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Integrating SolidWorks 3D Design and Simulation Modules into Introductory Biomedical Engineering Courses for the Development of Employability Skills

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Abstract

Current trends in the biomedical engineering industry indicate that rapid prototyping using 3D design tools such as computer aided design (CAD)-based software is a desirable skill for immediate employability. However, the implementation of 3D design modules is less prevalent in biomedical engineering courses due to the breadth of topics implicit in the consolidation between biomedical sciences and engineering principles. We designed a Simulation Toolkit using the SolidWorks Simulations add-in for a second semester sophomore Biomechanics course to enrich existing course content while developing a useful skill for biomedical engineering industry occupations. The toolkit contains simulations of lecture or homework problems that use the finite element method (FEM) to derive solutions that students are also capable of solving by hand. Student responses to the toolkit delivered as an extra credit assignment with video demos were collected to determine the effectiveness of instruction and student opinions on SolidWorks as a tool for their future careers. The resulting responses derived from 23 volunteering students out of a 51 student class indicate that the Simulation Toolkit assignment increased positive student opinions on the interest in and likeliness to use 3D design and simulation ($p < 0.001$). However, student confidence and difficulties in operating the SolidWorks Simulations software remained low due to a lack of basic ability to operate SolidWorks. These data demonstrate the effectiveness of integrating a SolidWorks Simulations module in improving student awareness of useful 3D design skills and FEM for students lacking previous SolidWorks training.

1. Introduction

The rapidly growing field of biomedical engineering has historically presented a difficulty in developing pedagogical methods consolidating the wide breadth of both biomedical sciences and engineering principles in addition to a sufficient education in ethics and business [1]. Integrating applications and ensuring that students exit their undergraduate program with marketable skills sufficient for immediate entry into biomedical industries provides further impetus to broaden offered content. Current trends in the industry have necessitated that engineering design professionals have a working knowledge of 3D design software [2]. In response, integrating 3D design through computer-aided design (CAD) -based services in engineering courses is expected to support the preparation of engineering students for industry positions [3]. Biomedical engineers are similarly expected to possess sufficient 3D design knowledge for biomechanical applications and medical device development, but the implementation of 3D design in biomedical engineering courses is less prevalent compared to alternative engineering subdisciplines owing, in part, to the broad scope of the field.

CAD-based software packages such as SolidWorks have been increasingly emphasized as a valuable tool for biomedical engineers. At the University of Arkansas, SolidWorks is currently integrated into the biomedical engineering curriculum primarily during the two-semester Senior Design course where students identify and create novel technology in response to a clinical need. The extent of SolidWorks education provided in the course is a simple self-driven tutorial and replication of a PVC pipe fitting during a lab section. Upon receiving feedback that these brief labs were insufficient for the degree of SolidWorks skills necessary to develop a product, a SolidWorks module was included in the prerequisite introductory course for first semester sophomore Biomedical Engineering students that provides a more extensive tutorial throughout the entire semester. The ability to generate and interpret finite-element-based simulations using CAD tools such as SolidWorks Simulations is also a crucial skill for prototyping devices and simulating loads acting upon an object. Notably, the aforementioned introductory SolidWorks module does not include a simulations component. Biomechanics is also a required second semester sophomore course for which SolidWorks applications can be easily implemented. To supplement the newly developed introductory module for first semester sophomore students, we suggest that integrating SolidWorks tools, such as the Simulations add-in, in subsequent courses enhances student ability to operate SolidWorks and increases the development of desirable skills.

Criticisms of the restrictiveness of a curriculum entirely based around 3D design elements have also been previously raised, which warn educators against potentially limiting imaginative and innovative thinking [4]. The process of utilizing and outputting models in 3D design software such as SolidWorks follows a very linear and structured design process. Noted distinctions between commonly used design processes such as the tendency to place an emphasis on specific results as opposed to outlining a cognitive process in the progression of creative thought outlines a discrepancy between the engineering and psychological or sociological definitions of creativity [5]. Furthermore, over-reliance on CAD programs that have implicit limitations due to the computational method used can cause the engineer to focus too much on functionality within the software, which may not translate to real-life physical behavior [4]. Combining SolidWorks with the creative process as a supplement rather than a crutch for model design is positively associated with creative motivation and reducing bounded ideation [4]. Here, we suggest that integrating 3D design-related modules into existing course material is sufficient to supplement the development of desirable employability skills without distracting from the foundational course material and curbing creative thought. SolidWorks Simulations can generate fluid flow, thermal, vibrational, and static simulations, which provides a broad range of skills for research or product design. Given that a sufficient knowledge of basic 3D design in SolidWorks is provided in the introductory biomedical engineering course, integrating SolidWorks Simulations with downstream courses can easily impart this additional skillset.

We designed a simulation toolkit for the Biomechanics course given to second semester sophomore students who were not a part of the cohort receiving introductory CAD training as an optional extra credit assignment, which familiarizes students with 3D design elements by modeling and simulating biomechanics problems in SolidWorks for early-career CAD training. The toolkit consists of 14 different simulations of homework problems and lecture examples with supplemental videos guiding students through a simple exercise demonstrating how to use the software. Through the assignment, students would be able to familiarize themselves with SolidWorks design elements and simulations in addition to applying 3D visual learning to familiar biomechanics problems. This applies CAD tools to relevant class topics without distracting from the core of the class and allows students to compare the results to in-class problems that are solvable analytically -by hand- due to at times inaccurate assumptions to finite element analyses. Feedback from before and after the assignment was solicited through a pre- and post-assignment survey to gauge student confidence in operating the software, assess student interest and knowledge in 3D design, and evaluate the effectiveness as well as any errors that occurred in accessing the assignment. This study aimed to accomplish a holistic assessment of whether incorporating a SolidWorks Simulations component in the Biomechanics course could facilitate students' ability to produce and analyze 3D models without formal training in the SolidWorks software.

2. Methods

2.1 Designing SolidWorks simulations

SolidWorks models for the simulations were derived from homework and lecture problems in the Biomechanics course analyzing values related to moment, stress, axial loading, bending, shear, beam deflection, and static equilibrium depending on the problem statement. The SolidWorks Simulations software uses the finite element method (FEM) to determine the displacement or stress within each element of a discretely approximated model object connected by nodes. A mesh defining the polygonal representation of the object, including the number of nodes, and physical restrictions due to the presence of supports or assumptions were applied to the model within SolidWorks before the simulation study was run. After running the study, students can determine the value of any variable asked by the problem statement through probing for values at specific locations.

The static simulation parameter was used for each model generated in this study, simplifying the calculations significantly. As most problems in the introductory Biomechanics course are 2D, additional approximations were made to convert models into a 3D problem, which further increases discrepancies between the 2D static solution and simulation result. Supports that are assumed rigid in the static solutions are assumed to be composed of the same material and models are assumed fixed at simply supported locations.

Three problems asking the student to derive support reactions, confirm that a uniform distributed load does not exceed a given maximum bending stress, and determine the displacement due to a point force, respectively, were selected as demos for the initial delivery of the extra credit assignment from the 14 simulations provided in the toolkit (Figure 1 & 2). Support reactions were determined by defining the face at which a result force should be calculated in SolidWorks Simulations, which causes the software to output the FEM-derived estimate. Displacements and the von Mises stress were similarly determined in the SolidWorks Simulations software using the probe results option to output a graph of the stress along with a defined parameterized geometry (Figure 1b & 2b). The von Mises stress accounts for the maximum distortion energy theory, which states that once the distortion energy per unit volume experiencing non-uniaxial stress or non-simple tension load becomes equal to the yield stress in a uniaxial tensile test at any point in the object, failure by yielding may occur [6]. The von Mises criterion for yield more accurately models complex loads applied to ductile objects, which is often the case in problems used in the Biomechanics course. The resulting displacement calculations are additionally impacted by the usage of the von Mises criterion.

Two demos in the toolkit's initial assignment delivery generated data that could be compared to in-class results based on static equilibrium and superposition assumptions. The first problem (Figure 1a) provided the students with a given distributed load of 937.5 N/m on a simply supported beam and asked to confirm that the bending stress in the beam does not exceed a maximum of 10 MPa, which can be verified via FEM analysis through generating a graph across the beam determining the stress at the edges (Figure 1b). The second problem (Figure 2a) asked students to determine the displacement at a point on an assembly consisting of an A36 steel cantilevered beam and a simply supported beam under a 15 kip point load with a given moment of inertia about a principal axis of 118 in^4. The FEM results were output through probing at the edge of the beam to determine the displacement along with a parameterized distance with the displacement being evaluated at the center of the beam (Figure 2b). Comparing the results derived from FEM simulations in SolidWorks to manual calculations of the displacement of the cantilevered assembly under a load (Figure 1) and the stress in a beam under a distributed load produced an error percent of 2.1% and 4.7%, respectively. Considering 3D approximations and natural error in FEM solutions, the error percent is sufficiently low for the simple problems students are expected to be able to solve in Biomechanics based on the two samples described in the demo videos.

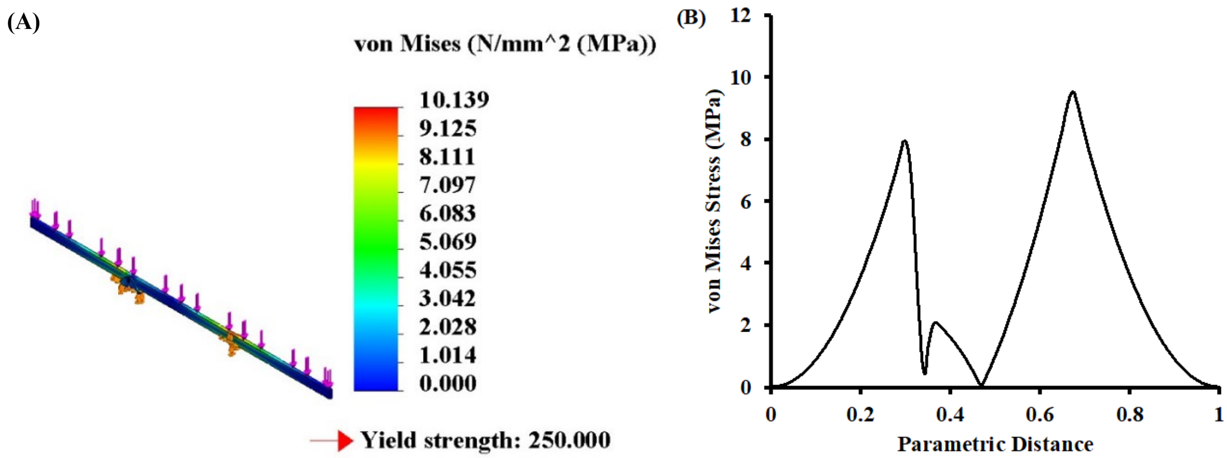

Figure 1: (a) A cantilevered assembly of simply supported A36 steel beams under a 15-kip distributed load. (b) Displacement with respect to the front beam's parametric distance under the applied load.

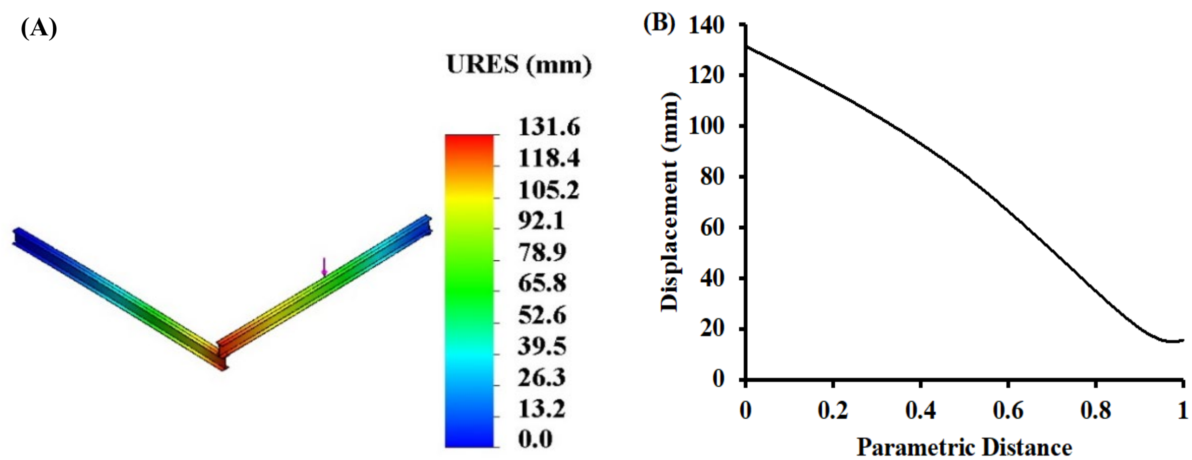

Figure 2: (a) Carbon steel alloy beam with a distributed load applied to across the top face. (b) Von Mises stress of the beam with respect to the parametric distance of the top face.

2.2 Content delivery method

The resulting Simulation Toolkit is composed of 14 simulations and 5 videos that provide a tutorial for accessing and navigating SolidWorks and step-by-step solutions for creating and analyzing SolidWorks Simulations. Students could access SolidWorks through (1) downloading the student license provided by the University on a windows-running computer or (2) through the Citrix Workspace app, allowing students to run SolidWorks through cloud computing. The introductory demo videos briefly introduced the students to developing parts in the SolidWorks software and showed students how to access SolidWorks on their computers. If their computer was insufficient for running the software or if they were encountering persisting errors, the students were also invited to work through the extra credit assignment in the Teaching Lab, which contains computers that have already installed SolidWorks. The introduction video for SolidWorks consisted of a static simulation tutorial using the skills and tools necessary to complete the assignment. The students were also later encouraged to explore and attempt running the remaining simulations provided in the toolkit.

The workflow through which students were coached to run and analyze three example simulations is as indicated in Figure 3. Rather than provide students with the completed simulation, the demos allowed the students to work through developing parameters for their own static simulations, provided that the simulations are of relatively simple applications. Because all simulations were run under static default conditions, the same workflow could be repeatedly used for each model with differing applied loads and geometries. Depending on the model, the FEM solver and meshing were adjusted to increase the speed at which the simulation could be run, which was also conveyed in the demos. If students were unable to replicate the simulation they were assigned to generate, an existing static study was provided that students could run with the required assumptions. Students were asked to upload images of their simulation results, which can be confirmed for accuracy by students comparing their own results with provided correct simulation files. A completion grade regardless of accuracy was given to participating students.

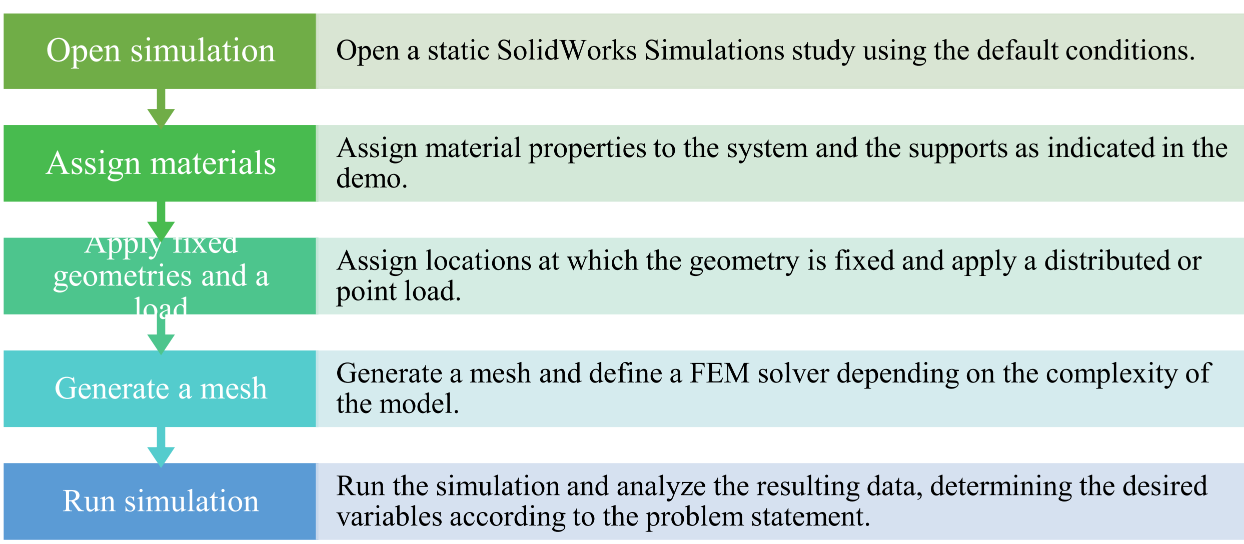

Figure 3: General workflow provided in a video demo for students to parameterize and run their own static simulations in SolidWorks Simulations.

2.3 Data collection from students

Experiments conducted in this study were performed with a formal exemption from the University of Arkansas Institutional Review Board (IRB) to conduct the study under a normal academic environment. A survey was distributed to students that participated in the extra credit assignment through the Qualtrics software (Qualtrics Core XM). Questions were sorted into three broad categories: (1) previous experience with 3D design and CAD-based software, (2) an assessment of the effectiveness of instruction and the ease with which students could complete the assignment, and (3) interest and likeliness to use SolidWorks as a 3D design tool in a survey conducted before and after the assignment. These data were used to determine whether the layout and instruction of the assignment provided sufficient background such that students could conduct their own simulation studies.

2.3 Statistical analyses of selected responses

Statistical analyses were performed using nonparametric tests as opposed to descriptive statistics due to the data being on a Likert-type scale that assigns a numerical value to ordinal data [7]. There is little meaning in the average between 'moderately likely' and 'not likely' and, therefore, alternative methods must be used to conduct a statistical analysis on the data set. To appropriately analyze the data, a Wilcoxon signed ranked sum test was used to analyze statistically different responses based on a deviation from the median. Additional tests assessing whether the data from each question were normally distributed were performed (e.g., Anderson-Darling, Shapiro-Wilk, Kolmogorov-Smirnov, and D'Agostino & Pearson tests) to confirm the necessity to deviate from parametric statistics. Questions that sampled answers at two-time points before and after the assignment were analyzed for statistical significance using the previously discussed methods to determine shifts in the majority student opinion.

3. Results

From students taking the biomechanics course, 23 students participated in the extra-credit assignment. Student responses gauging the previous knowledge and experience students possessed in relation to CAD-related software and simulations were organized to represent the population of students based on the sample size that possessed experience prior to the assignment. From the survey, 89% of students had zero prior experience with any 3D design software while 11% had experience in 3D design, CAD programs, or SolidWorks specifically (Figure 4).

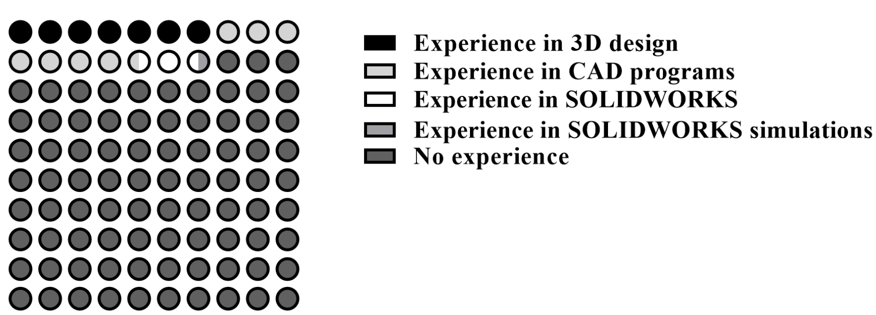

Figure 4: Distribution of student experiences in 3D design, CAD programs, SolidWorks, and SolidWorks simulations.

Likert-like data based on responses that allowed students to grade their likeliness, interest, confidence, or difficulty in completing an assignment are represented as Likert plots that centralize with respect to the most neutral response through assigning each response a number increasing with the positivity of the response from 1 to 5. The student interest prior to the extra credit assignment majorly fell within the range of no interest to a mere slight interest in CAD-based software (Figure 5a). Negative responses collected after the survey decreased from 62% to 23% and responses indicating that the student is very or extremely interested in CAD software increased from 12% to 46% ($p < 0.001$) (Figure 5a). The question gauging the likeliness of students to use SolidWorks in their future career followed a similar pattern with responses indicating extremely or somewhat unlikely decreased from 67% to 19% while responses indicating extremely or somewhat likely increased from 12% to 66% ($p < 0.001$) (Figure 5b).

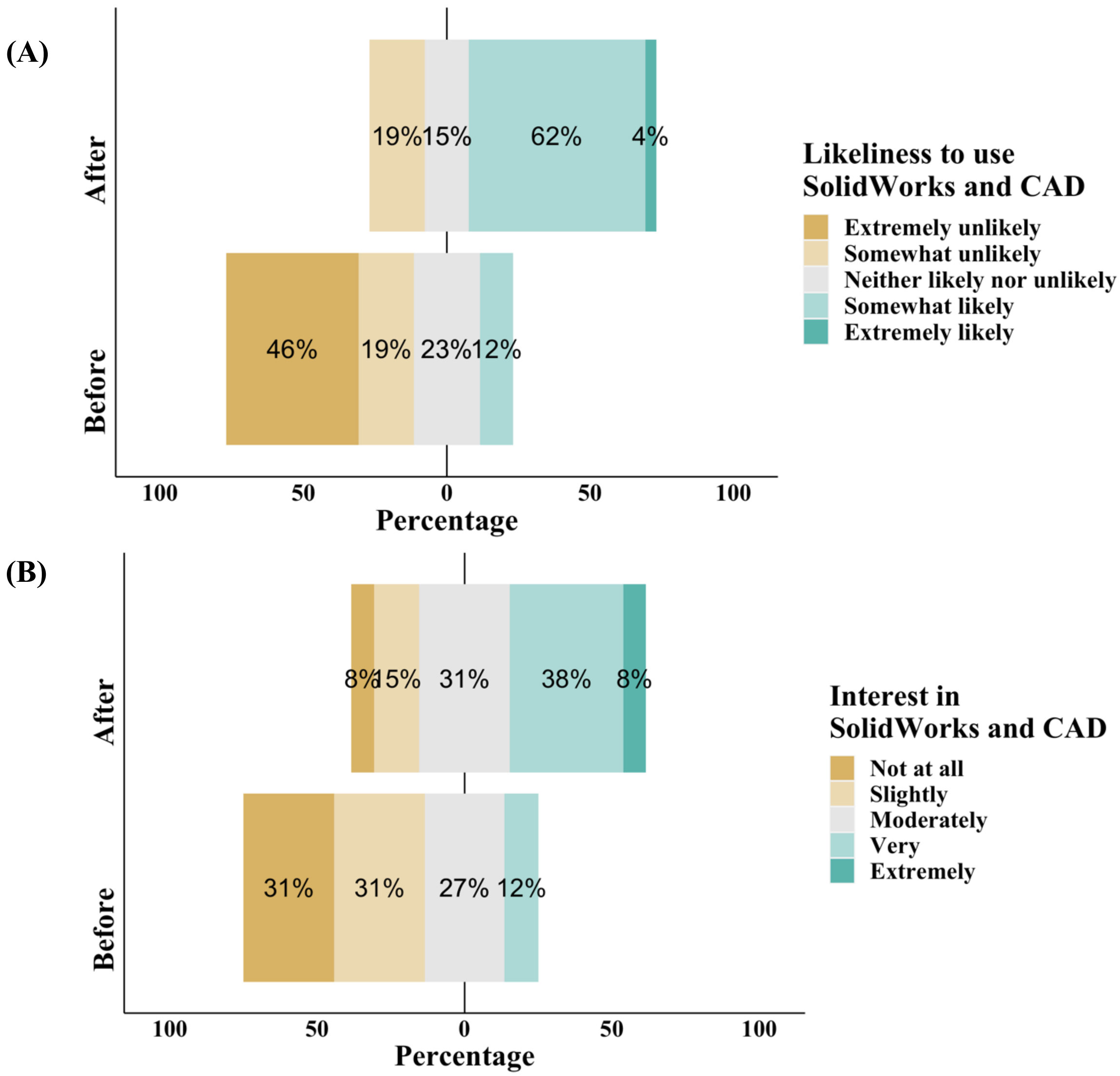

Figure 5: (a) Likert plot of student responses regarding likeliness to use CAD and SolidWorks in a survey assigned before and after the assignment. (b) Likert plot of student responses regarding interest in SolidWorks in a survey before and after the assignment.

The student confidence in using SolidWorks, analyzing simulations, and creating simulations was heavily biased toward 65%, 69%, and 57%, respectively, of students responding with no or slight confidence (Figure 6). The self-assessment of confidence in using SolidWorks and developing simulation is based on comprehension of skills imparted through the demos.

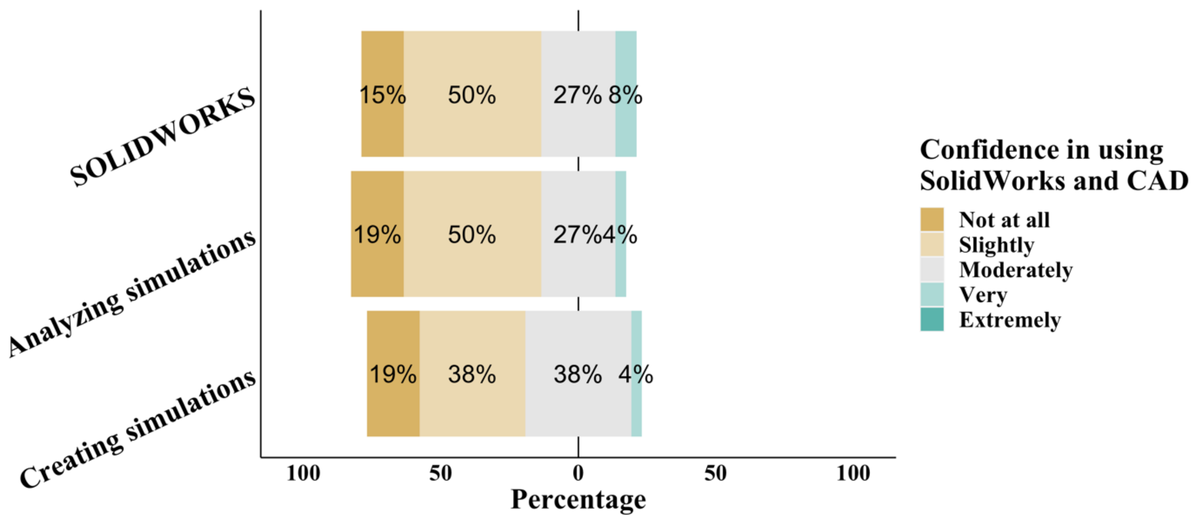

Figure 6: Likert plot of student responses assessing confidence in using SolidWorks and SolidWorks Simulation software in the assignment.

Students were also asked to assess the usefulness of SolidWorks Simulations, their ability to complete the assignment and to provide additional feedback after the assignment (Figure 7). Consistent with the increasing positive opinion of SolidWorks and CAD in previous questions (Figure 5a & 5b), 85% of students indicated that SolidWorks Simulations is a very or extremely useful tool (Figure 7a). Most students participating in the study also encountered errors but were ultimately able to compare the results of the simulation with their theoretical solutions for the problem (Figure 7b). Based on the student feedback solicited after completion of the assignment, the errors encountered were primarily due to long runtime, the inability to access SolidWorks through Citrix, and other nebulous technical difficulties (Figure 7c). Around 38% of students indicated that more detailed instruction within the assignment that addressed and developed countermeasures for these errors are needed (Figure 7c).

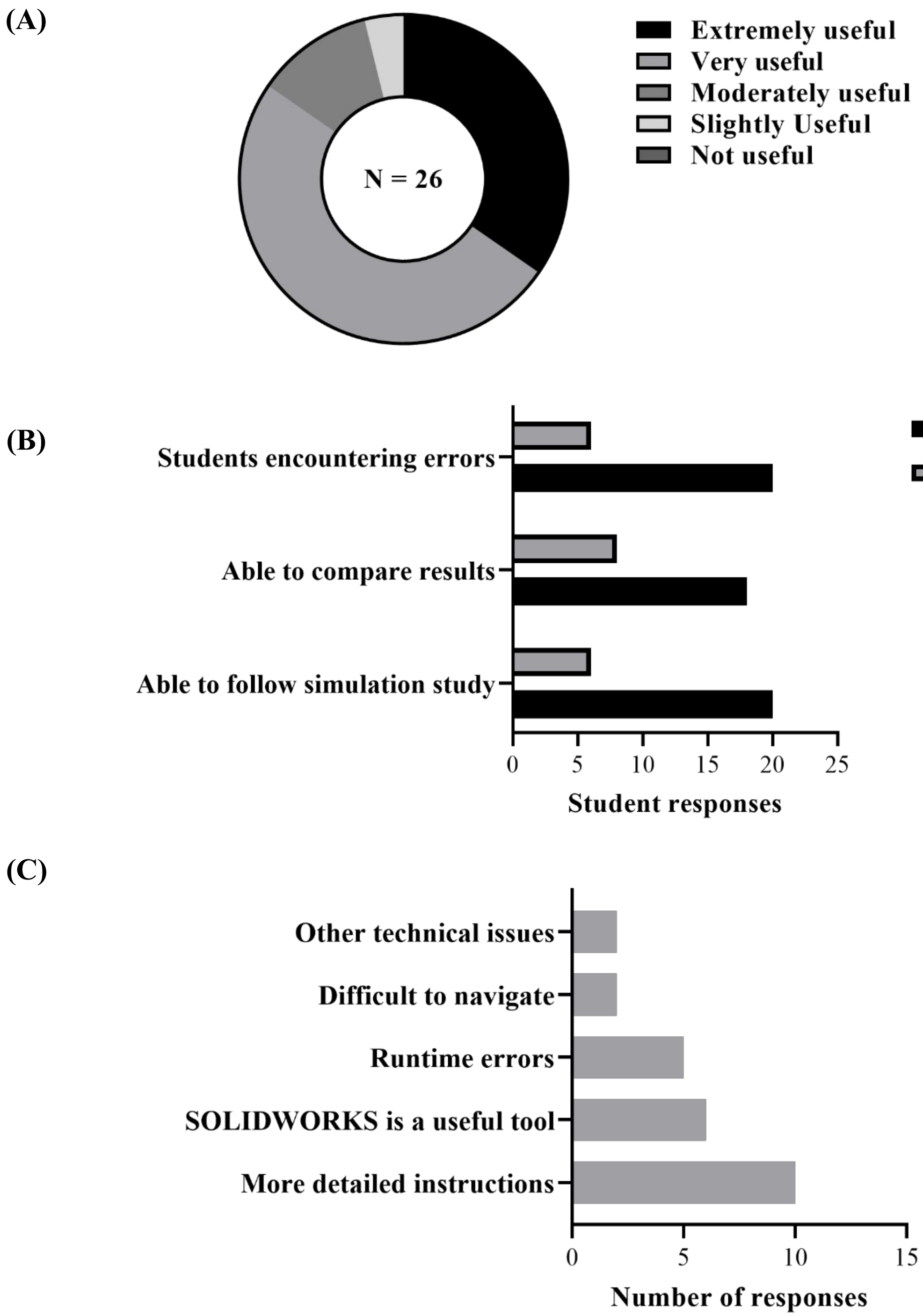

Figure 7: (a) Student responses regarding their perception of the usefulness of SolidWorks Simulations after completion of the assignment. (b) Student responses on the ability to complete and follow the assignment. (c) Additional student comments after completing the assignment.

Questions indicating the difficulty students had in completing and working through the assignment and the confidence of students in operating CAD-related software in the future were included to determine the effectiveness of the content delivery method. While most students responded that their ability to follow along with the demo videos was easy (50%), a relatively large batch of students also displayed difficulty in following along (35%), which may indicate that the videos need either a more in-depth tutorial or a slower delivery (Figure 8). Furthermore, 76% of students indicated that navigating instructional videos was difficult (Figure 8).

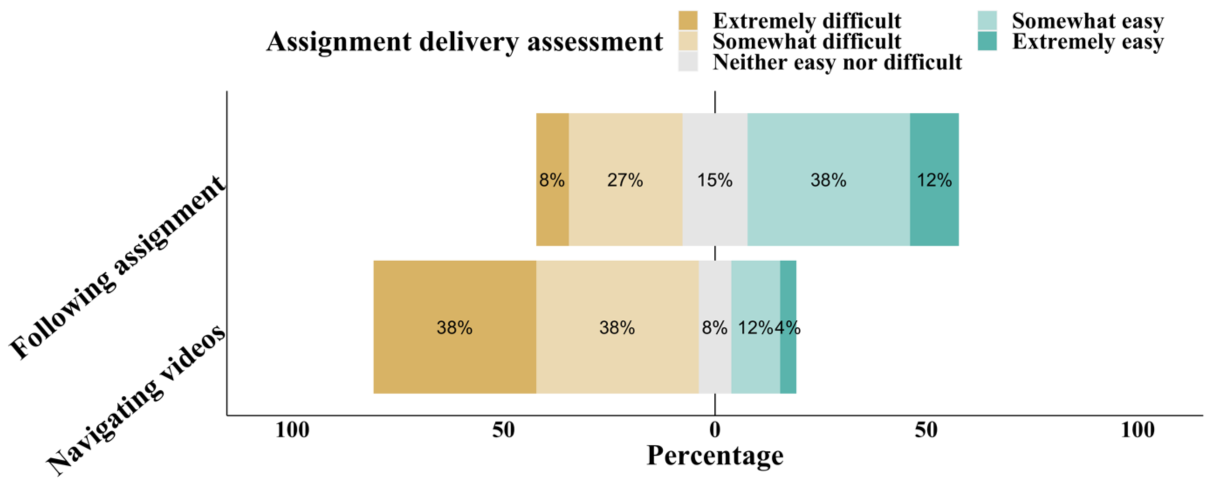

Figure 8: Likert plot of student responses grading the ease with which the assignment could be navigated and interpreted.

4. Discussion

Student responses gauging the previous knowledge and experience students possessed in relation to CAD-related software and simulations were heavily biased toward no experience (Figure 4), which confirms that students are not likely to have used SolidWorks in their undergraduate career prior to this Sophomore class. Notably, the students in this study were not included in the cohort that was provided a SolidWorks module in the intro course for biomedical engineering and has yet to take the Senior Design course that typically requires SolidWorks for prototyping. Therefore, their curriculum up to this point has included zero basic SolidWorks training and the distribution of students with training in 3D design reflects this.

For questions gauging likeliness to use SolidWorks in students' future careers and student interest in SolidWorks, extremely negative responses prevailed prior to the assignment while extremely positive responses only emerged after the assignment was distributed (Figure 5a&b). These data indicate a lack of prior knowledge in the value of 3D design tools and the capability of CAD-based software, which is an opinion that can be amended through three simple SolidWorks simulation tutorials. An increased interest in SolidWorks and the likeliness to use SolidWorks in the future can enhance student awareness of useful skills for biomedical industries, which was accomplished here through a short SolidWorks assignment that takes little time to complete. These videos were distributed in a Box file that students could additionally use to download the SolidWorks part/assembly and Simulations files. Based on the difficulty students had in navigating the assignment format (Figure 7b&c, Figure 8), a more user-friendly method of delivering the video content is required to improve students' ability to navigate the video files perhaps through a blackboard page clearly providing links to each video.

A significant lack in student confidence in repeating the steps demonstrated in the assignment videos is likely a product of a lack of experience in SolidWorks as a general 3D design tool (Figure 6). Without familiarity with the software apart from the Simulations add-in, independently navigating and using SolidWorks can be difficult for students. A lack of confidence supports the need for a SolidWorks introductory module to facilitate the ability of students to use auxiliary software that enriches biomedical engineering course content. Through the extra credit assignment, students discovered that SolidWorks Simulations is a valuable tool that they are likely to use in their future careers, but a lack of basic training is a major barrier in developing a reliable skill in this area.

Due to errors with the Citrix cloud software, students that did not possess a Windows-running computer used the computers in the Teaching Lab to complete the assignment. An alternative to Citrix for Mac-users or simply conducting the assignment delivery in a location where all students will have access to SolidWorks such as the Teaching Lab is required to reduce the amount of time spent troubleshooting the software. However, because the cohort following those participating in this study will have already taken the introductory SolidWorks module, it is likely that this issue will have been preemptively solved through preliminary instruction.

5. Conclusions

In this work, a SolidWorks Simulations Toolkit was developed for the Biomechanics Sophomore biomedical engineering course to increase student 3D design skills and enrich existing content. The Simulation Toolkit effectively demonstrated the benefits of SolidWorks Simulations with a sufficiently short tutorial, which will supplement students' ability to generate prototypes in their Senior Design course and their future careers. Based on Wilcoxon matched-pairs signed-rank tests, students that completed the assignment expressed an increased interest in and likeliness to use SolidWorks design for their future careers.

This work also confirms an insufficient implementation of 3D design in our 1st and 2nd-year Biomedical Engineering courses, which hinders the ability to integrate 3D design elements into coursework. Despite an increased interest in the software, the student confidence in navigating and operating SolidWorks simulations remained low and the primary obstacle in completing the assignment was a need for more detailed instruction. Taken together, these data demonstrate the benefit that incorporating SolidWorks simulations modules in relevant courses can develop marketable skills for undergraduate students. As a future direction to address these issues, our department has introduced a SolidWorks module into the Intro to Biomedical Engineering course that is expected to improve students' basic ability to use 3D design techniques. Additional improvements in the content delivery of the Simulation Toolkit, including more in-depth instructions in a manual format to supplement the demo videos, are also being developed.

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