cardiovascular function. We present examples of in-class and take-home assignments as well as outcomes and anonymous feedback from the students.

Course design and activities

The course was offered to both undergraduate and graduate students in engineering. A summary of student demographics is provided in Table 1. The course content followed the text by Westerhof et al. [6] which provides “snapshots” of concepts in cardiovascular physiology with their engineering or mechanistic representations. The course was co-taught by the authors twice a week. The first class of the week was a traditional lecture style class with group discussion. Students were asked to read several chapters in the textbook and take online reading quizzes prior to attending class. The second class of the week was an in-class coding session using MATLAB (MathWorks, Natick, MA). Students were provided “skeleton” code related to the concepts discussed in the textbook and were then asked to adapt this code and test various physiological hypotheses related to the reading. An brief overview of topics covered in both sessions are provided in Table 2. An example of in-class coding outcomes and homework questions can be found in Figure 1. At the end of the quarter, students were required to do a final project that involved (i) finding a research article on cardiovascular function, (ii) giving a “journal club” style presentation of the article, and (iii) replicating and/or innovating on the results using computational modeling. Students were given 12-15 minutes to present their results.

Table 1. Student demographics. URM – underrepresented minority

Quarter	Undergraduate/Graduate	Female/Male	URM/white
Spring 2022	3/8	4/7	6/5
Fall 2022	4/5	6/3	5/4

Example reading, coding sessions, and homework

Here is an example of how lecture-style and coding sessions were combined to understand the importance of blood vessel radii in determining vascular resistance and blood flow.

Lecture: Students read chapters based on vascular resistance and Poiseuille's law. Class discussions focused on (a) how resistance, viscosity, and radius change in disease and (b) how Poiseuille is used clinically. *Coding*: Students were walked through MATLAB code that calculated resistance based on length, radius, and viscosity. Students were asked to use circuit theory to predict mean blood flow in a bifurcation based on vessel geometry and Poiseuille resistance relationships.

Homework: Students expanded their code to include seven vessels (Figure 1). Students were asked to simulate mean flow and wall shear stress at baseline, and then simulate a "stenosis" in one vessel and draw conclusions on how this affected blood flow and shear stress valueds.

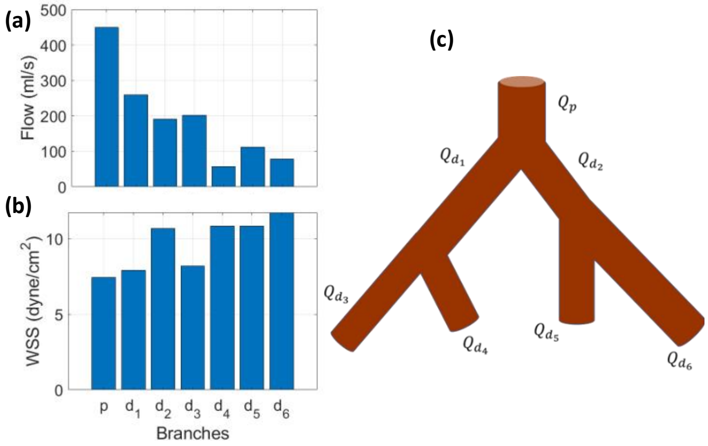

Figure 1: Class homework to simulate steady, mean blood flow. Baseline predictions of (a) mean flow and (b) mean WSS in a network of blood vessels (c).

Table 2. Topics, questions, and coding problems used for class and homework assignments.

Topic	**Example questions and topics**	**In-class and take-home coding**
Vascular resistance and compliance	• Use Poiseuille's law to calculate changes in resistance with vasoconstriction/dilation.	• Calculate total resistance in vessels in series or parallel.
Mechanics of blood flow	• What are the implications of Murray's branching law?	• Use Poiseuille's law to forecast mean blood flow in a network.
Windkessel models	• What information is gained from Windkessel modeling?	• Perform a sensitivity analysis on 2- and 3-element Windkessel models.
Wave propagation and reflections	• How does vascular stiffness affect wave propagation?	• Calculate wave speed using multiple pressure waveforms.
Sarcomere force-tension relationships	• What are the mechanisms of the Frank-Starling relationship?	• Simulate sarcomere experiments using the Hill model [7].
Ventricular elastance	• What are end-systolic and end-diastolic elastance?	• Simulate pathologies using pressure-volume relationships.
Systems-level dynamics	• What are the physiological responses to exercise?	• Use a lumped parameter model to simulate an aortic stenosis and a myocardial infarction.

Student outcomes and perspectives

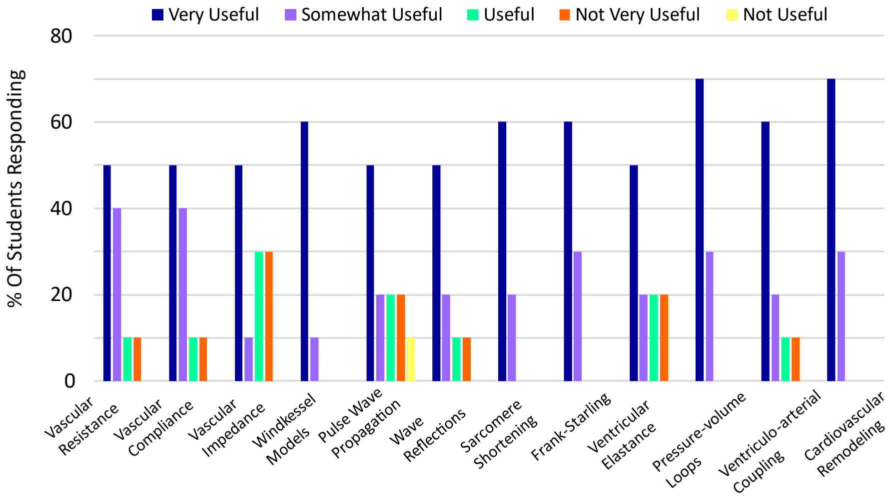

Figure 2: Student perception of modeling as being "useful" in explaining class content.

We retrospectively asked students to participate in an anonymous survey, in which half of the students (10 total) responded. Students were asked to rate their comfort with MATLAB before and after taking the course, whether coding sessions assisted in learning content, and to rate topics from least to most difficult. Figure 2 depicts student response to the prompt "Rate how useful MATLAB was in understanding the following content." Students identified pressure-volume relationships and cardiovascular remodeling as the concepts most enhanced by computational modeling, whereas vascular impedance was the topic least enhanced by computational lessons. In general, students found that vascular resistance, compliance, and impedance were the easiest concepts covered. Wave reflections, the Frank-Starling mechanism, and cardiovascular remodeling were the most difficult concepts; most students found computational modeling useful in better understanding these topics. A majority of students marked computational work as "very useful" or "somewhat useful" for the latter two topics; hence, using coding as a teaching mechanism for these concepts may increase understanding moving forward. Students were also asked to provide any other feedback for the class. One student noted that "I believe this course could be separated into two different courses," which would likely result in a "vascular" and "cardiac" section if implemented. Other students reported that they "Loved the way MATLAB was utilized to teach us complex topics," and "learning topics in MATLAB was really helpful." Several students mentioned a disconnect between reading material and coding sessions or assignments, which was attributed to our innovation on the published class text [3].

Discussion

This work in progress provides insight into the integration of computational modeling and key engineering concepts in cardiovascular physiology. Many BME students are required to enroll in coding or mathematical modeling courses, yet these are typically taught in isolation from core biology and physiology classes. We argue that computational modeling can be used as a tool for understanding these concepts. Using coding and modeling as a tool also exposes students to a wider range of applications for computer programming and provides them with opportunities to apply computational thinking to real-world applications. We plan to continue innovating our course and move towards more accessible tools, such as Jupyter Notebooks, CVSim [8], and CircAdapt [9], as platforms for enhanced learning of cardiovascular function in BME curricula.