Cognitive Benefits of Using the Kinetic Diagrams in Teaching Introductory Dynamics

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Abstract

Whether kinetic diagrams should be used in teaching dynamics has been discussed in the literature. It was recommended to use free-body diagrams without kinetic diagrams in solving rigid-body kinetics diagrams. This paper will examine the cognitive benefits of using kinetic diagrams in terms of reducing unnecessary cognitive load and facilitating efficient practice. I will first evaluate the benefits from the perspective of cognitive load theory. Then, I will show how to exploit the benefits through deliberate practice to enhance learning efficiency. Examples and assessment results will be provided to demonstrate the effectiveness as well as the challenges when teaching with this approach.

Introduction

A kinetic diagram (KD) is a graphical representation of the right-hand side of Newton's second law of motion. It is often used together with a free-body diagram (FBD) to represent the relationship between the external forces on a body and the body's inertial response [1-4] (see Figure 1).

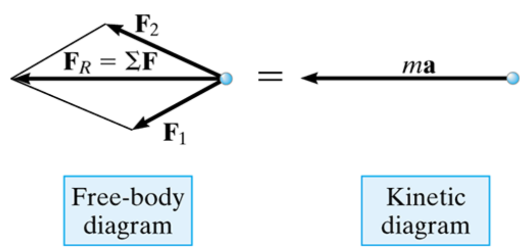


Figure 1FBD and KD [1]

As elaborated in [5], from the perspective of solving kinetics problems, it is not necessary to use a KD. However, we need to examine pedagogical benefits from students' learning perspective. Just like we cannot underestimate the role of a user manual for beginning users because of its redundancy for experienced users, we need to revisit the role of the kinetic diagram in the teaching of introductory dynamics. In this paper, I will demonstrate the cognitive benefits of using kinetic diagrams based on Cognitive Load Theory, an instructional design framework derived from the cognitive architecture.

Just like we need to follow laws of motion to design machines as engineers, we, as mechanics instructors, should develop instruction strategies by following principles of learning. According to Cognitive Load Theory, learning will be hindered if the cognitive load exceeds working memory capacity [6]. The cognitive load could be imposed by either the intrinsic nature of learning materials (i.e., intrinsic cognitive load) or the instruction manners in which the materials are presented (i.e., extraneous cognitive load). Therefore, we need to keep students' working memory limitation in mind when we design teaching materials. This concern is crucial for teaching dynamics because of the inherent complexity of the subject which can easily result in high cognitive load especially for students with insufficient prior knowledge. Cognitive load theory has provided strategies that address this issue by sequencing learning tasks in an appropriate order. The use of a kinetic diagram is derived from these strategies.

In this paper, I will first provide a cognitive load explanation based on cognitive load theory to illustrate the benefits of using a kinetic diagram. Then I will show how I use kinetic diagrams in teaching dynamics followed by the results and discussion.

Theoretic Framework: Cognitive Load Theory

Based on human cognitive learning processes, cognitive load theory has provided a comprehensive set of instructional principles [6]. Since our working memory can only process 7 ± 2 individual items at one time, learning will be hindered if information to be processed exceeds those limits [1-2]. Based on this rule, cognitive load theory provides specific instructional guidelines which minimize wasted mental resources and put limited mental resources to work in ways to maximize learning.

Cognitive load imposed on working memory can be divided into two categories: intrinsic cognitive load and extraneous cognitive load [6]. As indicated by the names, intrinsic cognitive load refers to the mental work determined by the intrinsic nature of learning materials that the learner needs to acquire for achieving learning goals while the extraneous cognitive load refers to the mental work which is unnecessary and extraneous to learning goals. Intrinsic load is primarily determined by instructional goals or the intrinsic nature of the materials; extraneous load is solely caused by the instructional procedures in use. Since intrinsic load is related to the complexity of learning materials, difficult learning materials will of course impose more cognitive load than easy ones. Generally, we cannot change intrinsic load during instruction due to its intrinsic nature. By contrast, extraneous load must be controlled through instructions because it wastes limited mental resources which should be committed to intrinsic load to maximize learning. Instruction guidelines provided by cognitive load theory are to balance mental work load to achieve efficient learning.

Instructional Implications from Cognitive Load Theory

Cognitive load theory could explain why dynamics is deemed as one of gauntlet courses for engineering students. If learning materials of a subject result in excessive cognitive load, the subject will be challenging. Solving dynamics problems requires students to have both solid conceptual understanding and detailed procedural knowledge. For example, solving a particle kinetics problem about a circular motion requires at least the following knowledge elements:

1. Be able to draw an FBD to show all external forces acting on the particle.
2. Be able to choose the normal/tangential coordinates to analyze the motion.
3. Understand the relationships between the normal/tangential accelerations and the direction/magnitude of the velocity.
4. Be able to set up the equations of motion by applying Newton’s second law of motion.
5. Be able to find kinematics relationships.
6. Be able to solve the system of equations.

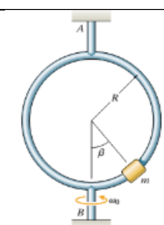
If students do not have strong prior knowledge, each element will be treated as a piece of new information to be processed in working memory. These elements altogether impose excessive cognitive load due to the intrinsic nature of the complexity. This learning challenge is interpreted as a high level of element interactivity. After new elements are learned, they will be incorporated into a single unit known as a schema stored in long term memory. Even a schema is consisted of several elements, it can be treated as a single item in working memory because all elements are coherently related instead of in isolation. As you may realize that we could reduce the cognitive load by helping students develop schemas to unite individual elements. The use of kinetic diagrams serves this purpose. In cognitive load theory, this strategy belongs to the category known as “the element interactivity effect” which provides strategies proved to be effective in altering element interactivity such that the level of intrinsic cognitive load is compatible with learners’ working memory [6].

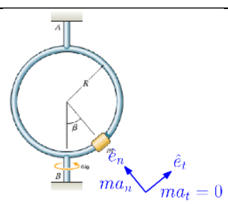
As explained above, solving kinetics problems involves several elements which must be processed simultaneously in working memory. However, we do not have to teach all the elements at the same time. Instead, we could focus on a specific element at one time to help students develop relevant prior knowledge if each element can be learned in isolation. This strategy is referred to as *pre-training* [6]. For example, drawing an FBD or a KD does not rely on knowledge from other elements in solving kinetics problems. Therefore, we could offer such pre-training to help students build and consolidate the essential skills for later use. On the other hand, compared to learning all elements at the same time, learning how to draw a KD presents significantly reduced intrinsic cognitive load because of the much lower level of element interactivity.

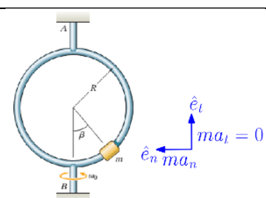
You may argue that drawing a KD is too trivial to be isolated in instruction. Let’s use an example to illustrate that such seemingly trivial step for instructors is often a hurdle for students. In this example (Table 1), students were asked to choose the correct KD (also known as mass-acceleration diagram or MAD) from the following four options listed in the table. Only 6 students, one fifth of the class, chose the correct answer and there were only 2 of them indicating that they can justify the answer which implied that some of them may just guess the right answer.

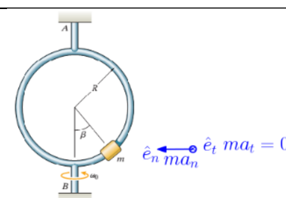
Table 1 An example of finding a KD.

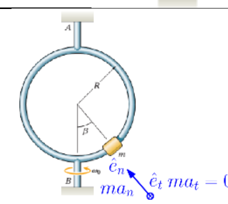
Problem Statement: the smooth circular bar rotates with constant angular velocity about the vertical axis. The mass m remains stationary relative to the circular bar. Choose the KD for finding the value of the constant angular velocity [7].











This example shows that trivial steps for instructors could be stumbling blocks for students. Teaching how to draw a KD as an explicit step will greatly reduce the intrinsic cognitive load to consolidate the important skill for solving kinetics problems. Without doing so, we might not even notice this knowledge deficiency.

In addition to the benefit of reducing the intrinsic cognitive load, using a KD could also increase intrinsic cognitive load when students' knowledge and skills grow with learning. After students have built more effective schemas through learning, intrinsic cognitive load requires fewer cognitive resources and the level of element interactivity could be increased. Since the FBD and KD represent the two sides of Newton's second law of motion, showing correct diagrams has indicated that students could set up equations of motion if they know how to represent and resolve vectors in the chosen coordinate system. Since showing diagrams of a given problem could only take several minutes while solving the whole problem might need half an hour, we could ask students to solve more problems by showing diagrams only. In this way, students will be exposed to a variety of scenarios without excessive practice time. This strategy is known as "the variability effect" in cognitive load theory.

In summary, the use of kinetic diagrams in teaching dynamics could alter intrinsic cognitive load to use limited working memory resources more efficiently to facilitate learning.

Instruction

Over the fifteen weeks of instruction, topics are organized as preliminary knowledge, particle kinetics, rigid body kinetics, energy methods, and momentum methods. Both FBD and KD are introduced in the preliminary knowledge module to provide pre-training as explained in the previous section.

The lectures on KD include two parts: particle and rigid body. Particle kinematics is part of KD because it requires understanding of particle kinematics relationships to choose an appropriate coordinate system and determine whether the inertial vector is nonzero. In contrast, drawing a KD for a rigid body kinetics problem only needs identifying ma_{Gx}, ma_{Gy}, and $I\alpha$ which can be perceived intuitively without knowing rigid body kinematics in depth. Therefore, rigid body kinematics is introduced as the last step in solving kinetics problems.

To help students structure their thought process more efficiently, a detailed procedure is provided as illustrated in Table 2. The logic underpinning the procedure is presented in class to help students understand the procedure instead of memorizing it by rote.

Assignments

Before solving any kinetics problems, students only need to draw FBDs and KDs. Assignments on KD have two types: online and on paper. Online assignments focus on addressing common mistakes in drawing KDs as listed in Table 3 and the assignments on paper let students practice drawing KDs. Problems are usually presented online first to direct students' attention to important aspects of drawing KDs such that students are prepared better for drawing KDs on paper. When students are asked to solve kinetics problems, they usually have seen these problems twice: first as an online assignment followed by an assignment on paper. With such preparation, most students are able to draw FBDs and KDs effortlessly so they could focus their limited working memory capacity on the rest of work such as resolving vectors in each direction and setting up sufficient equations for unknowns.

Table 2 Procedure for drawing a KD.

Particle	$\hat{\imath}/\hat{\jmath}$	1. Draw the unit vector of each direction near the FBD. 2. Write ma for each direction beside the corresponding unit vector. If the acceleration is zero, explicitly indicate it (e.g., $ma_y = 0$).
	$\hat{e}_n/\hat{e}_t/\hat{e}_b$	1. Draw $\hat{e}_n$ towards the center of rotation and write ma_n beside $\hat{e}_n$. 2. Draw $\hat{e}_t$ along the tangential direction. If v or ω changes, write ma_t beside $\hat{e}_t$. Otherwise, write $ma_t = 0$. 3. If necessary, draw $\hat{e}_b$ and write $ma_b = 0$.
	$\hat{e}_r/\hat{e}_\theta$	1. Draw $\hat{e}_r$ and $\hat{e}_\theta$. 2. Write ma_r and ma_θ beside the corresponding unit vector.
Rigid Body $\hat{\imath}/\hat{\jmath}$		1. Draw the unit vectors $\hat{\imath}$ and $\hat{\jmath}$ near the FBD. 2. Write ma_G for each direction beside the corresponding unit vector. If the acceleration is zero, explicitly indicate it (e.g., $ma_{Gy} = 0$). 3. Determine whether the object of interest is in translation or rotation. Write $I\alpha = 0$ for translation and $I\alpha$ for rotation.

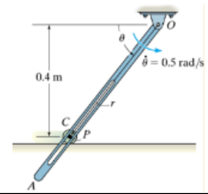
Table 3 Common Mistakes in drawing KDs

		Common Mistakes
Particle	Cartesian	• Misrepresenting the body of interest as a rigid body; • Choosing Cartesian for straight-line motion which requires polar; • Choosing Cartesian for projectile motion which requires normal/tangential.
	Normal/ Tangential	• Misrepresenting the directions of $\hat{e}_n$ of $\hat{e}_t$ when motion is in front view; • Unable to recognize $a_t = 0$; and • Missing $\hat{e}_b$.
	Polar	• Misrepresenting the direction of $\hat{e}_r$.
Rigid Body		• Unable to recognize the body of interest is a rigid body; • Using ma rather than ma_G; and • Missing $I\alpha$.

Lectures are offered three times a week. After each lecture, students are assigned with an online assignment, an assignment on paper, and a MATLAB assignment. All online assignments are presented as quiz problems on Canvas. Students will receive feedback immediately after submission and get access to the assignments on paper which are inserted in a comment box. For all assignments on paper, students are required to scan their work and submit it online. Upon submission, students will have access to the solutions to the assignment which are attached in the comment box and students are required to check the solution on their own and mark all mistakes. Each week, students are required to scan all homework pages with mistakes. For all assignments, students will receive full credits for completion which account for 10% of the final grade. Students, however, will be quizzed on a weekly basis to check their learning performance and the quizzes account for 30% of the final grade.

Let us use a particle kinetics problem as an example to explain how this problem is presented to students as different assignments.

Table 4 An example of different types of assignment on KD.

<table>
<tr><td colspan="2">Problem Statement: The smooth 2-kg cylinder C has a pin P through its center which passes through the slot in arm OA. If the arm is forced to rotate in the vertical plane at a constant rate $\dot{\theta} = 0.5$ rad/s, determine the force that the arm exerts on the peg at the instant $\theta = 60°$ [1].

</td></tr>
<tr><td>Online Assignment
(Assigned on Wednesday of Week 5)</td><td>Choose a coordinate system for the problem.
(a) Cartesian (b) Normal/Tangential (c) Polar</td></tr>
<tr><td>Assignment On Paper
(Assigned on Monday of Week 6)</td><td>Draw an FBD and a KD of the problem.</td></tr>
<tr><td>In-class Quiz
(Friday of Week 7)</td><td>Draw an FBD and a KD of the problem.</td></tr>
<tr><td>Online Assignment
(Assigned on Monday of Week 9)</td><td>Use MATLAB code to represent the summation of forces in the radial direction.
The FBD and KD are included in the problem description.</td></tr>
<tr><td>Assignment On Paper
(Assigned on Monday of Week 9)</td><td>Solve the problem.</td></tr>
</table>

For this problem, students were first asked to select a coordinate system in the online assignment. Only 56% of students chose the correct answer. Then they were asked to draw the FBD and KD of the problem on paper in the following week and 64% of students drew a correct KD. Nine days after this assignment, students were quizzed on the same problem and 74% of students got it right. As a companion assignment to solve the problem, the second online assignment was to identify whether students were able to set up the equation of motion correctly before they solved the problem on paper.

It is a predictable result with such frequent repetitions and the gradual transition in the level of difficulty. It is noteworthy that students may not learn very much if they were asked to solve the whole problem for the first time. As indicated in the result, many students still struggled with the selection of a coordinate system. Not to mention completing the other parts of the solution. Breaking the problem solving process down to small chunks matching students' working memory will make learning achievable. Using kinetic diagrams provides such pedagogical benefit by reducing intrinsic cognitive load to facilitate learning.

As students' knowledge improves, intrinsic cognitive load should be increased accordingly because students' working memory could process more information. Using kinetic diagrams could also serve this purpose. If students are able to draw an FBD and a KD correctly for a given problem, students should be able to solve the problem as long as they could resolve vectors properly and find kinematics equations. Therefore, we could simply let students solve kinetics problems by showing the FBD and KD only, which will substantially reduce the practice time. In other words, students will solve more problems with less time. By increasing the variation of problems, we could efficiently enhance students' learning.

Conclusion

In this paper, I have provided the rationale of using kinetic diagrams in teaching dynamics from the perspective of human cognition architecture. I also shared how I use kinetic diagrams in my class. Future research should improve the experiment design to enhance the reliability and validity of the study.

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