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Work-in-Progress: Computer Simulations to Deliver Inquiry-Based Laboratory Activities in Mechanics

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Introduction

Although students can often use algorithmic substitution and pattern matching to solve mechanics problems, many do not understand the underlying principles [1], [2]. It is critical that students develop a strong conceptual understanding of mechanics to transfer this knowledge to new types of problems and for follow-on courses [3], [4]. To help promote such understanding, we have developed several hands-on inquiry-based learning activities (IBLAs) [5], [6]. During these activities, students are presented with a range of physical scenarios and guided through several predict-observe-explain cycles using a corresponding worksheet [7], [8]. The IBLAs are completed in a team environment, but students are asked to make their predictions individually first before engaging in collaborative discussion [5].

In past work, we were able to show learning gains following the activities, and students reported that they found the IBLAs to be interesting and motivating [6]. However, the IBLAs have not seen widespread adoption at other schools, partially due to the extra time to build and distribute the physical manipulatives. This constraint was particularly problematic in large lecture halls, where dozens of experimental setups would be needed. Additional challenges arose with the move to emergency online teaching. Although some schools mailed out laboratory kits to their students, this tactic did not appear to be a viable solution for our IBLA's.

To alleviate the situation, we created a fully virtual experience - or a remote IBLA (rIBLA). In this work-in-progress paper, we discuss the development and implementation of the Spool rIBLA which has students examine the relationships between forces, moments, linear accelerations, and angular accelerations. In this activity, students are asked to predict the direction of acceleration and the direction of the applied friction force when pulling gently on the string of a spool. The four different scenarios that are included in the spool activity are shown below in Figure 1. Students interacting with the physical manipulative can be seen in Figure 2.

Remote IBLA Instructional Design

For the remote IBLA, we created both a video showing the results of the experiment as well as a simulation of the phenomena. The computer simulations were developed assuming a 2D rigid-body physics model and rendered as a HTML canvas object. A key modelling challenge was mitigating non-idealities such as energy losses and approximating continuous-time models with discrete time steps. Correspondingly, we implemented our simulations with the open-sourced Chipmunk Physics library, which has been transcribed by GitHub contributors from C++ into JavaScript. This engine offers excellent compute times since it was originally developed for mobile applications. Using our web simulation tool, we recreated the laboratory exercises and computed them with sub-millisecond increments in real-time. Additionally, students can rapidly replay the simulation using an on-screen reset button. Other buttons can be used to slow down, speed up, and pause the simulation if desired.

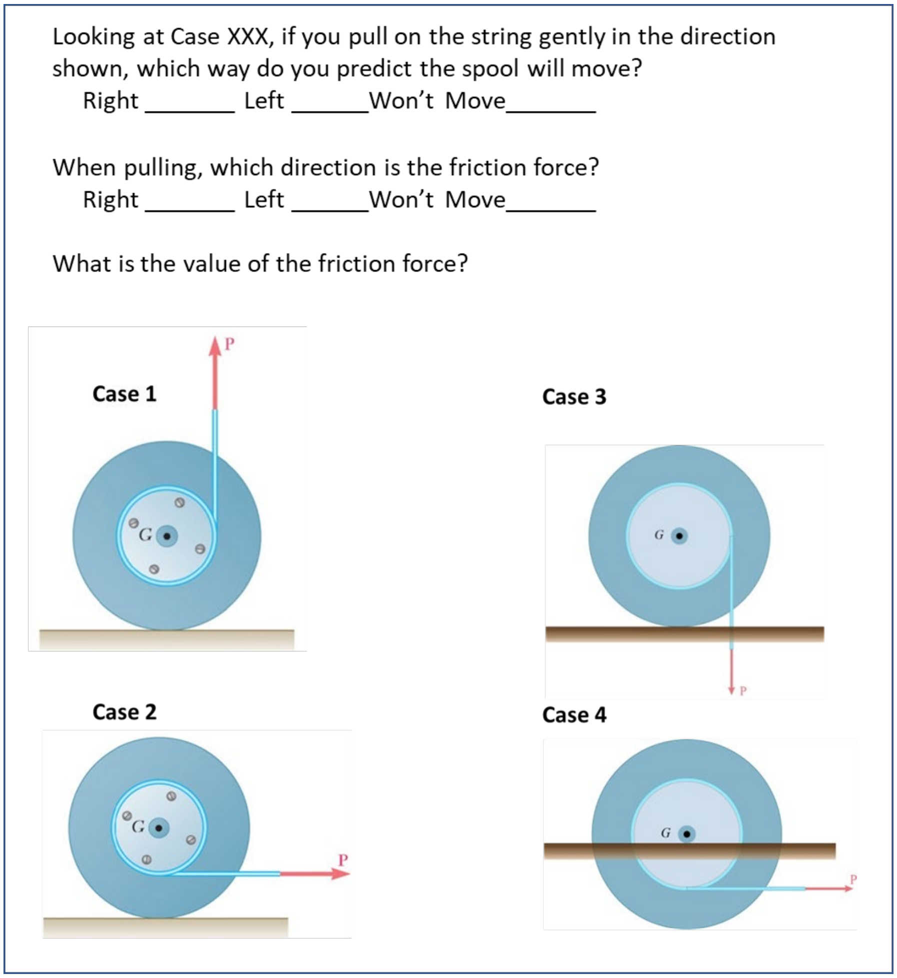

Figure 1. Spool Worksheet Questions. Students are tasked with predicting the outcome of each case prior to the experiment. The same three questions are prompted for each case.

Figure 2. In-Person Spool IBLA Implementation. In the foreground a student recreates Case 1 by tugging the string upwards. Several students are shown in the background discussing their predictions as a group.

Throughout the course of a simulation, time-dependent variables are sampled at even intervals and plotted on a graph adjacent to the simulation window. We selected the Dygraph JavaScript library as our graphing tool since it is lightweight, fast, and can be updated frequently with new simulation data. For the Spool IBLA, we opted to graph the string tension (blue), spool normal force (black)and the spool friction force (red), as seen in Figures 3 and 4.

Figure 3 highlights Case 2 and shows a screenshot from the video as well as the simulation (which can be accessed through the Concept Warehouse, https://newjimi.cce.oregonstate.edu/concept_warehouse [9]. Many students erroneously

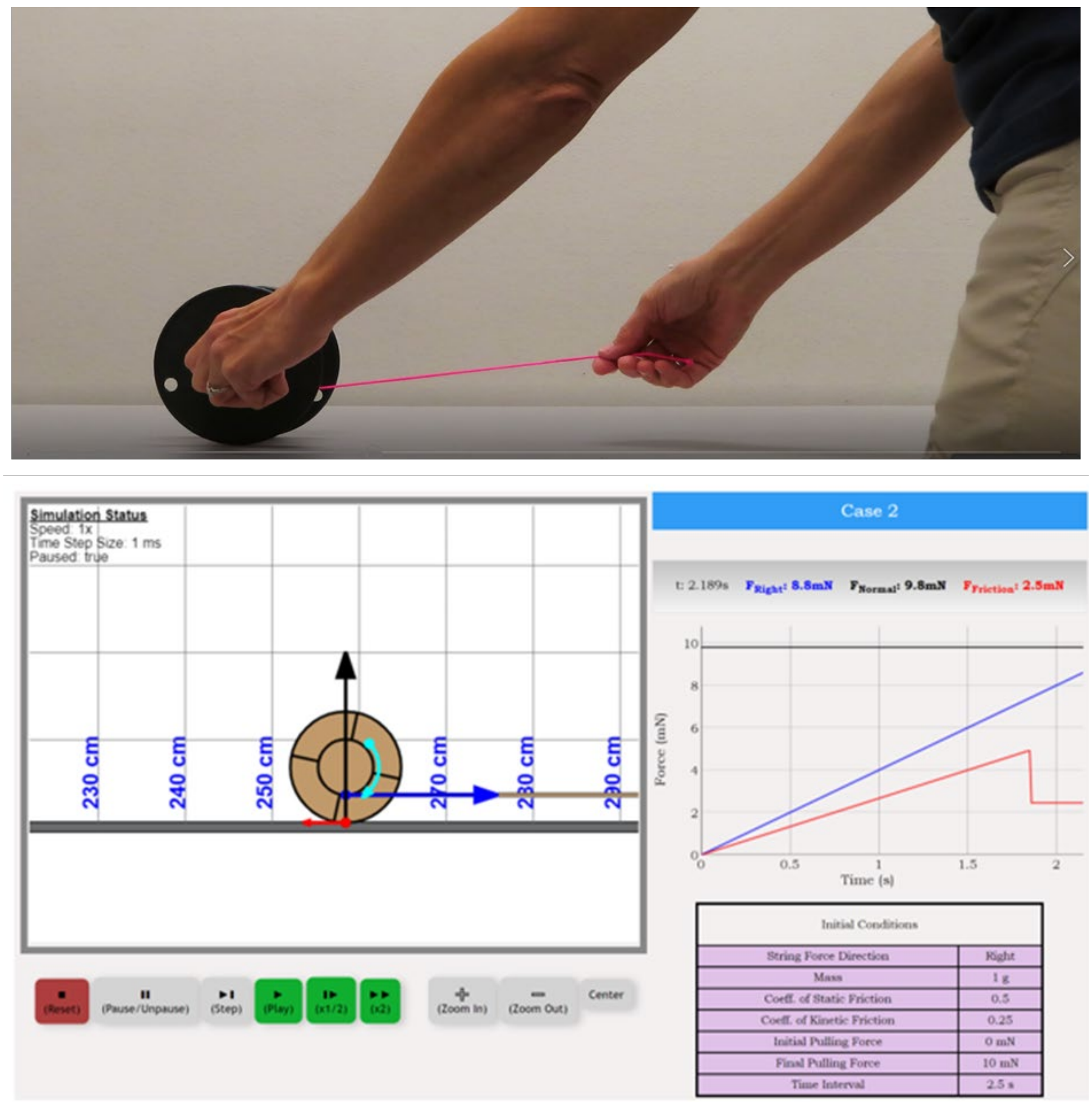

Figure 3. Video and Simulation Screenshots for Case 2. The video recording of Case 2 was provided to students via YouTube. Students were also provided a link to a Concept Warehouse page containing the corresponding simulation.

predict that the spool will accelerate to the left, and seeing the actual video helps them to visualize the physical scenario. In the simulation, the pull force P increases from 0 to 10^{-3} Newtons. The three force vectors (tension, normal, and friction) are rendered in the simulation window and are proportional to their magnitudes. Like the graphs, the friction force is shown by the red arrow while the normal force is depicted by the black arrow. The direction of the angular velocity of the spool is shown by the cyan curved arrow, which changes proportionally to its magnitude. Other pertinent parameters, such as mass and coefficient of friction, are also provided in a table.

A major advantage of the simulation is that students can now visualize the direction and magnitude of the friction force on the spool. Although the video shows the direction of the acceleration, it does not depict the direction of the friction force. Because the simulation linearly increases the pull force P, you can also see when the spool begins to slip. Just before 2 seconds on the simulation graph in Figure 3, there is a large drop in the friction force F. Seeing this force depicted can generate additional discussion with the students, such as the effects of changing the coefficients of friction as well as the angle of the pull force. Instructors can also have students perform calculations to match different points of the simulation.

Case 4 is particularly interesting, because it ends up that the friction force F is greater than the pull force P while the spool is rolling without slip (Figure 4). Students often erroneously think that the friction force can *never* be more than the applied force on an object. Screenshots from the video and from the simulation for this scenario are shown in Figure 4. Note that, like in Case 2, the wheel begins to slip once the friction force required is greater than $\mu_s N$. In this case, however, the spool actually reverses direction of acceleration as the net force becomes directed to the right. Towards the end of the simulation the spool linearly accelerates to the right and angularly accelerates counterclockwise as it slips.

The Spool rIBLA has been integrated into the Concept Warehouse for use at collaborating universities. Figure 5 describes Case 2 of the spool activity, where students are asked to make a set of initial predictions. Students are subsequently provided a second screen where they can open the simulation window and record their observations, as shown in Figure 6.

Assessment

We initially developed the IBLA in the Canvas LMS and delivered it to over 150 students. While we considered a split design using video only and simulation only, we decided to provide both media to the students and then survey them as to their effectiveness as we believed that approach would best support their learning. For this pilot test, the IBLA was administered synchronously with the use of undergraduate Learning Assistants (LAs). Students submitted predictions using a Canvas quiz, discussed their predictions with their teammates using breakout rooms in Zoom, and then came back into the main room to have the LAs lead a discussion of the results and show students how to examine them using Newton's second law, by summing moments, and by looking at the linear and angular accelerations. Students then went on to the next case as described in Figure 1.

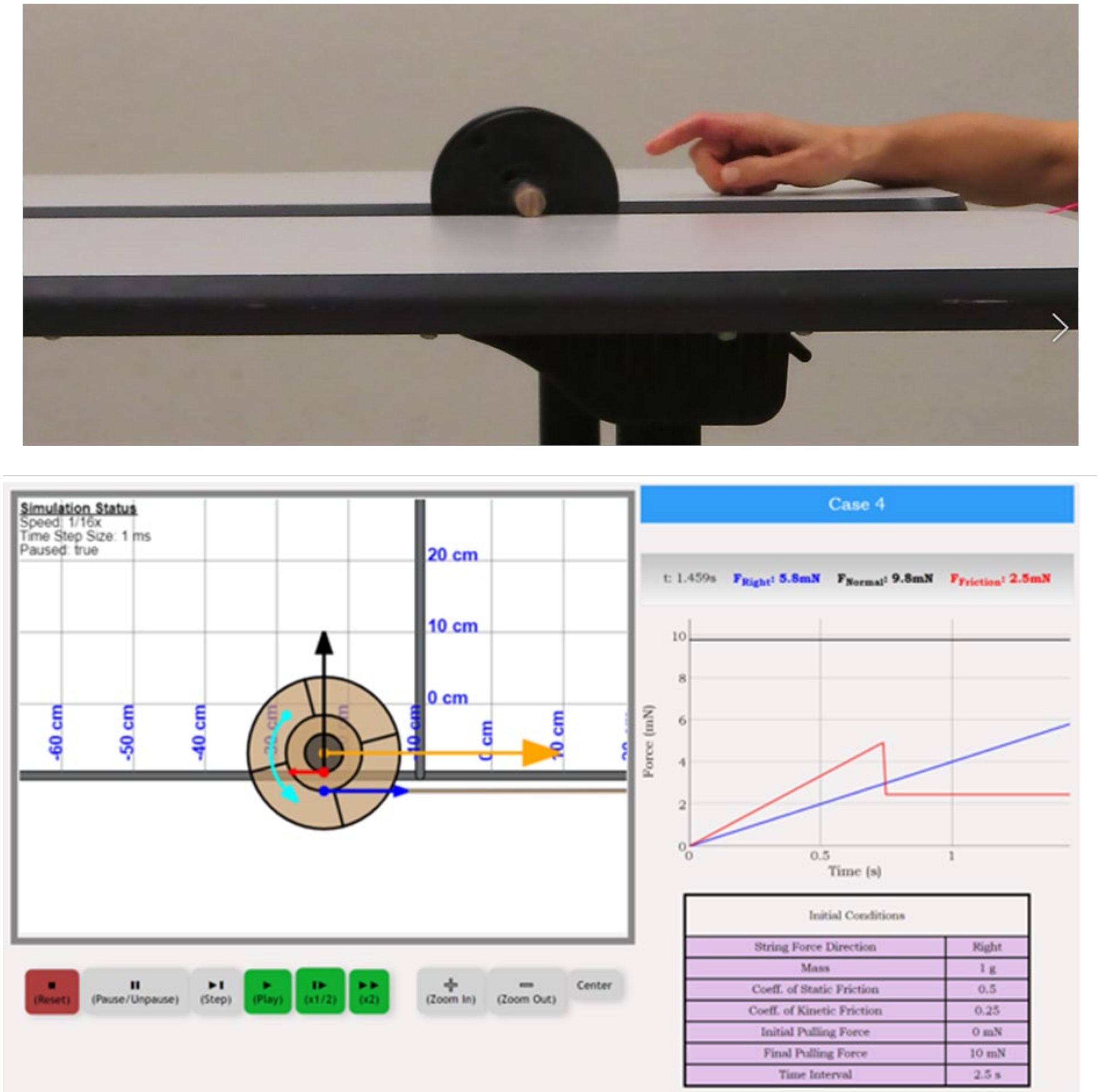

Figure 4. Video and Simulation Screenshots for Case 4. Students are provided a side-view of the Case 4 spool rolling on an axle suspended between two tables. To help visualize the spool simulation, we use a velocity vector (orange) and an angular velocity arced vector (cyan) to describe the dynamics.

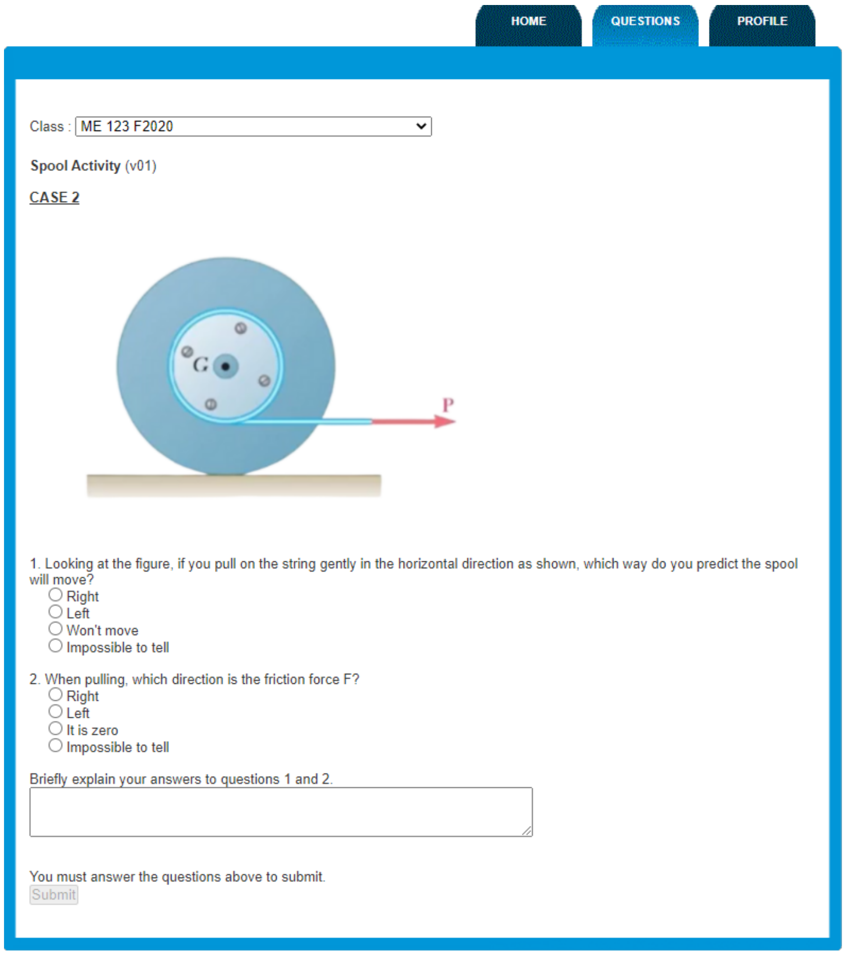

Figure 5. Screen shot of the Spool instructional tool in the Concept Warehouse student interface. In this page, the student is asked to predict the dynamic behavior of a spool in the Case 2 configuration.

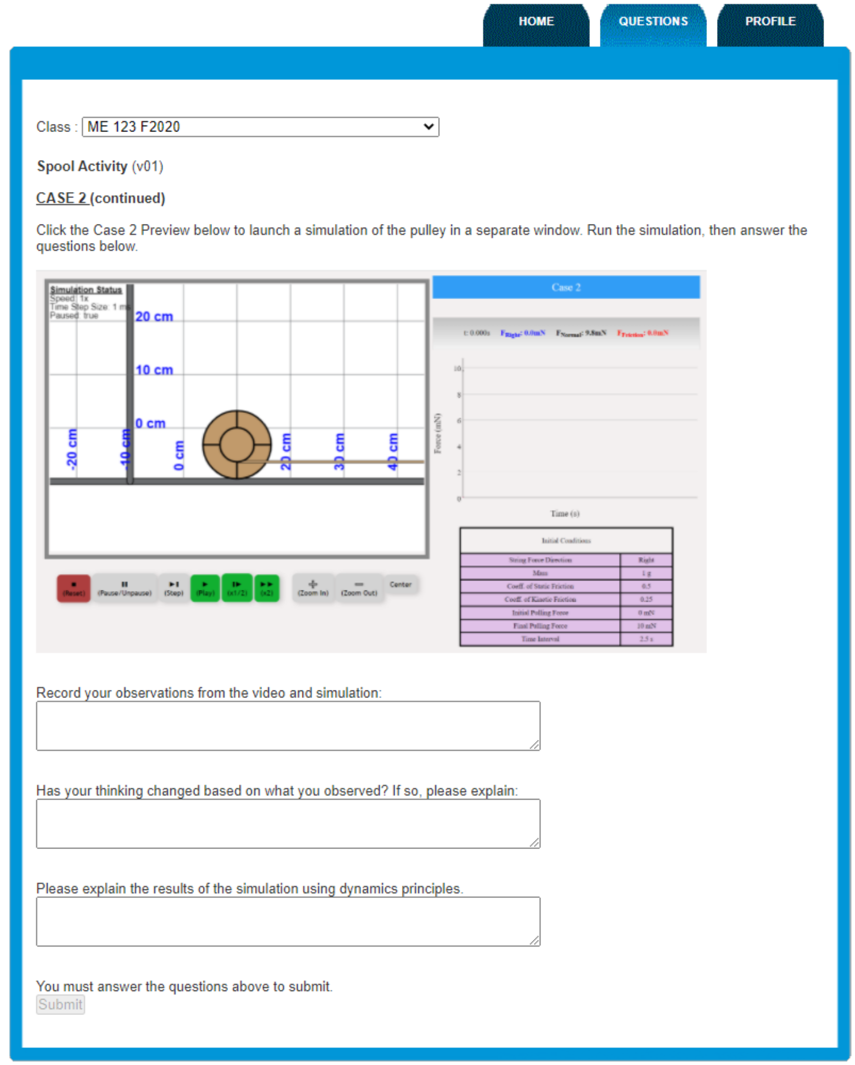

Figure 6. Another screen shot of the Spool instructional tool. In this page, the student is asked to launch and run the Case 2 simulation, then explain observed behavior relative to the student's original predictions

At the end of the activity, students were asked to rate on a Likert scale from 1-5 (1 = Strongly Disagree, 5 = Strongly Agree) how much they agree to the following three questions:

- Seeing only the video (no simulation) would allow me to understand the phenomenon and would result in the same learning (e.g., I don't really need the simulation).
- Seeing only the simulation (no video) would allow me to understand the phenomenon and would result in the same learning (e.g., I don't really need the video.)
- Both the video and the simulation contributed to my understanding of the phenomenon and contributed to my learning (e.g., I prefer having both the video and the simulation).

The student responses are summarized in Figure 7. Students clearly believed that the combination of simulation and video together better supports their understanding and learning using the Spool rIBLA.

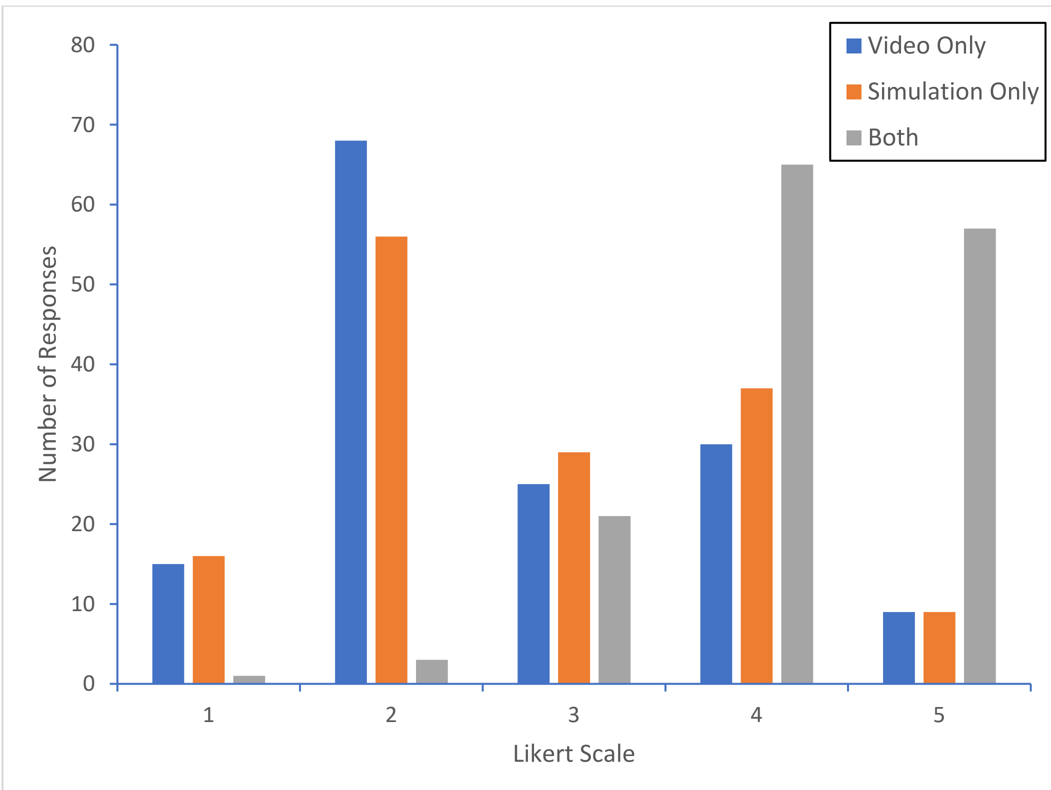

Figure 7. Likert Responses for Delivery Mode Preferences.

Discussion and Future Work

The transition to remote learning amid a global pandemic has led to significant challenges for providing an effective alternative to in-person instruction. The physical IBLAs previously reported are a useful instructional tool but require bulky equipment that cannot be practically recreated remotely. In contrast, the rIBLAs provide much greater utility during the online transition, with two modes of delivery available. Both the video and simulations described are available at no cost on the Concept Warehouse, thus allowing other universities to use the same content for their own instruction. Following the return to in-person teaching, the rIBLAs will further diversify the tools available for dynamics instructors. Classes can use hands-on worksheets, individually assigned rIBLAs, or in a synchronous virtual collaborative learning environment where an instructor leads the discussion.

The results from our survey indicate students have a strong preference for having both the video and simulations in the rIBLAs, as compared to either the video or the simulation by itself. This can be attributed to the distinct affordances provided by each case. The video provides a realistic physical case while the simulation provides several additional layers of information to students, including force vectors and graphed parameters. Further work will include analyzing student survey data to explain student perceptions and to determine how student comprehension and learning compares between remote instruction vs. in-person.

Acknowledgements

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