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Hands-On Statics to Improve Conceptual Understanding and Representational Competence

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Abstract

Mechanics instructors frequently employ hands-on learning with goals such as demonstrating physical phenomena, aiding visualization, addressing misconceptions, exposing students to "real-world" problems, and promoting an engaging classroom environment. This paper presents results from a study exploring the importance of the "hands-on" aspect of a hands-on modeling curriculum we have been developing that spans several topics in statics. The curriculum integrates deep conceptual exploration with analysis procedure tutorials and aims to scaffold students' development of representational competence, the ability to use multiple representations of a concept as appropriate for learning, problem solving, and communication.

We conducted this study over two subsequent terms in an online statics course taught in the context of remote learning amidst the COVID-19 pandemic. The intervention section used a take-home adaptation of the original classroom curriculum. This adaptation consisted of eight activity worksheets with a supplied kit of manipulatives and model-building supplies students could use to construct and explore concrete representations of figures and diagrams used in the worksheets. In contrast, the control section used activity worksheets nearly identical to those used in the hands-on curriculum, but without the associated modeling parts kit. We only made minor revisions to the worksheets to remove reference to the models. The control and intervention sections were otherwise identical in how they were taught by the same instructor.

We compare learning outcomes between the two sections as measured via pre-post administration of a test of 3D vector concepts and representations called the Test of Representational Competence with Vectors (TRCV). We also compare end of course scores on the Concept Assessment Test in Statics (CATS) and final exam scores. In addition, we analyze student responses on two "multiple choice plus explain" concept questions paired with each of five activities covering the topics of 3D moments, 3D particle equilibrium, rigid body equilibrium (2D and 3D), and frame analysis (2D). The mean pre/post gain across all ten questions was higher for the intervention section, with the largest differences observed on questions relating to 3D rigid body equilibrium. Students in the intervention section also made larger gains on the TRCV and scored better on the final exam compared to the control section, but these results are not statistically significant perhaps due to the small study population. There were no appreciable differences in end-of-course CATS scores. We also present student feedback on the activity worksheets that was slightly more positive for the versions with the models.

Introduction

There is a consistent strain of reporting on the use of hands-on models and manipulatives in statics instruction dating back decades [1] - [7]. Purported benefits of using models in the classroom include demonstrating physical phenomena, aiding visualization, addressing misconceptions, exposing students to "real-world" problems, and promoting an engaging environment. Our motivations focus on promoting conceptual understanding, supporting students' developing spatial abilities, and engaging them in active learning. We have described our approach extensively in prior work [8], [9] and have made the models and associated worksheets available at https://staticsmodelingkit.wordpress.com. To summarize, the models and associated activities we have designed target conceptual knowledge along with complementary analysis skills embedded within a problem-solving context in guided activity worksheets. Class session design for face-to-face instruction follows the Process-Oriented Guided Inquiry Learning (POGIL) model in which the instructor's role is to serve as a facilitator of student learning teams by asking probing questions, providing time for productive struggle, and encouraging students to explain their understanding to each other using their own words and the models as reference [10]. The worksheets prompt application of multiple representations (e.g. diagrams, symbolic math, and graphs) and representational translations as students work with the models to complete problem-solving oriented tasks. Through this process, students work with each other and with the instructor to resolve misconceptions (or naïve conceptions) and build mental models of the underlying meaning the representations communicate [11]. Understanding what each representation means and how to apply it effectively in problem solving is important to students' development of both conceptual and procedural knowledge in mechanics. The construct of representational competence (aka representational fluency) embodies this skill - the ability to use multiple representations of a concept as appropriate for learning, problem solving, and communication - is commonly used in the science education literature and is seen as a marker of domain expertise [12] - [14].

In prior work, we described how the model-based curriculum received positive student feedback when implemented as a series of in-class activities in a flipped classroom implementation. Students consistently reported the activities were useful for developing their understanding of concepts such as 3D vector operations, moments, and support reactions [8], [9]. Our implementation of the curriculum as a series of group learning activities; however, made it impossible to disaggregate the elements of the activities that made the models effective. Classroom observations, focus groups, and student feedback all pointed to the usefulness of the models as a communication aid, both for student-to-student and student-to-instructor interaction. Analogously, they serve as a powerful formative assessment tool. Students are better able to articulate their understanding and/or confusion when they can point to and/or manipulate model elements to complement their developing mechanics vocabulary when asking questions or attempting to explain concepts.

One lingering question in the development of the curriculum has been to what extent the hands-on elements of the activities in and of themselves might offer some intrinsic benefit to student learning besides their utility as a communication tool. Others have reported inconclusive results as to whether the student learning benefits of a hands-on learning session are materially different compared to an instructor demonstration [15]. The transition to remote learning brought on by the COVID-19 pandemic provided an opportunity to investigate this question in the context of an online class implementation. We previously reported on our hasty efforts to adapt the modeling curriculum from a platform for classroom group learning activities to a take-home kit for each individual student [16], [17]. Figure 1 on the next page shows excerpts from the take home version of a week 2 activity introducing 3D vector concepts and notation. Students perform calculations and answer concept questions related to the system diagram depicted in Figure 1a. Figure 1b shows the model students are instructed to build with their kit to represent the position vector $\boldsymbol{r}_{AB}$ and force vector $\boldsymbol{F}$. Figure 1c is an example student submission demonstrating their understanding of the concept of a 3D coordinate direction angle.

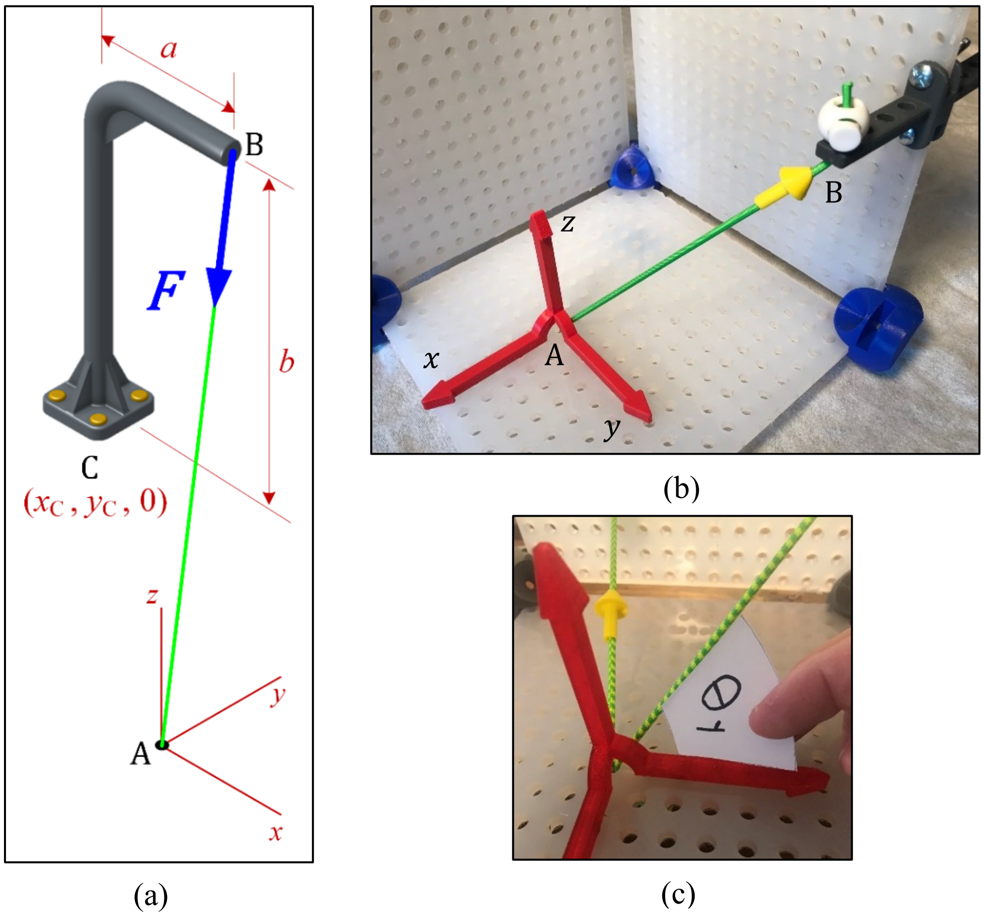

Figure 1. Example vector activity. (a) System diagram. (b) Model. (c) Sample student submission of photo demonstrating their understanding of coordinate direction angles.

Student feedback was generally positive, but decidedly less so compared to prior face-to-face implementations. Written comments indicated that some students found model assembly to be time-consuming and/or expressed frustration due to minor fitment issues associated with 3D printing tolerances. As a result, students expressed mixed feelings about whether their experiences with the modeling activities were helpful for learning or otherwise beneficial to their overall course experience.

Study Design

Based on the experience and feedback from implementing the take-home version of the model kits that we describe above, we concluded it would not be obviously detrimental to withhold the models the following term. We would still incorporate nearly identical activity worksheets, but with modifications to remove explicit instructions to manipulate model elements and any other model references. Hence, we would have a controlled experiment to investigate our question described above – are there benefits to the hands-on elements of the curriculum besides their utility as a communication aid and platform for engaging classroom activities? We conducted the study over two subsequent quarters: fall 2020 (intervention section with take-home model kits) and winter 2021 (control section without models). There were only three substantive differences between these two course sections:

1. We modified the weekly activity worksheets in the winter 2021 control section to remove instructions prompting students to construct and manipulate the models.
2. The fall 2020 intervention section had two additional assignments in which they recorded short videos using their models to explain a statics concept of their choice.
3. The fall 2020 intervention section included a "design your own problem" on the first exam prompting students to use their kit to build a system and demonstrate some basic 3D vector operations.

There is additional information on the learning activities common to both courses in the next section to provide more context. We used the following assessments to compare learning outcomes between the control and intervention sections.

- Pre (week 1) and post (week 5) administration of the Test of Representational Competence with Vectors (TRCV) [18], [19].
- Pre and post administration of two "multiple-choice plus explain" (MCE) concept questions paired to each of five activities in the study.
- The Concept Assessment Test in Statics (CATS, formerly known as the Statics Concept Inventory) [20].
- Course final exam.

Students earned full credit for their work completing the first three assessment types, regardless of the accuracy of their responses. The final exam accounted for 15% of students' cumulative course grade.

Study Population and Context

This study took place at a community college in the Pacific Northwest. The course is part of an engineering transfer program and serves a variety of engineering majors and transfer goals, with mechanical engineering being the most popular. Integral calculus and one quarter of calculus-based physics (mechanics) are both required course prerequisites for Statics. Table 1 on the next page summarizes the study population. The overall number of students in the study is too low for demographic breakdowns to be meaningful.

Table 1. Study population.

Term	Enrollment (last week)	Number Consenting to Study	Mean MATH prereq grade	Mean PHYS prereq grade
Fall 2020	21	16*	3.61	3.29
Winter 2021	13	11	3.43	3.42

*In F20, there were 17 consenting students, but we subsequently omitted one student due to multiple missing assessment scores and a cheating incident.

Both sections were taught online in the context of the COVID-19 pandemic with two hours per week of synchronous instruction over Zoom (40% of contact for this 5-credit course) and course administration using the Canvas learning management system. Synchronous class sessions generally consisted of concept question-driven peer instruction using the Concept Warehouse [21], instructor-led discussion and examples, and group problem solving exercises using virtual whiteboards. The remaining learning activities occurred asynchronously and included reading reflection assignments introducing new topics with selected readings [22] and videos [23], instructor-authored auto-graded problem sets [24], and the modeling curriculum activity worksheets (without the models in the winter 2021 section).

Results and Discussion

TRCV Results

The TRCV measures students' representational competence with vectors in both 2D and 3D applications by using multiple representations in the presentation of a variety of conceptual analysis problems and answer choices. We administered the pretest in week one before any coverage of vector topics. We administered the posttest after students had submitted their problem set associated with the week 4 module on moments and force system resultants. The posttest assessment also serves as an opportunity for students to review vector concepts in preparation for the first midterm exam. Table 2 presents the results.

Table 2. Test of Representational Competence with Vectors (TRCV) scores.

Term	N	TRCVpre		TRCVpost		TRCV gain
		Mean	St. Dev.	Mean	St. Dev.	
F20 Intervention	16	46.7%	23.1%	70.2%	16.0%	23.5%
W21 Control	11	47.1%	23.7%	66.3%	21.0%	19.2%

Both course sections started with nearly identical pretest scores and distributions. The intervention section with the hands-on models appears to have made slightly higher gains with a slightly narrower distribution, but these results are not statistically significant with such small population sizes. That said, the first three activities in the modeling curriculum focus on 3D vectors with activities exploring 3D components, unit vectors, vector addition in 3D and dot product applications. The moments activity includes in depth exploration of the cross product and right-hand rule. 3D vectors are one of the topic areas for which past students specifically identified the models as being particularly helpful to their understanding [8].

MCE Concept Questions

The pre/post MCE questions cover five activities on 3D concurrent force systems, moments, 2D rigid body equilibrium, 3D rigid body equilibrium, and 2D frame analysis. For each of these topics, the "pre" administration took place as the final asynchronous assignment in the prior week's Canvas module before introduction of the relevant topic. The "post" administration happened asynchronously as one of the last assignments of the week after the deadline for the completed activity worksheet, but also after students engaged with relevant concepts in class sessions, reading, videos and the problem set. The MCE questions were developed and reviewed for accuracy, relevance and validity as part of another project developing mechanics ConcepTests (CTs) for the Concept Warehouse [25]. In addition to selecting an answer choice and writing a brief explanation, students gave a confidence rating for each response on a scale of 1 = substantially unsure, 2 = moderately unsure, 3 = neutral, 4 = moderately confident and 5 = substantially confident. Table 3 summarizes the results for the MCE questions.

Table 3. Multiple-choice plus explain (MCE) response results.

		F20 Intervention Section				W21 Control Section			
	CT	**Pre**		**Post**		**Pre**		**Post**	
Activity Topic	**IDs**	**%COR**	**CONF**	**%COR**	**CONF**	**%COR**	**CONF**	**%COR**	**CONF**
3D Concurrent	4928	60%	1.09	88%	1.02	80%	1.17	90%	1.10
Force System	4886	40%	0.94	63%	0.98	89%	1.02	100%	1.00
	4975	63%	0.80	63%	0.91	73%	0.86	64%	0.99
3D Moments	4976	38%	1.04	69%	1.11	27%	1.06	55%	1.00
2D Rigid Body	4990	80%	0.98	71%	1.20	60%	1.02	60%	1.06
Equilibrium	4989	33%	0.92	50%	1.04	40%	0.98	60%	1.03
3D Rigid Body	6037	27%	0.86	58%	1.14	27%	0.89	27%	0.93
Equilibrium	5014	31%	1.03	75%	1.09	45%	0.88	45%	1.06
	5133	36%	0.75	57%	1.02	50%	0.99	38%	0.84
Frame Analysis	5134	50%	0.75	36%	0.89	50%	1.09	25%	0.65
Mean		**46%**	**0.92**	**63%**	**1.04**	**54%**	**1.00**	**56%**	**0.97**

The CT IDs identify the specific ConcepTests from the Concept Warehouse that we used for this study – two paired to each activity. The "%COR" indicates the fraction of responding students who answered correctly. The "CONF" column indicates the mean normalized confidence response for students who selected the correct answer. We normalize their confidence response (scale of 1-5) for each specific question by their mean confidence response for all ConcepTests answered for the duration of the course, including all MCE questions in this study (listed in Table 3) and dozens of other questions used in various ways during class meetings. Hence a CONF greater than 1 indicates the student was more confident than usual in their response.

Looking at average results for the entire course, we see that gains in both correct answer choices and confidence in those answers are generally higher for the intervention section with the models. The largest differences are on the topics of 3D Rigid Body Equilibrium (CT IDs 6037 and 5014) and 3D Moments (CT 4976) where large increases in the fraction of correct responses are accompanied by normalized confidence scores of 1.09 and higher.

We also reviewed student explanations for their answers and could find no patterns of discernable difference between control and intervention section explanations for any topic. In summary, similar to the TRCV, it appears that students in the intervention section were able to leverage use of the models to make slightly higher gains in conceptual understanding of some topics, but again the study population is too small for statistical significance.

CATS results

We only administered the CATS at the end of the course (no pretest) to avoid assessment fatigue during the first week and consistent with suggestions that pretest scores differ little from random guessing [26]. Table 4 summarizes CATS results.

Table 4. Concept Assessment Test in Statics (CATS) Scores.

		CATS Score	
Term	**N**	**Mean**	**St. Dev.**
F20 Intervention	16	50.7%	19.0%
W21 Control	11	50.5%	19.5%

In this case, scores and distribution were nearly identical for the two sections. Note that the 3D topics identified above as areas where the models may have been helpful are not included in the CATS. This assessment consists exclusively of 2D systems as basis for the questions.

Final Exam

We administered the final exam asynchronously via Canvas with two parts. Part 1 consisted of 10 MCE concept questions with a 60-minute time limit and accounted for 40% of the total score. Each part 1 question was worth 4 points with 2 points given for the correct answer choice and 2 points for a correct rationale/explanation assigned as follows:

- 2 points: Explanation communicates sound and technically correct reasoning.
- 1 point: Explanation has some correct elements in reasoning, but also significant inaccuracies or evidence of conceptual errors.
- 0 points: Explanation is missing or contains mostly incorrect justification.

Part 2 consisted of two problems with numbers unique to each student, had a 90-minute time limit, and accounted for 50% of the total score. The correct numerical answer accounted for 5 points, with the remaining 20 points awarded for clear and accurate problem solving documentation. Students were also required to record a short video or meet live with the instructor to explain one problem solution of their choice for the final 10% of their final exam score. Table 5 on the next page summarizes the results.

Table 5. Final exam results.

Term	N	Part 1: Concept Questions		Part 2: Problem Solving	
		Mean	St. Dev.	Mean	St. Dev.
F20 Intervention	16	73.4%	14.1%	76.8%	12.7%
W21 Control	11	70.0%	13.7%	69.1%	13.4%

The students in the intervention section performed slightly better on both parts of the final exam, but again these differences are not statistically significant.

Student Feedback

We administered an end-of-course anonymous survey to collect student impressions of the curriculum with and without the models. Table 6 includes the survey prompts and mean student responses. The survey uses a standard Likert scale with 1 = Strongly Disagree, 2 = Somewhat Disagree, 3 = Neutral, 4 = Somewhat Agree, and 5 = Strongly Agree. Reported p-values use a two-tailed t-test.

Table 6. Survey response means for control (no models) and intervention (with models) sections.

Survey Prompt	F20 with models N = 16	W21 no models N = 11
The activities helped me…		
1. Understand vector notation and use it properly.	4.13	4.00
2. Interpret figures for 3D problems on homework and exams.	3.94	4.18
3. Visualize vectors in 3D.	4.44	4.18
4. Understand force equilibrium.	4.31	3.73
5. Understand support models.	4.56	3.82*
6. Conceptualize moments in 3D systems.	3.88	3.55
7. Understand moment equilibrium.	3.88	3.82
8. Develop my free-body diagram skills.	3.44	4.09
The activities provided…		
9. An effective context for discussing statics concepts with my classmates.	3.56	3.36
10. Opportunities for the instructor to explain statics concepts in detail.	3.31	3.45
Overall Response Mean	**3.94**	**3.82****

*significant at $p < 0.05$, **significant at $p < 0.1$, all using 2-tailed t-test comparison

The pattern in student feedback is analogous to the assessment results presented above. Students had a generally more positive reaction to the activities when they included the models. This difference was large enough to be statistically significant (at $p < .05$) for their understanding of support models, a result that lines up with the MCE results for rigid body equilibrium presented above. When aggregated across all question responses, the overall response mean was also higher (at $p < .1$) for the intervention section. We also note that the student response is less positive than it was for the two most recent terms of face-to-face implementation of the curriculum. The overall response mean on an identical survey, aggregating results for fall 2019 and spring 2020, was 4.43 (N = 28).

Study Limitations

There are limitations to this study that we should acknowledge. First and foremost, the data was collected in the context of online learning during the COVID-19 pandemic with associated extraordinary stressors on many in this community college student population. The students involved would otherwise be engaged primarily in face-to-face instruction if they had the choice. It is possible that the observed trend of higher learning gains in the F20 intervention section is attributable to the fact that it occurred three months earlier than the W21 control section, so the W21 students had three additional months of “pandemic learning fatigue.” We also acknowledge that the study population sizes are too small to make statistically significant claims. Lastly, our study population is not large enough to disaggregate across demographics to explore how the models may be more beneficial for some sub-groups of learners.

Conclusions and Future Work

Throughout our analysis of the assessment results above, we see moderately larger gains for the intervention section with the models across multiple measures. The improved gains come primarily on the topics of 3D vectors, moments, and rigid body equilibrium and line up reasonably well with areas where there are analogous differences in student feedback. While the sample size is small, the result that students with the models performed as well or better on nearly every assessment measure makes a compelling case that the models have benefits beyond facilitating communication.

Due to the limitations of this study, we can only speculate what these benefits might be at this point. The 3D nature of the topics identified above provides evidence that the models may help with spatial visualization for some students. It may also be that the tactile manipulations prompted by the activity worksheets gives students direct experience with forces and moments in a way that helps solidify their understanding of concepts such as force equilibrium and support models. We plan a future study with think-aloud interviews to explore how individual students make use of the models in their learning effort.

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