ChE COVID-19 special section

TEACHING PRINCIPLES OF BIOMATERIALS TO UNDERGRADUATE STUDENTS DURING THE COVID-19 PANDEMIC WITH AT-HOME INQUIRY-BASED LEARNING LABORATORY EXPERIMENTS

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INTRODUCTION

Biomaterials Education and the COVID-19 Pandemic

Biomaterials is a multidisciplinary field, encompassing biology, chemistry, medicine, materials science, and engineering.[1] Over the past several decades, biomaterials have advanced from inert implants to smart materials capable of responding to physiological stimuli to treat debilitating diseases in previously unimaginable ways.[2] As a result, the global market for biomaterials was estimated to be worth $106.5 billion in 2019, with projected annual revenues of $348.4 billion by 2027.[3] To satisfy the increasing demand for biomaterials, there is a societal need to educate students about their design, engineering, and testing.[4,5]

To meet this need, educators have developed numerous engaging experiments to teach undergraduate students the principles of biomaterials. Previously published experiments taught students about the properties of films,[6] fiber-reinforced ceramic composites, polyvinyl alcohol polymers,[7] and alginate-polyacrylamide hydrogels.[8] The publication of these experiments, and others, helps enhance the field of biomaterials education with hands-on learning experiences that are crucial in solidifying concepts of biomaterials and connecting theoretical content to practical applications.[9] However, an important limitation of these published experiments is that they must be completed in laboratory settings due to the use of sophisticated equipment and potentially hazardous chemicals.

With the outbreak of the COVID-19 pandemic in 2019, many schools of higher education transitioned to online learning platforms. The forced transition to online learning poses numerous challenges for education,[10] and these challenges are accentuated for engineering education because students cannot complete traditional formative hands-on experiments. To adapt to this unexpected situation, virtual experiments are proposed as a promising solution to provide engineering students with practical experience.[11] For example, in

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James C. Iatridis, PhD *is Professor and Vice Chair for Research in the Department of Orthopaedics at the Icahn School of Medicine at Mount Sinai (ISMMS). His research applies strong biomechanical principles to development of novel treatments for painful intervertebral disc degeneration. He earned his PhD from Columbia University in Mechanical Engineering and was Professor of Mechanical and Biomedical Engineering at the University of Vermont before joining ISMMS in 2010. ORCID: 0000-0002-2186-0590*

Jennifer R. Weiser, PhD *is an Assistant Professor of Chemical Engineering at The Cooper Union specializing in drug delivery, wound healing, and developing new polymeric biomaterials. At Cooper, she teaches courses in Materials Science, Biomaterials, and Drug Delivery. She earned her BS in Chemical Engineering from Rensselaer Polytechnic Institute and her MS and PhD in Biomedical Engineering from Cornell University. She is a member of the AIChE Education Division and the ASEE ChE Education Division. ORCID: 0000-0002-3578-3469* the context of biomaterials, educators at the University of Oklahoma planned to implement remotely-accessible experiments that allow engineering students to visualize real-time mechanical testing.[12] Such virtual experiments are entirely computational and require remote access to expensive testing equipment, which can inhibit their widespread use. As an alternative, we propose providing students with affordable and easily accessible tools that enable them to gain hands-on experiences in biomaterials in their own homes.

At-home experiments are increasingly popular in the fields of mechanical and electrical engineering as a means of providing low-cost, personal solutions that enhance educational experiences.[13] Such experiments were used to teach undergraduate students about control theory,[14] helicopter motion,[15] thermodynamics, fluid mechanics, and heat transfer[16] using inexpensive and readily available supplies. Although many of these experiments can overlap with traditional chemical engineering education, there is a dearth of published research using at-home lab kits to teach principles of biomaterials. To the authors' knowledge, Lee et al. were the only group to publish an at-home biomaterials experiment, which used a custom mechanical testing stage to measure Poisson's ratio in gelatin cubes of different concentrations.[12]

Research Objectives and Questions

Observing this lack of at-home biomaterials experiments, our objective was to design and evaluate a series of at-home, inquiry-based learning laboratory experiments relating to three major classes of biomaterials: ceramics, metals, and polymers. Specifically, we asked whether completion of our at-home laboratory experiments would result in positive learning gains for undergraduate engineering students. Additionally, we asked whether employing at-home, inquiry-based learning laboratory experiments could enhance student satisfaction with online learning. We hope that these experiments will be useful for biomaterials educators and, more broadly, inspire chemical engineering educators to devise creative, at-home experiments for their students due to COVID-19 or other disruptions to the traditional, in-person learning environment.

Pedagogical Framework for At-Home Laboratory Development

In the traditional learning model teachers pass knowledge directly to students. After encoding and decoding this information, students are given an examination to assess their knowledge.[17,18] A systematic critical review of traditional learning pedagogy found numerous flaws in this model,[19] including creating a power dynamic that limits student engagement in learning[20] and causing students to develop a superficial knowledge of tested material.[21] These drawbacks can negatively impact student learning[22] and hamper students from developing the problem-solving skills necessary for successful careers in science, technology, engineering, and mathematics (STEM).[23] The COVID-19 pandemic, which caused an abrupt switch to online learning, accentuates these existing challenges and poses the new challenge of fairly administering a traditional assessment online. To avoid the issues that would arise from using a traditional teaching approach in an online setting, alternative methods of teaching and assessment were explored.

An inquiry-based learning approach, whereby learners construct knowledge during the learning process, has been suggested to overcome the challenges associated with traditional learning.[24] The key features of inquiry-based learning are students engaging in discussions, suggesting and prioritizing evidence, formulating explanations from available evidence, connecting explanations to scientific knowledge, and communicating their findings.[25] Gibson and Chase found that learning outcomes for middle school science students were greater in the inquiry-based learning group compared to the traditionally educated group.[26] The success of this study, and others like it, motivated the PRIMAS project. This five-year project brought together 14 institutions across 12 European countries to assess the benefits of inquiry-based learning in STEM and found that inquiry-based learning enhanced the educational process and developed learner competence.[27] For these reasons as well as the difficulty of employing traditional learning virtually, our at-home experiments employed an inquiry-based learning approach to effectively teach principles of biomaterials and experimental design during the COVID-19 pandemic.

MATERIALS AND METHODS

Materials and Software

Materials were purchased from Amazon® and shipped directly to students. The choice of material, brand, and quantity was based on economic constraints and the option of free shipping within the United States. Each at-home laboratory kit cost less than \$100 per student and allowed students to complete all three experiments (Figure 1). Kits were funded by The Cooper Union through the CU@Home Project, which provided engineering students with packages of materials to complete a variety of laboratory- and project-based courses at home in response to the COVID-19 pandemic. Materials for each experiment with Amazon Standard Identification Number (ASIN) can be found in later sections. It was assumed that all students had access to tap water, salt, a stovetop for boiling water, a refrigerator for cooling hydrogels, a freezer for cooling oil, a ruler, and some set of uniform weights (e.g. paperclips or coins). If it is possible for educators to distribute the materials directly to students, they may purchase similar materials in bulk to further reduce costs.

Figure 1. Materials provided to students in each at-home laboratory kit.

In addition to physical materials, students were trained to use a variety of open-access software packages commonly used in the biomaterials field. These software packages included R, ImageJ, and Tracker. To equip students to use the R packages, students were given a two-hour lecture about key biostatistics principles, including hypothesis testing and power analysis. For particle counting in ImageJ, the students were taught how to install and use the Cell Counter plugin. For the Tracker software, students were given a brief demonstration and made aware of sample video tutorials to use as practice prior to the experiment.

Student Demographics and Virtual Lab Groups

The experiments outlined in later sections were integrated into a multidisciplinary elective engineering course called Biomaterials that was open to students in all majors and as early as their sophomore year. Twenty-seven students took the course in Fall 2020, and most of these students were chemical engineering majors (three seniors, fifteen juniors, and four sophomores). The course also included two junior mechanical engineering majors, two electrical engineering majors (one senior and one sophomore), and one junior general engineering major. Students were allowed to choose their virtual laboratory groups, which consisted of 3-4 students, and were the same for all experiments.

Pre-Laboratory Exercises

Prior to starting the experiments, laboratory groups were guided through a pre-laboratory exercise using an inquiry-based learning approach. Pre-laboratory exercises were facilitated using Zoom® by placing each virtual laboratory group in a breakout room. Instructors moved between breakout rooms to help guide discussions and answer questions. These student-led discussions ensured all group members had an appropriate level of background knowledge to conduct the at-home experiments and were comfortable using inquiry-based techniques. Since laboratory groups were virtual, a special emphasis was placed on rigor and reproducibility in their methods[31] so that testing could be reliably repeated at different homes. To address rigor and reproducibility, instructors encouraged students to use one of the following experimental designs: (1) all students conduct testing for a control group, then distribute experimental groups; or (2) all students conduct testing for each condition using a small sample, which was pooled for group analysis. These methods would reduce the likelihood that differences between experimental conditions were an artifact of which student conducted testing for a particular condition.

After in-class discussion, teams conducted independent literature searches to generate a pre-laboratory report. In this report students introduced the broad class of biomaterial they were testing (i.e. ceramics, metals, or polymers), explained the independent variables they were manipulating, described their mechanical testing, and listed quantifiable output measurements they would record, with specific hypotheses they would test. Additionally, laboratory groups outlined which group members would conduct each specific test proposed for their conditions. All materials used in their experimental design were listed with appropriate detail so experiments could be easily replicated; this also introduced students to how formal research reports are written. Lastly, teams calculated their sample size in R using the "ss.1way" function in the "pwr2" package. Pre-laboratory reports were reviewed by instructors to ensure appropriate background knowledge, sound experimental design with necessary controls, and a robust testing scheme. Instructors provided students with feedback, then students were free to complete their at-home experiments.

Student Assessments

Pre- and post-tests were used to assess the learning outcomes for each experiment. Due to the inquiry-based approach used in these experiments, authors had difficulty finding validated questions for pre/post-test assessments. Instead, authors designed pre/post-test questions for each experiment using published pre/post-test questions from similar undergraduate biomaterials experiments.[7] Pre/post-test questions were related to specific learning objectives for the course, including understanding engineering design variables for different classes of biomaterials, relating biological responses to design considerations for biomaterials, and analyzing data from inquiry-based laboratory experiments.

Pre-tests were administered synchronously in class prior to virtual laboratory group discussions. Post-tests were administered asynchronously starting on the day students submitted their written laboratory reports and left open until the end of the semester; most students completed the test the day they submitted their report. Participation in our study was voluntary, and students enrolled in the Biomaterials course did not need to complete pre/post-tests to participate in the laboratory experiments. For our analysis we included all matched pre/post-test results for students who completed both the pre- and post-test assessment for a given laboratory experiment. The average pre/post-test scores were compared using a paired Student's t-test ($p < 0.05$), after confirming the groups had equal variance using an F-test. GraphPad Prism® software Version 9 was used to conduct all statistical analysis.

Additionally, students were able to complete an end-of-semester survey starting on the day they submitted their final laboratory report. The goal of the end-of-semester survey was to evaluate students' responses to these at-home laboratory experiments.[32] The survey consisted of eight questions that were answered on a Likert Scale of "Strongly Agree" to "Strongly Disagree," with a ninth optional question for soliciting additional comments. Descriptive statistics were used to assess the results of the survey data. All tests and surveys were administered using SurveyMonkey®. For anonymity, IP address tracking was turned off and reviewers were blinded to the responders' identities. All questions were approved by The Cooper Union Institutional Review Board (IRB). All questions for the pre/post-test assessments and the end of semester survey can be found at https://engfac.cooper.edu/jweiser/755. For additional information, please contact Dr. Jennifer Weiser (jennifer.weiser@cooper.edu).

CERAMIC TOUGHNESS EXPERIMENT

Background

Ceramics are a broad class of biomaterials composed of metal and non-metal atoms held together by ionic and/or covalent bonds. In the field of biomaterials, types of ceramics known as cements are commonly used as synthetic bone grafts.[33] As the population ages, the number of traumatic bone injuries and demand for innovative cement bone grafts have increased.[34] The major drawbacks of cement biomaterials are their mechanical properties. As biomaterials, cements are hard, brittle, and typically fail with little plastic deformation due to their molecular structure.[35] The goal of this laboratory experiment was for students to understand how the synthesis of a ceramic biomaterial affects its failure through impact testing.

This experiment was adapted from the "Engineered Concrete" experiment proposed by the American Ceramic Society in their Materials Science Classroom Kit.[36] In this activity students generated slabs of cement with varying water to cement (w/c) ratios to determine which formulation had optimal properties upon impact testing. Published studies researching the effects of the w/c ratio on ceramic materials demonstrated that modifying the w/c ratio in ceramic biomaterials changes their porosity, thus affecting their mechanical properties.[37] For our modified experiment students were given a more open-ended prompt of understanding how ceramic composition (i.e. w/c ratio of concrete) affects biomaterial microstructure (i.e. porosity) and ultimately changes how ceramics perform in biomaterial applications. Each laboratory group was challenged to design their own experiment exploring cement porosity that could be performed safely in and around their homes, devise a method for impact testing, quantifiably describe the breaking patterns of their various cement slabs, and summarize key findings in a written report in the context of ceramic biomaterial applications.

Materials and Software

The following materials were purchased and shipped to students:

- RRRP Gloves (ASIN: B0865SSK9T)
- MVZAWINO Digital Precision Gram Scale (ASIN: B07CL1HD8K)
- Hartline 10006 Rockite Cement (5 lb) (ASIN: B000SDXGUU)
- Hefty Everyday Foam Bowls, Soak Proof (x1 per concrete slab) (ASIN: B08FJGR6FK)

Students had access to the following software packages:

- ImageJ
- R

Procedure

Students were guided through inquiry-based, pre-laboratory discussions and pre-report writing as previously described. In their report students were asked to introduce ceramic biomaterials, describe the w/c ratio and how it impacts ceramic porosity, then discuss how the w/c ratio may be used as a design variable to control *in vivo* failure. Additionally, students described their impact testing scheme with specific output variables. After instructor feedback, students were given three weeks to complete the experiment and collaborate on a written laboratory report.

In order to modify the porosity of ceramic biomaterials, all groups varied the weight concentration of cement powder in their casting solution from 1-5 g/mL (100-500% w/v). This concentration range was provided by instructors based on previous experimentation with the material. An example of other variables tested included a group that explored "whisked" and "tapped" conditions to add and remove air bubbles from setting cement slabs, respectively. After creating cement slabs students dropped slabs from a set height (approximately 5 ft) and took images of the shattered cement (Figure 2A and 2B). Using ImageJ software students quantified the number of pieces each cement slab broke into and the area of each of those pieces. While ImageJ wasn't strictly necessary to count the pieces, it was an opportunity to introduce the students to that piece of software as a tool commonly found in biomaterials research. Using R, students carried out a one-way analysis of variance (ANOVA) with Tukey's *post-hoc* test ($p < 0.05$) to find significant differences in breaking patterns between their groups (Figure 2C). After completing the experiment, each virtual laboratory group completed a laboratory report that summarized their results and discussed them in the context of ceramic biomaterial applications.

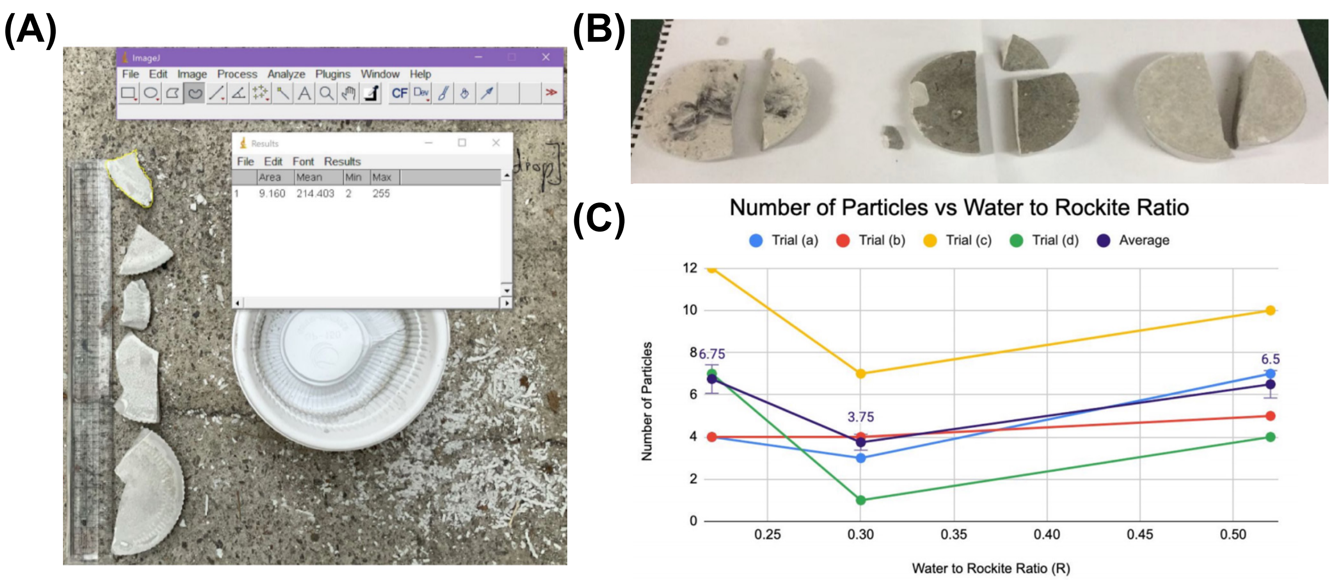
Assessment

Twenty students (N = 20) participated in the pre/post-test assessments for this laboratory activity. Questions were written to test students' understanding of ceramic toughness and biomedical applications of ceramic biomaterials; the complete list of six questions can be found at https://engfac.cooper.edu/jweiser/755. The results of our assessment showed that the average scores significantly increased from 57.5% on the pre-test to 70.0% on the post-test assessment (Figure 3A). In addition to significant overall score increases, we found that the percentage of students who correctly answered questions Q1, Q3, and Q6 was greater in the post-test than the pre-test (Figure 3B). This was particularly striking for Q3 because only 40% of students answered correctly in the pre-test while 100% of students answered correctly in the post-test. These questions tested the concepts of ceramic toughness and engineering ceramic biomaterials for bone replacement. Moreover, the increase in pre/post-test scoring indicates that the at-home experiment effectively taught these concepts. Q4 was the only question that showed a slight decrease in the percentage of students who answered correctly. This question tested the concept of energy consumed during brittle and ductile fractures, a topic that wasn't explicitly explored in the Ceramic Toughness Experiment.

METAL CORROSION EXPERIMENT

Background

Metals are a class of biomaterials composed of metal atoms from one or more elements held together by metallic bonds. Metals have an ordered, repeating three-dimensional crystalline structure that allows them to be forged and fabricated into a variety of shapes for diverse biomedical applications.[1] Due to their excellent mechanical properties, metal biomaterials are commonly used as load-bearing implants (e.g. hip prostheses). Additionally, the delocalization of electrons in metal biomaterials makes them highly conductive and valuable components of a wide range of medical devices (e.g. pacemakers).[35] One major consideration for metal biomaterials is



	Area	Mean	Min	Max
1	9.160	214.403	2	255

Figure 2. *Data from student laboratory reports demonstrating successful fabrication and impact testing of cement slabs of varying water to cement (w/c) ratio. (A) ImageJ software quantifying the number and size of each broken cement slab piece. (B) Representative images of broken cement slabs at different w/c ratios. (C) Representative graph of the average number of broken cement slab pieces vs. w/c ratio.*

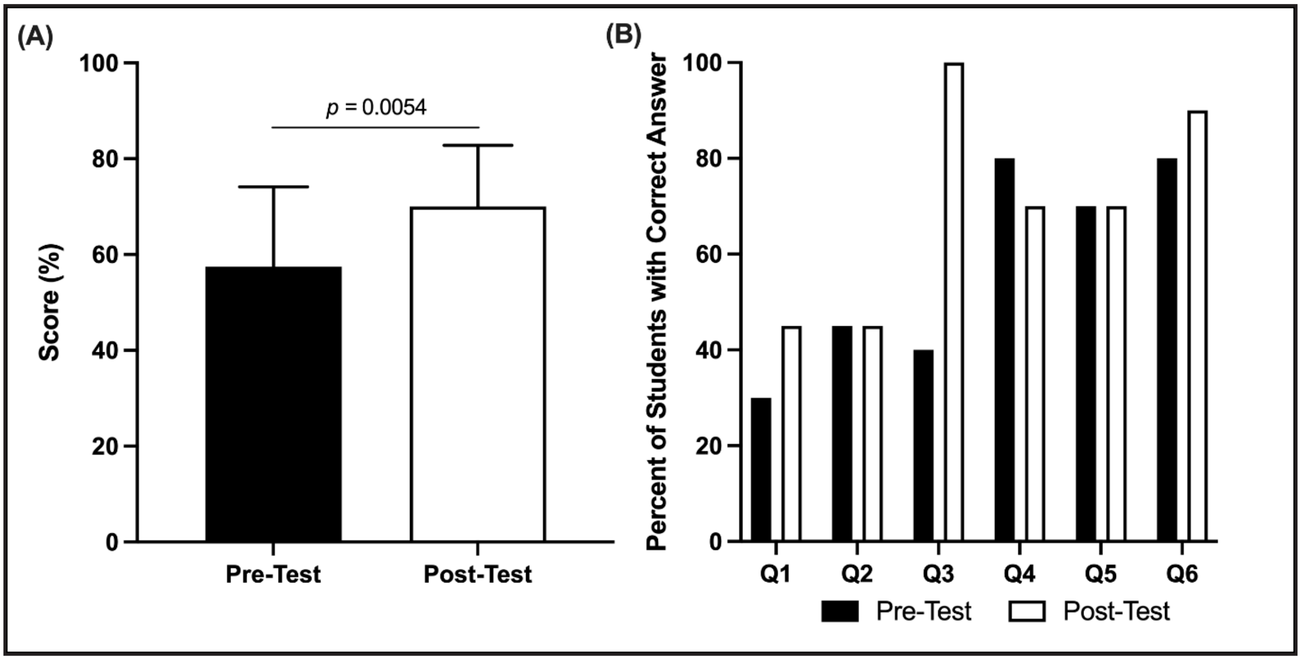


Figure 3. *Students scored higher on Ceramic Toughness Experiment post-test evaluation, demonstrating significant learning gains. (A) Average student pre/post-test scores. (B) Percentage of students who answered individual questions correctly on pre/post-test assessments.*

their corrosion. When placed in the human body, metals are exposed to a reactive interstitial fluid containing water, ions, plasma, and proteins at a physiological temperature of 37°C and pH 7.4. These conditions may cause metals to corrode within the human body. This is concerning because corrosion releases potentially toxic metal ions into the body, and corroded metal biomaterials have inferior mechanical properties. To overcome this challenge, surface modifications are often applied to metal biomaterials.[38] The goal of this laboratory experiment was for students to understand what variables affect the rate of metal corrosion, how surface modifications influence this rate, and how corrosion affects metal fatigue failure properties.

This experiment was a novel adaptation of the classic paperclip fatigue bending experiment.[39] In the traditional version of this experiment, students fatigued paperclips at different bend angles to measure the effect of bend angle on failure limit. For our modified experiment students were asked to explore the effects of three different environmental conditions (e.g. temperature, salinity, and pH) on the corrosion of metal paperclips. In addition to the three environments, all students were asked to explore metal surface coatings as a variable. To test surface coatings, students incubated galvanized paperclips, which is analogous to protective passivation found on many metal biomaterials, and compared those to sanded paperclips, which removed the galvanization layer. Students incubated paperclips in the different environments for 5-10 weeks to allow corrosion to occur prior to fatigue testing. Students were challenged to devise a quantifiable method of fatigue testing so they could compare the effects of the environment on corrosion to the material's fatigue limit. After completing their experiments, students summarized key findings in a written report in the context of metal biomaterial applications.

Materials and Software

The following materials were purchased and shipped to students:

- RRRP Gloves (ASIN: B0865SSK9T)
- MVZAWINO Digital Precision Gram Scale (ASIN: B07CL1HD8K)
- Nicole Home Collection 3 fl oz Mini Round Containers (ASIN: B0199IIM9Y)
- Officemate No.1 Smooth Paperclips Each (ASIN: B008GVZEOW)
- 3M 9019 General Purpose Sandpaper Sheets, Assorted Grit (ASIN: B00004Z47W)
- Goya White Vinegar (16 fl oz) (ASIN: B004SRXM4W)

Students had access to the following software packages:

- R

Procedure

Students were guided through inquiry-based, pre-laboratory discussions and pre-report writing as previously described. In their report students were asked to introduce metal biomaterials, describe metal corrosion in the context of biomaterials, and then discuss methods by which metal corrosion can be prevented. Additionally, students described their fatigue testing scheme with specific output variables. After instructor feedback, students were given twelve weeks to complete the experiment and collaborate on a written laboratory report.

All students were asked to explore surface modifications as a variable affecting the rate of metal corrosion. Since all paperclips were galvanized, each laboratory group devised a systematic method of sanding paperclips to remove the coating (e.g. sanding for a set amount of time). Beyond this, students were given free range to explore other biologically relevant variables of interest that might affect the rate of metal corrosion. Some examples included pH, temperature, salinity, time, humidity, and exposure to sugar. Students incubated paperclips in their proposed environments for at least five weeks, with appropriate controls, to allow corrosion to occur. After incubation, students took pictures of the paperclips in different conditions and qualitatively described the corrosion in each environment (Figure 4A). Next, students implemented their fatigue testing scheme (Figure 4B) to quantitatively assess the effects of metal corrosion on the paperclip fatigue limit (Figure 4C). Using R, students carried out a one-way ANOVA with Tukey's *post-hoc* test ($p < 0.05$) to find significant differences in the number of bends required to break paperclips in each environment. After completing the experiment, each virtual laboratory group completed a laboratory report that summarized their results and discussed them in the context of metal biomaterial applications.

Assessment

Twenty-one students (N = 21) participated in the pre/post-test assessments for this laboratory activity. Questions were written to test students' understanding of metal corrosion and biomedical applications of metal biomaterials. All six questions for the pre/post-test assessments and the end of semester survey can be found at https://engfac.cooper.edu/jweiser/755. The results of our assessment showed that the average scores increased from 55.6% on the pre-test to 61.1% on the post-test assessment (Figure 5A). Though this increase was not statistically significant, the average score change between pre- and post-test assessments was 5.56 points, demonstrating gains in knowledge. It was found that the percentage of students who correctly answered Q1, Q3, Q4, and Q5 was greater in the post-test than the pre-test (Figure 5B). This was particularly striking for Q3 because only 71.4% of students answered correctly in the pre-test while 100% of students answered correctly in the post-test. These questions tested the concepts of corrosion mechanisms, metal passivation, how metals corrode in salt solutions, and how metals corrode in acidic environments. The increase in pre/post-test scoring indicates that the at-home experiment effectively taught this concept. Q2 and Q6 showed decreases in the percentage of students who answered correctly. These questions were more exploratory and tested whether students could apply their knowledge of metal corrosion to translational applications of biomaterials. To ensure students can make these connections in the future, we will specifically ask them to address clinical translation in their laboratory reports.

POLYMER STIFFNESS EXPERIMENT

Background

Polymers are a class of biomaterials composed of repeating monomer subunits arranged into various architectures by primarily covalent and secondary bonding.[1] Compared to ceramics and metals, polymeric biomaterials typically have lower mechanical moduli. However, polymers can be deformed to a greater extent before failure, which makes them highly versatile in biomedical applications.[35] Of the diverse types of polymeric biomaterials, hydrogels are extremely popular in biomedical applications. Hydrogels are characterized by high water content and a soft, rubbery consistency that mimics living tissue. Interestingly, hydrogels can be tuned to mimic the mechanical properties of various soft tissues by varying their composition and preparation.[40] Furthermore, these modifications impact their ability to deliver cells and bioactive agents. To better control the delivery of cells and bioactive agents in hydrogel-based therapies, researchers have investigated composite hydrogel systems consisting of microbeads embedded in a bulk hydrogel matrix.[41] The goal of this laboratory experiment was for students to understand how the composition of polymeric biomaterials affects the stiffness of single-network and composite hydrogels materials.

This experiment was an at-home adaptation of a challenge-based hydrogel compression experiment.[7] In the Vernengo and Dahm experiment,[7] students synthesized polyvinyl alcohol hydrogels with different polymer concentrations, then tested them in compression using a mechanical testing system with a load cell. Generally, increasing the macromer concentration of pre-crosslinked polymer solutions increases the stiffness of resulting hydrogels.[42] For our modified experiment, students were asked to explore the effects of polymer concentration on hydrogel compressive mechanical properties using gelatin. Additionally, students were asked to explore this relationship for composite hydrogels by incorporating gelatin beads into gelatin matrices of varying polymer concentrations. In a simple model the modulus of composite biomaterials obeys a rule of mixtures, whereby the modulus of a composite biomaterial is the weighted average of its

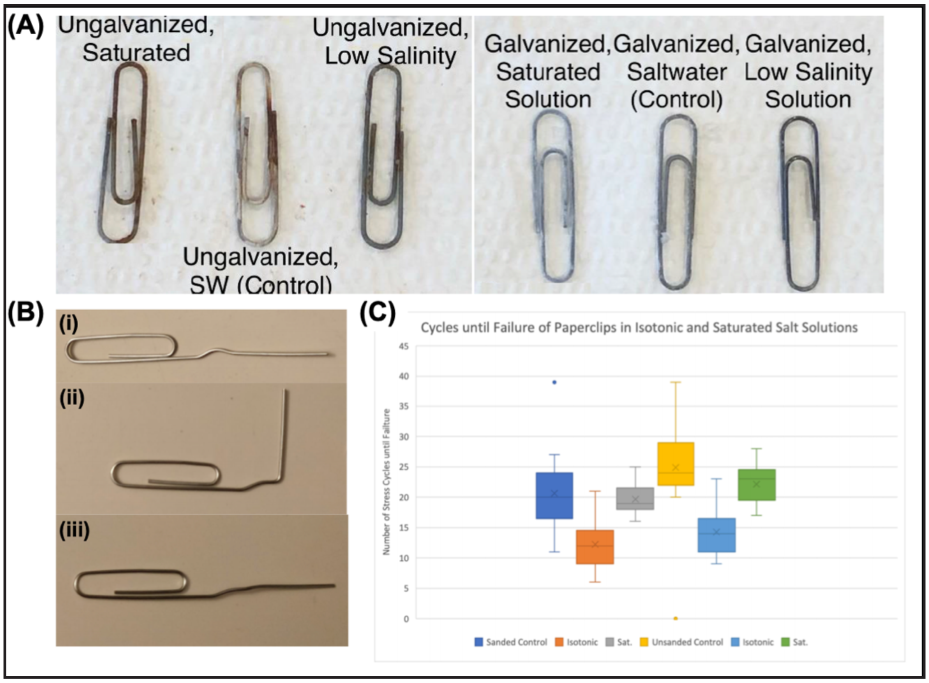


Figure 4. *Data from student laboratory reports demonstrating successful paperclip corrosion and quantitative fatigue bending tests. (A) Representative images showing galvanized and ungalvanized paperclips incubated in various salt solutions. (B) Schematic representation of a paperclip fatigue bending test. (C) Representative graph of the average number of bends for paperclips to fail after incubation in various salt solutions. Sanded and Unsanded Control paperclips were incubated in water, Isotonic paperclips were incubated in 0.9% (w/v) salt solutions, and Saturated paperclips were incubated in saturated salt solutions.*

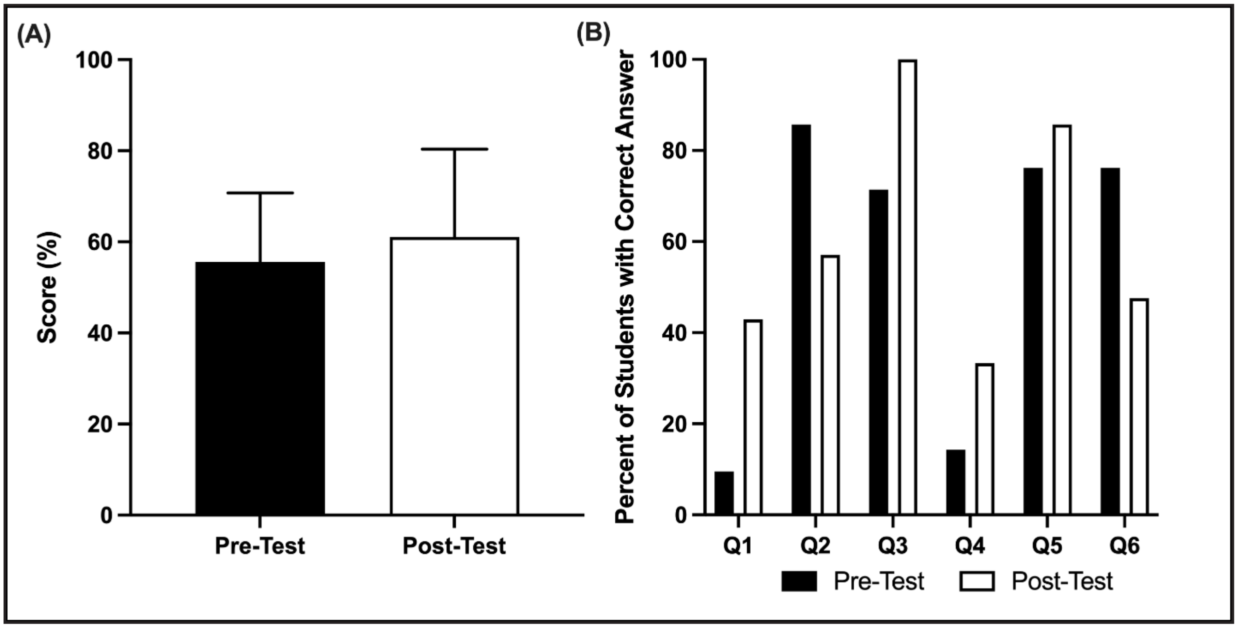


Figure 5. *Students scored slightly higher on Metal Corrosion Experiment post-test evaluations, demonstrating learning gains. (A) Average student pre/post-test scores. (B) Percentage of students who answered individual questions correctly on pre/post-test assessments.*

components' moduli by volume fraction.[43] After synthesizing their single-network and composite hydrogels, students were challenged to devise a quantifiable, at-home compressive testing system for the hydrogels. After completing their experiments, students summarized key findings in a written report in the context of polymeric biomaterial applications.

Materials and Software

The following materials were purchased and shipped to students:

- RRRP Gloves (ASIN: B0865SSK9T)
- MVZAWINO Digital Precision Gram Scale (ASIN: B07CL1HD8K)
- Tovolo Silicone King Cube Tray of 2" Cubes (ASIN: B00395FHRO)
- Hefty Everyday Foam Bowls, Soak Proof (ASIN: B08FJGR6FK)
- Knox Unflavored Gelatin, 1 lb (ASIN: B001UOW7D8)
- Kinglake 3 mL Plastic Transfer Pipettes (ASIN: B00WLIQHQ0)
- Amazon Brand Happy Belly Canola Oil, 48 fl oz (ASIN: B07P5V4DCR)

Students had access to the following software packages:

- Tracker
- R

Procedure

Students were guided through inquiry-based, pre-laboratory discussions and pre-report writing as previously described. In their report, students were asked to introduce polymeric biomaterials, describe single-network and composite hydrogels, then discuss how the concentration of polymer in the bulk hydrogel and embedded beads could affect biomaterial stiffness. Additionally, students described their compression testing scheme with specific output variables. After instructor feedback, students were given three weeks to complete the experiment and collaborate on a written laboratory report.

All students were asked to explore how the concentration of gelatin pre-crosslinked polymer solutions would impact the compressive properties of resultant physically entangled, single-network, and composite hydrogels. To do so, students created gelatin solutions with concentrations ranging from 3-8% (w/v). This concentration range was provided by instructors based on previous experimentation with the material. Students created single-network hydrogels by pouring freshly boiled gelatin into ice cube trays and allowing physical entanglements to occur in their refrigerator as the bulk gelatin cube cooled and set. For composite hydrogels, students first created gelatin beads by dropwise pipetting the boiled gelatin solution into a container of cold oil. After generating beads, students incorporated them at varying mass or volume ratios into their bulk hydrogel cubes and allowed the composite to cool in the refrigerator, making sure to occasionally stir the mixture to keep the beads from settling (Figure 6A). After all the hydrogels were synthesized, students implemented their compression testing scheme to calculate the modulus of their single-network and composite hydrogels. Generally, this consisted of placing a Styrofoam bowl on top of the hydrogel, then adding weights (e.g. paperclips or coins) into the container over time. Testing was recorded with a ruler in frame so that displacement was accurately measured using Tracker software (Figure 6B). After extracting force-displacement data, students generated stress-strain graphs and calculated the modulus of each hydrogel (Figure 6C and 6D). Using R, students carried out a one-way ANOVA with Tukey's *post-hoc* test ($p < 0.05$) to find significant differences in the moduli between their hydrogels. After completing the experiment, each virtual laboratory group completed a laboratory report that summarized their results and discussed them in the context of polymer biomaterial applications.

Assessment

Eighteen students (N = 18) participated in the pre/post-test assessments for this laboratory activity. Questions were written to test students' understanding of polymer stiffness and biomedical applications of polymeric biomaterials; the complete list of six questions can be found at https://engfac.cooper.edu/jweiser/755. The results of our assessment showed that the average scores increased from 55.6% on the pre-test to 64.8% on the post-test assessment with trending significance (Figure 7A). Though this increase was not statistically significant, the average score change between pre- and post-test assessments was 9.26 points, demonstrating gains in knowledge. Looking more deeply at specific questions, it was found that the percentage of students who correctly answered Q1, Q2, Q4, and Q6 was greater in the post-test than the pre-test (Figure 7B). This was particularly striking for Q4 because 100% of students answered correctly in the post-test. These questions tested the concepts of polymer crosslinking, compressive strength, and biomaterial applications of hydrogels. The increase in pre/post-test scoring indicates that the at-home experiment effectively taught this concept.

STUDENT END-OF-SEMESTER SURVEY RESULTS

Twenty students (N = 20) completed the end of semester survey, and a compiled list of nine questions can be found at https://engfac.cooper.edu/jweiser/755. Most students agreed that experiments were easily conducted at home with virtual

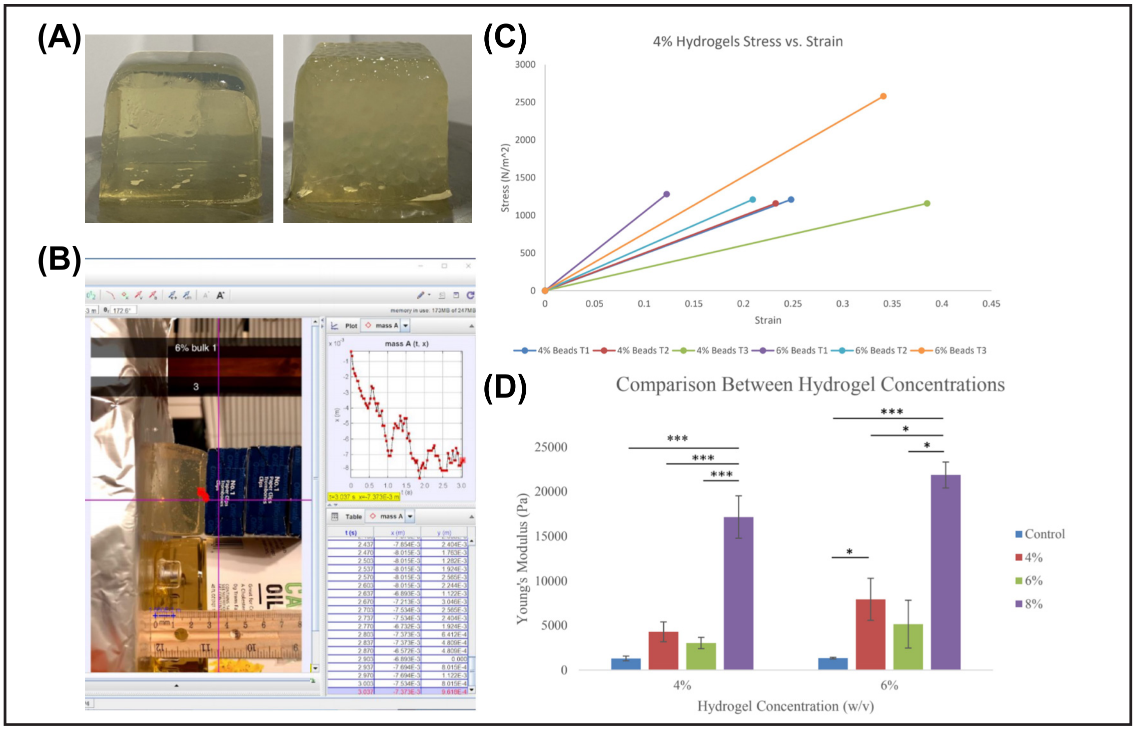


Figure 6. *Data from student laboratory reports demonstrating successful fabrication and compression testing of hydrogels of varying concentration and bead composition. (A) Representative images showing single-network hydrogels (left) and bead-laden hydrogel composites (right). (B) Tracker software was used to measure hydrogel deformation in unconfined compression. (C) Representative stress-strain curves showing the effects of polymer concentration and presence of beads on material modulus. (D) Representative graphs of the modulus of various concentration bulk hydrogels seeded with either 4% (w/v) gelatin beads (left) or 6% (w/v) gelatin beads (right).*

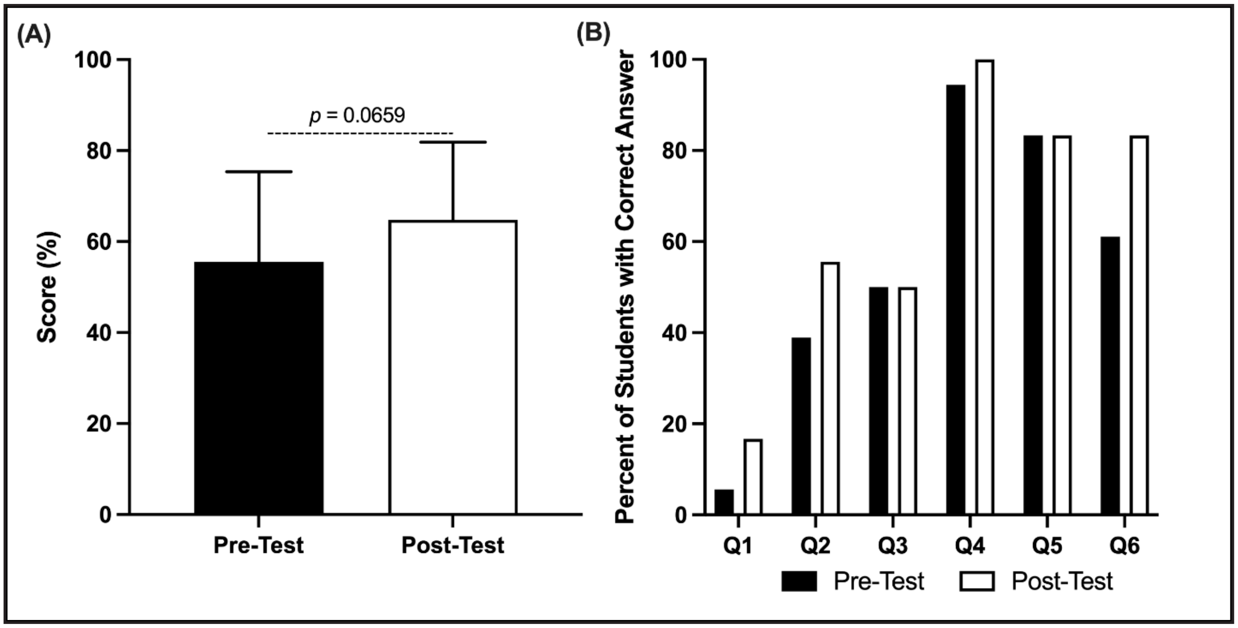


Figure 7. *Students scored higher on Polymer Stiffness Experiment post-test evaluations, demonstrating learning gains with trending significance. (A) Average student pre/post-test scores. (B) Percentage of students who answered individual questions correctly on pre/post-test assessments.*

laboratory groups (Figure 8, Q1 and Q2). The overwhelmingly positive responses to Q3 showed that students felt they learned principles of experimental design and data analysis by completing at-home experiments. Approximately half the students agreed that completing at-home experiments helped develop their comprehension of metal (Q4), ceramic (Q5), and polymeric (Q6) biomaterials. Interestingly, students most strongly agreed with this statement for the Metal Corrosion Experiment and least strongly agreed with the Ceramic Toughness Experiment, despite the pre/post-test assessments showing the opposite trend in learning gains (Figure 3 and Figure 5). By incorporating at-home experiments into the course, a majority of students were more satisfied with the course (Q7) and felt they learned more than having theoretical problem sets (Q8). Though the majority of the students felt they learned more by using at-home laboratory experiments, 25% of students felt that at-home laboratory experiments diminished their satisfaction with the course.

The final question of our survey allowed students to provide additional comments and valuable suggestions to improve the impact of these at-home experiments in the context of our biomaterials course. Most comments addressed the time commitment required to complete these experiments and noted that it was difficult to balance three inquiry-based learning experiments in one semester. Two students noted that at-home experiments may be prone to error, given they are using simplified testing systems; thus, pairing experiments with theoretical problem sets could help to solidify concepts. Lastly, students indicated that the most difficult experiment to conduct was the Polymer Stiffness Experiment because synthesizing composite hydrogels was challenging.

DISCUSSION

Experiments were designed with an inquiry-based learning approach, which was demonstrated to be effective for STEM education.[26,27] We hypothesized that this learning style would be especially effective during the COVID-19 outbreak because the major challenges of inquiry-based learning — (1) motivation, (2) accessibility of investigation techniques, (3) background knowledge, (4) management of extended activities, and (5) practical constraints of the learning environment[28] — are more easily overcome in our proposed virtual format. First, students designed and completed experiments in small, virtual laboratory groups, which was shown to be motivational.[29] Next, students led instructor-facilitated discussions prior to the start of each experiment, which was shown to effectively enhance student learning.[30] One way these learning gains are explained is that instructors ensured students had sufficient background knowledge to complete experiments and the inquiry-based techniques were accessible to everyone in the class. Lastly, students received kits with all necessary materials to complete at-home experiments, which indirectly empowered them to circumvent traditional laboratory constraints and complete experiments within their desired timeframes.

Based on our pre/post-test assessments, we found that students who completed at-home, inquiry-based learning experiments had positive average learning gains, up to 12.5 points. Post-test scores were significantly greater than pre-test scores for the Ceramic Toughness Experiment and showed an increasing trend for the Polymer Stiffness Experiment. It is worth noting that the high variability in our post-test scores

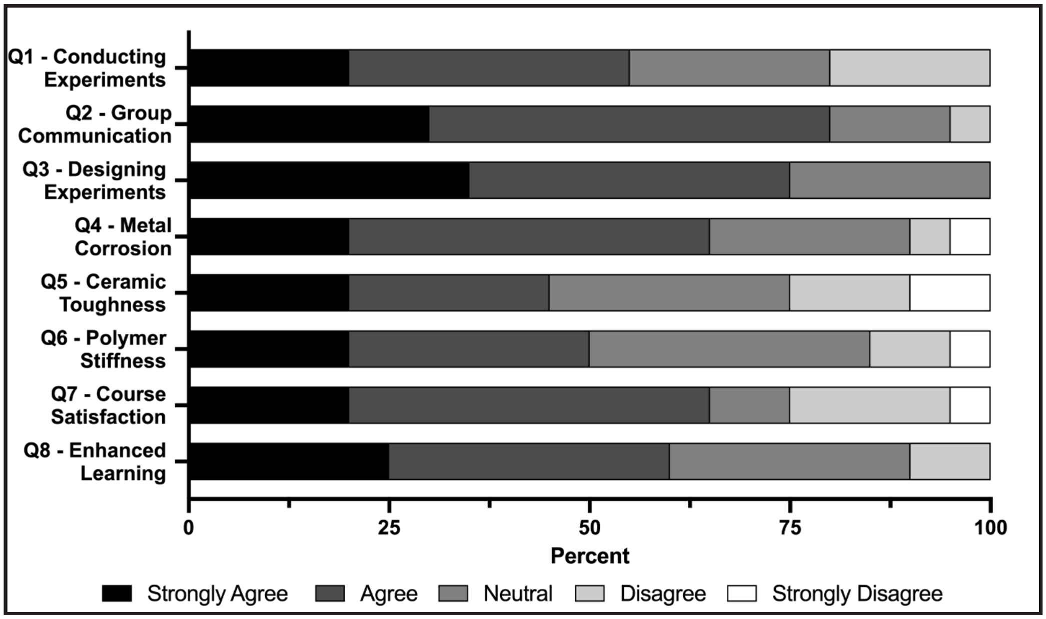


Figure 8. *Student end of semester survey data showing students were highly satisfied with the at-home experiments.*

for the Polymer Stiffness Experiment was mostly driven by one student whose score dropped from 66.67% to 33.33%, while most other students showed positive learning gains. Since this was the first time these experiments were used in the Biomaterials course, we could not directly compare learning gains to traditional experiments completed at The Cooper Union in the same course. We plan to gather this data in future iterations of this course for comparisons of traditional and at-home experiments. As a point of comparison, learning gains of approximately 10-15 points were measured using pre/post-test assessments for a set of traditional published laboratory experiments.[7] The learning gains quantified from our at-home experiments fell approximately in this range, indicating that these at-home experiments are a comparable alternative to traditional laboratory experiments in the constraints brought about by the COVID-19 pandemic.

Average learning gains were positive but not significant for the Metal Corrosion Experiment, which could be attributed to the more open-ended nature of this experiment. For example, a similarly low percentage of students correctly answered Q4 on pre- and post-tests (Figure 5B) about whether paperclips would fail more easily after being placed in tap water, a low concentration salt solution, or a saturated salt solution. All groups explored salinity as a variable, but students were not required to use a saturated salt condition. Therefore, the experiment wouldn't have led all groups to empirically determine that metals corrode less in saturated salt solutions.[49] On the other hand, we found that all students correctly answered Q3 on the post-test about how metal passivation can prevent corrosion. Metal passivation was a variable we explicitly asked students to explore by using galvanized and ungalvanized paperclips in their experiment; thus, our emphasis on this topic promoted strong learning gains. A similar phenomenon was observed in the Ceramic Toughness (Figure 3B) and Polymer Stiffness (Figure 7B) Experiments, whereby all students correctly answered questions in the post-test on topics that they were specifically asked to explore. This outcome demonstrates the effectiveness of our at-home experiments and flexibility of these experiments to focus inquiry-based learning techniques on specific concepts of interest.

The success of our at-home experiments was further demonstrated by the overwhelmingly positive responses to our end-of-semester survey. Most students felt that they could easily complete at-home experiments, that their knowledge of biomaterials increased by completing at-home experiments, and that their satisfaction with the course was enhanced by including at-home experiments in the curriculum. Additionally, most students felt that their ability to design experiments and analyze data using appropriate statistics improved after completing at-home experiments. This sentiment was reflected in the enhanced quality of data presentation and statistical analysis in laboratory reports over time. In the Ceramic Toughness Experiment, which was due first, most students displayed their data in long tables, and those who used graphs neglected to include appropriate statistical analysis (Figure 2). In the Polymer Stiffness Experiment, which was due last, students used a variety of figures and graphs to report their data and included appropriate statistical analyses (Figure 6). A consortium of leading scientific organizations recommend improving the knowledge and use of statistical significance testing as a means of combating the crisis of reproducibility and replicability in science.[31] Our experiments heeded this recommendation by challenging students to present quantifiable results and use appropriate statistics for comparison. We encourage other educators to include statistics in undergraduate experiments to help mitigate future concerns of reproducibility and replicability among the next generation of biomaterials researchers.

It was noted that some students felt that having three inquiry-based learning experiments was overwhelming. The approach of inquiry-based learning, while powerful, is more time-consuming than traditional teaching approaches,[25] and this should be a consideration for educators. For future iterations of this course, we plan to reduce the number of inquiry-based learning experiments and incorporate some traditional problem sets to help solidify concepts. We believe this would provide students with the benefits of inquiry-based learning while respecting their commitments to other courses. Taking this feedback another way, each activity was sufficiently challenging and intellectually stimulating; thus, each experiment could be adapted as an independent activity for STEM outreach purposes.

The final piece of student survey feedback we hope to address in future iterations is the rates of error that can occur because of our simplified at-home testing methods. To address this, we plan to host post-laboratory exercises where instructors facilitate student-led discussions about their results and whether they adhere to the current body of scientific knowledge. This model would simulate a scientific data presentation in which students would present their experimental design and results to their peers, then receive constructive feedback. We hypothesize that this would help ensure that students learned correct principles from their experiments more uniformly. After students are brought back on campus, we plan to have students in the next Biomaterials class complete similar inquiry-based learning experiments using more sophisticated equipment that may incorporate similar principles of impact, fatigue, and compression testing.

DIVERSITY, EQUITY, AND INCLUSION

Outreach is an important activity for increasing the number of students studying STEM at the university level.[50,51] This is especially important for increasing the representation of individuals who are traditionally underrepresented in STEM-based on race, ethnicity, gender, sexual orientation, socioeconomic status, etc.[52–54] We hypothesize that our at-home laboratory experiments with virtual instruction could be adapted for STEM outreach purposes. These activities have the potential to be highly impactful because they are inexpensive and can be conducted remotely; thus, they can more easily reach broad communities throughout the world. This is especially useful for underrepresented students who may not live near universities.[55]

To test the efficacy of our experiments to promote STEM in underserved communities, we partnered with the Young Eisner Scholars (YES) Program, a program designed to empower middle and high school students from underserved communities.[56] The YES Program currently has 140 middle school students, 56% of these students identify as female and 83% identify as black/African American or Latino/Hispanic. In a pilot experiment with YES, we adapted the Metal Corrosion Experiment to a two-day virtual outreach activity for approximately 45 middle school students.[57] Using similar pre/post-experiment evaluations, we found that middle school students had significant learning gains and increased positivity towards science after completing our activity. As a future direction for our work, we plan to modify the Ceramic Toughness and Polymer Stiffness Experiments for future K-12 outreach with the YES Program.

CONCLUSION

This study presents three inquiry-based, at-home experiments that were used to effectively teach principles of biomaterials remotely during the COVID-19 pandemic. The experiments were uniquely designed to transform the challenges of remote learning into strengths that mitigate the challenges of inquiry-based learning. The power of this methodology was demonstrated by positive learning gains in pre/post-test assessments and affirmative survey results, indicating enhanced learning as a result of at-home experiments. The success of these experiments highlights their utility for remotely teaching biomaterials to undergraduate engineering students during the COVID-19 pandemic and beyond. Furthermore, they may be adapted to STEM outreach activities for diverse K-12 students to help address systemic underrepresentation in STEM due to logistical concerns about access to supplies or instructors.

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