The Rigid Body Dynamics Concept Inventory - Development and Initial Results

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The Rigid Body Dynamics Concept Inventory - Development

Abstract

The Rigid Body Dynamics Concept Inventory (RBDCI) was developed to measure students' conceptual understanding of fundamental topics on rigid body dynamics. Building on the initial development work, this paper describes the refinement and reduction of the instrument using multiple sources of validity evidence using the Evidentiary Validity Framework. Evidence was collected through several sources including expert ratings to identify content validity and student explanations to understand how students are understanding and responding to the questions. The team is also in the process of gathering question correlations for the final inventory to determine question alignment and results with the proposed concepts. These processes have allowed the team to refine the RBDCI and sharpen the conclusions that can be drawn from its results.

Experts reviewed each question for conceptual alignment, clarity, and difficulty which was classified as easy, medium, or hard. They also used rank ordering to sort each question for inclusion. Additionally, multi-semester and multi-university student testing resulted in both quantitative results and written explanations. These have been analyzed to determine common misconceptions and question effectiveness. These results identified questions that students found too easy, too hard, or confusing based on the written response. Combining expert feedback and student results, the instrument was reduced to 11 concepts with three questions per concept, creating a 33-question beta version of the RBDCI.

Introduction

Concept Inventories are calibrated instruments that allow faculty to measure student deficits and student learning. When given prior to course instruction, the concept inventory allows faculty to identify misconceptions so they can be directly addressed during instruction. When given after course instruction, concept inventories allow faculty to measure how well students grasp the core concepts of the course [1,2,3,4]. Concept inventories can be used to benchmark student learning against internal goals, over time, or across institutions.

In the past 30 years, over 1200 papers have been published at ASEE alone on the topic of concept inventories. These papers cover the development of inventories and their use in academic settings. Concept inventories are used across many disciplines including physics, engineering, biology, and geology [5].

With regard to introductory engineering courses on dynamics, three concept inventories are used primarily to evaluate student conceptual understanding related to particle dynamics. These are the Force Concept Inventory (FCI) [6], Force and Motion Concept Evaluation (FMCE) [7] and the Dynamics Concept Inventory (DCI) [2,6]. The Rotational Kinematics Inventory (RKI) was designed to evaluate student conceptual understanding related to the dynamics involving rotation, but it does not focus on rigid bodies. Of the three sections in the RKI, two sections cover the rotation of particles and only the third section covers the rotation of rigid objects [8].

The FCI, FMCE, and RKI were developed in the physics community and are focused on high school and early college level conceptual understanding. The DCI was developed in the engineering community and is designed to be appropriate for a second-year introduction to dynamics course taught in an engineering department. The DCI covers some rotational and rigid body topics, but the emphasis is on conceptual misunderstandings of the dynamics of particles. Rigid body dynamics is considered by students to be the most conceptually challenging aspect of engineering dynamics [9]. Thus, there is a need for a rigid body concept inventory that complements the DCI and measures content typically covered in an introduction to engineering dynamics course.

To address this gap, the research team has developed a new Rigid Body Dynamics Concept Inventory (RBDCI). The goal of the RBDCI is to measure students' conceptual understanding of key rigid-body concepts typically taught in an introductory dynamics course. The current beta version includes 11 concepts, with the expectation that the final instrument will likely be reduced to 10 concepts. The intent of this diagnostic tool is to allow faculty members to identify and address gaps in students' conceptual understanding of rigid body dynamics.

The RBDCI topics have been developed based on feedback from subject matter experts from the Mechanics Division of the American Society for Engineering Education [10,11]. The RBDCI research team used the Delphi process [2,12,13] to understand the expert consensus and the result was 11 concepts. Table 1 lists the initial 11 concepts proposed for the RBDCI.

Table 1: Initial 11 concepts proposed for the new Rigid Body Dynamics Concept Inventory.

Concept	Title
1	Different points on a rigid body have different velocities and accelerations.
2	The inertia of a body affects its acceleration and velocity.
3	The forces and acceleration of a rigid body are dependent on one another.
4	A rigid body can have both translational and rotational kinetic energy.
5	In general, the total mechanical energy is not conserved during an impact.
6	Coriolis acceleration occurs in rotating reference frames.
7	The angular momentum of a rigid body depends on the reference point.
8	If the net external force F on a rigid body is not zero, then there is an acceleration of the center of mass of that body.
9	Angular velocities and angular accelerations are properties of the rigid body.
10	Points on an object that is rolling without slipping have velocities and accelerations that depend on this constraint
11	The action of friction opposes relative motion at the contact point, or acts to prevent relative motion at the contact point.

Question Development

A good concept inventory must balance the time necessary to complete the inventory with the need to make multiple measurements of each concept. The RBDCI is being designed to have three measurements for each concept. Importantly, each question is designed to measure one and only one concept. At approximately one minute per problem, the inventory should take about 30 minutes to complete.

The researchers developed 62 questions, an average of almost 6 questions per concept, but with some concepts having only 4 questions. The questions are housed at the Concept Warehouse [14] which assigns numbers to questions for ease of use. A detailed view of each problem can be found on the Concept Warehouse, searchable using the numbers in Table 2.

Table 2: Summary of concept questions developed and corresponding Concept Warehouse numbers

Concept	Number of Draft Questions	Concept Warehouse Numbers
1	6	7358 7359 7360 7361 7371 7372
2	7	7334 7341 7443 7444 7445 7446 7447
3	6	7367 7375 7376 7377 7378 7379
4	7	7336 7337 7335 7425 7433 7434 7435
5	5	7362 7363 7370 7373 7374
6	7	7338 7339 7340 7441 7442 7449 7450
7	4	7364 7366 7368 7369
8	5	7436 7437 7438 7439 7440
9	5	7395 7396 7397 7398 7399
10	4	7407 7408 7411 7415
11	6	7427 7428 7429 7430 7431 7432

Question Reduction and Modification (Pruning)

A large number (62) of questions were developed in anticipation that some questions would not adequately measure the intended concepts and would need to be removed. The removal process followed an Evidentiary Validity Framework [12] where the developed questions were reviewed by the research team, external members of the dynamics community (subject matter experts), and students enrolled in a dynamics course (subject matter novices).

Each question was evaluated according to the following criteria:

1) Did the question measure the intended concept?
2) Did the question measure more than one concept?
3) Was the language of the question clear?
4) Was the image used in the question clear?
5) Is the question adequately different from related questions?
6) Is the question too hard or too easy for novice learners?
7) Are the distractors adequate?
8) Is the cognitive load required to understand the question excessive?
9) Does the question require experiential knowledge that may not be common?

The question reduction (or pruning) process used two sets of data: expert feedback and novice feedback. Expert feedback was collected for the top 5 candidate questions for each concept. Novice feedback was collected in pieces with only a few concepts being tested at one time. Early novice feedback allowed for a few rounds of edits prior to the solicitation of expert feedback. At the time of pruning, novice feedback was available for every question in Table 2.

Data: Expert Feedback

The subject matter experts (the research team and external experts not affiliated with the project) reviewed the top 5 candidate questions for each concept. For concepts with more than 5 candidate questions, early novice testing was used to eliminate questions. Questions with uncharacteristically high or low scores were removed from the candidate pool.

The experts provided an estimate of the difficulty of the question on a 3-point scale with 1 being easy, 2 medium, and 3 hard. The experts ranked the questions (from among other questions of that same concept) where 1 was the most useful question and 5 was the least useful. The experts also provided open-ended comments. The open-ended comments addressed the criteria provided above. However, since the comments were open-ended and optional, not all questions received comments and not all criteria were addressed for each question.

A summary of the data provided by the subject matter experts for Concept 1 is provided in Table #3. Question 7361 was not evaluated by the experts because in initial testing of the question with novice learners, 100% of the students identified the correct answer.

Table 3: Example of Subject Matter Expert Data Used for Pruning. A question difficulty of 1.0 means all experts considered the question easy. A question ranking of 4.0 means that most experts ranked the question least useful. Question 7361 was not evaluated by experts.

CW Question Number	Question Difficulty (averaged)	Question Ranking (averaged)	Comments (sample)
7372	1.0	3.5	Reword; don't need "The scenario here…"
7358	2.2	2.2	
7359	1.4	3.0	The curved arrow and label ω may provide a strong hint towards the correct answer.
7360	1.0	4.0	Would rather see question about accelerations
7361	**	**	
7371	2.0	2.3	The current list could be confusing. Increase the number of distractors so the distractor option A,B,C matches the possible points A,B,C…

Data: Novice Feedback

Novice feedback was collected over several semesters at a variety of academic institutions. Novice learners were given subsets of the proposed concept questions. The novices answered the question, explained their reasoning, and in some cases provided additional feedback on factors such as their confidence, their perceived understanding of the question, and the effectiveness of the question in prompting them to consider the concept.

The primary data used in evaluating the effectiveness of the question was student answers. Questions with either very high or very low correct-response rates were examined by comparing them to the other questions in the concept group. Questions that appeared too easy or too difficult were early candidates for pruning. For example, questions 7372 and 7360 appear to be too easy relative to the other questions; see table 4.

Student reasoning was used to identify questions where a correct answer was selected, but for the wrong reasons. This happened frequently on a few Coriolis questions where students ignored Coriolis, but a misunderstanding of other accelerations resulted in a correct answer. In some cases, the distractors could be changed; in other cases the question had to be pruned.

Table 4: Example of Subject Matter Novice Question Answer Data Used for Pruning.

CW Question Number	Number of Student Attempts	Number of Correct Attempts	Percent of Correct Answers	Percent of Top Distractor	Percent of Next Distractor
7372	26	23	**88.5**	7.7	3.8
7358	9	6	66.7	22.2	11.1
7359	23	13	56.5	39.1	4.3
7360	16	15	**93.8**	6.2	0.0
7371	17	8	47.1	41.2	5.9

The Concept Warehouse allows faculty to ask students up to four types of follow-up questions.

1. Explanation – a short answer follow-up to explain reasoning.
2. Confidence – a numerical follow-up to rate confidence in their answer (Likert scale with 5 being very confident)
3. Clarity– numerical and short answer follow-up to allow the student to rate how clearly the question was asked. (Likert scale with 5 being clear and effective)
4. Probing – numerical and short answer follow-up asking the student if the question made them think deeply about the subject matter.

The faculty that assigns the concept warehouse quiz to the students can select which follow up questions they would like to ask. In most student testing, only 1 or 2 of the four follow-up types were available to students to prevent overwhelming them with questions. However, all four types were added to a short quiz involving question ID 7358 and examples of student feedback are provided in Table 5. The question itself is seen in Figure 1.

Question statement:

The arm of a pendulum swings back and forth. When the arm is at its maximum angle (as shown), which statement is true about the acceleration of points A and B?

A) $a_A > a_B$
B) $a_A < a_B$
C) $a_A = a_B$ and are non-zero
D) $a_A = a_B = 0$

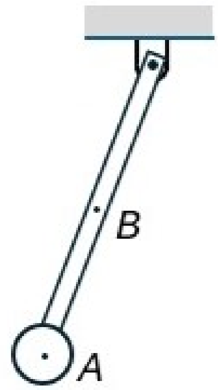

Figure 1 – RBDCI Question 7358 - Accel of pts on a pendulum. *This question is designed to measure student understanding of Concept 1. Concept 1 - Different points on a rigid body have different velocities and accelerations.*

Table 5: Example of Subject Matter Novice Feedback Data Used for Pruning. The feedback is from question ID 7358. The question has five multiple-choice options (A–E). Answer A is correct, and answers B–E are distractors. Three examples are provided for students with the right answer, and three examples are provided for students with the wrong answer.

Student	Type	Num.	Comment
1 Correct	Explanation	A	The highest acceleration is at the amplitude or top of its swing.
	Confidence	4	
	Clarity	5	Clear question statement.
	Probing	5	I thought about concepts from multiple classes including dynamics and physics etc.
2 Correct	Explanation	A	The acceleration at point A has to be greater to "keep up" with point B when swinging.
	Confidence	5	
	Clarity	3	At first, the maximum angle part of the question confused me but after some thinking it makes sense.
	Probing	5	Once again, this question relates a lot of things we encounter in class to a simpler conceptual question.
3 Correct	Explanation	A	This is because point A is farther from the center of rotation.
	Confidence	5	
	Clarity	5	It was a clear question.
	Probing	5	It made me think about how acceleration is related on a body.

7 Incorrect	Explanation	D	If the arm is at its max angle, then it has to swing back meaning the acceleration will be 0 until it starts to move again.
	Confidence	3	
	Effectiveness	4	It was clear.
	Helped	4	It related to what we learned.
8 Incorrect	Explanation	D	The acceleration will be zero because the object will be at rest, meaning that its velocity is zero, therefore so is its acceleration.
	Confidence	4	
	Clarity	4	I needed to see when the pendulum reaches its highest point of motion, what will happen to the acceleration.
	Probing	3	I had to understand how the kinematics of the pendulum works applied at the given angle.
9 Incorrect	Explanation	B	Acceleration depends on the length of the pendulum arm.
	Confidence	4	
	Clarity	-	-
	Probing	-	-

The combination of expert and novice data that included both quantitative and qualitative feedback was used by the research team to validate questions in a way similar to the Evidentiary Validity Framework that has been used for other concept inventories [12].

RBDCI – Beta Version

After examining the expert and novice feedback the research team pruned the 62 questions of Table 2 down to 33 total questions (3 questions for each concept). In general, there was consistent agreement on the difficulty of questions as ranked by experts and evaluated by novices. For example, among the candidate questions for concept number 1, Table 3 shows that experts uniformly agreed that questions ID 7372 and ID 7360 were easy and ranked them as less desirable. Table 4 shows that novice learners were much more likely to get these questions correct.

Conversely the feedback from novices for question ID 7358 shows a strong relationship between correct reasoning and a valid answer and a strong relationship between incorrect reasoning and an invalid answer. Experts ranked this question as the best candidate and on average felt it was moderate in difficulty.

After reviewing all of the data the question pool was pruned to the list shown in Table 6.

In addition to reducing the total number of questions to 33, the research team reviewed the expert and novice feedback to improve the question wording, answer format, and image. The result is a set of questions with lower cognitive load, added clarity, consistent images, and less reliance on systems that require experiential knowledge. In cases where problems required significant updates, they were rewritten in the Concept Warehouse, resulting in new Concept Warehouse identification numbers.

Table 6: Summary of beta version concept questions for the RBDCI.

Concept	Number of Questions in Beta Version	Initial Concept Warehouse Numbers	Beta Version Concept Warehouse Numbers
1	3	7358 7359 7371	Same
2	3	7341 7443 7447	Same
3	3	7376 7377 7379	Same
4	3	7337 7434 7435	Same
5	3	7370 7373 7374	Same
6	3	7442 7449 7450	7521 7534 7535
7	3	7366 7368 7369	Same
8	3	7436 7437 7439	7520 7437 7510
9	3	7396 7398 7399	Same
10	3	7407 7411 7415	7524 7523 7522
11	3	7427 7428 7430	Same

The questions in Table 6 are available at the Concept Warehouse [14] located online at https://conceptwarehouse.tufts.edu/cw/CW.php. To access the questions, click on "Faculty Apply Now" to set up an instructor account. The questions can be found by clicking on the Concept Inventories Tab, selecting view under Rigid Body Dynamics Concept Inventory, and selecting the Questions Tab.

Next Steps

This paper describes the development of a beta version of the Rigid Body Dynamics Concept Inventory (RBDCI). The beta version has been provisionally validated through expert and novice data. Up to this point, students have only completed a subset of the questions and not the full RBDCI.

To fully validate the RBDCI, the research team will collect data from student cohorts taking the full 33-question beta version. The beta version of the RBDCI will be tested at multiple universities to determine difficulty indices. This data will provide evidence on the internal structure of the instrument.

Finally, the research team plans to remove one of the candidate concepts being tested, resulting in a final RBDCI with 30 questions covering 10 concepts. This calibrated RBDCI will measure student understanding of rigid body concepts and support educators in improving instruction and preparing students to become better engineers.

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