AC 2009-357: IMPROVING STUDENTS' ABILITY TO MODEL DURING PROBLEM-SOLVING IN STATICS

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Improving Students' Ability to Model during Problem-Solving in Statics

Introduction

In this paper, we report the results of an educational intervention designed to improve students' ability to create models as part of the engineering problem-solving process in Statics. Statics was selected for this study because it is often the first course in which students learn to apply an engineering problem-solving method. In this study, we focus on the early steps in problem-solving when students model the system being studied to create a set of equations describing the system. The overall goal of the current study was to design and test an intervention to help students better understand the concepts involved in solving these problems.

The intervention we describe here was developed as part of an on-going program of research designed to better understand the major difficulties that students encounter as they learn to develop and apply models to solve Statics problems. In the first phase of this research,[1] more than 300 students completed three inventories - math skills, spatial reasoning and statics concepts. The results from the inventories were used to identify clusters of students with common characteristics, and therefore, presumably common deficiencies in their problem-solving in Statics. Students from each cluster were invited to participate in think-aloud problem-solving sessions to identify the weaknesses in their problem-solving. Although the think-aloud analyses did not reveal differences among the clusters of students, it did uncover differences in the problem-solving processes used by separate groups of successful and unsuccessful students.[2] Most notably, successful students were far more likely to generate self-explanations during problem-solving in comparison to unsuccessful students. A self-explanation is strategy that helps the learner to access prior knowledge[3] and connect this knowledge to new instances.[4] The findings of our think-aloud study are consistent with other research, which has shown that college students who self-explain acquire more knowledge of a problem-solving procedure[5] and generate better problem solutions[6] than do students who do not generate explanations.

Based on these findings, the research team developed an intervention in which students were prompted to generate self-explanations when solving problems from Statics. The version of the intervention tested in this study was developed using an iterative process in which the interventions were tested, refined to enhance their effectiveness, and then re-tested.[2] The interventions focused on having students reason through, or self-explain, the reaction forces and couples present at a given connection and then apply this reasoning to select the correct model of a particular support or the overall free-body diagram of the system. In addition, a pre/post-assessment was developed to test the effectiveness of the interventions. This paper reports results from the initial full-scale testing of the effectiveness of the intervention.

Relationship to Previous Work

This study has been influenced by a number of studies of problem-solving in general and of problem-solving in engineering specifically. The relationship to past work was discussed at some length in a previous paper[7] and therefore it is only briefly summarized here. Three subsets of the literature have had the most influence on our work: problem-solving processes, translations between symbol systems, and domain knowledge.

Since Polya's seminal work in mathematics,[8] the utility of learning and using a sequence of steps during problem-solving has been widely accepted. Although several specific models exist, a generic 4-step model captures major problem-solving processes: (1) represent the problem, (2) goal setting and planning, (3) execute the plan, and (4) evaluate the solution. In the first step, problem representation, the student must read the problem statement and discern the objective. There are instructional interventions for engineering education that are grounded in this theoretical model of problem-solving. For example, Gray *et al.*[9] developed a systematic approach to solving Statics and Dynamics problems. Their intervention recommends that students be taught the sequence of: Road Map (Planning), Modeling (Representation), Governing Equations (Representation), Computation (Execution), and Discussion and Verification (Evaluation). Don Woods completed some of the most thorough work that has been done in this area while developing the McMaster Problem-solving program.[10] In his most recent work,[11] Woods has focused on the processes of problem-solving and has developed a model to describe ideal problem-solving.

Without a doubt, the quantity of prior domain knowledge affects problem-solving.[12] It is also widely accepted that qualitative aspects of knowledge matter. Prior knowledge is believed to act as an important scaffold for problem-solving. The structure provided by the knowledge base can, for example, act as a constraint during analogical reasoning,[13] support strategic processing during reading,[14] and contribute to positive motivational states during problem-solving.[15] In short, the effects of prior knowledge are wide-reaching and powerful. Within the domain of Statics, Paul Steif closely examined the role of misconceptions[16] and developed a concept inventory in collaboration with Dantzler[17] to determine the effect of these misconceptions on problem-solving. Mehta and Danielson have developed and used a Statics skills and knowledge inventory.[18, 19]

A final approach to understanding problem-solving in engineering focuses on the symbol system translations inherent in the analysis process. By symbol system, we refer to the semiotic system used to understand and express elements and their relations. Mathematical expressions are an example of a semiotic system in which numbers and operators act as elements. How these elements are configured in relation to one another communicates the full meaning of the expression. Translations are required when problem solvers move between symbol systems. McCracken and Newstetter[20] developed the Text-Diagram-Symbol (TDS) model to capture the transformations that take place during analysis. This model includes verbal (Text), visual (Diagram), and mathematical (Symbol) semiotic systems through which the student must pass to complete an analysis task, with each phase corresponding to a different symbol system. The importance of visualization in transforming from a problem statement to a free-body diagram and the well documented gender effects on visualization skills, see for example,[21, 22, 23] led us to include spatial reasoning instruments in the study.

Methods

In this study, a Solomon's Four-group Design[24] was used that allows for an experimental test of the intervention while also controlling for any influence of the pretest. A Solomon Four-group design is a 2x2 factorial in which both the intervention and the pretest serve as independent variables; the dependent variable is the posttest score. With this design, it is possible to determine if there is an interaction between the pretest and the intervention while still maintaining the advantages of a pretest-posttest design. We chose this design because the pretest required participants to provide justifications for responses. We were concerned that prompting this atypical thinking could influence how students thought about the intervention problems.

The sequence of testing for each group is summarized in Table 1. The two phases of the testing were completed within one week. Students in Groups 1 and 2 completed the intervention and the posttest, but only Group 1 completed the pretest. Students in Groups 3 and 4 followed a similar pattern, but completed a filler activity in place of the intervention. The filler activity was also offered to students in Group 2 in place of the pretest. Because we anticipated that students would benefit from the interventions, Groups 3 and 4 also were given the intervention materials at the end of the second phase. Students in Groups 1 and 2 received part of the intervention during the first phase and another part during the second phase. The intention here was that students would have time in between the phases to reflect upon information presented. The Motivated Strategies for Learning Questionnaire [25]served as the filler activity.

Participants in this study were students enrolled in Statics and the intervention was administered just prior to the midterm exam. Participation in the study was one of several activities for which the students could receive extra credit in the statics class. The intervention and all instruments were delivered through the course web site and students could complete the activities at any time during each phase. The web-based system randomly assigned students to one of the four experimental groups.

Table 1. Summary of activities used in each phase of study across the four groups

	Group 1	Group 2	Group 3	Group 4
Phase 1	Pretest + ½ Intervention	Filler activity + ½ Intervention	Pretest + Filler activity	-- Filler activity
Phase 2	½ Intervention + Posttest	½ Intervention + Posttest	Posttest + Intervention	Posttest + Intervention
Number of Participants	55	55	62	53

Development of Interventions and Pre/Posttest

The development process of the intervention and the pre/posttest for assessing the effectiveness of the intervention were reported previously,[2] therefore, only a summary of the process is provided here. Based on the key difficulties in problem-solving that were identified from think-aloud problem-solving by students, a cross-disciplinary team of experts from engineering and educational psychology worked to create and refine two interventions through a series of design experiments. The goal of the design process was to create materials-driven interventions that would be done by students outside of the classroom without direct action by the instructor.

The interventions were designed to address three major difficulties:

- Students did not grasp fully the concept of a free-body diagram including the distinction between internal and external forces.
- Students relied mostly on memory to decide what reactions to include based on the type of connection/interaction.
- Students did not have a physical understanding of the reactions that could be supported by different types of connections/interactions between bodies.

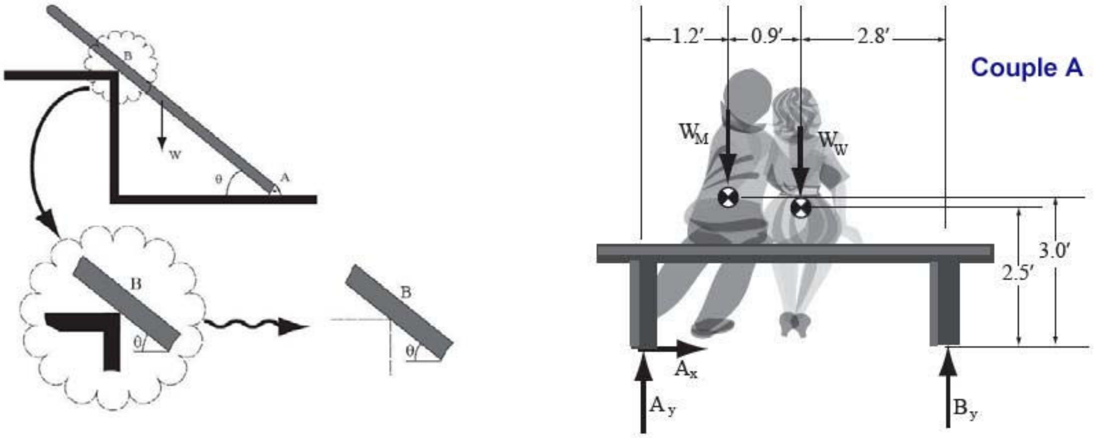
Two types of items were developed to address these difficulties: (1) identify the reactions at single connection/interaction and explain why those reactions exist, and (2) analyze a given free-body diagram, identify whether the reactions shown are correct, and explain the analysis with physical reasoning. Representative figures from the two types of items, referred to as "Single connection" and "Free-body diagram," are presented in Figure 1.

The six items of "Single connection" were presented as the first part of the intervention, and the five items of "Free-body diagram" were presented as the second part of the intervention. The intervention included an instructional video for each type of item that demonstrated how to enter answers and justifications. These instructional videos, prepared by the course instructor, also demonstrated the type of physical reasoning that was expected. During the intervention, students were asked to type a justification for their answers as a way to prompt self-explanation. After completing each item in the intervention, students could access either a videotaped or written explanation of the correct solution. Students could select one, both, or neither of these instructor-provided explanations.

In order to assess the effectiveness of the interventions, a 10-item pre/posttest was developed and refined throughout the series of design experiments. The final form of the test contained eight items that required students to select the correct reaction forces and/or couple that could exist at a connection; Figure 2 presents the figure from one of these items.

The physical problem in each item and the type of connection that was involved in these eight questions are summarized in Table 2. Each of these items also required students to select statements from a list to justify their answer. The list of justifications, presented in the Appendix, was created based on the answers that students gave during the think-aloud sessions. The same set of justifications was repeated for every question. In each case, only one selection was correct although participants were permitted to select more than one.

The remaining two posttest items asked students to select a correct free-body diagram for a body, but these items did not require selection of justification statements. The internal consistency reliability coefficient for the ten multiple choice items on the pretest was 0.615, for the posttest the reliability coefficient for the ten multiple choice items was 0.714.



"Single connection" intervention

"Free-body diagram" intervention

Figure 1. Representative images from the interventions

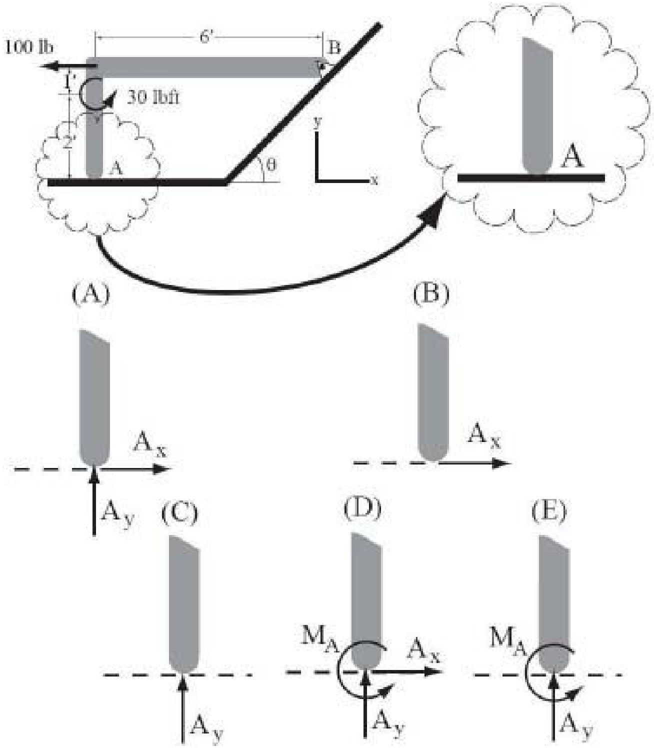


Figure 2. Problem figure and answers for Q5 on the pre/posttest

Table 2. Items on simple connections on assessment test

Item Number	Physical problem	Connection type
S1	Bent bar resting on inclined surfaces	Point contact on rough inclined surface
S2	Bar leaning on inclined wall	Point contact on rough inclined surface
S3	Bar leaning on vertical wall	Point contact on smooth vertical surface
S4	Sliding collar on bicycle trailer	Collar
S5	Bridge	Point contact on smooth inclined surface
S6	Ladder on roof	Point contact on rough vertical surface
S7	Ladder brace	Pin connection
S8	Tractor-trailer hitch	Fixed support in x-y plane

Results and Discussion

The pretest/posttest results for each of the groups are presented in Table 3. The table includes three subscores from the test. The first is the average number of correct answers, i.e., correct free-body diagrams, selected out of a maximum of 10. The other two scores are the average number of correct and incorrect justifications selected by each group across the eight corresponding items. It is important to note that a *decrease* in the number of incorrect justifications selected is a positive outcome.

Three 2x2 ANOVAs were conducted to determine the effects of the pretest and intervention on each of the dependent variables: the number of correct answers, number of correct justifications, and number of incorrect justifications. For the number of correct answers, there was a significant main effect of the intervention, $F(1, 221) = 15.40$, $p < .001$. Neither the pretest nor the interaction had a significant main effect. This pattern was repeated for both the number of correct and incorrect justifications selected. Students who completed the intervention selected significantly more correct justifications; $F(1, 221) = 17.97$, $p < .001$; and fewer incorrect justifications; $F(1, 221) = 6.21$, $p < .01$; than did students who did not complete the intervention. There was not, however, a main effect of pretest or an interaction effect on either of the justification variables. This pattern of results suggests that the intervention improved students' performance. There was not a significant effect of the pretest nor a significant pretest-intervention interaction effect on any of the measured dependent variables.

Because Group 1 was the only group that completed the intervention and took both the pre and posttests, we now focus our discussion on this group.

The magnitudes of the changes between the pre and posttests for Group 1 correspond to medium effect size,[26] defined as magnitude of the change divided by pooled standard deviation. For the correct answer score, the effect size is 0.5. The effect sizes for the correct and incorrect justifications are 0.6 and -0.6 respectively.

Table 3: Summary of pre/posttest performance of the four groups

	Score range	**Group 1**	**Group 2**	**Group 3**	**Group 4**
Pretest					
Average number of correct answers	0 to 10	6.1		6.1	
Average number of correct justification statements selected	0 to 24	14.4		14.0	
Average number of *incorrect* justification statements selected	72 to 0	19.9		19.1	
Posttest					
Average number of correct answers	0 to 10	7.4	7.3	6.2	6.0
Average number of correct justification statements selected	0 to 24	18.0	16.7	13.5	13.4
Average number of *incorrect* justification statements selected	72 to 0	12.7	14.5	16.9	18.5
(Posttest) – (Pretest)					
Average number of correct answers	0 to 10	1.3		.1	
Average number of correct justification statements selected	0 to 24	3.6		-.5	
Average number of *incorrect* justification statements selected	72 to 0	-7.2		-2.2	

To assess the efficacy of the intervention, the results were analyzed in several ways, as shown in Figs. 3-6 and Table 4.

Figure 3 shows the change in the number of correct free-body diagrams selected plotted against the pretest score for each study in Group 1. (The actual changes were adjusted slightly in magnitude for this plot when more than one student had the same set of scores, so that each student is represented in the plot.) The inclined solid line in the plot represents the ceiling of the possible improvement for students with a given pretest score. The dashed lines represent the estimated mean standard error in the pretest score; only points lying outside of these lines show statistically significant changes. Given of the magnitude of the estimated mean standard error, ten students who scored 9 or 10 on the pretest could not achieve statistically significant increases on the posttest. Twenty-four of the 45 students who could achieve statistically significant increases did so on the posttest. Only three students showed a statistically significant decrease in score, two decreased by 2, and one by 4. Twenty students had changes of 1 or -1, which are not statistically significant, and the balance had identical scores on the pre and posttest.

Figures 4 and 5 are cross-plots of pre and posttest results for the number of correct and incorrect justifications chosen. A positive outcome would be that the number of correct justifications increases toward the maximum possible score of 24 and that the number of incorrect justifications decreases. The maximum number of incorrect justifications that are logically consistent is three for each of the reactions. Given three reactions for each problem, two force components and a couple, and eight items, the maximum number of logically consistent, incorrect justifications is 72.

In Figures 4 and 5, the student who decreased by 4 in the number of correct answers on the posttest is circled. The number of correct justifications decreased substantially and the number on incorrect justifications increased substantially for this student. The justification statements typed by this student during the intervention seem to indicate that he was making a good faith effort. In contrast to this student, a number of the students showed equally dramatic gains between the pretest and posttest as illustrated in Table 4. Further investigation into the effect of the intervention on the students with substantial changes in their performance is clearly warranted. Human subjects permission is being sought for interviews of representative students with extreme changes in performance.

Table 4: Summary of scores for individual students who showed the most dramatic improvements in scores

Pretest scores			**Posttest scores**		
Correct answers	Correct Justifications	Incorrect Justifications	Correct answers	Correct Justifications	Incorrect Justifications
7	9	24	9	23	1
6	11	24	9	23	2
3	5	39	8	22	2
5	21	25	8	23	5

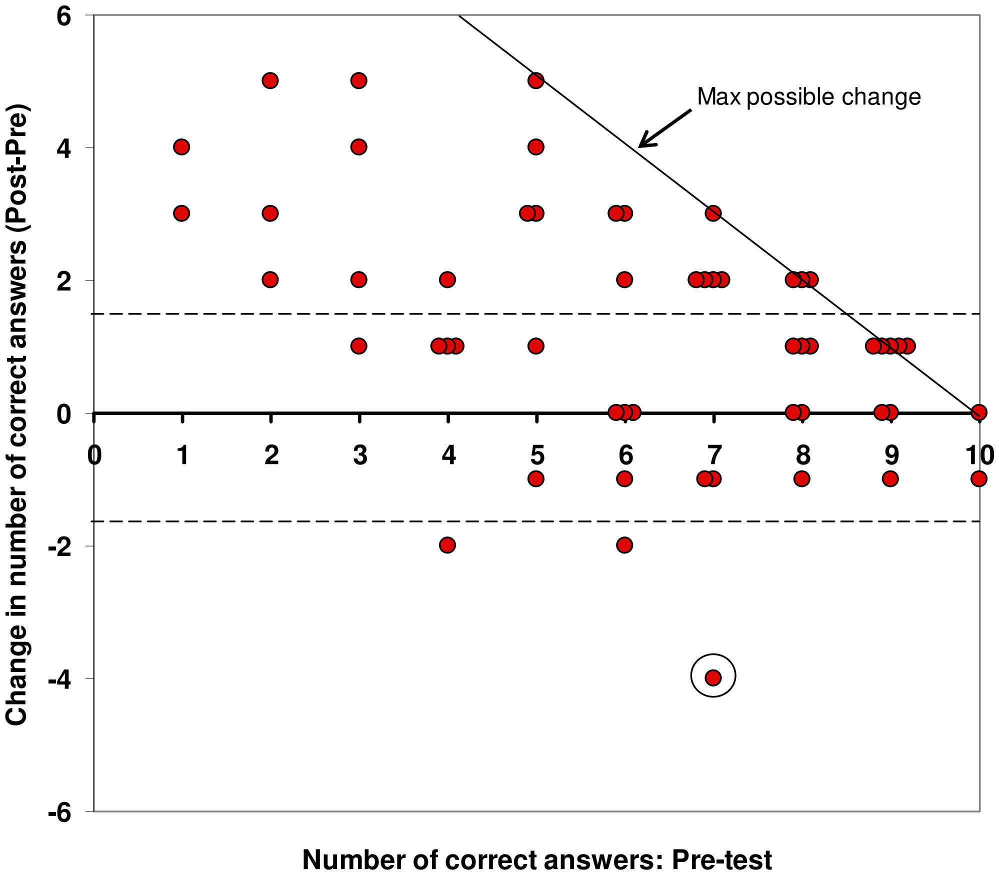


Figure 3. Gain in number of correct free-body diagrams selected vs. number correct on pretest

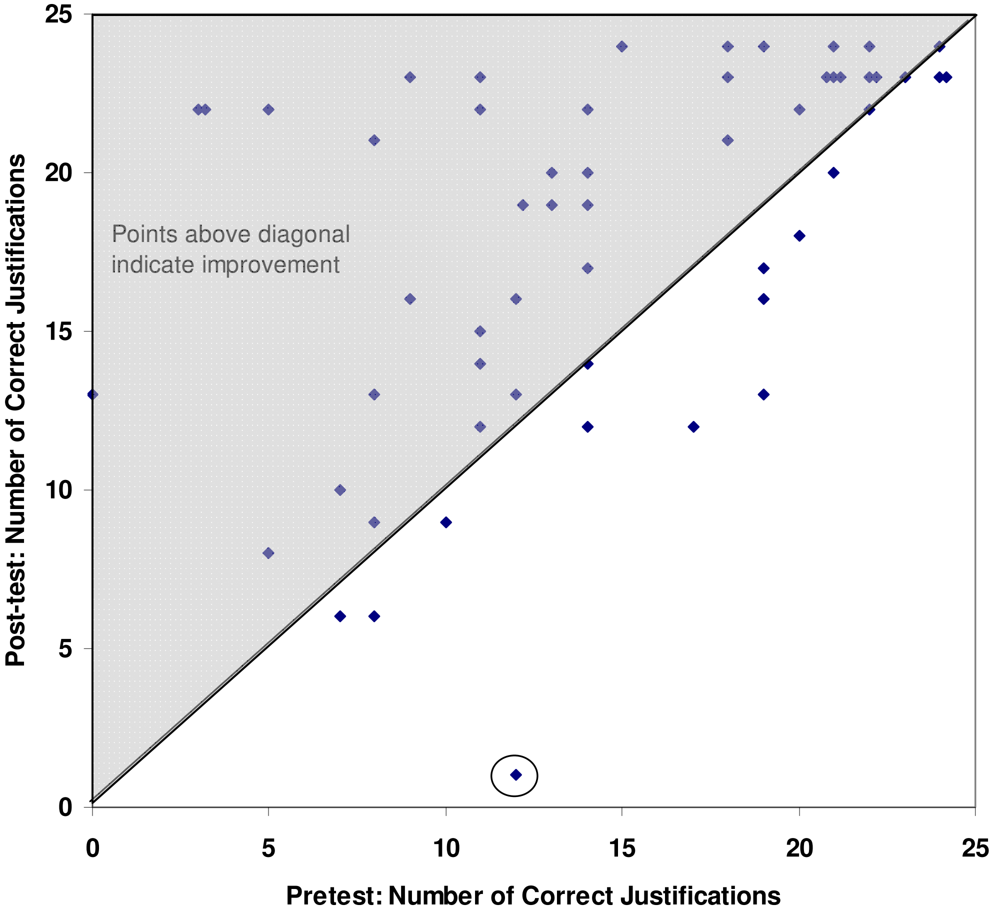


Figure 4. Number of correct justifications selected on posttest vs. number selected on pretest (Points above diagonal indicate improvement)

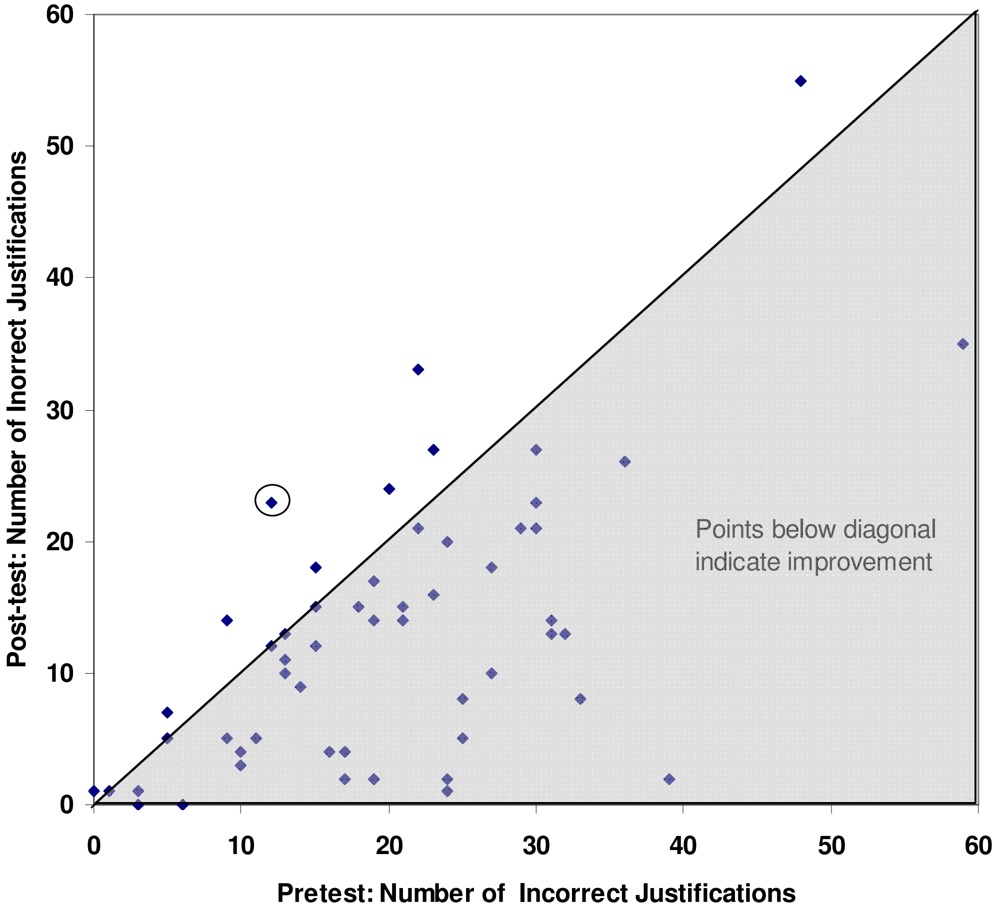


Figure 5. Number of incorrect justifications selected on posttest vs. number selected on pretest (Points below diagonal indicate improvement)

Changes in performance on individual items between the pre and posttest were also investigated. Figure 6 shows the change in the fraction selecting the correct score for the eight items in which students had to select free-body diagrams and justification statements. Seven of eight items show improved performance in the fraction of students who picked the correct free-body diagram. However, the eighth item showed a substantial decrease in performance. As indicated in Table 2, this item involved the modeling of the trailer hitch on a tractor-trailer, considering only in-plane motion. A review of the justification statements selected by the students for this problem on the pretest and posttest revealed that students' answers regarding the presence of a reaction couple were actually worse on the posttest, on average. It seems that students may have been exercising the correct physical reasoning in the problem, realizing that the trailer could rotate out of the plane shown, while forgetting that the problem asked them to consider only the in-plane effects. This item will either be restructured or replaced prior to the next administration of the interventions.

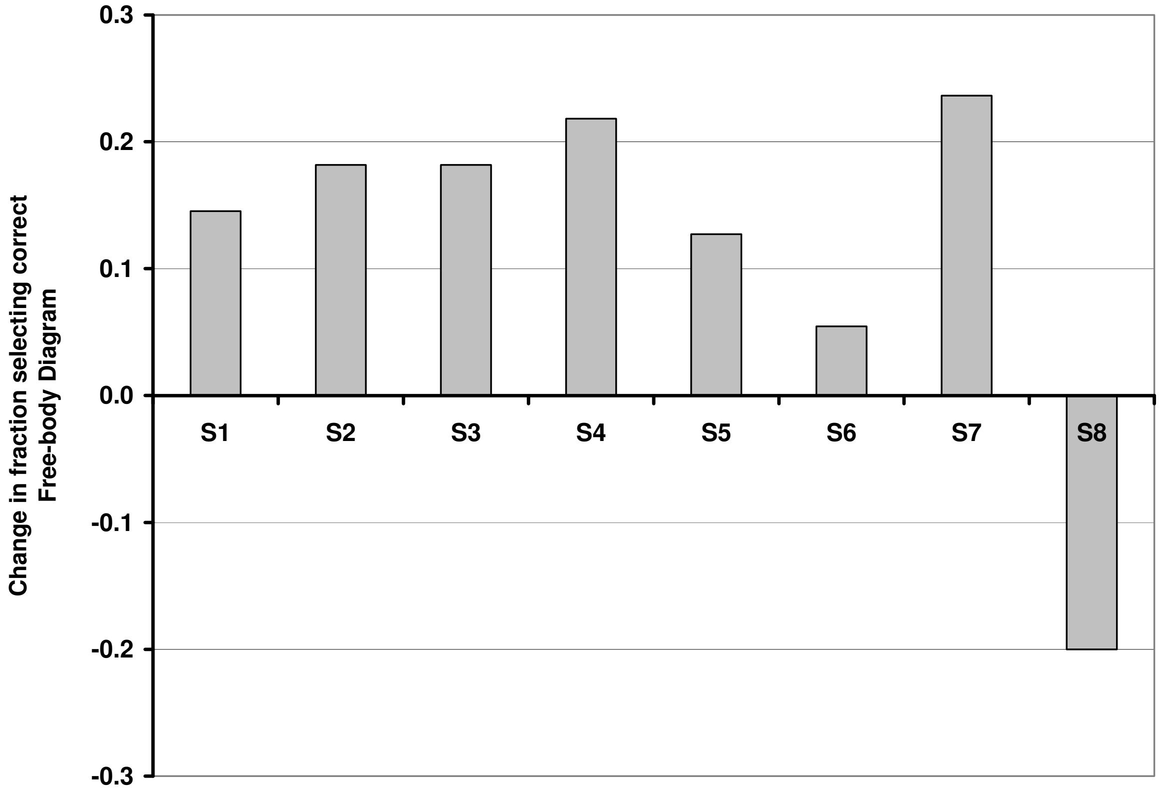


Figure 6. Change in fraction selecting correct free-body diagram for simple connection items

Conclusions

The intervention designed to enhance students' ability to identify correct reaction forces at simple connections and to justify their answers with sound physical reasoning appears to be successful. Average scores improved substantially on the assessment test for the group of 55 students who completed the pre-test, intervention, and posttest for all three subscores: correct answer, correct justification, and incorrect justifications. The effect sizes in each case were moderate, ranging from 0.5 to 0.6. The performance on individual items in the assessment test indicated that one item should be reworked. On-going data analysis will dig more deeply into the results in an attempt to correlate performance with other data. Currently, our team is analyzing data associated with students' behavior during the intervention including the explanations that were generated and the time spent studying the solutions provided. This analysis should reveal aspects of the intervention that had the greatest effects and guide refinements of the current intervention.

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Appendix – Justification Statements

Table A-1: Justification statements for reaction force (X-component)

At point A, the free-body diagram

a) should include an X-reaction because the connection prevents motion in that direction.
b) should include an X-reaction because the connection does not prevent motion in that direction.
c) should include an X-reaction because applied forces must be balanced.
d) should include an X-reaction because no other connection prevents motion in the X-direction.
e) should **NOT** include an X-reaction because the connection prevents motion in that direction.
f) should **NOT** include an X-reaction because the connection does not prevent motion in that direction.
g) should **NOT** include an X-reaction because there are no forces applied in the X-direction.
h) should **NOT** include an X-reaction because the connection prevents motion, making friction irrelevant.

Table A-2: Justification Statements for reaction couples

a) should include a reaction couple because the bar is free to rotate about that point.
b) should include a reaction couple because the bar cannot rotate about that point.
c) should include a reaction couple because forces on the body create moments that must be balanced.
d) should include a reaction couple because no other connections prevent rotation about that point.
e) should **NOT** include a reaction couple because the bar is free to rotate about that point.
f) should **NOT** include a reaction couple because the bar cannot rotate about that point.
g) should **NOT** include a reaction couple because there are no couples applied to the body.
h) should **NOT** include a reaction couple because other connections prevent rotation about that point.

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