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Affordances and Constraints of Physical and Virtual Manipulatives for Learning Dynamics*

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This study investigated the affordances and constraints of dynamic physical and virtual models integrated into a dynamics course. Students in a dynamics course were assigned to one of three groups: traditional instruction, traditional plus physical manipulatives, and traditional plus virtual manipulatives. Using observations of problem solving sessions, student questionnaires, and pretest/posttest written assessments we triangulated affordances of physical and virtual manipulatives for learning dynamics. Key affordances of the manipulatives included direct experience of motion of the mechanism, the ability for students to test or verify their ideas about the mechanism's operation and facilitating communication for collaborative learning. Pretest to posttest changes in mechanical reasoning favored the use of physical or virtual manipulatives over traditional instruction alone. Results suggest that adding physical and virtual manipulatives to traditional instruction in dynamics may help students better reason about mechanical systems than with lecture and problem solving using static diagrams alone. By exploring how different manipulatives can help students understand dynamic systems, this study contributes to the larger body of research on helping students develop mechanical reasoning in engineering.

Keywords: dynamics; manipulatives; affordances

1. Introduction

Dynamics, or the study of bodies undergoing accelerated motion [1], is a foundational course in mechanical and aerospace engineering, and is also useful for students in other disciplines such as civil or biomedical engineering. Typical dynamic systems involve some combination of translational and rotational motion, and often contain elements of projectile motion (like the motion of particles falling), sliding, or constrained kinematics of various kinds of joints. Although the nature of the material is inherently dynamic, the course is traditionally taught as a combination of lecture and problem solving using static textbook diagrams of moving systems. Students often find dynamics to be challenging, and difficulty in dynamics can negtively impact performance in subsequent courses [2–3].

Difficulties understanding dynamic mechanical systems can lead students to make incorrect inferences and thereby negatively impact their performance in dynamics classes. Research has demonstrated the effectiveness of integrating various kinds of physical and virtual models for learning engineering [4–9]. Particular to dynamics, physical and virtual models of mechanisms may add specific affordances to the learning environment that may contribute to students' ability to reason about dynamic systems. In this study, we explored the use of physical and virtual manipulatives to help students understand dynamics concepts. Specifically, this study provides insight into what kinds of affordances physical and virtual manipulatives have for learning dynamics compared to static diagrams alone.

2. Background

2.1 Affordances of learning tools

Learning is shaped by interactions between both internal and external sources. Both the prior knowledge of the individual as well as the environment influences cognition [10–11]. Interactions with people, tools, and resources provided in the environment have an effect on learning. For example, interactions with a more able peer or tutor can have a profound impact on what a student learns, or having a graphing calculator can dramatically alter how students learn certain problems and concepts.

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Intelligence can even be considered as "distributed" across the learning environment, affecting how students interact and learn within their surroundings and learning resources [12].

An *affordance* is something that an object or tool offers, provides, or furnishes to an agent in that environment [13–15]. In terms of learning, educational affordances are characteristics of tools that provide opportunities for specific learning behaviors [16]. The prior knowledge of the user, the culture and context of using the object, and the design of the object all influence affordances. For instance, an affordance of a diagram of a mechanical system for an expert might be that it portrays how each component works together, but that may not be an affordance for a novice student with no familiarity with dynamic systems.

Affordances can be thought of as "preconditions for activity" [15] in that although the affordances are available for the learner, there is no guarantee that the activity will occur. For example, an object may permit a certain behavior on the part of the agent, but if the agent is unable (or unwilling) to perform that behavior it does not happen. Thus, designers of learning environments need to pay attention to the affordances of learning tools in specific contexts as there can be great variability in how students interpret and use materials and resources. For instance, when an expert looks at a static diagram of a dynamic system, the expert can draw upon experience and prior knowledge with similar machines and diagrams to determine how it works. The novice, on the other hand, may lack such experience and have difficulty using the diagram to help solve a problem, focusing only on the most basic salient features of the representation [17].

2.2 Mechanical reasoning

Success in mechanical or aerospace engineering courses depends on students' ability to reason about mechanical systems. Mechanical reasoning occurs through a process called *mental simulation* [18], which involves determining how a system will move by creating and running a mental model of the system and making inferences based on that model. The mental simulation is not only limited to a visual representation of the machine but also incorporates non-visible entities and properties like force and velocity. Research demonstrates that students struggle to develop mechanical reasoning of dynamic systems [19–20]. Novice students tend to run a mental simulation of a complex system not in its entirety, but rather as a collection of interacting subassemblies. For example, a mental simulation of a pulley system may not be analyzed as an entire machine with all of its parts operating simultaneously, but instead as a stepwise causal chain. If a student is asked what happens to a bucket attached to a pulley, connected to the end of a rope that is wound through a series of pulleys, the student may analyze the behavior of the system one pulley at a time, stepping down the causal chain, rather than running the whole system simultaneously and immediately knowing what happens to the bucket. These kinds of step-wise or piecemeal reasoning processes can hinder students' problem solving abilities if they make an incorrect inference in one step of the chain. Experts, on the other hand, have the experience and technical expertise to integrate all the elements of the casual chain directly into a holistic mental model.

2.3 Physical and virtual manipulatives

Manipulatives are learning tools that have the potential to improve understanding by helping students develop mental simulations of mechanical systems. Manipulatives can be physical (tangible in the real world) or virtual (rendered in computer software) and are not limited to dynamics instruction. Physical manipulatives that might be used in engineering education are objects like balls, magnets, and simple machines. Virtual manipulatives can be computer analogs of physical manipulatives [21] or external graphical dynamic (video and animations) and interactive or non-interactive representations [22]. CAD software programs in engineering can provide virtual manipulatives of mechanical systems, including very sophisticated system models such as three-dimensional mechanical assemblies.

Mechanical reasoning in dynamics requires spatial information, such as the location and connectivity of objects, but also depends on reasoning about the movement of components within mechanical systems. Static representations (i.e., textbook diagrams) typically used in dynamics instruction provide information about the location and connectivity of objects, but inherently fail to provide direct information about movement of components. Incorporating physical and virtual manipulatives of dynamic systems can help students develop dynamic mechanical reasoning by providing explicit information about the movement of system components. Although physical and virtual manipulatives each show the motion of dynamic systems, they each offer unique affordances to learning [23].

2.4 Physical manipulatives

Physical manipulatives provide concrete examples that students can directly touch and interact with, and as real objects they convey a sense of real-world engineering issues such as measurement error and manufacturing tolerances. Physical objects can also contribute to cognition through embodiment or grounding of concepts [24]. For example, learners have been observed performing kinesthetic actions, such as tracing the motion of parts, while engaging in mental simulation of mechanical systems [25]. When people mentally simulate machines, they often use gestures that simulate the motion of objects, such as using their fingers to trace the direction of rotation of gears in a gearset [19]. Indeed, engineering students often say that they learn better if they can hold something in their hands and see how it actually works rather than just looking at a picture and imagining how it would work.

Many studies have investigated best practices with physical manipulatives in engineering education. Providing physical manipulatives may give students familiarity and confidence with systems before tackling a problem or design project [26], as well as motivational benefits [4]. Research suggests that students using physical manipulatives can gain *immediate intuition* of how key variables affect a system [9]. However, other research demonstrates no difference between students in Statics using physical models of textbook problems and students engaged in thought experiments of difficult concepts, as measured via concept inventory-type questions and performance on exams [5].

2.5 Virtual manipulatives

Virtual manipulatives provide somewhat similar affordances to physical manipulatives in that learners can interact and manipulate virtual models of systems. However, virtual manipulatives also offer learners the ability to replicate objects quickly and efficiently; modify objects on the fly, including adapting them in response to user behaviors; stop, fast-forward, and reverse time; record actions; and transmit objects over long distances very quickly [23]. Virtual environments also provide a safe way for students to explore systems that are too large, costly, or dangerous to introduce into an academic environment.

Research suggests that virtual manipulatives can help students develop dynamic mechanical reasoning. For example, students learning about pulley systems benefitted from the ability to control the pace of an animation [27]. Electrical engineering students with simulated labs outperformed students with only physical labs on final written exams, and performed equally well in physical labs [28]. The authors attribute the higher performance to the additional guidance, tutorials and increased accessibility of the virtual labs. Simulations can also help students visualize dynamics problems [8]. Other research suggests that students like the use of multimedia, simulations, and visualizations in dynamics lectures [29] and self-report improved understanding of course concepts [30].

However, research also demonstrates mixed results on the benefit of virtual manipulatives for learning engineering. Some research has found no difference in student outcomes between the use of physical and virtual manipulatives [31–32], while others find that engineering students in physical labs outperform students with simulations [33]. Results suggest that if there is no difference in student outcomes between the use of physical and virtual manipulatives, virtual manipulatives may be preferred due to their other advantages (such as cost, interactions, storage requirements, etc.) over physical manipulatives.

Prior research suggests that giving novice engineering students exposure to mechanisms in the form of physical and virtual manipulatives can potentially help them develop mechanical reasoning of dynamic systems., Prior work also presents mixed results in terms of relative advantages of physical or virtual objects on learning, and very few studies, if any, investigate affordances of physical and virtual manipulatives in authentic dynamics classes. Although dynamics is inherently about understanding physical, dynamic systems, students are rarely given the opportunity to interact with tangible dynamic systems. In addition, prior research examines the effect of physical manipulatives in engineering education, but few, if any studies investigate how physical manipulatives can benefit students in dynamics classes. This study explores the use of physical and virtual models of mechanisms depicted in textbook problems to help students understand dynamics concepts. Specifically, we asked the following questions:

1. What are observed affordances and constraints of students using physical and virtual manipulatives to solve rigid body kinematics problems?
2. What are students' perceived affordances and constraints about static diagrams, physical manipulatives, and virtual manipulatives as learning tools?
3. How does mechanical reasoning compare for students with traditional instruction supplemented with physical manipulatives, traditional instruction supplemented with virtual manipulatives, and traditional instruction alone?

By triangulating observations, students' perceptions, and how students reason about dynamic systems on written assessments, this study extends the current literature by providing insight into what affordances physical and virtual manipulatives have for learning dynamics in authentic classroom and

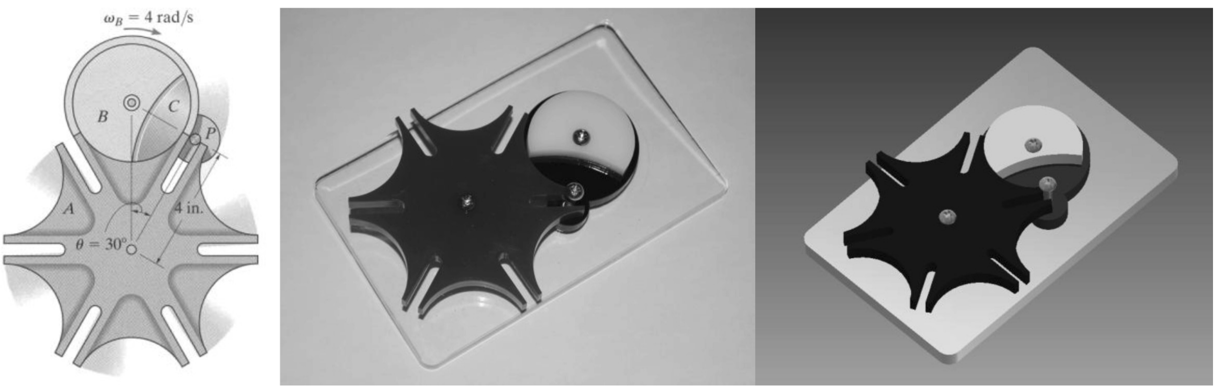

Fig. 1. The textbook diagram (left) of the Geneva drive mechanism and its corresponding physical (center) and virtual (right) manipulatives. Textbook diagram from R. C. Hibbeler, 2010, Engineering Mechanics: Dynamics (12th ed.), p. 390. Copyright 2010 by Pearson Prentice Hall (used with permission).

problem-solving settings. This study adds to prior research by comparing the effect of physical and virtual manipulatives to static diagrams on mechanical reasoning.

3. Methods

3.1 Participants

Undergraduate students enrolled in a semester-long Dynamics class at a public university in the mid-Atlantic United States participated in this study. Students were sorted by performance on a multiple-choice test composed of nine questions testing spatial ability, taken from the Purdue Spatial Visualization Test (PSVT) [34], and 19 questions testing subject matter from the Dynamics Concept Inventory (DCI) [35] given on the first day of the course. Questions were selected to reflect relevant skills and concepts covered in the first portion of the class. Students were assigned based on this test score to one of three treatment groups (Traditional, Physical, Virtual) to achieve a balanced design. After attrition (primarily due to students failing to appear for the treatment sessions), the number of participants dropped from 107 to 70, with 26 in the Traditional group, 21 in the Physical group, and 23 in the Virtual group. Statistical comparison of pretest performance between the three groups after attrition showed them to be functionally equivalent. Of the resulting 70 participants, 73% were male, 76% white, 10% Asian, 10% black, and 4% Hispanic/Latino. 94% were mechanical/aerospace engineering majors and 4% were engineering majors in another field.

3.2 Treatment

All three groups (Traditional, Physical, and Virtual) worked on three textbook problems involving the same mechanisms. The Traditional group only used static diagrams of the systems provided by the textbook, the physical group was given physical manipulatives of the each of the systems in addition to the static diagrams, and the virtual group was given CAD models of the systems in addition to the static diagrams. Fig. 1 illustrates the three learning resources used in this study. The physical manipulatives were functionally equivalent scale models of the textbook problem mechanisms, designed in a computer-aided design (CAD) program, and assembled from plastic parts cut by a laser cutter from acrylic sheets. The virtual manipulatives were computer analogs of the physical manipulatives derived from the CAD models used to create the physical models. Although in previous studies (such as those described in the preceding section) students interacted with simulations by adjusting numeric parameters using onscreen interface controls or entering numbers into form fields, the virtual manipulatives used in this study were designed such that the students used computer mice to click and drag parts of to the virtual manipulatives to make them move (rather than changing problem parameters), making it analogous to moving a physical manipulative with one's hand.

3.3 Data sources

To understand the affordances and constraints of the different learning tools, observations of students were conducted during the problem solving sessions. Both live and videotaped observations were used. A random pair of students was video recorded from each treatment group during each session to facilitate observation of students working in each group.

To capture the students' perceived affordances and constraints about the different learning tools, students were given a questionnaire that asked for their opinions about the utility of the models for their problem solving tasks (static diagrams or manipulatives, as appropriate for their treatment group). The questionnaire asked (1) if their respective model helped them learn the subject matter, (2) how their model helped or did not help them, (3) how their model could be improved, and (4) what other tools might have helped them (Appendix B).

Pretests and posttests were given to capture any differences among groups on mechanical reasoning. Both pretests and posttests consisted of identical open response questions that asked students to describe the behavior of mechanisms given a static diagram and a brief description of some initial conditions (similar to how they are presented in textbook problems, see Appendix C). The three mechanisms referenced on both tests were the same three (planetary gear set, rack and pinion, Geneva drive) that were used during the treatment sessions. In these problems, students were given input data and asked to describe the direction and speed of each mechanism's output. The posttest included one additional problem that was not included on the pretest or in the problem solving sessions, to test near transfer (the same planetary gear set, but this time with the ring gear as the input and the sun gear held fixed).

3.4 Procedure

Students were given the pretest two weeks before the first treatment session. The problem solving sessions were on two separate days, one week apart. Each problem solving session lasted for one hour, during which students worked on the textbook problems in pairs. Pairs were randomly assigned from within their treatment group. Students worked on two problems during each session (the first session included a four-bar linkage problem which was later excluded from the study due to an external contamination threat from students having access to a detailed video solution of the problem), and were told to move on to the second problem after half an hour, even if they were not done with the first problem (to ensure exposure to both mechanisms). Students took the posttest during the next problem solving session the following week. Students completed the questionnaire at the end of the posttest. In total, there were four weeks between the pretest and the posttest with two hours of treatment time.

3.5 Data analysis

Classroom observations were recorded as text notes, and these notes were then iteratively analyzed, looking for common ideas and themes. Questionnaire responses were analyzed qualitatively using a simplified form of content analysis [36]. Analytic categories were created to reflect perceived affordances and constraints, and common ideas and themes in the written responses were identified by reading and rereading the data to detect common responses; codes were merged as appropriate. Codes were then counted to find those that occurred the most frequently.

Analysis of pretest and posttest open response questions also used content analysis. Categories were developed to reflect an understanding of the mechanism, including direction and speed of the output. These categories were then used to code the data and grounded categories were created as necessary. For example, a category of *intermittent* motion (as opposed to merely *varying* speed) was created because the intermittent motion is the salient aspect of the operation of the Geneva drive (it converts constant rotational motion into intermittent rotational motion).

4. Results

4.1 Observed affordances and constraints

Classroom observations during the treatment sessions revealed potential affordances and constraints of static, physical and virtual manipulatives. The common themes found from the observations are described below.

4.1.1 Observed affordances

Tool for Testing/Verification. Students used both the physical and virtual manipulatives to test theories or verify assumptions they had about the operation of the mechanism. Students were observed making statements about how something worked, sometimes using hand gestures while describing the motion of a component, and then actuated either the physical or virtual manipulative to test their prediction. A student in the Physical group even tried to get specific measurements from the model, actually marking the planetary gear set with a pencil, apparently as a way to measure displacement or relative speed.

Aid for Communicating. Often occurring hand-in-hand with use of the manipulatives for testing and verification, students would use the manipulatives to communicate and convey information about how the mechanism moved. For instance, one of the students in the Virtual group gestured with his hands to describe the motion of the machine to his partner, and then he actuated the virtual manipulative to show the motion to his partner. His partner looked at the manipulative and made comments about it, pointing at the screen to draw attention to key areas. This sort of behavior was observed in the Traditional group as well, but with the static diagrams as the foci of the discussions, students had to gesture around the diagrams to show the direction of motion of parts while discussing it with their partners. Traditional group students gestured in the air in an attempt to give their partners a dynamic visual of the motion they were describing.

Playing with Models. Students frequently picked up the physical model and moved the parts repeatedly. This was observed much more often in the Physical group than in the Virtual group. For example, students would interact and manipulate the physical model somewhat randomly during the problem solving sessions, twisting and turning the gears while solving the problem. Students would repeatedly interact with the physical manipulatives either while fixated on it (and not communicating with a partner or appearing to use it for any specific purpose) or while visibly paying attention elsewhere.

4.1.2 Observed constraints

Challenges related to model construction or use. Both Physical and Virtual groups experienced technical difficulties due to the nature of the tools. Students in the Physical group had difficulties due to the fact that some of the physical models were difficult to actuate due to tight/loose manufacturing or assembly tolerances. For instance, in the physical model of the rack-and-pinion, the slider does not appear to move at all for about one-quarter rotation of the pinion gear due to loose tolerances. Students were often observed attempting to tighten the nuts on the models (the models were assembled using nylon-insert locking nuts, so their attempts to turn the nuts by hand were ineffectual).

Students in the Virtual group had difficulties loading their CAD models (almost always due to failure to follow directions), and experienced problems while trying to manipulate the models as a result. Slow computer performance sometimes caused the virtual model to skip and introduced lag times between user input and seeing the result on the screen. Students would also actuate parts beyond their normal design constraints, as the system did not restrict their actions. When students actuated the mechanism in ways that were not expected, the behavior of the mechanism became unpredictable (it "broke"). Once this happened, the easiest way to fix it was to reload the model. Since many students had difficulty loading the model, they usually just used the model in its "broken" state. Unfortunately, using the virtual manipulatives in the "broken" state sometimes showed inaccurate behavior of the dynamic system, as in the case of the rack-and-pinion problem.

Limited Use. Students' actual use of the physical and virtual manipulatives was very limited relative to the amount of time they spent working on the problems. The majority of the time was spent reading the problem, deriving answers/doing calculations, or thinking about the problem (they were assumed to be thinking about the problem when observed staring at the problem or the work they had done). For example, a student working on the planetary gear set problem took about 15 minutes to solve the problem. During that time span, the student interacted with the physical model a total of seven times, with an average interaction time of about 20 seconds (the actual range was 9–29 seconds for this case, but observed interactions took as little as five seconds). This level and pattern of interaction was observed in students working with the virtual manipulatives as well.

4.2 Students' perceived affordances and constraints

Responses from the questionnaire reveal that the majority of students in all three treatment groups felt that their respective tools helped them (Traditional: 84%; Physical: 81%; Virtual: 65%; Table 1).

Table 2 presents frequencies of students' perceived affordances and constraints for learning by treatment group. For the Traditional group, students reported the static diagram was useful because it was better than not having any diagram, it provided a basic idea of how the parts go together, and it provided information (such as dimensions and velocities) necessary for solving the problem. However, students indicated that a static diagram is not very helpful in showing the movement of the parts or how the machine worked. For example, one student wrote, "While the diagram gave me the physical form of the object, it didn't help to convey how the pieces moved and worked together." A few students reported the static diagram was not helpful because they already understood how the mechanism worked.

Students in the Physical group reported that the physical manipulatives were helpful in showing the operation of the mechanisms. For example, one student stated, "The model helped by allowing me to visualize exactly how the device worked and see how moving/rotating the different components affected each part." Students also reported that the physical model facilitated making predictions prior to calculations (e.g., "I was able to confirm how I thought the model should act before trying to

Table 1. Opinion Questionnaire Responses Indicating the Model/ Diagram Helped

Treatment	N	Frequency of Yes	Proportion of Yes
Traditional	25*	21	0.84
Physical	21	17	0.81
Virtual	23	15	0.65

* Missing a questionnaire from one participant in the Traditional group. If a student did not respond *Yes* then the response was coded as *No.*

Table 2. Frequencies of Students' Perceived Affordances and Constraints for Learning by Treatment

Code	Frequency
Traditional	
Affordances	
Better than just a description	8
Gives basic understanding of machine	6
Provides information necessary to solve problem	2
Constraints	
Difficult to visualize motion	4
Didn't help understand how machine works	3
Geneva mechanism hard to visualize	3
Could visualize without model	3
Physical	
Affordances	
Helps see how machine works	11
Seeing/interacting instead of imagining	3
Helps verify/check assumptions/theories	2
Allows you to manipulate how machine moves	2
Constraints	
Could visualize without model	2
Virtual	
Affordances	
Helps see how machine works	12
Seeing machine move helps	2
Constraints	
Problems with model	5
Could visualize without model	2

solve a problem.") Similar to the Traditional group, students in the Physical group reported that the physical manipulative was not as helpful if they could already visualize the machine from the static diagram.

Students in the Virtual group reported that the virtual manipulative was helpful in showing the operation of the machine, and in facilitating predictions prior to calculation, similar to the physical group responses. For example, one student responded, "The virtual model really helped me be able to visualize what was happening in the problem. It especially helped me understand the way different components interacted - particularly in the star wheel [Geneva] problem." Students' reported constraints for learning with the virtual manipulative matched the observed constraints, with students' frustrations with technical problems evident in their responses. For instance, one student wrote, "While the model made it more clear for me to understand the question, for the questions that we did it made me more confused because things look like they were moving faster when they were slower or vice versa" and another student wrote, "Many times the CAD software had glitches which prevented the model from operating as it would in real life. Gears would skip or slide, and it was a pain. Most of the time [I] could already tell what it was doing." Aside from the technical problems, students in the Virtual group also indicated that the manipulative was of limited help if they could already visualize the motion of the mechanism.

Table 3. How the Models Could Be Improved

Code	Frequency
Traditional	
Multiple views (time)	11
Better description of motion	6
Multiple views (angle, +3D)	4
Physical	
Fix bugs/jams	12
Improve user controls	2
Virtual	
Fix bugs/jams	9
Real time measurements (e.g., velocity, acceleration)	5
Animation on loop (w/start/stop/pause)	2

In response to the question of how their models could be improved (Table 3), the most frequently occurring theme in the responses of the Traditional group was that the static diagram could show movement better by having multiple views of the machine at different times in its operation (like multiple frames from an animation). Student responses in the Physical group focused on the jamming or loose tolerances of the physical manipulatives, which was the most frequent response on the questionnaire. Other suggestions from the Physical group were to improve the user controls such as adding reference or measurement markings. Students in the Virtual group were fixated on the technical problems that they experienced loading and using the CAD models. The most frequent comments were to fix the technical problems. Other frequent suggestions were to add real-time measurement information (such as the velocity of parts), and hands-free animation (as opposed to manipulation).

Not surprisingly, the most frequent response from the Traditional group students to the question of what else would be helpful was to give them physical models (Table 4). The second most frequent response was to give them virtual models. Sometimes the students wanted both physical and virtual models ("I found myself wishing I had either a physical or CAD model multiple times"). Other suggestions include videos or animations of the machines ("A short video of the 3D models might have been helpful"). The most frequent requests from the Physical group students were for some kind of equations sheet, a detailed description of how the mechanisms work ("A better explanation of the exact movement of the physical model to emulate the problem"), and some way to take measurements from the model ("If you were able to see quantitatively how fast things were moving"). Two individuals from the Physical group also requested virtual manipulatives ("Using the CAD models along with the physical models may have helped more"). Students in the Virtual group requested a physical model more than anything

Table 4. What Other Things Might Help

Code	Frequency
Traditional	
Physical model	12
Virtual model	6
Better knowledge of math/theory	3
Explanation of how mechanism works	3
Video/animation of 3D models	3
More problem solving	2
Multiple views (time)	2
Unspecified visual instruction beyond traditional	2
Physical	
Equations sheet	3
Explanation of how mechanism works	3
Measurement (e.g., velocity)	3
Virtual model	2
Better knowledge of math/theory	2
Virtual	
Physical model	8
Explanation of how mechanism works	3
Video/animation of 3D models	3
Better knowledge of math/theory	3
Equations sheet	2

else ("I would have liked to try the physical models because I feel those would help me the most"). They also requested video/animation ("While it helped my understanding to be able to manipulate the model myself, I think it would have been additionally helpful if I had set the rotation to a set speed and watched that. Sometimes my inability to rotate or move parts at a precisely constant speed made it more difficult to grasp the relations between parts completely"), a description of how the mechanisms work, and better understanding of mathematics and theory ("A hint as to which variables in which equations was related to which component").

4.3 Changes in mechanical reasoning

Results suggest that physical and virtual manipulatives might help students' mechanical reasoning better than traditional instruction alone (Table 5). Students in the manipulatives groups were more likely than the Traditional group students on the posttest to identify the correct relative speed of the output shaft in the planetary gear set, the correct direction of the output in the rack & pinion machine, the correct speed of the Geneva Drive, and the correct speed of the near-transfer planetary gear set. The percentage of correct responses for either speed or direction for the treatment groups ranged from 55% (on the near-transfer problem) to 92% (on the Geneva drive). The Traditional group showed lower performance, with percentage correct responses ranging from just 37% on the near-transfer problem to 83% on the Geneva drive problem. This observation of treatment groups outperforming the control group is broadly consistent with prior reports [37] that conclude the nature of the manipulative (physical or virtual) is not as important as its availability to students during the treatment.

Question 1: Planetary Gear Set (Sun Driven). For this item, the problem (see Appendix A for a schematic and full problem statement) asked students to describe the rotational speed (angular velocity) of the output (the shaft attached to the planet carrier) relative to the rotational speed of the input (the sun gear). The correct answer is that the output shaft should rotate slower than the sun gear. Students in the manipulatives groups were more likely on the posttest to identify the correct relative speed of the output shaft than the Traditional group. The Physical and Virtual groups, in the

Table 5. Pretest and Posttest Open Response Code Frequencies

			Pretest			Posttest		
Mechanism	**Code**		**T**	**P**	**V**	**T**	**P**	**V**
Planetary gear set (sun-driven)	Direction	Correct	13	9	15	15	7	16
		Incorrect	9	5	6	8	8	6
	Speed	Correct	6	5	5	9	12	12
		Incorrect	15	10	13	9	3	4
Rack & pinion	Direction	Correct	10	7	8	13	12	15
		Incorrect	13	13	11	10	5	4
	Speed	Correct	15	14	13	14	13	16
		Incorrect	1	2	2	9	3	4
Geneva drive	Direction	Correct	16	17	14	21	14	16
		Incorrect	5	1	4	1	1	2
	Speed	Correct	4	2	6	11	17	18
		Incorrect	11	8	5	6	1	2
Near-transfer planetary gear set (ring-driven)	Direction	Correct	n/a	n/a	n/a	13	12	13
		Incorrect	n/a	n/a	n/a	9	6	7
	Speed	Correct	n/a	n/a	n/a	3	7	8
		Incorrect	n/a	n/a	n/a	18	9	11

identification of speed of the output for the planetary gear set, flip from majority incorrect (by about 2:1) on the pretest to majority correct (by about 4:1) on the posttest. Students in the Traditional group were mostly incorrect (2.5:1) on the pretest and changed to an even split on the posttest.

On both the pretest and posttest, many students had difficulty interpreting the speed and/or direction of the movement. Many students violated the problem statement or initial conditions of the problem by assuming that the ring gear was rotating or that the input was coming from something other than the sun gear. Content analysis revealed that student explanations often took a causal chain approach starting with the interaction between the sun gear and planet gears, then a planet gear and the planet carrier, and finally the planet carrier and the output shaft. Students often ignored the effect of the stationary ring gear, typical of student responses with the wrong direction.

Question 2: Rack & Pinion. The rack and pinion question asks students to describe the speed and direction of the slider/sleeve, B, given that the input is constant rotational motion of the pinion gear, O. Students in the Physical and Virtual groups made progress in the identification of direction of the output for the rack & pinion from pretest to posttest, changing from the majority incorrect (almost 2:1 for the Physical group, about 1.5:1 for the Virtual group) on the pretest to a wider margin of majority correct (about 2.5:1 for the Physical group, almost 4:1 for the Virtual group) on the posttest. The Traditional group remained about the same from pretest to posttest.

Many students incorrectly indicated a rightward direction for the slider, B. This response was so frequent that it outnumbered the correct response across all treatments in the pretest. Rightward motion of B is consistent with analysis that does not take into account the leftward translation of the pinion, or that the leftward translation is not sufficient to negate or overcome the action of the linkage "pushing" B to the right. Some students tried to accommodate the leftward translation of the pinion gear by describing the pinion as dragging the oscillating slider gradually to the left. Additionally, many responses described the rotation of the pinion as if the pinion rotated about a fixed (not translating) point (in which case B would oscillate back and forth, a behavior which many students described). B is actually moving to the left and accelerating to the right (i.e., decelerating) at the instant depicted in the diagram. Additionally, most students with incorrect responses ignored the effect of the stationary rack and the existence of an instant center at the contact point between the rack and pinion. Instead, many students used a causal chain from the center of the pinion gear O (which they assumed to be a fixed point) to the connection point A, A to the linkage, and the linkage to B, which resulted in the incorrect direction.

Question 3: Geneva Mechanism. The Geneva problem asked students to describe the direction and speed of the star wheel, A, as a result of constant rotation of the drive wheel, B. The correct answer is that for B rotating clockwise with constant angular velocity, A rotates counterclockwise with intermittent motion. Although there was little change in the direction from pretest to posttest across groups, all groups improved on correctly identifying the intermittent output on the posttest. Results suggest that both Physical and Virtual groups may have derived benefit (17:1, 9:1, respectively) compared to the Traditional group (11:6) on the identification of the correct speed. On the pretest, many students explicitly stated that they did not understand the diagram (six in the Traditional group, two in the Physical group, and five and the Virtual group). For instance, one student stated, "I have no idea what this is or how it is turning," while another wrote, "I can't tell what this machine does, the picture is kind of confusing." However, by the posttest, no students reported any such confusion.

Question 4: Planetary Gear Set (Ring Driven). The posttest included one near transfer item not used on the pretest. The item asked students to reason about the behavior of output shaft A in the same planetary gear set from open response problem 2, given a different set of initial conditions where the ring gear R is now the input and the sun gear S is held fixed. The correct answer is that the output shaft rotates at a slower rate but in the same direction as the ring gear. Students performed similarly on identifying the direction of motion across groups. However, a larger proportion of physical and virtual students (7/9 and 8/11, respectively) had the correct response for speed as compared to the traditional group (3/18). Across all groups, larger proportions of students gave an incorrect answer than the proportion of students giving a correct answer.

5. Discussion

In this study, we compared the use of static diagrams in dynamics augmented with physical and virtual manipulatives to instruction with static diagrams alone. Using observations, student questionnaires, and pretest/posttest open response assessment items, we aimed to triangulate affordances of physical and virtual manipulatives for learning dynamics in authentic contexts.

Results from observations and questionnaires reveal major trends across groups. All groups used the models as an aid for communicating their ideas, similar to other research that demonstrates the utility of external representations as communication tools [12], but the Traditional group supplemented their diagrams with gestures to indicate motion. All student groups tended to use the models for a very small amount of time (seconds at a time) compared to the overall time spent working on a problem.

Students reported that actually seeing how the mechanisms worked and moved was a benefit of both the physical and virtual manipulatives for learning, mirroring inherent differences between the static diagrams and dynamic models. Students in both the Physical and Virtual groups reported that it was helpful to see the parts move, whereas students using the static diagram alone overwhelmingly reported that the key constraint of the static diagrams was that they did not depict motion and that some way to see the motion would have been helpful.

Another inherent difference between the static diagram and the dynamic models were the ability for students to interact with the physical and virtual manipulatives. Observations and students' perceptions revealed that both physical and virtual manipulatives enabled students to test their ideas or make predictions about the behavior of the machine. The physical and virtual models enabled students to interact with the system and see the results of those interactions, providing feedback to the students on their ideas or predictions. Similarly, the ability to interact with the physical models seemed to afford play or constant manipulation more so than the virtual or static representations. Having the physical model readily available on the desk seemed to promote direct manipulation.

Major constraints of the different representations align with inherent differences of the tools. The physical manipulatives had constraints due to real-world issues such as manufacturing and assembly tolerances. Major constraints observed for the virtual manipulatives involved technical issues in loading the manipulative, moving parts beyond their intended limits, and lag times.

Another constraint of the physical and virtual manipulatives resulted from design decisions of the researchers. Neither the physical nor virtual manipulatives had any numerical indication of parameters of the mechanism (such as the angular velocity or acceleration of components). Other dynamics studies have included this affordance in simulations [8]. Numerical readouts could be incorporated as part of the virtual manipulatives. However, we decided to use virtual manipulatives that were intentionally analogous to their physical counterparts (which did not have any kind of real-time numeric displays) as well as omit the numerical inputs or readouts to focus students' attention on the overall motion of the mechanism, instead of getting specific numbers correct.

Overall, pre/post results suggest that the physical and virtual group had an advantage over the traditional group in identifying direction or speed of the three mechanical systems. Students in the Physical and Virtual groups also tended to provide correct responses more often than the Traditional group on the near transfer planetary gear set, suggesting that the students in the Physical and Virtual groups may have been better able to mentally visualize the planetary gear set and use that understanding in another related context.

The combination of observations, questionnaire responses, and pre/post results suggests interesting ways that the static, physical, and virtual representations may have helped or hindered reasoning about dynamic systems. Pre/post results suggest that improvement in the physical and virtual groups was generally only observed for either direction or speed, but not both. Why one and not the other? The answer may be due to the prior knowledge of the students and the related most salient (or troublesome) aspect of motion. For example, for the planetary gear set (Question 1) the Physical and Virtual groups exhibited slightly better improvement of performance than the Traditional group on the identification of correct speed on the posttest, but there were no differences on the identification of direction across groups. Students in dynamics classes may generally understand how gearsets transmit motion and thus are able to determine the correct direction a component rotating at the end of a causal chain of gears equally well with static, virtual, or physical representations. However, physical and virtual manipulatives may help students understand the more difficult aspect of relative speed, as static diagrams typically are limited in their representation of changes over time—crucial to understanding relative speed. Similarly for the Geneva drive, results suggest that students could generally reason about direction, but did not understand that the star wheel moves intermittently on the pretest. The physical and virtual dynamic manipulatives make this motion instantly clear, and it is therefore reasonable that students exposed to a manipulative would remember this behavior. Those with only a static diagram had a less helpful experience from which to guess (or reason) about the Geneva drive's behavior. Results align with other studies demonstrating the role of prior knowledge in learning with dynamic and static representations [38].

A very interesting related result was the role of stationary components on students' reasoning. Results suggest that none of the representations made the role of the stationary component particularly salient to these students—these include the rack in the rack-and-pinion problem and the fixed gear in the planetary gearset problems. Many incorrect student responses across questions revealed that students tended to overlook stationary components that were not in a direct path from the input motion to the output motion, which resulted in faulty reasoning about the system in pretests and posttests. Although these components may not be in the direct path of motion, the stationary component dictates the direction of motion.

The underlying concept from rigid body kinematics in these two problems is the *instant center*, and previously-reported DCI results support the notion that students struggle with this concept [39; Question 22]. We suspect that while the physical and virtual manipulatives reveal motion to students using them, they do not explain critical underlying concepts such as the instant center. As such, while students generally perform better on the posttest (for the same problem), they may not perform as well on the near-transfer problem because they do not fully understand the important underlying concept. This suggests that interventions involving manipulatives could also be accompanied by textual descriptions or other learning resources that fully describe the foundational concepts at play in a particular problem.

6. Limitations

The transfer problem (ring-driven planetary gear set) aside, it is possible that what we have measured in the posttest is experiential recall for the Physical and Virtual groups. However, all three groups solved problems for these mechanisms, and many students in the Traditional group—despite having used proper mathematical procedures to solve the problems—still did not correctly describe how the mechanisms operate. These findings suggest that giving students exposure to manipulatives can help with their mechanical reasoning (versus just solving math problems).

Additionally, both virtual and physical manipulatives had observed constraints due to design and manufacturing (e.g. slow computer performance, sticky physical mechanisms). These constraints may have limited the amount of time and/or the willingness of the students to use the manipulatives, which may have affected the results. Similarly, students' focus on mathematical problem solving instead of conceptual understanding may have influenced the results. Although affordances and constraints are highly situated in particular learning contexts, with more research the field can begin to distill design principles for effective dynamic manipulatives. Future research should investigate how manipulatives may provide different affordances and constraints for students learning dynamics in different authentic situations.

Although providing students access to how these mechanical systems work may contribute to their understanding of the particular system, research suggests that giving students visualization supports may actually short-circuit crucial cognitive processes of having to mentally animate the components [40]. However, other research suggests the potential of giving students equal experiences to ameliorate any visuo-spatial skill differences [41]. Future research should investigate how the benefits of manipulatives may interact with students of varying spatial ability.

7. Implications

As reported by the students, manipulatives are less beneficial when one's math proficiency and/or theory knowledge is insufficient to tackle the problem. Instead of simply adding manipulatives without direction, manipulatives should be included as part of a curriculum that takes advantage of their affordances, making the best use of them in the ways that they are most useful. For instance, instructors can integrate manipulatives to help students understand the motion of systems alongside helping students understand governing concepts and learn how to perform calculations. Without proper integration, instructors should not expect significant benefits.

Results also suggest that dynamics instructors should pay particular attention to helping students understand not only how elements in dynamic systems move, but also how stationary components and the concept of instant center are involved in determining the direction and speed of the mechanism. Results demonstrate that neither static, nor physical or virtual models made the importance of stationary components or instant center particularly salient to students. Helping students develop strategies to reason using all parts of the mechanism may enhance student success in dynamics.

The small amount of usage time for physical manipulatives suggests potentially limited use of physical manipulatives due to the expense, maintenance, and storage requirements of the physical models. Physical manipulatives could concentrate on a few prototypical mechanisms from which students can abstract principles of operation and transfer them to other systems. The similar outcomes from physical and virtual manipulatives also suggests that virtual manipulatives can be used if instructors have access to sufficient computing hardware and software, as the virtual models have relatively minimal replication costs, storage costs, transmission costs, and are much easier to customize and change than physical manipulatives.

This study points to the importance of the design of the manipulatives and iterative refinement based on authentic implementation in classrooms. As was evidenced by the widespread discontent in the Virtual group with the CAD models, implementation details can have a significant impact on user perceptions (and the consequent helpfulness of the manipulatives). Future research could perhaps investigate developing specific software designed to be used for this purpose (as opposed to repurposing a general CAD system). Implementation details also affected the physical models, serving to distract the students (many students were observed fidgeting with the physical manipulatives, attempting to tighten the fasteners). Improvements in mechanical reasoning gained from using the manipulatives seem to be highly dependent upon the nature of the manipulatives (in this study, the particular machines and manipulatives that did not have numerical input/outputs), and thus more research is needed to clarify what kinds of manipulatives work in what contexts with particular learners.

8. Conclusions

Although dynamics courses are inherently about dynamic systems, instruction often relies on static representations of mechanisms. This work explored affordances and constraints of adding dynamic physical and virtual models for learning dynamics. Primary affordances of both physical and virtual models for learning dynamics included direct experience of motion of the mechanism, the ability for students to test or verify their ideas about the mechanism's operation, and facilitating communication for collaborative learning. Pretest to posttest gains suggest adding physical or virtual models to instruction can help students develop dynamic mechanical reasoning. This study contributes to the larger body of research on helping students develop mechanical reasoning in engineering.

Results provide insight to dynamics instructors, as students need help to understand not only movement, but also how stationary components and the concept of instant center affect dynamic mechanisms. Providing strategies to help students reason about mechanisms holistically may enhance student success in dynamics. Additionally, adding dynamic manipulatives along with learning resources or instruction that focus on fundamental concepts may provide the most benefit to students.

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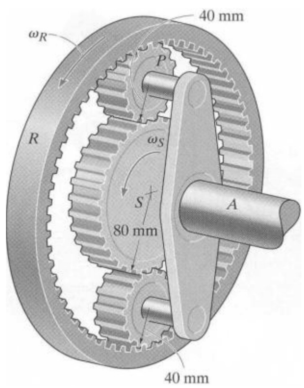
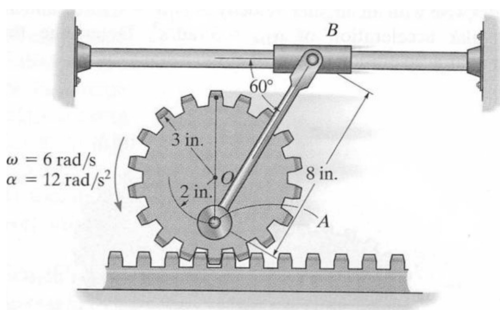
Appendix A: Problem Solving Session Problems

The problems are taken directly from *Engineering mechanics: Dynamics* (12th ed.), by R. C. Hibbeler (2010), and used with permission from the publisher (Pearson). Each problem was presented on a separate sheet of paper, with blank space beneath the diagram for students to write their work and answers.

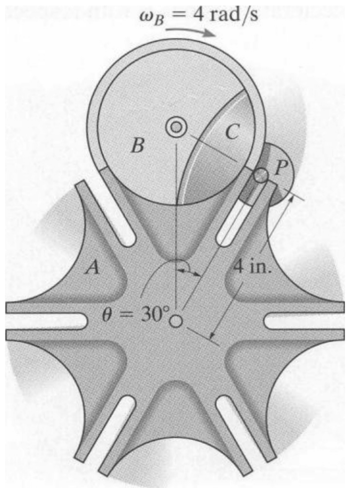
Problem 1 (Hibbeler problem 16–64, p. 347)
The planetary gear system is used in an automatic transmission for an automobile. By locking or releasing certain gears, it has the advantage of operating the car at different speeds. Consider the case where the ring gear R is held fixed, $\omega R = 0$, and the sun gear S is rotating at $\omega S = 5$ rad/s. Determine the angular velocity of each of the planet gears P and shaft A.



Problem 2 (Hibbeler problem 16–128, p. 375)
At a given instant, the gear has angular motion shown. Determine the accelerations of points A and B on the link and the link's angular acceleration at this instant.



Problem 3 (Hibbeler problem 16–160, p. 390)
The Geneva mechanism is used in a packaging system to convert constant angular motion into intermittent angular motion. The star wheel A makes one sixth of a revolution for each full revolution of the driving wheel *B* and attached guide *C*. To do this, pin *P*, which is attached to *B*, slides into one of the radial slots of *A*, thereby turning wheel *A*, and then exits the slot. If *B* has a constant angular velocity of ωB = 4 rad/s, determine ωA and αA of wheel *A* at the instant shown.



Appendix B: Student Opinion Questionnaire

The participants were asked to answer the following questionnaire after submitting their posttests.

Please answer the following questions. You can skip any questions that you are uncomfortable with.

1. Which treatment group were you in? (circle one)

   Traditional Virtual (CAD) Physical

2. Did the model (diagram for the Traditional group) help you understand and solve the problems?

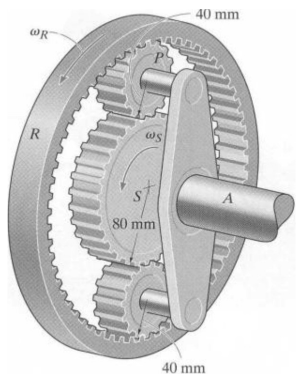
   Yes No

3. Please explain how the model (diagram for the Traditional group) helped or did not help you understand and solve the problems:
4. What could be done to the model (diagram for the Traditional group) to improve its usefulness in helping you understand and solve the problems?
5. What else would have been helpful to have to aid you in understanding and solving the problems?
6. Please write any other comments/suggestion that you have regarding your experience:

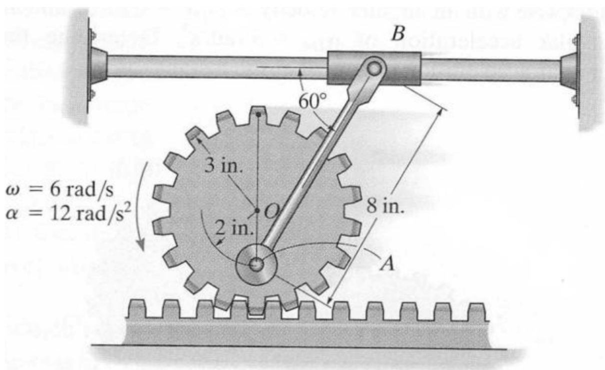
Appendix C: Pretest and Posttest Questions

The diagrams for these questions come from *Engineering mechanics: Dynamics* (12th ed.), by R. C. Hibbeler (2010), and used with permission from the publisher (Pearson).

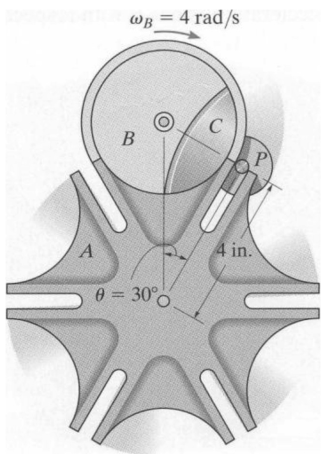
Question 1: Planetary Gear Set (Sun Driven)
Describe how this machine works. Please include a description of the direction (clockwise, counterclockwise) and speed (constant, varying) of the structure at A in relation to the input (constant rotational motion of the inner gear S) when the outer gear R is held motionless. If the speed varies, please describe how it varies in relation to the input. If the speed is constant, please describe whether it is faster than, slower than, or the same as, the rotational speed of the gear S. DO NOT PERFORM CALCULATIONS.



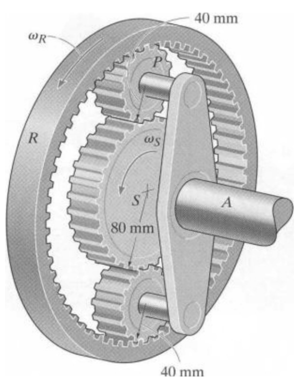
Question 2: Rack & Pinion
Describe how this machine works. Please include a description of the direction (left, right) and speed (constant, varying) of the structure at B in relation to the input (constant rotational motion of the circular gear O). Note that the gear O is free to move horizontally and the structure at B is also free to move horizontally. If the speed varies, please describe how it varies in relation to the input. DO NOT PERFORM CALCULATIONS.



Question 3: Geneva Mechanism
Describe how this machine works. Please include a description of the direction (clockwise, counterclockwise) and speed (constant, varying) of the star wheel A in relation to the input (constant rotational motion of the driving wheel B). Note that the guide C and pin P are fixed to the driving wheel B. If the speed varies, please describe how it varies in relation to the input. If the speed is constant, please describe whether it is faster than, slower than, or the same as, the rotational speed of the driving wheel B. DO NOT PERFORM CALCULATIONS.



Question 4: Planetary Gear Set (Ring Driven)
OR5. Describe how this machine works. Please include a description of the direction (clockwise, counterclockwise) and speed (constant, varying) of the structure at A in relation to the input (constant counterclockwise rotational motion of the outer gear R) when the inner gear S is held motionless. If the speed varies, please describe how it varies in relation to the input. If the speed is constant, please describe whether it is faster than, slower than, or the same as, the rotational speed of the gear R. DO NOT PERFORM CALCULATIONS.



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