SimVascular as an Instructional Tool in the Classroom

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***Abstract* — SimVascular is an open source software platform for cardiovascular simulation, providing a complete pipeline from medical image data to volumetric model construction, meshing, and blood flow simulation. Previous workshops and educational programs have utilized SimVascular, but learning assessments have not been used to rigorously quantify gains in conceptual understanding. Goal: The purpose of this study is to assess the learning of students enrolled in graduate engineering courses at two different institutions (Purdue University and Stanford University) who used SimVascular to perform image-based blood flow modeling projects as part of a course. Methods: Twenty-two engineering and medical students were given both pre- and post- assessments to quantify their initial familiarity and eventual progress learning computational techniques for biomedical blood flow simulations. The students rated their agreement with eleven different statements. Results: Initial responses were relatively low, suggesting that there was substantial room for student learning. Students then utilized the SimVascular platform to run multiple hemodynamic blood flow simulations. The post-assessment showed a significant increase in agreement with all 11 statements (p<0.05). Conclusion: These initial efforts demonstrate the effectiveness of SimVascular as a teaching tool in a classroom setting.**

Keywords — Computational fluid dynamics; simulation; modeling; blood flow; active learning; classroom activity

I. Introduction

Finite element modeling of blood flow in arteries has become a common strategy to study cardiovascular hemodynamics over the past two decades [1]. Computational fluid dynamics is of particular value in vascular surgery where a primary goal is to restore blood flow to organs and tissues. Surgeons currently rely on diagnostic and empirical data to make decisions when creating a treatment plan. This has created the need for a simulation-based medical planning tool that uses computational methods to help patients suffering from cardiovascular disease. Ideally, patient-specific image data can be used to evaluate alternative surgical options before treatment or provide functional information regarding the physiology not possible through medical imaging alone. Thus, the open source software platform, SimVascular [2], has been recently developed to provide a widely-accessible and comprehensive tool for cardiovascular simulations (http://simvascular.org). The SimVascular package has currently been downloaded over 6,700 times by more than 1,800 unique users around the world since it was first released.

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Fundamental biomechanical principles are also important for many engineering graduate students to learn and understand. While designed primarily for research, SimVascular has recently been used as an innovative education tool to help teach both the steps of computational fluid dynamic (CFD) simulations *and* the underlying biomechanical and physiological principles. Indeed, this unique learning technology offers the potential to improve the learning environment for engineering students and suggest a reexamination of common instructional paradigms [3]. While previous SimVascular workshops and modules have proved successful in providing training, a robust learning assessment has not been used previously to rigorously quantify gains in conceptual understanding in the educational context. The purpose of this study is to assess the learning of students enrolled in graduate engineering courses at two different institutions (Purdue University and Stanford University) who used SimVascular to perform image-based blood flow modeling projects as part of a course. The data presented below focuses on self-assessments the students completed at the beginning of the course and after the SimVascular project was completed.

II. Methods

A. Student Participants

Twenty-two students (1 BS, 3 MS, 14 PhD, 1 MD, 3 MD/PhD) in bio/medical engineering, mechanical engineering, or computational mathematics programs were given both pre- and post-assessments to quantify 1) their initial familiarity and 2) improvement in understanding of computational techniques for biomedical blood flow simulations. Of these, 15 were from Purdue University and 7 from Stanford University. The students in these courses were all enrolled full-time and came from a broad range of demographics (12 male, 10 female). Category 1 Institutional Review Board exemptions were granted for this study as it was conducted in established educational settings and involved normal educational practices.

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B. Instructional Efforts

As part of graduate-level courses within the BME/BioE curriculum, these students were exposed to didactic lecture, multiple tutorials, and a case study example. For the case study, the students followed a step-by-step guide that covered general imaging, path planning, vessel segmentation, lofting, meshing, boundary conditions, and simulation tasks from a magnetic resonance angiography scan of the aortofemoral region from a normal volunteer (http://simvascular.github.io/clinicalCase1.html). This simple case study was then followed with an opportunity for students to build their own models from a variety of anonymized patient data sets. Each student was allowed to choose their own data set depending on their interest. Similar to the image repository that is available publically (http://www.vascularmodel.com/sandbox/doku.php), these data sets include patients with common vascular diseases including abdominal aortic aneurysms, thoracic aortic coarctation, peripheral artery disease, and pulmonary hypertension, among others. Further image data sets were from patients after undergoing coronary artery bypass, Fontan, or Glenn surgeries, some of which were utilized by students with interest in surgical planning. The information on how to use SimVascular was covered over a course of two months with multiple in-class discussions, working sessions, and external office hours for questions. We estimated that students spent on average 30-40 hours working with the SimVascular software as part of this project.

C. Assessment Statements

The students were asked on a scale of 1 - 10 to rate their agreement with 11 different statements. A response of 1 meant the students strongly *disagreed*, while a response of 10 meant they strongly *agreed*. These statements are below:

1) I am familiar with the role of hemodynamics in cardiovascular disease initiation or progression.
2) I am familiar with different volumetric biomedical imaging techniques.
3) I am familiar with the concept of volume rendering.
4) I am familiar with different image segmentation techniques.
5) I am familiar with the difference between a discrete and analytic solid models.
6) I am familiar with the concept of a boundary representation.
7) I am familiar with different computational meshing techniques.
8) I am familiar with a variety of boundary conditions and their effects.
9) I am familiar with the process of running a computational fluid dynamic simulation.
10) I am familiar with a variety of different applications of patient-specific cardiovascular simulations.
11) I am familiar with how cardiovascular simulations results can be quantified.

The responses to each student's agreement with these statements underwent a data anonymization process.

D. Statistics

All data are shown as mean±standard deviation (SD). A Shapiro-Wilk test was used to determine if the data were normally distributed. A Student's t-test followed by a Bonferroni-Holm correction was used for multiple comparisons. An unpaired t-test was used for a comparison between institutions, while a paired t-test was used between pre- and post-assessments from the same individual students. An alpha (p) less than 0.05 was considered significant. Cronbach's alpha was calculated to determine internal consistency, a Wilcoxon Signed Rank test was used to determine if pre and post assessments were different, and Cohen's d was calculated to indicate the effect size.

III. Results

A. No Difference Between Institutions

The Shapiro-Wilk test rejected the null hypothesis that the data were normally distributed (pre W=0.94; post W=0.85; p<0.001 for both). Given the moderately large sample size, the two-sample t-test was considered to be robust to non-normality due to the central limit theorem. No statistical difference was observed when comparing the mean responses of either the pre- or post-assessments between institutions (Purdue University and Stanford University). This suggests that the student populations and previous experiences with SimVascular were similar in both settings. The combined response data had a Cronbach's alpha of 0.97, meaning the pre and post surveys were internally consistent.

B. Assessment Results

Below are the results from the mean pre- and post-assessment for each question from all students participants (Figure 1).

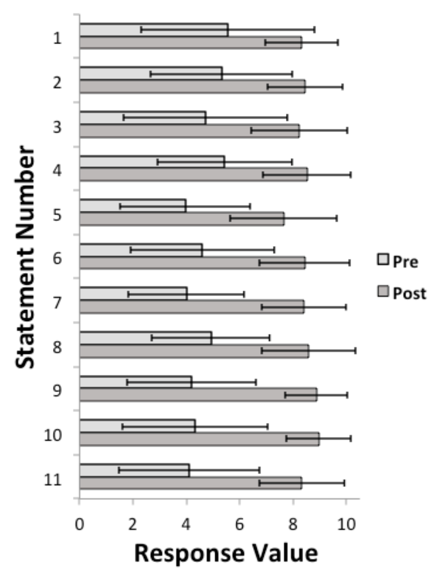

Fig. 1. Student responses for agreement with the eleven assessment statements as mean±SD. The difference between pre and post values suggests an improvement in understanding of image-based blood flow modeling principles, techniques, and applications. There was a significant increase in the post-assessment answers compared to the pre-assessment levels for each statement (p<0.05).

The student assessment revealed an increase in mean response to each of the eleven assessment statements ranging from a minimum of 44% for statement one to a maximum of 109% for statement nine (Table 1). A Wilcox Signed Rank test showed that post assessment survey responses were significantly larger than pre assessment responses ($p<0.001$), and the large Cohen's *d* values suggest a large effect size for each statement.

Statement	***Pre to Post Gain***	***Percent Increase***	***Effect Size***
1	2.5	44%	0.9
2	3.1	58%	1.2
3	3.6	75%	1.2
4	3.3	61%	1.2
5	3.4	85%	1.2
6	3.7	79%	1.3
7	4.3	108%	1.5
8	3.5	71%	1.3
9	4.6	109%	1.5
10	4.5	99%	1.5
11	3.9	90%	1.3

Table 1. The absolute gain and percent increase in mean student responses for the eleven assessment statements (n=22). Cohen's *d* was used to determine effect size for each statement.

C. Student Feedback

We also collected student feedback after the project to better understand what the students learned in specific areas and what areas may have generated questions or confusion. While qualitative, this was helpful to understand what was most helpful for the students and how to target future educational materials and tutorials. Responses varied, but below are a few typical examples highlighting the general student consensus.

Q: *What did you learn about the steps involved in performing a computational fluid dynamics simulation?*

A: Image acquisition, followed by creating pathlines, segmentation, creating a model, meshing, creating boundary conditions, and running the simulation.

Q: *What biomedical applications or diseases did you find most interesting?*

A: Definitely abdominal aortic aneurysms since this is where my research is focused. Cerebral aneurysms were really interesting too.

Q: *What helped you learn the most efficiently when trying to understand a new technical process?*

A: Starting with a simple demo case to go through the entire pipeline and then doing a more complex model. Having someone show me ways to debug problems if they occur to understand technical process.

Q: *For what reasons (if any) will you use this open source software package in the future?*

A: I am interested in coronary artery disease, and this can help in understanding changes in flow patterns.

Q: *What did you most get out of this project?*

A: Really got a feel for medical imaging. How to use SimVascular and how to apply computational fluid dynamics.

A: I feel like I can now use this tool reproducibly on various data sets.

IV. Discussion

Recent development efforts have made SimVascular completely open source, documented, and available on all major operating systems (Mac, Windows, and Linux). This has enabled global community use for both research and education with over 40 research groups actively using this platform. The results of this educational self-assessment study demonstrate that SimVascular can be used to teach hemodynamic and patient-specific modeling principles. While others have developed and described interactive training resources for simulation-based teaching and learning [4-6], SimVascular is a unique open source software package that provides a complete pipeline from medical image data segmentation to patient specific blood flow simulation and analysis. This is ideal for students who want firsthand experience using CFD for biomedical applications.

SimVascular is an active software project undergoing continuous optimization with many further improvements in the works from a team of developers. A newly released graphical user interface has helped improve the handling and processing of image data. Furthermore, new methods for optimized image segmentation based on machine learning and artificial neural networks are also in development [7]. These methods will provide users with improved capabilities to reduce the time to construct accurate models based on patient-specific images. Lastly, new techniques to convert a discrete model to a standard analytical computer-aided design (CAD) model being developed will enable users to both import and export models in most CAD frameworks. These improvements will make it even easier for a wide audience of students and researchers to utilize the SimVascular platform. To provide increased access for education and research, development of a Gateway portal is currently under development, which will enable users to run computational jobs using XSEDE high performance computing resources.

Despite the assessment data presented here, further work is still needed to fully demonstrate the usefulness of SimVascular as an effective educational tool in the classroom and beyond. While using data from two institutions is a strength as it suggests this is experience is generalizable, an obvious limitation in this study is the use of self-report data about students' perceptions of their knowledge and improvement over time. Future research could use more direct and quantifiable measures of students' knowledge to assess the efficacy of SimVascular as an instructional tool. Furthermore, a workshop at the Summer Biomechanics, Bioengineering, and Biotransport Conference (SB^3C) in Tucson, Arizona, in June of 2017 provided another opportunity to reach a broad audience of engineering students and researchers. Quantitative feedback from this 60-minute SimVascular workshop that is still being analyzed will be useful to compare to data from this study of students that lasted for more than two months. Ideally, the basic workflow and principles could be highlighted in both short workshops and longer course modules, helping to encourage more users of this versatile cardiovascular modeling platform. Beyond biomedical research applications, the use of SimVascular shows promise as an innovative educational tool to illustrate hemodynamic principles and the current state of the art in image-based modeling.

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CONFLICTS OF INTEREST

The authors do not have conflicts of interest relevant to this study.

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