Task-Analysis-Guided Deliberate Practice for Learning Free-Body Diagrams

Abstract

Free-body diagrams (FBDs) are diagrammatic representations of external forces and moments exerted on an object of interest for solving kinetics problems. Several studies have reported different ways of teaching FBDs in terms of pictorial representation of forces (e.g., placement of vectors or labeling). However, little research exists on practice strategies for helping students learn how to draw FBDs. Using task analysis and a subgoal learning model, we develop task-analysis-guided deliberate practice to enhance learning.

Task analysis is often used in instructional design to identify knowledge requirements for a skill. Skill acquisition is usually divided into three phases: forming a declarative representation of the skill, knowledge compilation, and forming a procedural representation. Task analysis in our study identified relevant declarative and procedural knowledge needed for drawing FBDs. The knowledge identified is the "raw material" around which a deliberate practice scheme is then developed. Deliberate practice can help novices develop good representations of the knowledge needed to produce superior problem solving performance. This has been viewed as a gold standard for practice. Although deliberate practice is mainly studied among elite performers, recent literature has revealed promising results for novices. We apply cognitive load theory to develop deliberate practice to help students build declarative and procedural knowledge without exceeding their working memory limitations.

In this study, a knowledge extraction expert took an iterative approach to conduct task analyses with a subject matter expert (or experts) to distill knowledge to a level that is appropriate for students in the dynamics course. We then integrated the task analysis results with instructional design strategies derived from cognitive load theory and the subgoal learning model to develop deliberate practice and assessment materials. Examples and assessment results will be provided to evaluate the effectiveness of the instructional design strategies as well as the challenges.

Introduction

Free-body diagrams (FBDs) are diagrammatic representations of external forces and moments exerted on an object of interest for solving kinetics problems. Several studies have reported different ways of teaching FBDs in terms of pictorial representation of forces (e.g., placement of vectors or labeling) [1-4]. However, little research exists on practice strategies for helping students learn how to draw FBDs. Using task analysis and a subgoal learning model, we will develop task-analysis-guided deliberate practice to enhance learning.

Task analysis is often used in instructional design to identify knowledge requirements for a skill. Skill acquisition is usually divided into three phases: forming a declarative representation of the skill, knowledge compilation, and forming a procedural representation. Task analysis in our study identified relevant declarative and procedural knowledge needed for drawing FBDs. A knowledge extraction expert (KEE) took an iterative approach to conduct task analyses with a subject matter expert (SME) to distill knowledge to a level that is appropriate for students in the dynamics course.

The knowledge identified is the "raw material" around which a deliberate practice scheme is then developed. Deliberate practice can help novices develop good representations of the knowledge needed to produce superior problem solving performance. This has been viewed as a gold standard for practice. Although deliberate practice is mainly studied among elite performers, recent literature has revealed promising results for novices. We apply cognitive load theory to develop deliberate practice to help students build declarative and procedural knowledge without exceeding their working memory limitations.

In this paper, we will first provide an introduction to task analysis (TA) and task analysis by problem solving (TAPS) we use in this study. Next we will describe how we applied TAPS in teaching drawing FBDs. Examples and assessment results will be provided to evaluate the effectiveness and challenges of using TAPS in learning and teaching.

Task Analysis by Problem Solving

When creating training or instructional materials, educational researchers and instructional designers must determine both the learning objectives and the specific procedural and declarative (including conceptual) knowledge to be taught; specifying only learning objectives is insufficient. For example, one learning objective is that students should know how to draw FBDs and use FBDs to solve kinetics problems. However, this objective says nothing about what declarative knowledge students might need to achieve this learning objective. Students might have seen an instructor's demonstration on how to draw FBDs. They probably do not understand the procedure’s underlying mechanisms which justify the procedural steps. As a result, they are not able to apply the same mechanism to seemingly different problems. It is important to provide support to help students gain underlying declarative knowledge from the procedures. Therefore, we need to identify these knowledge requirements first. This is where task analysis (TA) can be applied.

Early TA methods focused on improving physical aspects of work to enhance efficiency and safety. As the nature of work has changed from predominantly physical and behavioral to cognitive, cognitive task analysis (CTA) has found broader applications [5-6]. CTA generally involves identifying the knowledge components that underlie task performance, including information processing and representation components in addition to behavioral components.

CTA has been used in the design of training and instruction materials because CTA can help align the content of instruction with learning goals. There are a variety of CTA methods. Task Analysis by Problem Solving (TAPS), the approach we use in this study, is based on observations and interviews [7]. In TAPS, a KEE asks an SME to talk aloud while solving problems, observes the SME solving the problems and explaining his or her reasoning, takes detailed notes, asks questions when needed to clarify what the SME said or did, and uses the notes to solve similar but new problems. Figure 1 provides a diagram of the general procedure of TAPS.

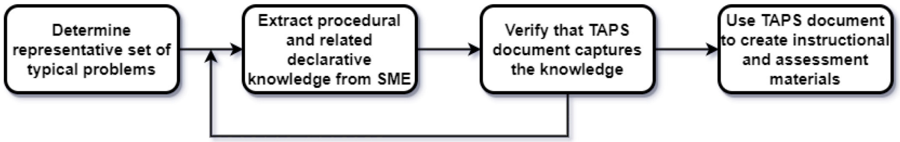


Figure 1 Major steps in using TAPS to create instructional and/or assessment materials

TAPS in Practice

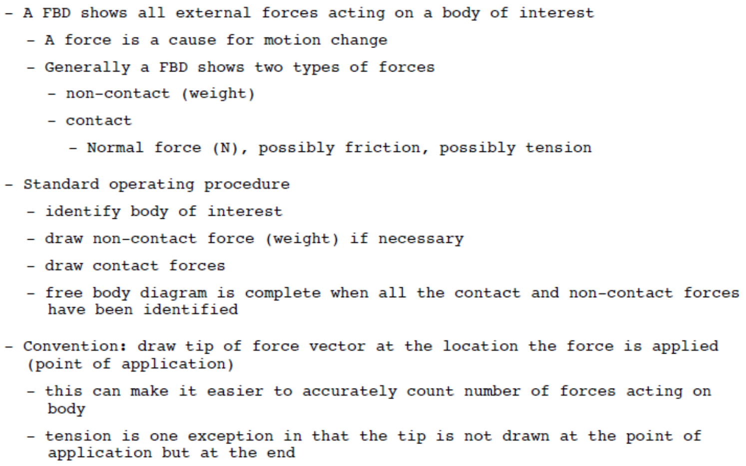
Now we will show how we applied TAPS in developing instructions and assessment materials in teaching how to draw FBDs. In the text below, the SME is the first author while the KEE is the third author.

Step 1: Determine a representative set of typical problems. This is the first session of TAPS. The SME identified a set of typical FBD diagrams from dynamics homework problems. The problems were divided into two sets: one set to be solved by the SME and subsequently by the KEE and one set to be solved by only the KEE. The knowledge extraction sessions began after these problems were selected and divided.

Step 2: Extract knowledge from the SME. The SME solves some problems. The SME and KEE worked together throughout the sessions. The SME drew FBDs in one subset of the problems while the KEE took notes. As the SME drew the FBDs, the KEE prompted the SME to justify the steps.

Step 3: Verify that TAPS document captures the knowledge. In this step, the KEE not only drew FBDs of old problems but also drew FBDs of new problems. After several sessions, using the notes, the KEE first attempted to draw FBDs the SME previously had drawn, and the SME provided help and justifications when requested. After the KEE successfully completed the FBDs of the old problems, he attempted the new subset with the notes he took during his attempt on the first subset while receiving help and justifications from the SME when requested.

Throughout the process, the KEE continuously updated and reorganized his notes. During this iterative process, the KEE developed a procedure of drawing FBDs that was independent of specific examples (see Figure 2 for a subset of the procedure). When the KEE used the notes without receiving any help from the SME to correctly draw FBDs in all the old and new problems, the notes represent a complete TAPS document. The whole process took approximately four hours to complete. Since the KEE's expertise is not related to engineering, the notes are written in his own words to solve problems. In other words, notes might not be written with engineering terminology although they must be technically correct.



- A FBD shows all external forces acting on a body of interest
  - A force is a cause for motion change
  - Generally a FBD shows two types of forces
    - non-contact (weight)
    - contact
      - Normal force (N), possibly friction, possibly tension
- Standard operating procedure
  - identify body of interest
  - draw non-contact force (weight) if necessary
  - draw contact forces
  - free body diagram is complete when all the contact and non-contact forces have been identified
- Convention: draw tip of force vector at the location the force is applied (point of application)
  - this can make it easier to accurately count number of forces acting on body
  - tension is one exception in that the tip is not drawn at the point of application but at the end

Figure 2 Example of the KEE's notes

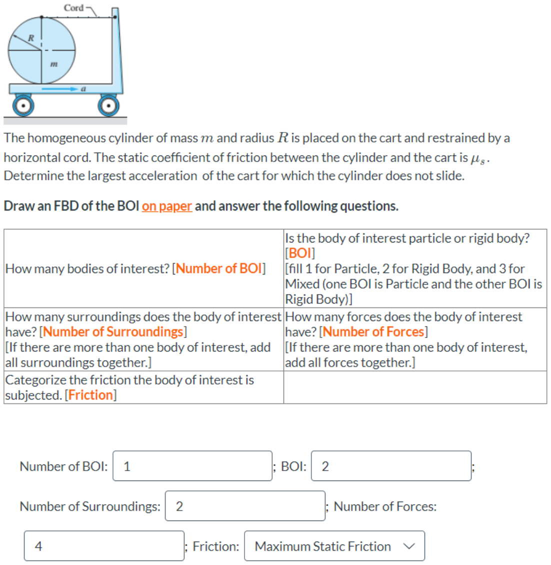
Step 4: Use TAPS document to create materials. The TAPS document was then used as a resource for creating instructional and assessment materials. The document included procedural information along with relevant conceptual information and generally organized around subgoals. The SME uses the document as a record that identifies what students need to know and what can be assessed. It includes detailed information about actual problem solving procedures and steps she might not include because they might be in her expert blind spot. The document is critical to designing effective instruction and assessment as it includes what students need to know to learn the procedure involved in drawing FBDs.

TAPS-Guided Deliberate Practice Design

By analyzing the TAPS notes and typical students' mistakes in drawing FBDs, the SME identified the general procedure for drawing FBDs.

- Step 1: Identify the body of interest.
- Step 2: Draw the non-contact force, which is the weight, if necessary. For diagrams in top-view, no need to show the weight as a cross to indicate the weight is going into the page.
- Step 3: Draw contact forces.
  - Step 3a: Identify all surroundings of the body of interest.
  - Step 3b: Draw forces exerted by each surrounding. Place the tip of each force at the point of application with the only exception with tension. Place the tail of a tension at the point of application. This step helps students use the number of tips to determine whether they have drawn extra forces as there should be at most two forces at each surrounding in a planar motion.
- Step 4: If there is more than one body of interest, repeat steps 2-3 to draw an FBD of each body of interest.

To help students use this procedure to draw an FBD, a series of practice problems were created. As shown in Figure 3, this example asks five questions related to the procedure. All these problems are auto-graded.



The homogeneous cylinder of mass m and radius R is placed on the cart and restrained by a horizontal cord. The static coefficient of friction between the cylinder and the cart is μ_s. Determine the largest acceleration of the cart for which the cylinder does not slide.

Draw an FBD of the BOI on paper and answer the following questions.

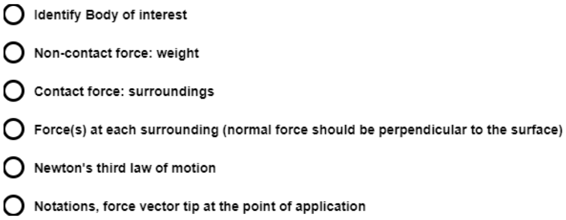
How many bodies of interest? [Number of BOI]	Is the body of interest particle or rigid body? [BOI] [fill 1 for Particle, 2 for Rigid Body, and 3 for Mixed (one BOI is Particle and the other BOI is Rigid Body)]
How many surroundings does the body of interest have? [Number of Surroundings] [If there are more than one body of interest, add all surroundings together.]	How many forces does the body of interest have? [Number of Forces] [If there are more than one body of interest, add all forces together.]
Categorize the friction the body of interest is subjected. [Friction]	

Number of BOI: 1 ; BOI: 2 ;

Number of Surroundings: 2 ; Number of Forces: 4 ; Friction: Maximum Static Friction

Figure 3 A practice problem example.

After completing these online practice problems, students were asked to draw FBDs on paper. A checklist (Figure 4) was provided to help students verify their results.



○ Identify Body of interest
○ Non-contact force: weight
○ Contact force: surroundings
○ Force(s) at each surrounding (normal force should be perpendicular to the surface)
○ Newton's third law of motion
○ Notations, force vector tip at the point of application

Figure 4 A Checklist for Drawing an FBD

Study Design

Our aim was to compare the effects of deliberate practice (guided by TAPS-derived materials) versus "business as usual". A quasi-experimental research design was used for this quantitative study. A total of 59 students enrolled in ES204 Dynamics at Embry-Riddle Aeronautical University in Fall 2020 participated in the study. Two sections were selected and students were randomly assigned to the treatment (28 students) and control group (31 students). The students in the treatment group completed two assignments designed with deliberate practice illustrated in the previous section. The two assignments included 20 problems on drawing FBDs. The students in the control group completed the same problems without being provided with any subgoal information. For example, students in the treatment were given problems like the example shown in Figure 3 while students in the control group were asked for the number of forces in the FBD.

The sample consisted of 64.4% male and 35.6% female. The ethnicity compositions were 50% White, 21.7% African American, 8.3% Hispanic, 11.7% Asian, and 6.7% others. The students' GPAs were equally distributed between the two groups. Institutional Review Board approval was obtained for data collection for the current project. The post-test data were collected through an online class test after the treatment (two assignments created by one of the authors teaching this course).

Quantitative Study Results

Quantitative data analyses were conducted to answer our main research questions:

1. Are there any statistically significant differences in the post-test scores between students in the treatment and control groups after the treatment period? If yes, what are the differences?
2. Are there any statistically significant differences in the post-test scores between students who went through the practices guided by the treatment procedures vs. those who did not go through the practices in the treatment group? If yes, what are the differences?

To answer our first research question, an independent samples t-test was conducted. The analysis results did not reveal any statistically significant differences in the post-test scores between students in the treatment and control groups after the treatment period with $p < .05$.

For our second research question, an independent samples t-test demonstrated a statistically significant difference in the post-test scores between students who went through the practice guided by the treatment procedures (the "Practice I" group) vs. those who did not ($t_{(25)} = -4.04$, $p < .001$; see Table 1). The first group outperformed the second group by 0.9 points (max score of 4). Similarly, the Practice II group outperformed those who did not receive that practice ($t_{(25)} = -3.65$, $p = .001$; see Table 2). The first group outperformed the second group by 0.8 points (max score of 4).

Discussion about the Quantitative Analysis Results

For the first research question, the independent t-test results did not reveal any statistically significant differences in the test scores of the treatment and control groups. This result may be due to the small sample size which resulted in low statistical power. As the project progresses, we are collecting more data with the hope to increase power.

Table 1 *Independent Samples Test for Students in the Practice I Group vs. not in the Practice Group*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	*P*	*t*	*df*	*p* (2-tailed)	Mean Difference	SE. Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Quiz	Equal variances assumed	5.23	.03	-4.04	25	<.001	-.90	.22	-1.36	-.44
	Equal variances not assumed			-2.93	5.90	.03	-.90	.31	-1.65	-.14

Table 2 *Independent Samples Test for Students in the Practice II Group vs. not in the Practice Group*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	*P*	*t*	*df*	*p* (2-tailed)	Mean Difference	SE Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Quiz	Equal variances assumed	3.77	0.06	-3.65	25	0.001	-.80	.22	-1.25	-.35
	Equal variances not assumed			-2.80	7.40	0.03	-0.80	0.29	-1.47	-0.13

The results of analysis for Research Question 2 are supportive of the program effectiveness because the focus of the project is to improve students' learning outcomes through deliberate practice. Due to the COVID-19 pandemic, all in-person classes migrated to online, resulting in difficulties in engaging students. The completion rate of these assignments dropped to less than 70% compared to over 90% in the past. Therefore, a few students were not exposed to the intervention even though they were assigned to the treatment group. This makes the significant results that much more encouraging.

Conclusion

In this paper, TAPS was successfully used to identify the knowledge for teaching students how to draw FBDs by revealing procedural and the associated conceptual knowledge that novice learners need. The TAPS method has been developed over more than 25 years of conducting cognitive task analyses, and it has been informed by cognitive theories such as novice-expert differences [5], the expert blind spot [6] and the subgoal-learning model [7]. TAPS is not tied to a cognitive architecture and does not demand formalized conventions for representing the extracted knowledge. TAPS has been used in many domains and is a powerful tool to enhance instruction and assessment. Although the KEE was an expert in TAPS, it is feasible for an SME to learn to apply TAPS in order to identify the knowledge that students will need to learn and thus, to improve instruction. Future research will explore more applications of TAPS in engineering topics so we can develop a practical tutorial to help the SMEs improve instruction by avoiding expert blind spots.

Acknowledgement

This study is supported by the National Science Foundation under Grant Nos. 1927284 and 1927290.

References

[1] J. E. Court, "Free-body Diagram Revisited – I," *The Physics Teacher*, 37(7), 1999.

[2] J. E. Court, "Free-body Diagram Revisited – II," *The Physics Teacher*, 37(8), 1999.

[3] D. Rosengrant, A. V. Heuvelen, E. Etkina, "Do students use and understand free-body diagrams?" *Physical Review Special Topics – Physics Education Research*, 5(1), 2009.

[4] I. Aviani, N. Erceg, and V. Mešić, "Drawing and using free-body diagrams: Why it may be better not to decompose forces," *Physical Review Special Topics – Physics Education Research,* 11(2), 2015.

[5] R. R. Hoffmann, L.G. Militello, *Perspectives on cognitive task analysis: Historical origins and modern communities of practice*, New York, NY: Psychology Press, 2008.

[6] J. M. Schraagen, "Task Analysis," in *The Cambridge Handbook of Expertise and Expert Performance*, K. A. Ericsson, N. Charness, P. J. Feltovich, and R. R. Hoffman, Eds. Cambridge: Cambridge University Press, 2006, pp. 185–202.

[5] M.T.H. Chi, R. Glaser, E. Rees, "Expertise in problem solving," *Advances in the psychology of human intelligence*, 1, 1-75, 1982.

[6] M. J. Nathan, A. Petrosino, "Expert blind spot among preservice teachers," *American Educational Research Journal*, 40, 905-928, 2003.

[7] R. Catrambone, "Task analysis by problem solving (TAPS): Uncovering expert knowledge to develop high-quality instructional materials and training," in *2011 Learning and Technology Symposium, Columbus, GA, June*.

[8] R. Catrambone, "The subgoal learning model: Creating better examples so that students can solve novel problems," *Journal of Experimental Psychology: General*, 127(4), 355-376, 1998.