Endovascular Device Testing with Particle Image Velocimetry Enhances Undergraduate Biomedical Engineering Education

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Abstract

We investigated the use of a new system, HemoFlow™, which utilizes state of the art technologies such as particle image velocimetry to test endovascular devices as part of an undergraduate biomedical engineering curriculum. Students deployed an endovascular stent into an anatomical model of a cerebral aneurysm and measured intra-aneurysmal flow velocities with HemoFlow™ before and after. The measurements were used as a basis for teaching biofluid mechanical principles. A detailed survey-based evaluation was administered before and after the curriculum. The pre- and post-survey passed reliability testing with Cronbach's alphas of 0.79 and 0.78, respectively. Further, the survey passed validity testing as questions testing the same latent variable factored together with weights all above 0.4. There was a statistically significant improvement in understanding according to a Wilcoxon signed ranks test. Our results indicate that using HemoFlow™ for endovascular device testing in an active learning-based curriculum improved student understanding of biofluid mechanics.

Keywords: particle image velocimetry, aneurysm, biofluid mechanics

Introduction

Endovascular treatments have gained popularity over traditional surgical techniques for cardiovascular repair due to their minimally invasive nature and shorter recovery time. Cerebral aneurysm treatment is one area that utilizes endovascular devices such as coils and stents extensively. Cerebral aneurysms are localized, sac-like dilatations in blood vessels of the brain that are present in about 6% of the world population (Schievink 1997; Lowenstein 2012). Aneurysmal rupture can lead to a critical medical condition known as subarachnoid hemorrhage, which accounts for about one-fourth of all cerebrovascular-related deaths (Wardlaw 2000). It is therefore important to successfully treat an aneurysm before rupture by isolating it from circulation. Unfortunately, endovascular treatment has been associated with a high degree of failure (Molyneux 2002). In order to gauge treatment effectiveness, it is essential to understand how the implanted endovascular device affects blood flow at the aneurysm site.

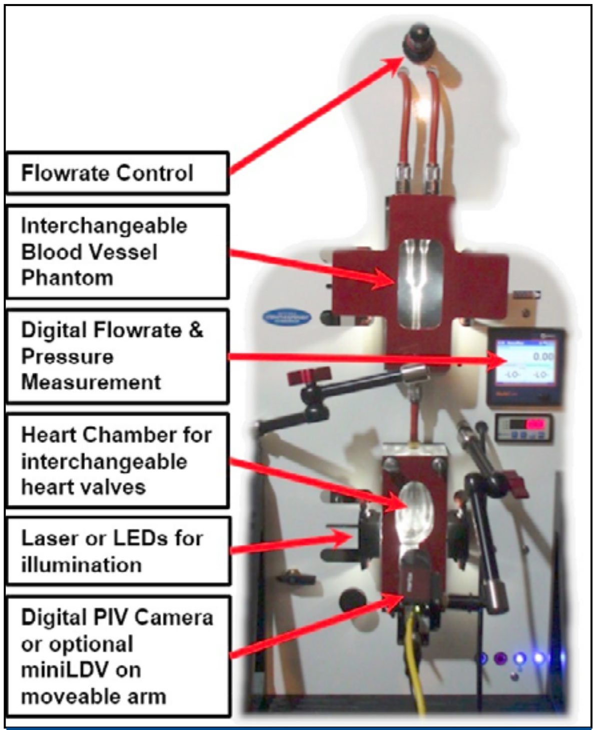

Figure 1. HemoFlow™ system hardware.

Understanding biofluid mechanical principles begins at the undergraduate level when theoretical concepts are often coupled with laboratory exposure. The importance of experimental and computational laboratory experiences in undergraduate engineering education has been well established by Feisal and Rosa (Feisal 2007). Observing theoretical concepts "in action" may help improve student understanding of theoretical concepts (Stern 1997; Ogot 2003). Advancement of technology has facilitated the growth of virtual and remote laboratories where students can better grasp concepts taught in classrooms through the use of computer simulations (Balamuralithara 2009). Although this approach provides a cost-effective alternative to conventional laboratories, simulation results are often dependent on parameters prescribed by the user and they do not necessarily replicate the physical environment (Balamuralithara 2009). Experiments are thus essential because they do not suffer from the same critical shortcomings.

Various techniques can be used to measure fluid flow through a system, one of which is particle image velocimetry (PIV) (Adrian 1991). PIV is a powerful flow visualization and measurement tool that is a cornerstone of medical device testing in biomedical research (Babiker 2010; Hochareon 2004; Leiber 2002). Unfortunately, conventional PIV systems use Class IV lasers, and the dangers inherent to the laser make it impractical to use in a classroom environment (Ransbeeck 2009). To facilitate the integration of such systems to large-scale undergraduate curricula, Interactive Flow Studies Corporation (Billings, MT, USA) developed a portable, light emitting diode (LED) or low power Class III laser-based flow visualization and analysis platform called HemoFlow™. This platform is a low-cost and safer alternative to a conventional PIV system that provides unique active learning experience in biofluid mechanical principles more effectively than traditional didactic programs. The system hardware, as shown in Figure 1, consists of a customizable flow loop with interchangeable blood vessel models (or phantoms), LEDs or a Class III laser as the illumination source, and a video camera to capture the particle image pairs, while a web-based interactive software is used to acquire and process the flow images. The blood vessel models can be custom designed to represent patient-specific geometries, either in-house or ordered from the company. The system also features a digital readout to report flow rate and pressure measurements taken from the interchangeable models,

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and a heart chamber where mechanical heart valves can be investigated. In this study, HemoFlow^{TM} was used to educate junior-level biomedical engineering students at Arizona State University (Tempe, AZ) about the applications of fluid mechanics in cardiovascular research, specifically endovascular device testing. The students learned biofluid mechanical principles by using HemoFlow^{TM} to experimentally visualize the effects that an endovascular device had on flow patterns and velocities in an anatomical model of a cerebral aneurysm. The effectiveness of the HemoFlow^{TM} platform as an educational tool was investigated by analyzing participant responses to a detailed survey administered before and after using the platform.

Methods

Junior-level biomedical engineering students performed hands-on flow visualization using an optically clear, anatomical model of a cerebral aneurysm with the HemoFlow^{TM} system. The students were introduced to various principles of physical modeling, fluid mechanics, and cerebral aneurysms including their treatments over the course of the semester. In order to enhance the depth of student experience, a clinician lectured the students on the different endovascular devices used for cerebral aneurysm treatment prior to the laboratory session. However, clinician involvement is not necessarily required to present the proposed material to the students. There were a total of eighty-eight participants, divided into groups of three during the laboratory sessions (total of 29 groups), and each group was provided with necessary software and materials to perform PIV. The instructors completed the physical modeling process prior to class, while the students performed the in-vitro experiments using the HemoFlow^{TM} and PIV data analysis using Tecplot360. A summary of the modeling and experimentation process is presented in Appendix A.

3D Modeling

Computational Modeling

The first step in the physical modeling and flow visualization processes called for a 3D reconstruction of medical data. Prior to class, the instructors segmented and reconstructed an aneurysm from a computed tomography (CT) angiography dataset describing a cerebral vasculature with an aneurysm at the downstream junction of the basilar artery. Mimics (Materialise, Lueven, Belgium) was used to accomplish reconstruction. The resulting file was exported in stereolithography (STL) format.

Physical Modeling

The final wax model was produced using a Solidscape 3D wax printer (Solidscape®, Inc., Merrimack, NH, USA). The wax model was encapsulated in a silica-based investment and placed in a kiln. The wax was burned off, leaving a hollow channel in the shape of the aneurysm. A lead-tin-bismuth alloy (at eutectic distribution) was heated until molten and poured into the silica channel. The result was a core in the shape of the blood vessel and aneurysm. The metal model was extracted from the investment and then sanded and polished.

The metal core was placed into an acrylic mold box; the size of the box precisely fit the dimensions required by HemoFlow^{TM}. Optically-clear urethane (PolyOptic 1411, Polytek Development Corp., Easton, PA, USA) was poured into the box, completely encapsulating the metal core. To remove optical impurities caused by trapped gasses, the box was placed into a pressure chamber until the urethane had a chance to cure. Following the curing, the urethane block (with the metal core) was placed back into the kiln at a temperature just above the eutectic metal's melting point. This evacuated most of the metal; any remnants were then removed by a bath of aqua regia acid. To enhance optical clarity, the urethane block was sanded and polished.

In-vitro Experimentation

Students were given a video tutorial describing the HemoFlow^{TM} system hardware, and data acquisition process. They were required to watch the tutorial prior to performing experiments.

Particle Image Velocimetry (using HemoFlow^{TM}):
PIV was performed on the physical aneurysm model using HemoFlow^{TM}. The model was mounted on the platform using metallic connectors and polyvinyl chloride (PVC) tubing. Water seeded with light-reflecting neutrally buoyant polymer microspheres was used as the circulating fluid. Fluid passing through the model was illuminated by light emitting diodes (LEDs), placed on either side of the model, and particle images were captured using a video camera (URL: https://www.dropbox.com/s/in33oncvk1sx3rh/Video1.mov?dl=0). A web-based interactive software, FLOWEX^{TM}, was used to control the camera settings including the frame rate. The acquired particle images were first pre-processed for the purpose of background subtraction. This step ensured the removal of all static components of the image. An example of the background subtracted image is shown in Figure 2. The next step was to set PIV parameters, the window size and window shift, to measure flow velocities. PIV estimates velocity vectors by tracking the movement of particle patterns between subsequent images using a cross-correlation algorithm. The images are divided into smaller windows (or regions) based on a user-defined window size, and windows from one frame are cross-correlated with windows from the subsequent frame. Correlation is highest when the particle pattern in a particular window matches the pattern within a window in the next frame. The centroid of the highest correlation peak, along with the time between LED pulses, provides an estimate of velocity (Adrian 1991). The overall data acquisition and processing took about 15-20 minutes per group. Furthermore, the platform has built-in instructions that guide users through data acquisition, processing and flow vector visualization, and requires only introductory training on the order of 5-10 minutes at the time of first use after viewing of the aforementioned video tutorial.

After experimenting with the untreated aneurysm model, a high porosity stent (Enterprise stent, Codman Neurovascular, Raynham, Massachusetts, USA) was deployed in the model in a half-Y configuration, as

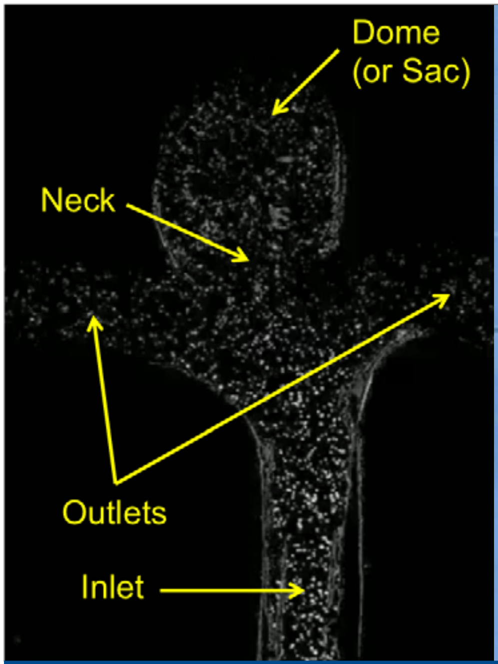

Figure 2. Pre-processed particle image in an untreated cerebral aneurysm model with several anatomical features identified.

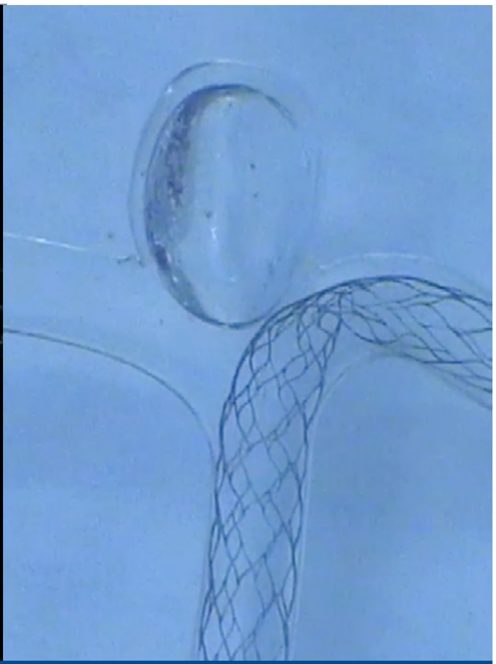

Figure 3. A high porosity stent deployed by a student in a half-Y configuration into the clear urethane aneurysm model. (Note that the bubble in the image would be evacuated prior to experiments).

shown in Figure 3, using a catheter and guide wire (URL: https://www.dropbox.com/s/hfao6byn6hlglv8/Video2.mov?dl=0). The treated cerebral aneurysm model was then mounted on the machine, and image acquisition and processing were repeated to generate a new set of velocity vectors.

In addition to comparing between flow patterns before and after treatment, the students were quizzed about the various aspects of the flow measurement technique during the experimentation process. They were encouraged to think about how PIV window size relates to vector quality and computation time, and how treatment with a different device might alter the flow velocities observed.

HemoFlow™ Data Analysis

Tecplot 360 (Tecplot, Inc., Bellevue, WA, USA), a flow visualization and analysis software, was used to view the velocity vector fields exported from HemoFlow™. Students reported images of the vector field and velocity contours along with a summary of the differences observed between the untreated and treated models.

Surveys

Data Collection

The participants were provided with identical, anonymous survey questions (Appendix B), before and after using HemoFlow™, to gauge their understanding of biofluid mechanics, PIV, and cerebral aneurysms (including treatment). In addition to understanding-based questions, three questions were included where the participants rated their interest towards learning about or working with biofluid mechanics, medical devices, and bioengineering. The survey responses were recorded on a scale of 1 to 4 with 1 being 'no understanding/interest' and 4 being 'strong understanding/interest'. The participants were also encouraged to provide anonymous unstructured feedback on the platform.

Data Analysis

Eighty-eight participants completed the pre- and post-survey. The survey consisted of both knowledge- and interest-based questions. The knowledge-based questions were broadly divided into the following categories: 1) biofluid mechanics, 2) flow measurement using PIV, 3) PIV experimental setup, 4) understanding simulated versus measured data, 5) cerebral aneurysm growth and 6) aneurysm treatment. The interest-based questions pertained to 1) biofluid mechanics, 2) medical devices and 3) bioengineering.

The survey was tested for reliability using Cronbach's alpha, a measure of internal consistency, in SPSS Statistics (IBM Corporation, Armonk, New York, USA). Further, a confirmatory factor analysis was completed to test for survey validity. In other words, the confirmatory factor analysis ensured that questions testing the same latent variable were grouped as anticipated. The responses were then analyzed using Wilicoxon Signed Ranked Test, treating the survey results as paired, non-parametric, and continuous.

Results

PIV results were obtained using HemoFlow™ and then further analyzed using Tecplot 360. Reliability test, factor analysis, and Wilcoxon's signed ranked test were used to determine if HemoFlow™ improved student understanding and interest towards biofluid mechanics and biomedical engineering.

PIV Data Analysis

PIV was applied to a cerebral aneurysm model before and after treatment with a high porosity stent. Velocity magnitude contour plots with vector overlays obtained from FLOWEX™ are shown in Figure 4. The flow jet into the aneurysm at the right side of the neck was alleviated by treatment with the stent. However, increased velocity magnitudes within the fundus and near the left side of the aneurysmal neck were also observed. Flow vectors color-coded by velocity magnitude, obtained from Tecplot 360, is presented in Figure 5.

Statistical Analysis

The reliabilities of both, pre- and post-tests were acceptable with Cronbach's alphas of 0.79 and 0.78, respectively. Confirmatory factor analysis showed that the understanding-based questions factored together with weights above 0.4 (Table 1), whereas the interest-based

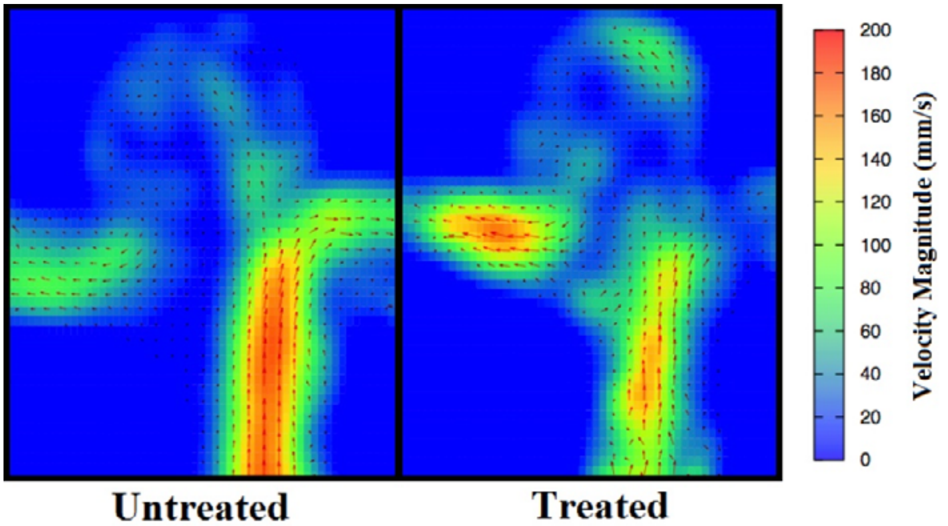

Figure 4. Contour plots of velocity magnitude with vector overlays in the untreated (left) and treated (right) model.The data shown were processed with FLOWEX.

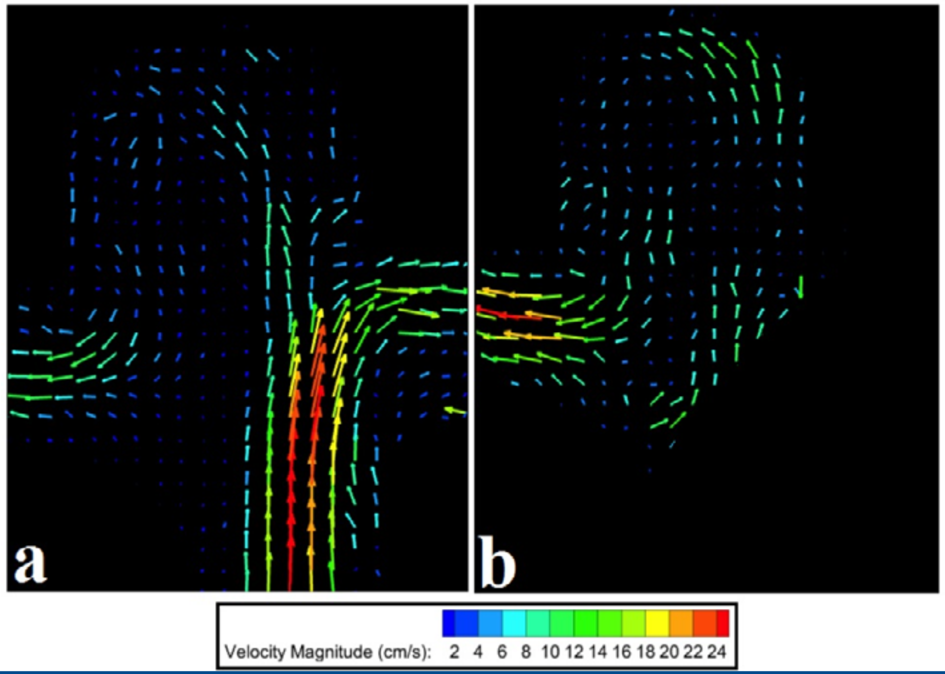

Figure 5. Velocity vector plots color-coded by velocity magnitude as obtained from Tecplot 360 in the untreated (left) and treated (right) model. The region containing the stent is masked in the treated image.

PRE-TEST		POST-TEST	
Categories	*Factor*	*Categories*	*Factor*
	1		1
Flow measurement using PIV	0.840	Aneurysm treatment	0.939
PIV experimental setup	0.773	Aneurysm growth	0.901
Aneurysm Treatment	0.701	PIV experimental setup	0.567
Aneurysm growth	0.674	Biofluid mechanics	0.564
Biofluid Mechanics	0.629	Flow measurement using PIV	0.490
Simulated vs measured data	0.575	Simulated vs measured data	0.409

Table 1. Confirmatory factor analysis results from the pre- and post-surveys.

questions did not factor together. This shows that the knowledge-based portion of the survey is both reliable and valid. The interest questions will be modified and piloted to improve validity of this portion of the survey.

The questions were also analyzed using a Wilicoxon signed ranked test and results are presented in Figure 6. From the statistical results, it is evident that student understanding greatly improved after experimentally performing fluid dynamic measurements using HemoFlow^{TM}. Enhancement in understanding was greatest for PIV theory and experimentation with positive ranks of 2663.50 and 2755.50, respectively. Although the interest-based questions did not show significant pre- and post-test variation, participant responses to interest-based questions were already high before using the platform.

Discussion

Endovascular device testing necessitates a strong understanding of fluid mechanic concepts, which begins at an undergraduate engineering level. Effective teaching of fluid mechanics benefits from parallel presentation of theoretical concepts coupled with laboratory experience. Among the various flow visualization and analysis tools available, PIV has extensively been used in biomedical engineering research to study the effects of cardiovascular devices on hemodynamics (Babiker 2013; Manning 2003; Leiber 2002; Yu 2000). However, the high costs associated with a conventional PIV system, and potential hazards of using a class IV laser, restrict the use of this tool in a classroom environment. HemoFlow^{TM} is a portable educational platform that allows students to experimentally visualize flow without risking their safety. The system is easy to setup and use, and was developed particularly for biomedical engineering applications. Junior-level biomedical engineering students used this platform in the laboratory to visualize the effects of a high-porosity endovascular stent on cerebral aneurysm fluid mechanics.

A flow jet into the aneurysm on the right side of the neck was observed prior to treatment. Smaller flow impingement regions and narrow flow jets have been found to be associated to aneurysm rupture (Cebral 2011). Treatment with a stent alleviated this jet, thereby lowering flow within the aneurysm. Lower flow environment within the aneurysm may promote intra-aneurysmal thrombosis, which over time may lead to vascular remodeling at the neck thereby excluding the aneurysm from circulation (Canton 2005; Lasheras 2007). However, some unexpected results of increased velocity magnitudes near the fundus and on left side of the aneurysm neck were also observed. Fluid mechanical experiments are thus important during endovascular device testing because it demonstrates how a device may have unforeseen effects on local hemodynamics, in addition to the intended effects. Due to the unanticipated increase in velocities at the fundus, a better treatment option may be to occlude the aneurysm with endovascular coils or deploy a flow diverter stent across the aneurysmal neck.

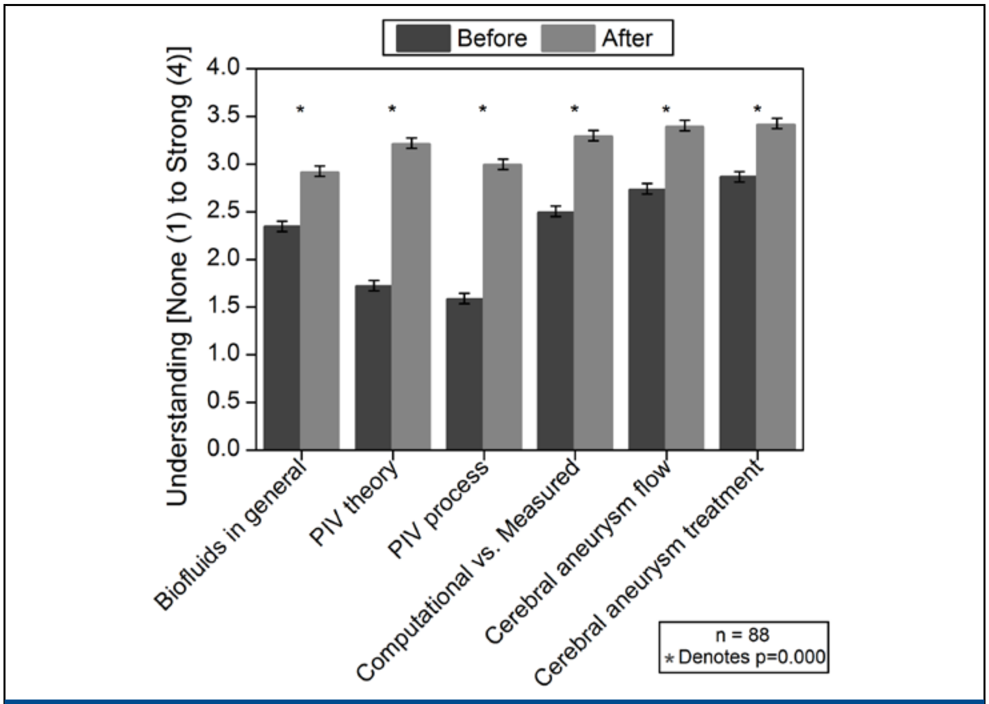

Figure 6. Survey results before and after using the platform using Wilcoxon signed ranked test.

Statistical analysis was performed on the survey results to assess the impact of the HemoFlow^{TM} as an educational platform. The knowledge-based portion of the survey proved to be both reliable and valid. Statistical analysis demonstrated a significant improvement in the aforementioned six concept categories. The interest-based questions, however, did not show significant increase, but student responses already indicated high levels of interest before using the platform. Feedback from the participants showed that an active learning-based environment helped enhance their understanding of biofluid mechanics. Some of the participant comments are listed below:

- "I enjoyed the opportunity to experimentally test data rather than only being able to do it in a computational fashion. I believe it is important to get this hands on experience, so these projects were beneficial."
- "I liked that I got to see the projects visually and experimentally first hand, which aided my learning."
- "It gave a much more hands on approach on how the research and observation of a real medical device is carried out. It was helpful in seeing the types of problems that can come up in these situations."

Future work will entail: (1) execution of a before-and-after knowledge assessment to improve upon the student perception-based assessment presented in this study, (2) employment of different stent configurations and stent designs to help students better understand the effects of endovascular treatments on cerebral aneurysm hemodynamics, (3) inclusion of other vascular defects such as blood vessel stenosis, and (4) increase in participant sample size, preferably from different levels of undergraduate and/or graduate biomedical engineering students.

Conclusion

The purpose of this study was to evaluate a curriculum designed to improve undergraduate biomedical engineering student understanding of biofluid mechanics using HemoFlow^{TM}. While the methods employed here do not relate directly to engineering pedagogy, their effects affirm that Hemoflow^{TM} can be a valuable active learning tool for biomedical engineering educators who are charged with delivering challenging biofluid mechanical curricula. The recorded survey responses showed greatest increase in understanding of PIV theory and experimental setup after using the educational platform. We have thus established that HemoFlow^{TM} had a positive impact on enhancing undergraduate student understanding of key concepts relating to endovascular device testing using PIV. Future work will focus on performing a more comprehensive before-and-after knowledge assessment to support the current and additional, broader findings.

Acknowledgements

The authors acknowledge funding from the National Science Foundation CAREER Award (#1151232) and American Heart Association Beginning Grant-in-Aid (#11BGIA7970009).

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Appendix A:

MODEL CONSTRUCTION AND EXPERIMENTATION PROTOCOL

The instructors perform steps 1-4, and the students perform steps 5-11.

1. Segment and reconstruct computational cerebral aneurysm from computed tomography (CT) angiography dataset using Mimics (Materialize, Lueven, Belgium).
2. Translate the computational aneurysm model to an optically clear, physical urethane model using lost-core manufacturing technique.
3. Divide students into groups of three for the laboratory sessions. (Note that groups of up to five have worked well.)
4. Provide a video tutorial describing the components of the HemoFlow^{TM}, setup, data acquisition, and data processing prior to class.
5. Connect the aneurysm model to the HemoFlow^{TM}.
6. Setup the camera to acquire particle images.
7. Acquire particle image pairs using FLOWEX^{TM}.
8. Setup the processing parameters to calculate flow velocities in the aneurysm model.
9. Export the velocity vectors to a data file.
10. Deploy a high porosity stent (enterprise stent) within the physical model and repeat steps 5-9.
11. Analyze the velocity vectors using Tecplot 360 (Tecplot 360,Tecplot, Inc., Bellevue, Washington, USA) to compare the differences in flow fields before and after treatment with a high porosity stent.

Appendix B:

SURVEY QUESTIONS

Scale:

1) No understanding
2) Little understanding
3) Moderate understanding
4) Strong understanding

Questions:

1) What is your understanding of biofluid mechanics?
2) What is your understanding of how particle image velocimetry (PIV) measures flow?
3) What is your understanding of how to perform PIV experiments?
4) What is your understanding of the differences between computational (simulated) and experimental (measured) fluid mechanical data?
5) What is your understanding of how aneurysmal growth affects flows in cerebral aneurysms?
6) What is your understanding of how treatment with a stent affects flows in cerebral aneurysms?

Scale:

1) No interest
2) Little interest
3) Moderate interest
4) Strong interest

Questions:

7) What is your interest in learning about/working with biofluid mechanics?
8) What is your interest in learning about/working with medical devices?
9) What is your interest in learning about/working with bioengineering?

Comments/Feedback: (Optional)

10) Please provide any comments/feedback on the platform.

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