Misconceptions in Rolling Dynamics: A Case Study of an Inquiry-based Learning Activity

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Abstract

Decades of research have shown that experts possess a hierarchical structure of contextualized knowledge organized around principles[1]. This prevents them from focusing on superficial aspects of a problem and allows them to determine relevant information and basic principles, which are the basis for strong conceptual understanding. Unfortunately, such knowledge organization is traditionally acquired tacitly through practice and is rarely emphasized explicitly in engineering courses, which are usually more focused on procedural skills for problem solving. During traditional lecturing, it can be hard for the instructors to gauge how students integrate their newly acquired knowledge with their existing knowledge since the instructors who are experts in the field might have difficulty realizing what concepts are difficult for students and why. Inquiry-based learning activities (IBLAs) help students to strengthen the connections between concepts and help them to build contextualized knowledge. With IBLAs, the focus is on conceptual understanding through the integration of hands-on activities in a cycle of predictions, observations, and explanations. Incorrect predictions create cognitive conflict which must be reconciled with the authority provided by the physical world. This requires the students to provide qualitative explanations based on concepts and principles to support their physical observations.

In this paper, we continue our investigation of IBLAs used in undergraduate dynamics by focusing on basic concepts in rolling kinetics. An exploratory study was pursued on a small sample of undergraduate students taking a course in dynamics. Each student participated individually in an IBLA that examined the relationship between forces and the direction of motion of a rolling object. The students drew diagrams and provided qualitative explanations of their reasoning. The responses were coded to highlight important dynamics concepts. The learning objectives of the IBLA were to help students understand that 1) the direction of acceleration of the mass center is in the same direction as the sum of the forces; 2) the direction of angular acceleration is the same as the direction of the sum of the moments about the mass center, 3) the directions of angular and linear accelerations must be compatible according to rolling kinematics, and 4) that the direction of the friction force does not necessarily oppose the direction of rolling. By analyzing the detailed student explanations, it was possible to extract various misconceptions. For example, some students believed that when the spool is pulled vertically, there is no friction force acting on it. The students also seem to have problems determining the magnitude of the moment of a force and connecting the sum of moments to the direction of rolling. This work informs instruction of dynamics and physics courses and the future development of more sophisticated teaching tools to facilitate conceptual understanding.

Introduction

Undergraduate dynamics is a particularly challenging course for students in engineering, since many of the principles seem to be in direct conflict with how they interact with the world (e.g., there is no magical centrifugal force that throws you out of your car when going around a curve). Traditional lecturing is still heavily used in dynamics courses. As Gray and collaborators mentioned *"for the most part, the teaching of dynamics continues to be patterned after how instructors were taught when they were students, rather than being informed by research on learning"*. Research in dynamics learning[2-4] has shown some aspects of this approach can lead to students' misconceptions, such as the role of the friction force in rolling objects and the difficulty for students to realize that translation and rotation occur simultaneously in rolling motion.

Concept inventories, such as the Dynamics Concept Inventory (DCI), are specifically designed tests that target these common misconceptions. Performance on the concept inventories can be used to determine the effectiveness of different pedagogies. A large size dynamics class taught by traditional methods shows a student average score of only 32.1% on the post-instruction DCI[5]. This low performance indicates that students who would score high in a traditional test based on mathematical intensive problem solving might have poor conceptual understanding.

In order to clarify these difficult concepts, novel instructional methods must be utilized. Active learning methods seem to be the most promising; for example, their use in large-size physics classes results in double the average gain than the traditional lecture-based teaching[6,7]. There is a wealth of engineering education research[8] showing that active learning methods produce similar positive gain for students in engineering disciplines.

An example of such active learning instructional methods are inquiry-based learning activities (IBLAs), which have been shown to help students strengthen the connections between concepts and help them to build contextualized knowledge. IBLAs are typically composed of a series of scenarios. For each scenario, the students are first required to make predictions about the physical phenomena of interest, then observe the system experimentally, and then explain the experimental results. If needed, direct instruction or team discussions can be easily incorporated together with these Predict-Observe-Explain cycles (Figure 1). With IBLAs, the focus is on conceptual understanding through the integration of hands-on activities in a cycle of predictions, observations, and explanations. Incorrect predictions create cognitive conflict, which must be reconciled with the authority provided by the physical world. This requires the students to provide qualitative explanations for their physical observations based on concepts and principles.

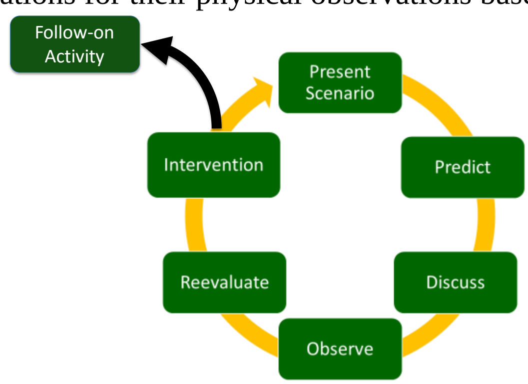

Figure 1.The building blocks of an Inquiry Based Learning Activity (IBLA).

Our group has done previous studies on the student performance during concept inventory tests and using the IBLAs. This study expands the investigation by using qualitative "think-aloud" interviews to investigate students' understanding of rolling dynamics. The goal was to identify common misconceptions and naïve ways of thinking about the physics of the rolling body.

Literature review

The spool can be a versatile object used to test students' conceptual understanding of rolling dynamics of a rigid body. A typical problem has a spool with a string wound around the inner radius (Figure 2). The spool rolls to the side (in the x direction) when the string is pulled. Different angles and configurations can be tested in order to identify misconceptions related to Newton's 2^{nd} law, net moment and friction. Questions 21 and 22 of the Dynamics Concept Inventory (DCI) are on the topic of rigid body kinematics exemplified by the motion of a car tire. In particular, question 21 tests if the students understand that the velocity of a point on the car tire is a combination of the rotation of the tire about the contact point and the translation of the tire. This problem is similar to the spool problems, since in both cases the students must analyze the rolling direction and the friction direction. Previous studies (Gray) showed that only 10-20% of the students were able to respond correctly to this DCI question pre-instruction. By the post-test, 60-70% selected the correct answer, which shows that targeted instruction can bring important learning gains in this topic.

Previous work by Coller[9] has shown that students who perform well in solving quantitative problems have difficulties in discussing conceptual problems related to the same topics in rolling dynamics. However, it is not fully understood why the students fail to apply automatically the Newtonian framework to conceptual problems as they typically attempt for the quantitative ones. Georgette's work[10] used a quantitative approach by analyzing pre- and post-IBLA quizzes from more than 200 students over several quarters of an undergraduate class on introductory dynamics. The quiz scores revealed that the students still had some struggles with their conceptual understanding of rotational dynamics of a spool with horizontal pull and spool with vertical pull even after the IBLA activity. This study utilizes a qualitative research approach to investigate in depth what challenges the students face when solving these conceptual problems in an IBLA setting and what misconceptions they might struggle with, in order to be able to improve the IBLA in an informed way.

The conceptual knowledge necessary to understand dynamics of rolling without slip relies on the concepts of translational acceleration (calculated based on Newton's second law), net moment and friction. The applied pull force $\boldsymbol{P}$ and the friction force $\boldsymbol{f}$ are important for determining the dynamics of the spool. The direction of $\boldsymbol{f}$ and the magnitude of $\boldsymbol{f}$ in comparison to $\boldsymbol{P}$ can be determined using the relationship between net force and linear acceleration, the relationship between the net moment and the angular acceleration, and the kinematic relationship between α (angular acceleration) and $\mathbf{a}$ (linear acceleration). Positive $\boldsymbol{a}$ (considered as pointing to the right) means that α must be clockwise (CW). Negative $\boldsymbol{a}$ (pointing to the left) means that α must be counterclockwise (CCW). Only one out of all possible combinations of directions and magnitudes of $\boldsymbol{f}$ with respect to $\boldsymbol{P}$ and their respective moments for one particular system in our IBLA can satisfy the relationship between $\boldsymbol{a}$ and α mentioned above. This conceptual procedure for determining the direction of the motion and the direction of the friction force is explained in Figure 2. The IBLA encourages conceptual understanding by exposing the students to nonintuitive situations that would be obscured by simply solving mathematical expressions. This knowledge is not limited to the spool example and can be expanded to other types of rigid body dynamics applications.

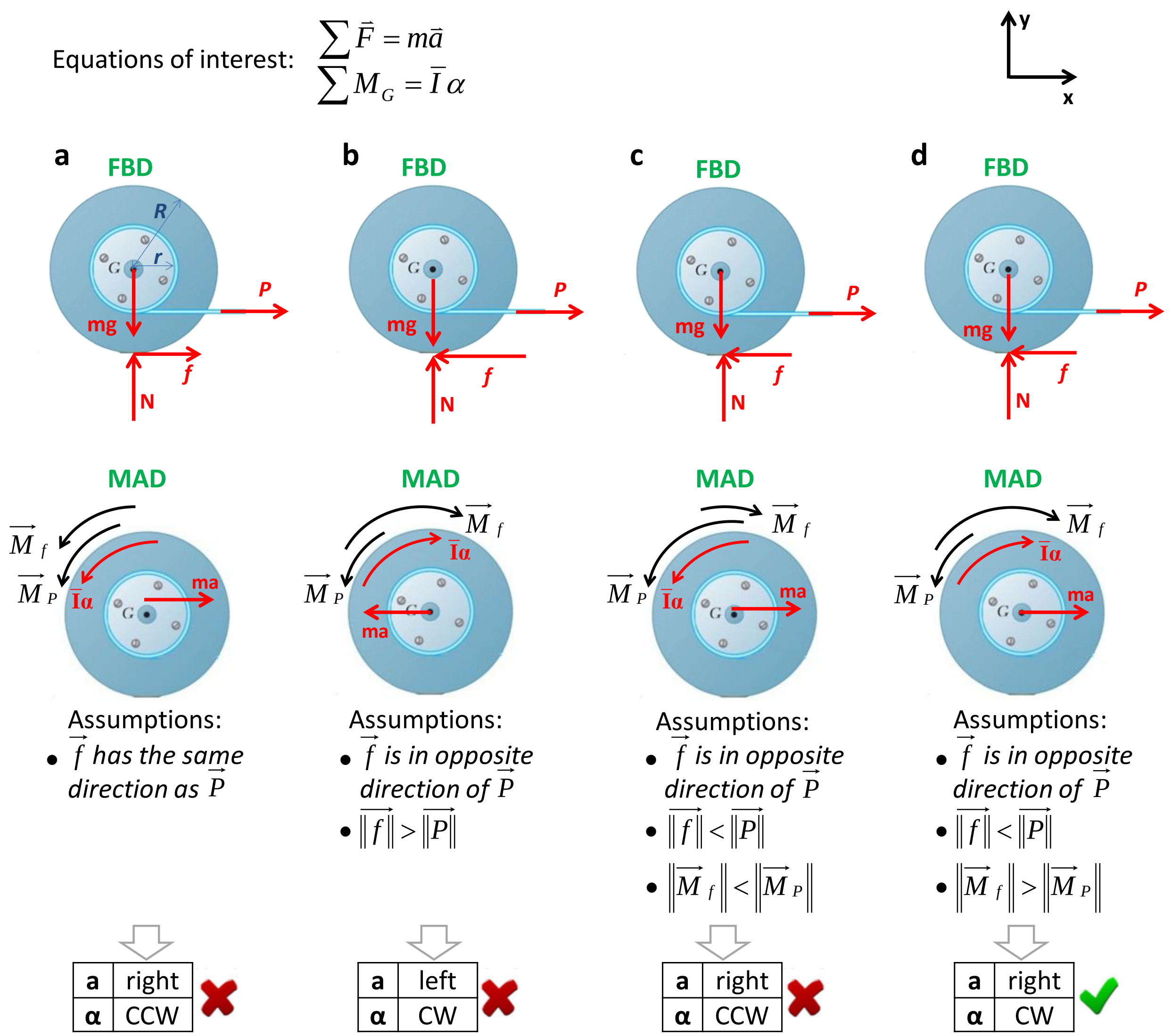

Figure 2. Conceptual attempts to determine the direction of motion (given by ***a****), the direction of rolling (given by* ***α****) and the direction of the friction force* ***f****. Only attempt d satisfies the kinematic relationship between* ***a*** *and* ***α****.*

Methods

Research goals

We investigated student's existing knowledge of Newton's 2nd law (Σ**F**=m**a**) and its adaptation for the rotational case ($\Sigma \boldsymbol{M_G} = I_G * \boldsymbol{\alpha}$). The research goals of the study are to determine how well the students understand the following scientific ideas:

1) the direction of acceleration $\boldsymbol{a}$ of the mass center is in the same direction as the sum of the forces ($\sum \mathbf{F} = m\mathbf{a}$);
2) the direction of angular acceleration (α) is the same as the direction of the sum of the moments about the mass center ($\sum \mathbf{M}_G = I_G * \alpha$)
3) the direction of rolling has to be compatible with the direction of translational movement (the directions of $\boldsymbol{\alpha}$ and $\boldsymbol{a}$ have to be compatible).
4) the direction of the friction force is not solely determined by the direction of rolling.

Qualitative semi-structured interviewing with "think aloud" was used in order to get a multitude of rich explanations from the students[11]. This allows us to investigate the depth of students' knowledge and expose their potential misconceptions (or alternate conceptions).

Participants

A small group of engineering students enrolled in an introductory dynamics course was interviewed for this study. Three males and two females participated in one-on-one ~30 minute semi-structured interviews. At the time of the interview, the students had already been exposed to the concepts of Newton's second law, angular velocity, angular acceleration and rolling kinematics. The students volunteered for the study and signed consent forms before the interview.

The Spool IBLA

Each student participated individually in an IBLA that examined his/her understanding of Newton's second law, the kinematics of rolling, friction and free-body diagrams (FBD) and mass-acceleration diagrams (MAD). The spool IBLA consisted of four scenarios (Figure 3) that vary the angle at which the pull force $\boldsymbol{P}$ is applied (scenarios #1 and #4 at 0°, scenario #2 at 90° and scenario #3 at -90°). For scenarios #1 and #4, the spool rests on the surface at different distances from G. By using these different scenarios, we were able to explore in depth how the students respond to different superficial changes and what elements they consider important.

For all the scenarios in the IBLA, each student was asked to 1) make a prediction for the direction of movement of the spool, the direction of the friction force and the magnitude of the friction force; 2) perform the hands-on experiment depicted for that scenario and 3) explain the experimental results by drawing the FBD and MAD. During this last step, the interviewer helped the students clarify their misunderstandings, by providing a 1-2 min description on how the $\sum \boldsymbol{F} = m\boldsymbol{a}$ and $\sum \boldsymbol{M} = I * \boldsymbol{\alpha}$ relationships would be applied to the particular scenario. The student was guided by the interviewer to draw the correct FBD and MAD. The interviewer also challenged the student by asking him/her to draw the friction force in the incorrect direction and explain what effects that assumption would have on the direction of movement and the direction of rolling.

Data collection and coding

Each participant was interviewed individually. The interviewer who conducted all five one-on-one interviews was a male undergraduate research assistant. At the beginning of the activity and during the activity as needed, the interviewer prompted the students to "think aloud" during the prediction steps of the IBLA in order to make their thinking process as transparent as possible.

Conceptual explanations were emphasized, but the students were allowed to use the whiteboard to draw the FBD and MAD.

The students' engagement in the IBLA was videotaped. The explanations were transcribed and coded in order to emphasize how well the students grasp the four scientific ideas listed in the research goals. Common misconceptions were also extracted and summarized during coding. The coding table was included in the annex.

1.Looking at the figure in scenario #X, if you pull on the string gently, which way do you predict the spool will move?

Right _______ Left ______Won't Move_______

2.When pulling, which direction is the friction force?

Right _______ Left ______There is no friction force _______

3.What is the value of the friction force?

$f = \mu_k N$ _____ $f = \mu_s N$ _____ $f \leq \mu_s N$ ______

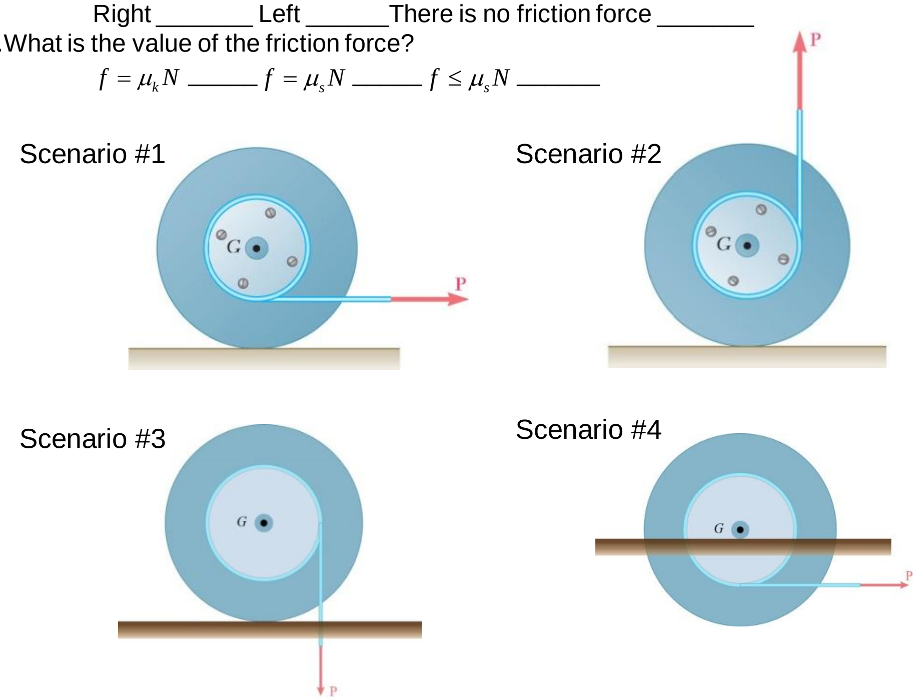

Figure 3. The four scenarios utilized for the IBLA

Findings

The students' answers for all four scenarios are summarized in Table 1. None of the students made all the predictions correctly. At the beginning of the IBLA, all the students except Male 1 seemed confused about where to start and made a prediction based on their intuition. Two students did not understand that the string was wound around the spool and could unwind as it was pulled, so they thought that the spool would have to slip when the pull force ***P*** is applied. The intervention after scenario #1 helped the students remember the scientific framework and draw the FBD and MAD. However, as the IBLA progressed, the students still seemed to struggle with the sum of moments and the direction of movement, despite the guided intervention after each experiment. In a few cases, the students predicted that the spool will be slipping, despite the interviewer mentioning repetitively that the applied pull force ***P*** is gentle. For scenario #3, the students were not able to visualize how the pull force ***P*** can be applied downwards, so the interviewer had to show them the arrangement of the spool on the table. These broad findings indicate that a more thorough intervention might need to be incorporated in future IBLAs with the purpose of teaching the required scientific ideas and of presenting the difference between rolling and slipping conditions.

Scientific idea 1 – The direction of acceleration of the mass center is in the same direction as the sum of the forces

Although Newton's second law is a concept that the students have been exposed to prior to the Dynamics class, they seem to experience difficulties in identifying all the forces acting on the object (particularly the friction force) and correctly determining the direction of acceleration based on the sum of all forces.

Table 1. Summary of IBLA answers for the five students. The answers highlighted in green are correct; the ones highlighted in red are incorrect.

Scenario 1	**Correct**	**Female1**	**Female2**	**Male1**	**Male 2**	**Male 3**
Friction force magnitude	**<= usN**	<= usN	<= usN	<usN	<usN	<usN
Friction force direction	**Left**	Left	Left	Left	Left	Right
Direction of movement	**Right**	Left	Left	Right	Right	Left
Direction of rolling	**CW**	CCW	CCW	CW	Not rolling	CCW

Scenario 2	**Correct**	**Female1**	**Female2**	**Male1**	**Male 2**	**Male 3**
Friction force magnitude	**<= usN**	<= usN (maybe ukN)	<= usN	<usN	<usN	<usN
Friction force direction	**Left**	Left	Left	Left	Right	Left
Direction of movement	**Left**	No motion (left?)	Left	Left	Left	No motion
Direction of rolling	**CCW**	CCW	CW	CCW	CCW	CCW

Scenario 3	**Correct**	**Female1**	**Female2**	**Male1**	**Male 2**	**Male 3**
Friction force magnitude	**<= usN**	<= usN	ukN	ukN	<usN	<usN
Friction force direction	**Right**	Right	Right	Right	Right	Right
Direction of movement	**Right**	Right	Right Sliding	Not moving	Right	No motion (Right)
Direction of rolling	**CW**	CW	CW	CCW	CW	CW

Scenario 4	**Correct**	**Female1**	**Female2**	**Male1**	**Male 2**	**Male 3**
Friction force magnitude	**<= usN**	<= usN	<= usN	ukN	ukN	<usN
Friction force direction	**Left**	Left	Left	Left	Left	Left
Direction of movement	**Left**	Right	Left	Right sliding	Right sliding	Left
Direction of rolling	**CCW**	CCW	CCW	CCW	CCW	CCW

Male 1 is the only one explicitly stating and consistently using Newton's second law, Σ**F**=m**a**, throughout all the four scenarios in order to determine the direction of movement of the spool. For example for scenario #2, he states:

> *"F=ma and a is going to be to the left, because f is the only force in x and it's in that direction [left]."*

All the other students (Male 2, Male 3, Female 1 and Female 2) show some difficulty in using the principles of Newton's second law in order to determine the direction of movement of the spool. For the first two scenarios, the students determine the direction of movement based 1) purely on the direction of the applied force ***P***, or 2) the direction of rotation (determined by α) without checking if the linear acceleration ***a*** as determined by the sum of forces in the x direction is compatible with this direction of rotation.

A common belief is that when the gentle applied force ***P*** does not have a component in the x direction, the spool might be slipping or lifting up (Female 1 for case 2 and Female 2 for scenario #3). This difficulty might be due to the fact that the friction force is not easily observable while the applied force ***P*** is observable and clearly drawn on each of the scenario sketches. Despite predicting that the spool will spin in place in scenario #2 and being proved wrong by the experiment, Male 3 student tried to make a similar prediction for scenario #3. However, he later changes his mind and starts using the scientific concepts taught to him during the discussion. Eventually he is the only student able to make correct predictions and provide correct explanations for both scenarios #3 and #4:

> *"My first reaction is that it doesn't go anywhere. I couldn't actually give you a why, but when I think about it in my head, it's pulling down and it will just slide* [showing rolling movement in place with his hands] *there. [...] But it's obviously not doing that, that wouldn't not make sense.[...] Ooh, if it's rolling to the right, the friction force has to be acting to the right!"(Male 3, scenario 3 before experiment)*
>
> *"Since we are expecting it to move to the left and the applied for is to the right, the friction force has to be to the left." (Male 3, scenario 4 before experiment)*

Another challenging idea is that the friction force ***f*** can have a magnitude greater than the applied pull force ***P***. This is exemplified by the challenges Male 1 had with the scenario #4:

> *[Before experiment] F=ma, so it is moving to the right, force of P is greater than f. Why do I think that? Maybe it's not. You can pull as hard as you want.*
>
> *[After experiment] So friction won out in the force battle.*
>
> *[During the intervention] How do you figure out which magnitude is going to be bigger? f or P? Is there any way of telling who is going to be larger just conceptually?*

Common misconceptions/ naïve practices for scientific idea 1:

- Difficulty identifying all the forces acting on the system, particularly the friction force (most common)
- Failing to use Newton's 2nd law to determine the direction of movement of the spool.
- When the applied pull force P does not have a component in the x direction, the spool has to move up or slip.
- Applied pull force ***P*** is always greater that the friction force ***f***

Scientific idea 2 – The direction of angular acceleration is the same as the direction of the sum of the moments about the mass center

The concepts of net moment and angular acceleration are introduced during the Dynamics course. They are a crucial part in understanding the physics of systems with rotational components. The spool IBLA activity investigates how well the students master these concepts and how they can combine them with concepts from translational dynamics.

The most consistent trend among almost all the students is that they fail to take into account the moment from the friction force ***f***. This is the case even when the students identify that there is a friction force acting on the spool and they take that force into account when calculating the linear acceleration ***a***. For scenario #1, four out of five students make this error and only describe the moment of the applied force ***P*** (see Female 1 example below). Male 2 never discusses the moment of the friction force when explaining his predictions before running the experiment for any of the scenarios. Female 1 only takes the moment of friction force into consideration in scenario #3. Female 2 included the moment of the friction force into her analysis after the intervention for scenario #1. Only Male 1 student described both the moment of ***P*** and the moment of the friction force ***f*** throughout all the scenarios.

> *"It looks like it is going to roll counterclockwise because of this force P." (Female 1, scenario 1)*
>
> *"You have a torque, you have r cross P, so it's rotating it this way (CCW). [...] the friction working to rotate it that way (CW)." (Male 1, scenario 1)*

The moment of the applied force ***P*** can have a larger or smaller magnitude than the moment of friction force ***f*** even if their respective distances to the center of mass G are unchanged (for example scenario #1 vs. scenarios #2 and #3). Female 2 and Male 1 struggled with this idea in their explanations.

> *"The friction is pointing to the left and it has a greater moment than P since it's at larger distance and it should be CW." (Female 2, scenario 2)*

Male 1 had difficulties understanding how to determine the magnitude of the friction force moment relative to the applied pull force. Since the spool is rolling and the pull force is gentle, the friction force is < $\mu_{S*}N$, not equal. The inequality makes its mathematical significance harder to understand.

> *"Friction is N∗μ, and [...] you are making that normal smaller in magnitude, because you are pulling up on it. So the moment from the friction is going to be smaller than the moment caused by the P." (Male 1, scenario 2 - before experiment)*

> *"Friction will have a moment CCW, greater than the moment of P because P will add to the normal force." (Male 1, scenario 3 - before experiment)*

> *"I thought that the more you pull, the greater the friction force is. And the friction force is further away, so I thought the moment of the friction will be greater." (Male 1, scenario 3 - before experiment)*

Common misconceptions/ naïve practices for scientific idea 2:

- Not including the moment of the friction force when determining the total moment, even when recognizing there is a friction force acting on the system (most common).
- Difficulties determining the friction force moment relative to the applied force moment

Scientific idea 3 – The direction of rolling has to be compatible with the direction of translational movement

A common practice among the students seemed to be to determine the direction of rolling and the direction of translational movement separately without checking for kinematic consistency. For example, in her prediction for scenario #4 Female 1 stated that the spool will move to the right while spinning in the counterclockwise direction. Similarly for scenario #2 Female 2 stated that the spool will move to the left while spinning in the clockwise direction. This kinematic consistency was not specifically stated during the intervention; therefore the students had no chance to correct this naïve practice.

Male 1 student was visibly preoccupied about their consistency although he did not know how to modify his explanation in order to reconcile them. Because he did not believe that they could act independently, he decided that the spool had to slip instead of roll.

> *"If it moves, it has to be to the right because I don't see any other opposing force, although the friction is trying to rotate it CCW. The moment seems to be CCW, but it wants to roll to the right, so do you use both in a different way? I think it doesn't move and it spins out" (Male 1, scenario #3)*

Only Male 3 explicitly stated in his explanations that the translational motion and the rolling motion have to be compatible:

> *"The force applied is trying to unwind it and roll it to the left while trying to have a translational motion in x to the right. But it still has to roll to the left since it's moving counter-clockwise. […].(Male 3, scenario #4)*

Common misconceptions/ naïve practices for scientific idea 3:

- Not checking for kinematic consistency between the direction of rolling and direction of translational movement (most common)
- The lack of kinematic consistency for a particular FBD means that the spool slips instead of rolling.

Scientific idea 4 – The direction of the friction force does not depend on the direction of rolling

The friction force direction is determined by satisfying the rule that the direction of rolling must be compatible with the direction of translational movement. Since this rule was not always clear to the students, they offered a variety of other misconceptions on how to determine the friction force. As the IBLA progressed, the intervention seemed to not be very effective at correcting these student misconceptions or at emphasizing the correct way to determine the direction and relative magnitude of the friction force.

The explanation used most often is that the friction force opposes the direction of translation motion. (Male 2 for scenarios #2 and #4 and Female 1 for scenario #1). Female 1 oscillated between different explanations. For scenario #1, she suggested that the friction opposes the applied force ***P***. For scenario #2, she said that friction force opposes the x direction of movement even if there is no other force in the x direction. For scenario #3, her explanation was that the friction force should oppose the moment of the applied pull force, which is a naïve idea that Male 3 also expressed during scenario #1 and #2.

Common misconceptions/ naïve practices for scientific idea 4:

- The friction opposes the applied force ***P*** (most common)
- The friction force opposes the x direction of movement even if there is no other force in the x direction
- The friction force opposes the moment of the applied pull force

Summary of findings:

- When the applied pull force was in the vertical direction, some students failed to identify the friction force as the only force acting on the horizontal direction. They either said that there was no translation or that the movement had to be in the opposite direction of the friction force.
- Some students did not take into account the moment of the friction force in determining the direction of rolling.
- Some students had problems understanding that since the applied force ***P*** is gentle and the spool is rolling, the applied force ***P*** can have a larger or smaller magnitude than the friction force ***f***.

- A common practice among the students seemed to be to determine the direction of rolling and the direction of translational movement separately without checking for their consistency.
- In determining the direction and magnitude of the friction force, different approaches were suggested, sometimes by the same student. For example, one student suggested for different scenarios that the friction opposes the applied force ***P***, then that friction force opposes the x direction of movement even if there was no other force in the x direction and lastly the friction force should oppose the moment of the applied pull force.

Implications

The results of this study help us understand how to design better IBLAs, particularly how to choose the given scenarios for the predict-observe-explain cycles and when to incorporate direct instruction. Firstly, it was observed the information that the forces were applied "gently" was insufficient and a source of ambiguity. The students should be explicitly instructed that the spool rolls without a slip. More extensive direct instruction might be needed after each scenario in order to insure that the students grasp the concepts. While the hands-on activities are good to make the spool activity relatable and involve the students, the direct instruction is important to highlight unobservable variables such as friction and to decouple complex phenomena happening simultaneously, such as translational and rotational motion acting on the same object. This study shows how important it is to highlight during the direct instruction the need for kinematic consistency between translational and rotational motion. Based on these findings, the new IBLA for rolling dynamics has the scenarios presented in a different order and includes more detailed interventions. The first and second scenarios are switched and detailed interventions are included after each of these first two scenarios. This allowed for the first intervention to focus on the direction of the friction force and its consistency with both Newton's laws and the kinematics of rolling. The second intervention then added the determination of the direction of motion. For the time being the fourth scenario was eliminated from the activity but used as a question on the quiz to assess the IBLA's effectiveness. For future work, more complex scenarios can be included, such as systems combining spools and pulleys.

Limitations

The current study is designed to be a small exploratory endeavor. The small sample size is by no means representative of the entire population of students. Some of the misconceptions and challenges seem to be widespread among almost all the students in the study which suggests that these challenges could play an important role in a large class. Larger quantitative studies are needed to test if these findings are representative of larger populations.

Conclusions

This exploratory study used simple spool problems to identify several common misconceptions and naïve ways of thinking among students studying rolling dynamics. The majority of the students seem to struggle the most with the friction force, both for its role in the translational motion and its rotational motion. Note that the friction force is unobservable during experiments and its direction can only be determined by considering both the kinetics and kinematics of rolling objects. The students sometimes did not take into account the moment of the friction force or failed to recognize that the friction force was the only force acting in the horizontal direction in scenario #2. This led to difficulties in determining the direction of translational acceleration. Also it was common for the students to determine the direction of rolling and the direction of translational movement separately without checking for their kinematic consistency.

As the IBLA progressed, the single intervention after scenario #1 did not seem to be very effective at correcting these students' misconceptions, and the students struggled to find the correct way to determine the direction and relative magnitude of the friction force. This finding suggests that a more in-depth targeted instruction might be needed after each scenario to insure that the students understand the concepts according to the scientific model.

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Appendix

Coding table

Category	Code name	Description	Example
Scientific idea 1 *The direction of acceleration of the mass center is in the same direction as the sum of the forces*	Identify all forces	Refers to all the forces (such as applied pull force ***P***, friction force ***f***, gravitational force etc) identified by the student during verbal communication or on the drawings such as FBD.	*"Only one force (P) to the right, so it moves to the right, but it might be some friction force"*
	Use Newton's 2nd law to determine acceleration	Refers to any student attempts to use Newton's 2nd law or any mention on how to determine acceleration based on the sum of all forces.	*"F=ma and a is going to be to the left, because f is the only force in x and it's in that direction [left]."*
	Misconceptions	Refers to any naïve conception related to the friction force, applied pull force only in the y direction and the relative magnitude between applied and friction force	*My first reaction is that it doesn't go anywhere. I couldn't actually give you a why, but when I think about it in my head, it's pulling down and it will just slide*
Scientific idea 2 – *The direction of angular acceleration is the same as the direction of the sum of the moments about the mass center*	Identify all moments	Refers to all the moments (such as the moment due to applied pull force ***P***, moment due to friction force ***f***) identified by the student during verbal communication or on the drawings such as FBD and MAD.	*You have a torque, you have r cross P, so it's rotating it this way (CCW). [...] the friction working to rotate it that way (CW)*
	Identify the direction of the angular acceleration based on the net moment	Refers to any student attempts to determine angular acceleration and the direction of rolling based on the sum of all moments.	*It looks like it is going to roll counterclockwise because of this force P*
	Misconceptions	Refers to any naïve conception related to the moments and the relative magnitude between applied and friction force moments.	*The friction is pointing to the left and it has a greater moment than P since it's at larger distance You have a torque, you have r cross P, so it's rotating it this way (CCW). [...] the friction working to rotate it that way (CW)*

Category	Code name	Description	Example
Scientific idea 3 – *The direction of rolling has to be compatible with the direction of translational movement*	**Check for kinematic consistency**	Refers to any student attempts to make sure that the linear acceleration ***a*** and the angular acceleration □ are compatible. Positive ***a*** (considered as pointing to the right) means that □□has to be clockwise (CW). Negative ***a*** (pointing to the left) means that □□has to be counterclockwise (CCW).	*The moment seems to be CCW, but it wants to roll to the right, so do you use both in a different way?* *But it still has to roll to the left since it's moving counter-clockwise.*
Scientific idea 4 – *The direction of the friction force does not depend on the direction of rolling*	**Ways to determine the direction and magnitude friction force**	Refers to any student attempts to determine the direction and relative magnitude (relative to the applied pull force P) of the friction force during verbal communication or on the drawings such as FBD.	*Force is opposing the CW rolling, so it's right* *Since P is to the right and it's moving to the left, friction force has to be to the left.* *I thought that the more you pull, the greater the friction force is.*