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Implementing active learning in a teaching–learning sequence on rolling motion for mechanical engineers

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Abstract

In this work, we describe a teaching–learning sequence (TLS) on rolling motion, designed and implemented within a Physics 1 course for Mechanical Engineers. The TLS was grounded in Physics Education Research findings and employed active learning strategies, particularly simulation-based exercises that included both conceptual questions and quantitative tasks. We detail and reflect on the development process of the TLS, focussing in particular on the alignment between the identified learning goals and the proposed instructional activities. We present data on students' attainment of these learning goals, utilizing a post-instruction conceptual survey and an analysis of students' performance in the final exam. Our research aims to contribute to the implementation of research-based, active learning sequences in large-enrollment contexts, specifically in those courses where both conceptual understanding and formal problem solving are valued.

Supplementary material for this article is available online

Keywords: engineering education, rolling motion, active learning, simulations, teaching–learning sequence

1. Introduction

The benefits of active learning for enhancing students' performance in science and engineering are well established [1, 2]. Given the robustness of findings supporting active-learning strategies, researchers have recommended focusing on 'second-generation research' investigating which specific active-learning strategies are most effective for specific topics and student populations [1].

However, merely introducing active learning techiniques is not sufficient for promoting a deep conceptual understanding of physics [3]. In designing physics lessons, it is equally important to consider the findings of Physics Education Research (PER) regarding students' difficulties and the actions that best support the teaching and learning of specific topics. A lesson cycle that emphasizes the connection between teaching and learning while incorporating PER results into its design is called a 'teaching–learning sequence' (TLS) [4]. A TLS is designed with explicit research value, producing a 'humble theory' about what works in a particular context [5, 6]. Various theoretical frameworks are employed in designing TLSs [7–9], all sharing three common features: an analysis of the physics content and associated student difficulties, a clear identification of learning goals, and a sequence of activities contributing to their achievement.

This paper describes a TLS on rolling motion designed for a Physics 1 course for mechanical engineers. The course is an important gateway and often a challenge for engineering students. The TLS designer and author of this paper is one of the instructors of the course and a researcher in Physics Education. Although this study was conducted during regular instruction rather than within a structured project, it was therefore carried out with a research attitude and foundation. Specifically, the guiding research question was: *How can PER results and interactive simulations be combined to design a TLS on rolling motion in large-enrollment, calculus-based engineering courses?*

In the following, after setting the context, I present the process of TLS design, describe the methods used to evaluate its effectiveness, and discuss the results. In the conclusions, I provide a summary of reflections drawn from this experience.

2. Context

The students involved in this study were enrolled in the first year of Mechanical Engineering at the University of Padua, a large research-oriented university in Italy. The Physics 1 course is a calculus-based, large-enrollment class (130–150 students) granting 12 ECTS credits. It covers mechanics and electrostatics and is taught by two faculty members of the Department of Physics and Astronomy. The author of this paper was responsible for the second part of the course, which included rigid body dynamics, collisions, gravitation, and electrostatics. The exam consists of a written component and an oral component, the latter being mandatory only for students in the tail ends of the grade distribution of the written part. Students can choose to either take a mid-term exam and end-of-term exam for the two parts of the course separately, or a whole-course exam administered in a separate session.

Throughout her part of the course, the instructor designed her lessons utilizing PER-based resources such as the textbook [10] and book [11] by Knight, harmonizing them with the course syllabus and the students' textbook [12]. Learning objectives for each topic were clearly articulated and communicated to the students. Various active learning strategies were employed, including: simulations-based activities using PhET (https://phet.colorado.edu), oPhysics (https://ophysics.com), and UNL resources (https://astro.unl.edu); modeling and estimation problems, often supplemented with video resources; and tutorial-like exercises inspired by the UW Tutorials in Introductory Physics [13]. Students worked through these activities in pairs or in small groups. The activities were complemented by traditional lectures and recitation sessions. Clickers (delivered via Wooclap) were used during both traditional lectures and interactive exercises.

3. Process of TLS design

When I begun teaching in this course in 2021/22, I approached the design of the course by asking myself two fundamental questions: (1) *What are the relevant learning goals for each topic?* (2) *What are the typical challenges encountered by students, and what strategies can facilitate a deeper conceptual understanding?*

I systematically considered these points in the design of my lessons. However, I encountered a tension between applying PER findings and accomodating the constraints of my context, which included a large-enrollment course, a tight schedule with a syllabus largely determined at the department level, and a department culture that favours traditional lecturing. This culture was reflected in aspects such as the large lecture hall setting and limited teaching assistant support. Specifically, I perceived that a third pivotal question remained unresolved: (3) What do students do in my lessons?

This prompted me to reflect on what active learning strategies could enhance students' engagement despite the large-enrollment classroom setting, while maintaining the PER grounding and, therefore, keeping my primary focus on student learning. While incorporating this attention throughout the course, I decided to design and implement a TLS on rolling motion as a case study. This topic was particularly suitable as it provided a clear focus, enabling the identification of a limited number of learning objectives. However, it also presented challenges. Rigid body dynamics, as taught in the Italian context, differs significantly in its level of mathematical formalization from PER resources developed in US contexts. For example, in the textbook by Knight, the equations describing rigid body dynamics are obtained through a simplified and intuitive derivation building on analogies with linear dynamics, whereas in our courses they are rigorously derived from Euler's laws of motion. Consequently, I could not rely solely on the same PER-based resources utilized for the other segments of the course and had to search for more specific works, preferrably developed within the European context.

The work that triggered my reflection was a paper by De Ambrosis *et al* [14]. Building upon prior research findings [15], the authors emphasize that understanding frictional forces is a key element for comprehending rolling motion. This entails (i) clarifying the role of static friction, especially when comparing pure rolling at a constant speed and pure rolling under the action of a force; and (ii) highlighting the role played by kinetic friction in both starting rolling motion and changing the relative magnitudes of linear and angular velocities, thus leading to the pure rolling condition.

Another significant challenge encountered by students regards velocity composition, an issue tackled in a work by López [16]. The author observes that the relationship $v_{CM} = \omega R$, relating center-of-mass (CM) velocity and angular velocity in pure rolling, is often introduced as 'the pure rolling condition'; however, it is actually a *consequence* of the 'true' condition, i.e. that the velocity of the contact point relative to the surface on which the object rolls is zero. A similar issue—confounding kinematic constraints with fundamental physical causality—was pointed out by Close *et al* [17] when discussing students' interpretations of the kinetic energy constraint in pure rolling. To reduce the risk of students misusing the above-mentioned relationship, López advocates dedicating instructional time to velocity composition at different points on the rigid body, relying on vector calculus. The author also proposes several problem scenarios (e.g. the yo–yo; rolling on a moving platform; rolling under the action of a force applied off-center) that encourage students to reason about the relationship between velocities and accelerations, rather than applying the formulas by rote.

I compared these suggestions with the curriculum requirements for my course and with the textbook. Rigid body dynamics, which includes rolling motion, is one of the core topics of the engineering curriculum. Students are expected to develop both a conceptual understanding of the topic and the ability to solve quantitative problems. The textbook, adopted in almost all engineering courses at our university, presents the 'pure rolling condition' in the way criticized by López and lacks a reflection on the role of friction. However, earlier chapters offer extensive discussions on velocity composition (e.g. in the context of relative motion and general plane motion). Therefore, I thought I could leverage these affordances of the textbook to promote a deeper understanding of rolling motion without imposing excessive cognitive burden for the students.

Combining the literature analysis described above with this curriculum examination, I established specific learning goals (LGs) for my TLS as follows:

(1) Describe the motion of a rolling body and analyze the conditions under which it rolls without slipping [LG1].
(2) Understand the role of friction in rolling motion, with or without slipping [LG2].
(3) Analyze rolling motion under the action of forces and torques [LG3].
(4) Solve problems on the dynamics of rolling bodies [LG4].

The overarching objective is to help students develop a 'Newtonian' (force-based) description of rolling motion [17]. These goals also align well with the broader course-level learning goals, which include understanding frictional forces and using velocity/motion composition.

I proceeded with sequencing the activities to tackle these learning goals. To check whether my students' difficulties actually aligned with those described in the literature and to establish the type of scaffolding to be offered in the activities, I designed a pre-test (see 'Tests and lesson materials') administered via the Moodle platform. With the exception of question A5, the pre-test did not focus on rolling motion (a topic in which students had no previous instruction) but rather on fundamental ideas of physics important for understanding rolling motion. It contained five questions, labeled A1 to A5. A1, A2 and A4 probed students' understanding of static and kinetic friction, particularly the threshold nature of the maximum value of static friction. In A4, students were asked to describe the motion of an object down a rough inclined plane as the tilt angle is increased, also aiming to assess students' ability of discussing the motion of an object as a condition varies. It was formulated as an open-ended question to see what ideas students would activate. A3 tested students' ability to reason using velocity composition to compare the speeds of different points on the rim of a wheel. Finally, A5 was the only question that specifically probed students' initial knowledge about rolling motion, asking them to consider how the answer to A4 would differ for a rolling object versus a point object. This was also an open-ended question in order to capture all possible initial student ideas.

The results revealed that:

- *Students had an incomplete understanding of static friction.* Only 40% of the respondents recognized $\mu_s N$ as a threshold value, while 50% incorrectly attributed a fixed value $f_s = \mu_s N$ to static friction. Only 4% acknowledged the presence of a threshold angle below which a point on an inclined plane remains stationary, and only 32% accurately described how slope affects the object's motion above this threshold.
- *Students did not use velocity composition to determine the speed of different points on a wheel.* Consistent with prior literature, 79% of respondents even failed to recognize that velocities at different points on a wheel differ.

Table 1. The structure of the TLS, highlighting the alignment between the activities and the learning goals.

Lesson	Learning goals	Activity
1	Revise friction	Guiding questions to be solved in pairs
	LG1	Derivation of the pure rolling condition from velocity composition Sim 1: reinforce understanding of the velocity components Sim 2: compare pure rolling with general rolling (ratio $v_{\mathrm{CM}}/\omega R$)
	LG1, LG2, LG4	Sim3: interactive tutorial (qualitative/conceptual) + problem (quantitative)
2	LG2	Completion of the simulation-based tutorial
	LG3	Derivation of pure rolling equations under the action of forces and torques
	LG2, LG3, LG4	Exercises on objects on an inclined plane (rough or smooth; rolling body versus point object; increasing slope)
	LG3	Energy conservation in pure rolling (derivation + conceptual and quantitative exercises)
	LG1, LG4	Problem: object rolling under the pull of a hanging mass attached off-center.

- *Students exhibited vague and often incorrect ideas about the motion of a rolling body on an inclined plane.* 20% of the students anticipated no differences between the motion of a rolling body and the motion of a point object as described in A4; 15% vaguely identified ‘rolling’ as a possible source of differences, yet only 2% mentioned that that a wheel would roll down for any value of the slope. Another 20% believed that friction would disappear or reduce, resulting in increased acceleration.

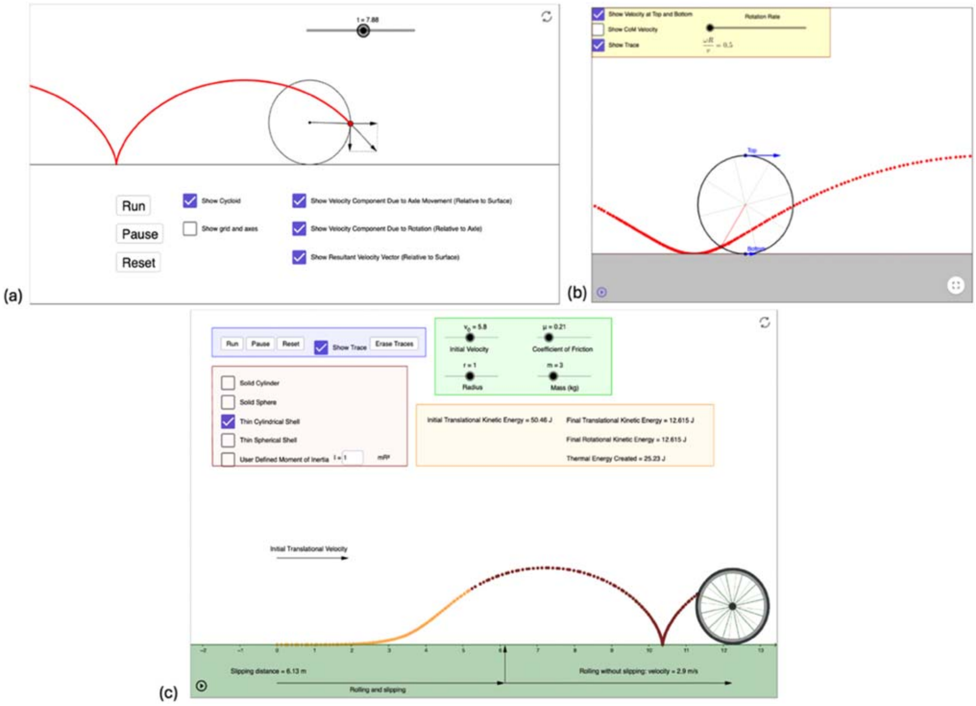
Based on these findings, I decided to include activities in which students would: (i) work on velocity composition in order to to develop a correct understanding of the pure rolling condition; (ii) engage in problem-solving activities where the pure rolling condition cannot be applied mechanically; (iii) deal with situations where an object transitions from general rolling motion to pure rolling, emphasizing the role of friction; (iv) compare the motion of rolling bodies and point objects, focussing on the roles of static and kinetic friction.

To implement this in my large-enrollment class, I identified interactive simulations as a valuable tool. Several studies have found that simulation-based activities can be highly beneficial for student learning when they are intentionally and carefully designed [18, 19]. Among the various possible pedagogical uses of simulations, outlined for instance in [19], I chose to leverage them for (i) conceptual scaffolding and (ii) problem-based learning. Specifically, I decided to couple conceptual questions aimed at fostering deeper understanding with simulation-based quantitative problems to reinforce students’ problem-solving and mathematization skills (LG4). A similar combination of qualitative and quantitative approaches was used, for example, by Low *et al* [20] in the context of engineering education.

4. The TLS

Table 1 illustrates the structure of the TLS, highlighting the active learning strategies employed in each segment. It comprised two 1.5 h lessons and one exercise session at the end of the course.

Day 1 started with a brief review activity. Working in pairs, students went through some guiding questions aimed at revising the characteristics of static and kinetic friction, the



☑ Show Cycloid
☐ Show grid and axes
☑ Show Velocity Component Due to Axle Movement (Relative to Surface)
☑ Show Velocity Component Due to Rotation (Relative to Axle)
☑ Show Resultant Velocity Vector (Relative to Surface)

☑ Show Velocity at Top and Bottom
☐ Show CoM Velocity
☑ Show Trace
$\frac{\omega R}{v} = 0.5$

☑ Show Trace
$v_0 = 5.8$ Initial Velocity
$\mu = 0.21$ Coefficient of Friction
$r = 1$ Radius
$m = 3$ Mass (kg)
☐ Solid Cylinder
☐ Solid Sphere
☑ Thin Cylindrical Shell
☐ Thin Spherical Shell
☐ User Defined Moment of Inertia I = 1 mR²
Initial Translational Kinetic Energy = 50.46 J
Final Translational Kinetic Energy = 12.615 J
Final Rotational Kinetic Energy = 12.615 J
Thermal Energy Created = 25.23 J
Slipping distance = 6.13 m
Rolling without slipping: velocity = 2.9 m/s

Figure 1. Screenshots of the three simulations used in the TLS. (a) Sim 1, used for visualizing velocity composition; (b) Sim 2, used to visualize the effects of changing the ratio $v_{\mathrm{CM}}/\omega R$; (c) Sim 3, used to frame the interactive tutorial and exercise.

relationship between static friction and the applied force, and the transition from rest to motion for a point mass. We then described rolling motion using velocity composition, and we defined the pure rolling condition as $v_C = 0$, where v_C is the velocity of the contact point relative to the surface. Following the established PER recommendation to use different representations to enhance understanding of physics concepts [21], the derivation was integrated with two simulations, run by the instructor while interacting with the students:

- Sim 1 (https://ophysics.com/r1a.html, figure 1(a)) was used to visualize velocity composition. The vectors corresponding to CM velocity (v_{CM}), the velocity component due to rotation (relative to the CM), and the resultant total velocity were activated one by one and commented. The simulation was paused to focus on the velocity of different points of the wheel during motion.
- Sim 2 (https://www.geogebra.org/m/kP5NVeaN, figure 1(b)) was used to compare pure rolling and rolling with slipping in terms of the ratio $v_{\mathrm{CM}}/\omega R$. We observed how the velocity at the top and bottom of the wheel, as well as the trace, change as the ratio deviates from 1.

A simulation-based problem, which was the core of the lesson, was then proposed using the simulation 'rotation, sliding, rolling, and friction' (https://ophysics.com/r1.html, figure 1(c)), which features a situation similar to the one in [14]. An object initially travels with a non-zero v_{CM} and zero rotational velocity ω, i.e. the object is not rolling; as the object enters the simulation frame, it encounters a rough surface and, as a consequence of friction acting on the contact point, it starts rolling. In the first (transient) part of the motion, the object both rolls and slips because the kinematic condition $v_{\mathrm{CM}} = \omega R$ is not met, meaning that the contact point has a non-zero velocity relative to the surface. As v_{CM} decreases and ω increases due to friction, the kinematic condition is eventually met, and the object starts rolling without slipping. The duration of the transient phase (and thus the distance traveled by the object before the onset of pure rolling) depends on different parameters of the simulation, such as the object's shape determining its moment of inertia and the coefficient of kinetic friction between the body and the surface.

Students worked through the exercise in pairs through a sequence of guiding questions. First, they were asked why the wheel starts to rotate in addition to sliding when it encounters the rough surface. The crucial point was recognizing that a torque is needed to initiate rotation, and that it is provided by kinetic friction. Students then focused on the transition to pure rolling. Before engaging in calculations, they were encouraged to answer conceptual questions about (i) the kinematic condition met when the object starts rolling without slipping and (ii) the dynamics leading to the fulfillment of this condition. Finally, they were asked to sketch a graph of v_{CM} and ω over time to reinforce the idea that v_{CM} decreases while ω increases until $v_{\mathrm{CM}} = \omega R$ and therefore $v_C = 0$ (pure rolling condition). Following this conceptual discussion, students were tasked with setting up and solving a quantitative problem to determine the time interval after which pure rolling starts, and the corresponding distance traveled by the wheel. The handout featured a sequence of guiding questions to provide scaffolding and step-by-step guidance. Specifically, students were prompted to write down the two fundamental equations of dynamics, to derive expressions for the linear and angular accelerations, to derive the equations of motion for translational and rotational motion, and to impose the kinematic condition for pure rolling. The remainder of the lesson was dedicated to solving the exercise in pairs, with whole group checkpoints and a final discussion.

Day 2 started with an analysis of the pure rolling phase in the simulation, focusing on why the wheel does not slow down despite the presence of friction. This scenario was used to introduce the topic of energy conservation in rolling motion. A final question asked what would happen if the wheel encountered a frictionless surface, concluding that it would continue in pure rolling motion as no external forces would act upon it. The lesson then moved to a traditional derivation of the equations of motion for pure rolling under the action of forces/or torques, again emphasizing the role of friction. Attention was then directed on a specific situation: an object rolling down an inclined plane, which was compared with a sliding point object as in [15]. An exercise was presented, asking what happens to the two objects as the slope θ is gradually increased, highlighting the different roles of friction in each case. A question about what would happen if the inclined plane were frictionless was also included. In the remainder of the lesson, students encountered various examples, from the classical 'downhill race' (e.g. [17]) to the opposite situation—a wheel rolling up an incline with and without friction, adapted from [22]. The lesson was concluded with an exam-like problem featuring an object rolling on a horizontal plane, connected through a pulley with an off-center hanging mass. Additional similar problems, some of which inspired by [16], were proposed during the exercise session. All materials, including links to the simulations, review questions, simulation guides for replicating the classroom exercises, and the interactive exercise, were uploaded to the Moodle platform for students' independent study. Some of these resources are provided in 'Tests and lesson materials'.

Table 2. Summary of questions included in the conceptual test and their correspondence with the learning goals (LGs).

Q. ID	LG	LG description	Specific situation
B1		[Check]	Static friction for a point object
B3	LG1	Describe the motion of a rolling body and analyze the conditions under which it rolls without slipping	Velocity composition
B7			Meeting the pure rolling condition
B6	LG2	Understand the role of friction in rolling motion, with or without slipping	Rolling on a horizontal plane
B8			Passing from rolling with slipping to pure rolling
B2	LG3	Analyze rolling motion under the action of forces and torques	Rolling on a horizontal plane
B4			Rolling down an incline (rough)
B5			Rolling down an incline (smooth)

5. Methods

To evaluate students' attainment of the learning goals, two measures were used: (1) a conceptual test administered via the Moodle platform just after the rolling motion segment, aimed at evaluating LG1, LG2 and LG3; (2) students' performance on rolling motion-related problem questions in the final exam for the second part of the course, aimed at evaluating LG4.

The conceptual test (see 'Tests and lesson materials') was self-designed and comprised 8 multiple-choice questions. Table 2 illustrates the correspondence between the questions and the learning goals. While some questions in the conceptual test were the same or referred to similar scenarios as in the pre-test, there was no one-to-one correspondence between the questions. It is worth recalling that the pre-test aimed to probe students' initial understanding of friction and velocity composition in order to determine the scaffolding required for the activities.

The final exam consisted of three problems covering rotations, rolling motion, and electricity. Each problem question was categorized under one of these topics, and an average score was calculated separately for each topic.

Both measures have limitations. The conceptual test was administered to students as a homework assignment, resulting in a limited response rate (31 students). Consequently, we cannot claim that these data represent the entire sample. On the other hand, data from the exam ($N = 87$) are more representative of the whole group, but we lack a direct comparison to evaluate the effects of the innovative approach against a more traditional learning environment (e.g. students' performance in a parallel course or results from the previous year). This constitutes a clear limitation of the study in terms of demonstrating impact. Despite this, I believe that these results still provide valuable information on the potential effectiveness of the TLS in achieving the learning goals, offering insights for instructors considering adopting or enhancing the proposed sequence.

Following the approach for TLS evaluation suggested in [23], I complement the assessment of learning outcomes with an analysis of the 'quality of implementation', in terms of students' engagement and accounting for any issues related to TLS implementation. The

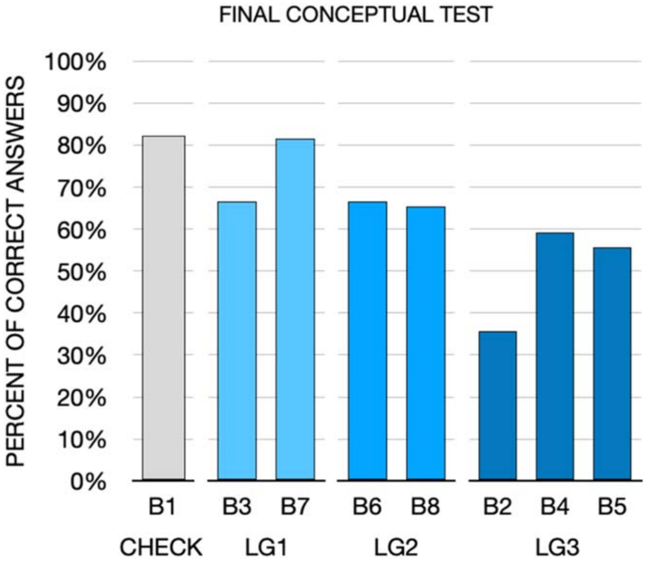


Figure 2. Students' results in the final conceptual test. The questions are grouped according to the learning goal they refer to. Question B1 did not refer to a specific learning goal but was included to probe students' understanding of the threshold nature of the maximum value of static friction.

instruments used for this purpose were the instructor's notes and students' response to questions assessing their appreciation of the activities, included in the final test.

6. Results

6.1. Conceptual test

In figure 2, we present the percentage of correct answers for each of the 8 questions in the conceptual test, categorized according to the learning goals they primarily aimed to assess. Question B1 (same as A1 in the pre-test) served as a check to gauge if students had developed a better understanding of static friction for a point object, a prerequisite for comprehending the role of friction in more complex situations, such as rolling motion. Indeed, over 80% of respondents answered correctly (compared to 40% in the pre-test).

For LG1 (*Describe the motion of a rolling body and analyze the conditions under which it rolls without slipping*), 67% of students correctly ranked velocities at different points on a wheel (question B3), a significant improvement from the pre-test result of 13% on the same question. This suggests that more students are now reasoning using velocity composition. Additionally, more than 80% of students acknowledged the presence two phases—a transient phase characterized by rolling with slipping, followed by pure rolling—in a situation similar to the interactive exercise (B7).

Regarding LG2 (*Understand the role of friction in rolling motion, with or without slipping*), 67% of students recognized that a body rolling without slipping on a horizontal plane is not slowed down by friction (B6). Similarly, 65% correctly identified *kinetic* friction as the force acting during the transient phase (B8). Examining incorrect answers is also insightful. For B6 (comparing the motion of two marbles with different coefficients of static friction), the most common incorrect answer (30%) was that *static* friction does more work on the marble with the higher coefficient. For B8, 30% of students stated that *static* friction is acting during the transient phase, with half of them also asserting that it does work on the wheel. These responses reveal an incomplete understanding of friction in rolling motion in terms of work and energy; further revisions of the TLS could focus on tackling these issues.

For LG3 (*Understanding rolling motion under the action of forces*), almost 60% of students provided a correct description of rolling motion down an incline. The majority of those who answered B4 incorrectly (26%) treated the rolling body like a point object. In the case of a frictionless plane scenario (B5), 55% of the students answered correctly, with the most common mistake being treating the plane as if it were rough.

In contrast to the other questions, only 36% of students answered question B2 correctly, recognizing the correct condition for static friction $f_s \leqslant \mu_s N$. Among students who answered incorrectly, some of them (25%) reverted to the common mistake $f_s = \mu_s N$, while others (25%) claimed that friction is zero. The latter response suggests a failure to recognize that a force is acting on the cylinder, necessitating static friction to ensure pure rolling. The former response may seem surprising, considering that most students answered the parallel question about point objects (B1) correctly. However, this answer is consistent with a knowledge-in-pieces perspective, suggesting that students' activation of the correct resource for describing static friction is context-dependent. For instance, the incorrect idea of static friction being always at its maximum value may have been triggered by textbook problems that consistently ask for finding threshold conditions [24]. Further implementations of the TLS could explicitly address this issue.

6.2. Final exam

Figure 3 shows students' normalized scores on questions pertaining rolling motion, displaying box plots and violin plots representing the score distribution. The median normalized score was 0.780 (interquartile range 0.240). This result is a measure of student achievement of LG4 (*Solve problems on the dynamics of rolling bodies*).

In evaluating my students' performance, I found it interesting to explore whether their scores on pure rolling questions differed significantly from their scores on other exam questions. I believed that such a comparison could provide insights into whether students were performing above their 'average' level of preparation in the 'experimental' section. In fact, students performed better on questions related to rolling motion compared to the remainder of the exam (median 0.690, IQR 0.285); a paired-samples t-test (student's test) confirmed that the difference was significant (t (86) $= 4.254$, $p < 0.001$), with a medium effect size (Cohen's $d = 0.46$). While attempting to isolate the effects of a particular course section from others presents challenges, similar methods have been employed in the literature [25]. Although I am mindful of the various factors that may influence student performance on different problems in an exam, the problems were designed by the same instructor (myself) with the intention of maintaining comparable levels of difficulty.

6.3. Quality of implementation

Overall, feedback from students regarding the active strategies employed was highly positive. All respondents to the final conceptual test reported finding the simulations useful, with 23% reporting they had already utilized them for individual study. Given that the final conceptual test was administered immediately after the conclusion of the course section on rolling motion, the majority (62%) had not yet tried to use the simulations independently; the remaining 15% mentioned finding it more difficult to utilize the simulation at home compared to the classroom. This suggests that group dynamics and instructor guidance may play a

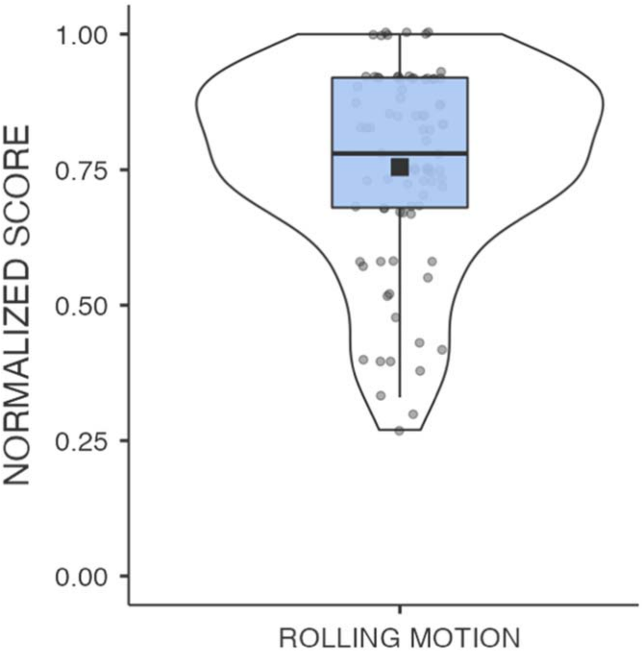


Figure 3. Students' normalized scores on questions pertaining rolling motion, with box- and violin plots of the distribution.

significant role in determining the effectiveness of the proposed strategies; this point warrants further investigation.

Throughout the course, students remained engaged and active, with attendance approaching 100% until its conclusion and beyond, including in recitation sessions held after the lesson part was completed.

No significant issues arose with the time allocated for the TLS, although some minor refinements could be made, such as allocating more time for the discussion of the final problem. Additionally, in a reiteration of the TLS, the Newtonian description could be further enhanced by better incorporating energy considerations into the model.

7. Discussion and conclusions

A TLS on rolling motion was designed and implemented in a first-year, large enrollment engineering class. The learning goals for the unit emphasized understanding the role of friction and the pure rolling condition, considering both conceptual understanding and problem-solving skills. These goals were delineated by combining an examination of the curriculum required for the course with an analysis of the conceptual nodes of the topic. The design of the activities took into account PER findings about students' difficulties with the topic and about the strategies that support understanding. An investigation of the group's initial knowledge further informed the design of the learning environment. Active learning strategies, particularly simulations and interactive exercises, were used to scaffold conceptual understanding and foster problem-based learning.

Although our results are preliminary, they indicate that the proposed TLS was effective in achieving the learning objectives. Importantly, they suggest that emphasizing conceptual understanding did not come at the expense of students' ability in problem-solving tasks. This, coupled with the positive student response in terms of engagement, encourages instructors to consider integrating these activities into the design of their lessons.

Beyond the specific outcomes, I believe that the most relevant contribution of this paper lies in the process through which the TLS was designed. Providing these details aligns with literature recommendations. For example, Zuza *et al* [23] advocate that TLS proposals should always be accompanied by a clear articulation of the methodology used in their design.

In my case, the challenge was to propose a sequence that (i) drew upon PER findings, (ii) actively engaged students, and (iii) fit within limited time and resource constraints. Clearly defining the learning goals and aligning activities with them was crucial in this regard. Interactive exercises conducted in pairs and discussed in the big group emerged as a particularly feasible and effective strategy, especially in the context of large-enrollment classrooms where the implementation of active learning strategies can be more difficult.

Balancing the incorporation of active learning approaches with the required mathematical level posed another challenge. This problem was addressed by leveraging mathematics as a resource for the TLS rather than a limitation. Specifically, velocity composition and the use of different representations of vectors were the pivotal elements. In fact, we believe that this TLS also helps students reinforce mathematics concepts and tools useful at future stages of their study of physics.

Our results suggests that simulation-based interactive exercises, underpinned by a robust mathematical foundation, can effectively promote both student performance and engagement in contexts characterized by limited time and large class sizes. Further implementations of the TLS will allow identifying the core elements contributing to its success and those that can be skipped or need refinement. Additionally, future research could explore the comparative effectiveness of alternative active learning strategies. By documenting and sharing these findings, we aim to provide insights for colleagues seeking to engage in the design or improvement of their lessons with a PER-based, active learning approach.

Data availability statement

The data cannot be made publicly available upon publication due to legal restrictions preventing unrestricted public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

Ethical statement

We confirm that our research was conducted in adherence with the journal's ethical policy and in compliance with local statutory requirements.

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