Simulations, Imaging, and Modeling: A Unique Theme for an Undergraduate Research Program in Biomechanics

Stephanie M. George[1]
Mem. ASME
Department of Engineering,
East Carolina University,
225 Slay Building, Mail Stop 117,
Greenville, NC 27858
e-mail: georges@ecu.edu

Zachary J. Domire
Department of Kinesiology,
East Carolina University,
332A Ward Sports Medicine Building,
Greenville, NC 27858
e-mail: domirez@ecu.edu

As the reliance on computational models to inform experiments and evaluate medical devices grows, the demand for students with modeling experience will grow. In this paper, we report on the 3-yr experience of a National Science Foundation (NSF) funded Research Experiences for Undergraduates (REU) based on the theme simulations, imaging, and modeling in biomechanics. While directly applicable to REU sites, our findings also apply to those creating other types of summer undergraduate research programs. The objective of the paper is to examine if a theme of simulations, imaging, and modeling will improve students' understanding of the important topic of modeling, provide an overall positive research experience, and provide an interdisciplinary experience. The structure of the program and the evaluation plan are described. We report on the results from 25 students over three summers from 2014 to 2016. Overall, students reported significant gains in the knowledge of modeling, research process, and graduate school based on self-reported mastery levels and open-ended qualitative responses. This theme provides students with a skill set that is adaptable to other applications illustrating the interdisciplinary nature of modeling in biomechanics. Another advantage is that students may also be able to continue working on their project following the summer experience through network connections. In conclusion, we have described the successful implementation of the theme simulation, imaging, and modeling for an REU site and the overall positive response of the student participants. [DOI: 10.1115/1.4036315]

Keywords: biomechanics, modeling, undergraduate research

Introduction

Undergraduate research experiences (URE's) are a powerful way to improve undergraduate education. The research has shown that participating in undergraduate research lowers attrition rates [1] and is related to graduating within 4 yr, even when natural student ability, as measured by ACT or SAT is considered as a covariate [2].

The improvements in program success are supported by additional research showing positive learning outcomes from participating in URE's. In a review of the effects of research on undergraduate education, Prince et al. call for more research in this area, but also suggest a link between participating in undergraduate research and learning gains or other forms of cognitive development such as being able to make the transition to independent knowing [3]. This is supported by findings from Bauer and Bennett [4] that show participating in undergraduate research significantly improved graduates perceptions of their skills and abilities in three critical areas (science, math, logic, and problem solving; literature, language, and mastery of contexts; personal initiative and communication). These improvements were still present even when adjusting for student grade point average (GPA).

Given the benefits of undergraduate research, universities and government entities have made efforts to expand the opportunities for undergraduates to participate in research. Programs such as the Research Experiences for Undergraduates (REU) funded by the National Science Foundation (NSF) allow for a group of students to complete summer research projects. These projects are typically organized around a broad central theme, such as solar energy research, nanoscale science and engineering, or optics. The results from Grimberg et al. [5] suggest that organizing around a research theme improves student satisfaction with their research experience and improves specific content knowledge related to the theme.

Biomechanics could be an organizing theme for an undergraduate research program. However, a more focused theme may help to further improve knowledge in a specific topic area. Modeling and simulations are often used in biomechanics to reduce the reliance on human and animal data, and expedite innovation. Modeling and simulation are involved in four of the Food and Drug Administration's (FDA) eight strategic priorities [6]. The priority most applicable is "stimulate innovation in clinical evaluations and personalized medicine to improve product development and patient outcomes." Currently, the FDA relies most heavily on laboratory, animal, and human data. According to the FDA, their goal is to rely most heavily on modeling and simulation data in the future [7]. For example, devices, such as flow diverters, can be tested computationally to understand the impact of device pore structure on the intraneurysmal flow [8].

Additional benefits of modeling and simulations include the ability to estimate difficult to measure variables and test hypothetical situations. For example, wall shear stress is an important contributor to endothelial cell function. However, direct measurement of wall shear stress is not possible. Through imaging and computational fluid dynamics (CFD), wall shear stress can be estimated and linked to histology [9]. Mechanical properties are important in assessing tissue but usually require dissection or removal. Powell et al. utilized a numerical model to determine the elastic modulus of a porcine lens capsule which did not require dissection or manipulation [10]. Simulations also offer a systematic way to

[1]Corresponding author.
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examine effects of individual parameters. For example, by using a finite element analysis, the impact of size and location on tear evolution in the supraspinatus tendon was investigated [11].

Modeling and simulation are intriguing as an organizing theme. These techniques are used across many different types of biomechanics research and are employed at scales ranging from cellular to whole body. However, there are central concepts to developing models in a wide range of applications, such as the importance of validation. Developing an understanding of these unifying themes would enable a student to better understand and appreciate modeling in a wide range of applications. Additionally, biomedical imaging is often used to inform models in biomechanics, by providing a source for model parameters or by providing a means for model validation. Therefore, imaging is a natural companion theme to modeling and simulation.

Given the importance of modeling in biomechanics, we chose the use of imaging to inform a variety of models in biomedical engineering as a theme for our REU Site Program, biomedical engineering in simulations, imaging, and modeling (BME-SIM). We hypothesized that this theme would (1) improve student's understanding of the important topic of modeling, (2) provide an overall positive research experience, and (3) provide an interdisciplinary experience.

Table 1 Summary of participant demographics ($n = 25$)

Demographic category	Subcategory	Count (%)
Gender	Female	14 (56%)
Race/ethnicity[a]	African American	7 (28%)
	American Indian	2 (8%)
	Hispanic	2 (8%)
	Total under-represented minorities	10 (40%)
	Asian	3 (12%)
	White/Caucasian	12 (48%)
College level	Rising junior	13 (52%)
	Rising senior	12 (48%)
Institution type (Carnegie classification)	Baccalaureate level	3 (12%)
	Master's level	9 (36%)
	Ph.D. level	13 (52%)
	R2 institution or lower	23 (92%)
Major	Engineering	13 (52%)
	Other STEM	9 (36%)
	Other	3 (12%)
GPA		3.77 ± 0.18

[a]Note some students fall into more than one category.

Program Structure

The REU Site Biomedical Engineering in Simulations, Imaging, and Modeling (BME-SIM) at East Carolina University (ECU) was funded by the National Science Foundation (NSF) for a 3-yr term from 2014 to 2017. The program brings together faculty from four departments, Engineering, Kinesiology, Health Education and Promotion, and Physical Therapy, representing three colleges. ECU's Department of Engineering is relatively small (~600 students) and offers a general engineering curriculum in which students select a concentration (biomedical, mechanical, electrical, industrial and systems, bioprocess, or environmental). Due to the general engineering focus, the department brings together engineering subspecialties under one roof, inherently fostering interdisciplinary research within and outside the department. For example, biomechanics research can be found all across campus from engineering to dance.

The goal of the program, which aligns with NSF's goal [12], is to provide quality research experiences to students who may not otherwise have the opportunity, increasing awareness of and application to graduate school. At the end of the program students are expected to have a better understanding of how to conduct research, increased awareness of graduate school, clarification and reinforcement of STEM career path, and greater identification as engineer/scientist. Students will also learn about modeling fundamentals and biomedical engineering applications of modeling, such as musculoskeletal modeling or cardiovascular modeling.

Our program is structured similarly to other REU programs [13], in which eight undergraduate students are funded to conduct an individual research project over 10 weeks in the summer. Each student is assigned a faculty mentor and a home institution mentor (faculty member from the student's home institution). The ECU faculty mentor guides the student through the research process providing training, career mentoring, and social support. The home institution mentor provides pre and postprogram mentoring along with support during the program. This novel mentoring model, previously discussed in the literature [14], allows us to bridge the students' home institution with the REU Site and faculty mentor.

Student recruitment occurs through a national campaign and collaboration with targeted partner institutions [14]. The goal is to recruit a diverse (gender, race, geographic location, institution, and major) group of students. From our three cohorts (25 students), 40% of our students were from under-represented minorities, 56% of our students were female, and 92% of our students were from R2 institutions or lower based on Carnegie Classification (48% were from Master's level or lower). While the majority of our students were engineering majors (mechanical, biomedical, etc.), 44% were nonengineering majors (physics, computer science, and biology). A summary of participant demographics can be found in Table 1. Many predominately undergraduate institutions do not have engineering programs and students may not know they can pursue engineering as a graduate program choice. However, by participating in programs, such as ours, students gain skills and confidence that they can pursue engineering as a graduate student.

The students' involvement in the program begins prior to their arrival on campus. Students interact with both their REU faculty mentor and home institution mentor. Upon arrival on campus, students begin the program with a 2-day intensive research course. The purpose of this course is to (1) promote camaraderie between students, (2) review program expectations, (3) provide information on important research resources, (4) discuss the ethical considerations when working with human subjects, and (5) provide an introduction to modeling and MATLAB.

The core of the BME-SIM program is the individual research project. Students are expected to work approximately 40 h per week and participate fully in their faculty mentor's lab. Faculty mentors carve out small components of active research projects to propose for REU student projects. These projects are then vetted to ensure that they align with the theme of the site and have a high probability of completion in 10 weeks. It is also important to be flexible and adapt the projects to the students skill set. Students made improvements to models of the knee and muscles, developed models of bone geometry, made advancements in image processing, and simulated blood flow. Representative projects can be found in Table 2 along with the software utilized.

In addition to the research, students participated in weekly lunch seminars which included information on graduate school, funding, degree program panel, and graduate student panel, along with research skills such as literature searching, networking, poster design, and presentation skills (Table 3). Both formal and informal social activities were planned throughout the summer.

To hold students accountable for their progress through the research process, the BME-SIM program incorporates several deliverables, (1) research plan signed by student and mentor, (2) progress monitoring (week 5), (3) informal oral presentation (week 8), (4) poster presentation (week 10), and (6) abstract submission to the Biomedical Engineering Society (BMES) Annual Meeting (week 10). It is important to identify struggling students

Table 2 Representative student projects

Title	Software utilized	Student contributions
Development of subject-specific musculoskeletal models to predict quadriceps strength	SIMM	Input parameters into existing musculoskeletal models. Compared active torque from two models to experimentally collected data [15]
Creating an average scalable tibia model to predict tibial stresses	IMAGE J MATLAB	Wrote image processing code to analyze MR images. Regression analysis to determine cross-sectional area based on anthropometric measures. Calculated tibial stress [16,17]
Optimizing quadriceps muscle parameters for a subject-specific model of human movement	MATLAB	Wrote a simple muscle model in MATLAB. Analyzed approaches for developing parameters [18].
MR-based wall shear stress calculation in pulmonary hypertension	MATLAB	Wrote code to calculate wall shear stress from phase contrast MRI using three methods found in the literature. Compared wall shear stress values between patients and healthy subjects [19].
Optimization of square channel micromixer for a variety of Reynolds numbers with two-phase liquid-liquid flow	SolidWorks ANSYS	Created varying model geometries, set-up and ran the CFD simulations, and compared the mixing index at various Reynolds numbers [20].
Three-dimensional microfluidic computational study in tissue engineering	Autodesk inventor ANSYS	Created models of tissue engineering scaffolds and investigated the impact of scaffold geometry on velocity and wall shear stress [21].

Table 3 REU activities

Week	Activities
1	Research training: Two-day intensive research course
2	Lunch seminar: How to apply to graduate school
	Deliverable: Research plan
3	Lunch seminar: NSF Graduate Research Fellowship Program
4	Lunch seminar: Literature review
5	Lunch seminar: Graduate program presentations
	Deliverable: Progress monitoring
6	Lunch seminar: Graduate student panel
7	Lunch seminar: How to compose a scientific poster
8	Lunch seminar: "Minute mentoring" Event
9	Lunch seminar: Student oral presentations
10	Lunch seminar: Research conferences: What to expect
	Research training: REU poster session
	Deliverable: BMES abstract submission
1–10	Various social events (e.g., kick-off cookout, low ropes course, ice cream social, bowling, game night, team trivia, women in STEM, and final celebration lunch)
	Various field trips (e.g., Robotics Lab, Medical Simulation Lab)

or project obstacles early so there is sufficient time to provide support and develop alternatives.

The BME-SIM program funds all students' attendance to a conference. This has been one of the highest impact activities of the program. BMES has a special deadline for undergraduate researchers, which is conveniently at the end of July, coinciding with the end of most REU programs. At the conference, students are exposed to a wide variety of research in biomedical engineering, professional development programs, and access to graduate schools from across the country. In addition, it is a chance for students to reconnect after the summer.

Program Assessment

This study was approved by the Institutional Review Board at ECU. Student surveys were completed on the first and last day of the program. Students reported their progress toward mastery of the following knowledge and skills (Table 4) using a ten point Likert scale. Exact wording of the question is included in Table 4. Students reported on their future career goals and past experiences. The presurvey also asked about the mode and quality of interactions with their home institution mentor and REU faculty mentor before the program. The postsurvey instrument also quantitatively and qualitatively assessed their experience in the program including the mode, frequency, and quality of interactions with their REU faculty mentor. After the program, the students are contacted once per year to monitor the impact of the program and plans after graduation.

Results

Students were successful at completing quality research projects. Twenty three of 25 students presented an abstract at a meeting outside of the REU program. Eighteen abstracts were presented at BMES with additional presentations at the state and local levels. One student project has been published as a peer reviewed article [18]. Several other projects are still being developed for manuscript submission.

Program Evaluation. Data from the pre and postsurveys of various learning outcomes clearly indicate that, on average, participants reported significant gains in all domains (Table 4). Across all learning outcomes, participants reported near mastery (10 point) upon completion of the BME-SIM program. In fact, all learning outcomes demonstrated a statistically significant increase (p-value < 0.05). The compilation of all three cohorts was also examined for differences in baseline and change for each learning outcome by race/ethnicity, institution type, and major. There were no statistically significant differences in baseline or change for any learning outcome for the previously mentioned parameters. When exploring the impact of gender, females reported statistically lower ratings on confidence in research skills, understanding the research process, and understanding how scientists work on problems when compared to the male student responses. Females reported greater gains in these learning outcomes resulting in no statistical difference in postassessment ratings. GPA was not significantly different for any comparison group.

It is clear from the open-ended responses that the students viewed the REU program as a positive experience. Nearly, all of the comments were overwhelmingly positive. For example, one student responded that: "Participation in the REU program has definitely encouraged me to pursue graduate school in the future. As a senior nearing graduation, I will be using many of the skills gained during the REU experience in the development of my

Table 4 Summary of BME-SIM evaluation results

Question: Please indicate on a scale of 1–10 your response to the following questions, with 1 indicating no progress/beginner competence and 10 indicating mastery/completeness	Baseline ($n = 25$)	Post ($n = 24$)	Baseline females ($n = 14$)	Baseline males ($n = 11$)
Understanding the research process (LO3)	4.44 ± 2.3	8.38 ± 0.99[a]	**3.77 ± 2.24**	**5.27 ± 2.09** [a]
My confidence in research skills (LO9)	4.64 ± 2.4	8 ± 1.12[a]	**3.54 ± 1.99**	**6 ± 2.17**[a]
Understanding how scientists work on problems (LO4)	4.60 ± 2.02	8.17 ± 1.11[a]	**3.77 ± 2.24**	**5.64 ± 2.01**[a]
Understanding how to design and implement a research project (LO6)	4.08 ± 2.68	7.83 ± 1.21[a]	3.54 ± 2.44	4.91 ± 2.75
The development of my identity as a scientist and/or engineer (LO8)	4.16 ± 2.54	8.13 ± 1.09[a]	3.15 ± 2.25	5.27 ± 2.45
Understanding the role of modeling in biomedical engineering (LO5)	4.24 ± 2.45	8.33 ± 1.21[a]	3.69 ± 2.52	5 ± 2.13
Understanding the importance of research experience for grad programs (LO7)	6.28 ± 2.86	9 ± 1.12[a]	6.46 ± 2.56	5.91 ± 3.18
Understanding the importance of grad education in STEM jobs (LO10)	6.12 ± 2.93	8.67 ± 1.18[a]	5.77 ± 2.94	6.18 ± 2.92
Understanding the various career opportunities in STEM (LO11)	5.6 ± 2.56	8.17 ± 1.25[a]	5.23 ± 2.24	6.09 ± 2.84
Development of meaningful/productive mentoring relationship (LO2)	4.48 ± 2.76	8.13 ± 1.45[a]	4 ± 2.48	5.09 ± 2.97

Note. 1 = beginner level or no exposure, 10 = mastery of domain. The boldface numbers indicate a statistical difference in baseline values between males and females which was not present in the post assessment.
[a]Indicates a p-value < 0.05.

senior project and I think I will be very comfortable explaining the projects in future job interviews. I also have a more solid understanding of what skills I have to offer future employers, as well as which traits I need to improve upon. The REU experience also brought a sense of reality and accomplishment; it let me see some of my true potential and I now see the benefit I can provide to the lives of others in potential career paths." A similar response was given for a student from a different year in the program: "This program helped me develop the confidence to continue research and a career in STEM. This program also helped me develop technical skill applicable to all fields like, computer programming."

Another important outcome is career path following graduation, and more specifically helping students make informed decisions about STEM graduate education. Data suggest that the program structure was effective at achieving this goal as well. Of our 12 graduates, 50% are enrolled in STEM graduate programs, which is well above the national average of 25.9% for females and 32.6% for males [22]. However, these national data may include students who participated in research programs. A true control population is not available. Analysis of our survey data supports that the program has been effective at providing information on graduate education. For example, one participant shared: "Participation in the REU program has definitely encouraged me to pursue graduate school in the future. The REU experience also brought a sense of reality and accomplishment; it let me see some of my true potential and I now see the benefit I can provide to the lives of others in potential career paths." Conversely, other students have learned more about graduate school and made informed decisions to pursue industry careers. For example, a different participant from the same cohort indicated: "It showed me what graduate school would be like and helped me to decide that grad school is not in my current interests. Finally, the program opened my eyes to the depth of topics within biomechanics, a field which I would be interested to stay in."

There was some concern that applying modeling to many different projects would make it difficult for students to see themselves as working on similar projects. However, student responses indicate this was not a problem. Asked about the theme of the program one student responded: "The projects were very diverse, however they were all connected in through processes that could be computerized for modeling or simulating different aspects of the human functions." Similar responses were given by other students, for example: "All projects were oriented towards some type of imaging, modeling or design oriented side of medicine or biomechanics." Students were able to see connections between the projects even when working at very different scales. One student responded: "These programs were connected in how everyone worked with models of biomedical systems. Some systems were as small as a cell and others as large as the human body." Furthermore, students were able to see the common themes of model development that apply across many different types of models. For example, one student shared: "All of the projects incorporated some sort of computational aspect, which differed by project. Additionally, most of the projects either directly correlated to comparison with collected data or could be correlated with data collected in the future for validation and general use."

Evaluation of Modeling Specific Outcomes. Knowledge of modeling was one of the lowest ranked items preprogram. This is to be expected as modeling may not be included in some curriculums, or it is reserved for senior level courses. After the program, students reported significant gains in their knowledge and understanding of modeling (Table 4). One interesting finding was that seniors had significantly higher (p-value < 0.05) gains in modeling knowledge compared to juniors. It was also clear from student responses that this theme enabled the students to learn modeling specific content. Example student comments on this topic include: "I found that there are many different ways that someone can do simulations, imaging, and modeling. I also found that there are a lot of different programs to perform these tasks in."; "My project expanded my knowledge drastically. Imaging in Matlab was a new experience for me, as a biology major. Processing this image to obtain data points was enlightening and it gave me a new appreciation for the Engineering Department."; and "I learned a great deal about computational fluid dynamics modeling and software through my project at the REU. Additionally, from others' projects I was exposed to a type of modeling in which certain deterministic parameters may be condensed or ignored due to other factors, and to form a better, more viable model."

When examining student responses, it was also clear that students learned the value of modeling. For example, one response indicated: "I understand why models are so important in the field of biomechanics. They are more complex than they seem."

Additionally, students gained appreciation for the number of biomechanical studies utilizing modeling. For example, students indicated that: "Before this, I was unaware of how many areas of research included simulations, imaging, and modeling." and "It made me realize how many applications there are in modeling. Also, I got to see some of the different software used in modeling such as SIMM and Matlab."

Discussion and Conclusions

Undergraduate research opportunities (URO) contribute positively to students' academic careers. However, further research is needed to understand the impact of program components and structure on the students perception of the value of the research experience. Students reported significant gains for all learning outcomes. Additionally, our data show no difference in baseline or gains for underrepresented minority students. Although our sample is small ($n = 25$), differences in baseline and gains based on gender were found. This is consistent with other findings in which female students reported greater gains in confidence than male students from UROs in chemistry and physics [23]. Another important outcome is enrollment in graduate programs. One of the challenges of determining the impact of UROs on graduate enrollment is identifying an appropriate control group. Students in the BME-SIM program came from a variety of institutions and majors and were racially and gender diverse. Some graduate enrollment rates include enrollment up to 3 yr postgraduation. This also makes it difficult to compare to program graduate enrollment rates since our students are within 1–2 yr of graduation. There is also bias in our population because participants sought out the research opportunity and, due to the competitive process, have strong GPAs. Students who applied for UROs but were not accepted into a program are a potential control group. More research is needed to understand the impact of UROs on graduate enrollment. Another limitation of determining the impact of UROs is the relatively small sample size. Most programs accept 8–10 students per year. Thus, the program directors need to work together to compile data.

Here, we seek to investigate if the theme, modeling, imaging, and simulations, has a positive effect on the students' experience by increasing their knowledge of modeling. As seen above, students made significant gains in their modeling knowledge which included the numerous applications of modeling in biomechanics and the use of new software and equipment. One of the challenges with summer research programs is to provide a challenging, yet scope appropriate project based on the students skill set. The theme of simulations, imaging, and modeling offers flexibility and opportunities to learn a new software, and, in most cases, to write code. Students learn basic research skills but the project specific skills are adaptable to other types of projects, a benefit of a skills-based theme.

In addition to the gains in knowledge and skills, students reported an overall positive experience. The structure of the program was based on other successful REU programs. Students provided positive feedback on the weekly lunch seminars and planned social activities. The students especially enjoyed interacting with the other summer program students on campus. The majority of students described working on their project and with their mentor as a positive experience. Our mentors tend to have face-to-face meetings daily with our students, and report working alongside their REU students. This level of interaction is somewhat unique in that the REU students are really working alongside their faculty mentor during the research process, in addition to interacting with other graduate students in the labs. Students reported that they enjoyed presenting their work at the end of program presentation, but most found greater value in presenting at BMES. It is difficult to untangle if this is due to the actual presentation or the other benefits of attending a conference. Attendance at BMES allowed students to directly interact with representatives from approximately 90 universities and institutions. Interesting future research questions include assessing the impact of conference attendance on the students' perception of the summer program and future career goals along with the perceived value of conference attendance.

When designing a program around modeling, it is important to incorporate active activities. Some students would have "liked to have a more hands-on experience. Most of my work involved sitting at a computer and writing code." While writing code is a hands-on activity, some students did not view it as such. Therefore, it is important to incorporate other types of activities such as data collection for boundary conditions or validation. The professional development and planned social activities also provided opportunities to be away from the computer.

Modeling can be accomplished with limited resources making it possible for students to continue to be involved in their projects after the summer is over. Most students have access to MATLAB at their home institution or remote connections are available to ECU's network. Over the past decade, open source software has become available such as OPENSIM (biomechanics) [24] and SIMVASCULAR (medical image processing and computational fluid dynamics) [25]. Recently, a vascular model repository has been created in which students can purchase imaging sets for a low cost [26]. These provide alternative options for students to continue their research or develop new projects using the skills they developed during the REU program. Even if these open source options are not used in the REU research project, students should be able to transfer their skills. We are in the process of acquiring longitudinal data to capture the program's impact on future research experiences and coursework.

Another benefit to a biomechanics modeling themed REU is the interdisciplinary nature of the work. With the push to train students to work on interdisciplinary teams and be creative and adaptive, there is a need for interdisciplinary research opportunities and learning skills that can be adaptable to other problems. This allows for mentoring across discipline lines and allows students to see how the modeling process is similar even though the application may be different. The environment at ECU is conducive to such an experience.

The importance of modeling in biomechanics research is increasing. The FDA's strategic priorities indicate that they will rely more and more on computational data to reduce their reliance on animal and human data [7]. The American Society of Mechanical Engineers is working on standards for verification and validation for computational modeling of medical devices [27]. Furthermore, as the trend toward personalized medicine spurs the development and refinement of models across scales from cells, to organs, to entire systems, multiscale modeling is becoming integrated into clinical decision support, for example, in cardiovascular flow [28]. Bright young students are needed, in both academia and industry, who understand the modeling process.

An REU Site centered on modeling as a theme provides students with a valuable skillset which through the interdisciplinary nature of the program they are able to adapt to other applications. Overall students responded positively to the program and reported learning gains on the research process, modeling, and graduate school. Given the success of this specific theme other potential research program mentors may want to also consider specific themes that can apply across many different types of research questions. Future cycles of this program could focus on verification and validation as regulatory agencies are increasing their reliance on simulations and modeling.

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