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Improving students' understanding of rolling motion

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ABSTRACT: Rolling motion is one of the most difficult topics for students studying the dynamics of rigid bodies. Students have difficulty in solving problems related to the topic, which is normally related to misconceptions about the topic. The aim of this study was to use an experiment on rolling motion to potentially improve students' understanding of the topic. The study employed a survey of 19 students enrolled on a year three course, Dynamics of Rigid Bodies, in the Faculty of Engineering at the University of Botswana, Gaborone, Botswana, in the academic year 2019-2020. The survey consisted of a questionnaire carried out before and after the experiment, related to students' understanding of rolling motion, and an additional questionnaire related to students' experience of the experiment. It was found that before the experiment, students had many difficulties in understanding, and in applying and interpreting fundamental concepts related to rolling motion. The results after the experiment indicated that the students' understanding of rolling motion improved and that the laboratory experiment was fun, exciting and interesting for them.

Keywords: Dynamics, rolling motion, students' misconceptions

INTRODUCTION

The rolling motion of a rigid body is important for mechanical engineering, both from an academic and practical perspective. The topic applies basic classical physics principles, but student understanding is often limited and unsatisfactory.

An important approach to improve students' understanding of a difficult problem is the use of experiments, which can enhance the grasp of a problem and eliminate misconceptions. Electronic devices can play an important role in an experiment by enthusing the students. An example is the use of high speed video recordings to analyse a cylinder rolling down an incline, which helps to relate the theory to the real motion [1]. However, high speed video recording devices and the necessary software for the analysis are expensive.

An attractive alternative is the use of smartphones, which have sensors: that can be used for measurements. One such sensor is the gyroscope, which can be used to measure angular velocity, and this in turn, can be used to verify several principles, such as the conservation of the rotational energy of a physical pendulum [2][3].

It is important for future engineers to understand the forces and torques involved in rolling motion, crucial in many engineering systems. However, students' understanding of this is limited and unsatisfactory [4]. The misconceptions relate to a failure to visualise rolling motion as a combination of translational and rotational motion. An approach considering the motion as an instantaneous rotation about the instantaneous centre of zero velocity is even more challenging. Approaches useful in other easier-to-imagine topics are normally not successful for rolling motion. An aspect of the difficulty related to understanding rolling motion is the lack of suitable experiments.

ROLLING MOTION

Rolling motion is a general plane motion, which can be considered as a combination of translational and rotational motions. Such motion can be seen in everyday life, including such common situations as wheels moving on a car along a road or a plane landing on a runway. Translational motion is when a body moves along a linear axis from one point to the other, with a consequence that each point on the body has the same common velocity v. Rotational motion is defined as the movement of a body on about a fixed axis, with an angular velocity ω [5].

An experiment of rolling motion on an incline can improve students' understanding of friction, conservation of energy and general plane motion.

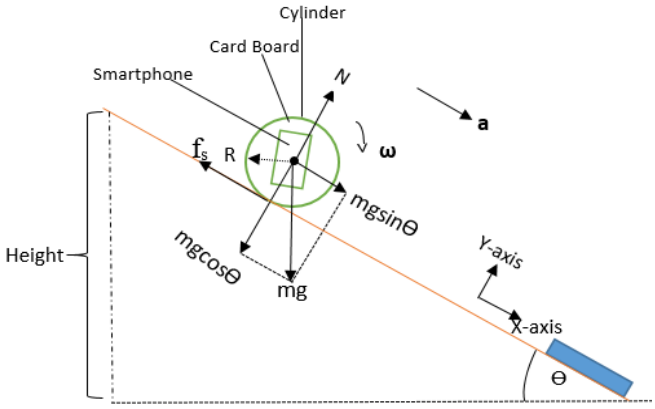


Figure 1: Experimental set-up of rolling motion of a cylinder.

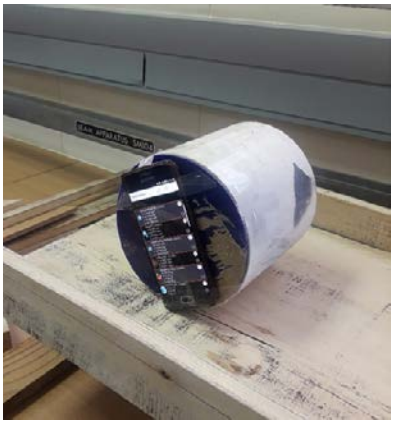


Figure 2: Rolling cylinder with a smartphone.

ROLLING MOTION EXPERIMENT

The traditional rolling motion experiment normally lacks any stimulating element that engages students. The use of the smartphone can counter that deficiency. Electronic devices can play an important role in the demonstration of phenomena, by creating an environment that improves the understanding of an experiment. Various authors have investigated the use of smartphone sensors. For example, Vogt and Kuhn studied oscillatory motion using the acceleration sensor to analyse a simple/spring pendulum [6]. The rotational and gyroscope sensors have been used to measure angular velocity, angular momentum [2] and the rotational energy of a pendulum [3]. Hochberg et al studied the relationship between angular velocity and centripetal acceleration using a smartphone gyroscope sensor [7]. Wattanayotin et al used magnetometer and gyroscope sensors in a smartphone to determine different parameters of rolling motion [8].

In an experiment developed by the authors, a smartphone was applied in the recording of data of the rolling motion of a cylinder down an incline. The experimental set-up (Figure 1) consisted of a cylinder released from the top of an inclined plane. The angular position of the cylinder was measured and recorded by the smartphone digital compass through the AndroSensor or Sensor Log found in Android and IOS systems. The results were then analysed through Excel.

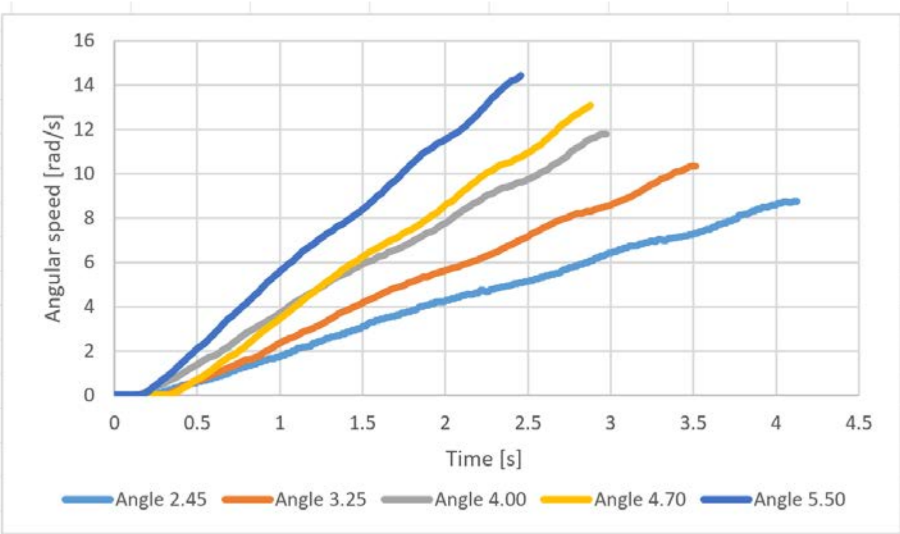


Figure 3: Angular speed of the cylinder for different incline angles.

The apparatus included a wooden inclined plane, sand-filled cylinder of polyvinyl chloride (PVC) and a smartphone, either iPhone 6s or Samsung Galaxy S6 (Figure 2). The inclined plane had a length of 1.520 ± 0.001 m and a width of 0.420 ± 0.001 m and could be adjusted to different angles. A smartphone, with the AndroSensor or Sensor Log application, was applied to the measurement of angular speed on the inclined plane. The cylinder of PVC had a mass (m_c) of 6.75 kg ± 0.01 kg and an outer radius of 0.08 ± 0.001 m. The acrylic plastic board was disc-shaped, with the inner cylinder fitting tightly to prevent spillage. The plastic board was mounted tightly at the inner end of both sides of the sand-filled cylinder using epoxy glue. The iPhone 6s or Samsung Galaxy S6 was then attached to the centre of the plastic board through thin double-sided tape (Figure 2). This was to prevent the smartphone from breaking.

The Sensor Log application was used to measure and record angular speed at a recording rate of 60 Hz, while the AndroSensor record had a normal time interval. The cylinder was released at the top of the inclined plane at various inclination angles. The data were obtained for the angular velocity and were further analysed as the rolling motion of the cylinder.

Results for the angular speed of the cylinder rolling without slipping at different incline angles are shown in Figure 3. In the students' experiment, results could be compared with theoretical values obtained by solving analytically the rolling motion of the cylinder.

ROLLING MOTION MISCONCEPTIONS

According to Lin and Chiu, the effectiveness of analogy-based teaching depends on whether the students perceive the analogy as familiar, as well as on the level of students' knowledge about the source domain [9]. Rimoldini and Singh found that students in introductory and physics junior courses very often do not understand the role of friction in rolling motion, as well as the distribution of linear velocities across a rolling wheel [10]. They have difficulty realising that a rolling wheel, even though it has contact with the surface and is rolling, and the bottom of the wheel deforms slightly, does not necessarily slip, and is at rest with respect to the surface for a measurable amount of time.

In their research, none of the 16 interviewed students was able to explain, the velocities at the top and bottom of the wheel, relative to the ground. It seems for these students it was hard to understand that, at an instant, a certain point of a moving object can be at rest even though the object, as a whole, is moving continually [11]. For a cylinder the contact point with the ground has zero-velocity, since the travelled distance of the contact point during the interval dt is zero [11].

Pure Rotational Motion

Students' understanding of pure rotational motion is normally quite reasonable, but only when that motion is happening on its own, not in combination with another motion. A typical misconception is the students' belief that linear velocities at bottom and top of the wheel are obtained by multiplying the angular velocity with the diameter of the wheel [12]. Galili et al opine that this reasoning results from *hybrid knowledge*, which is an erroneous mix of knowledge about pure rotational motion (velocity of the centre is zero and velocity at the bottom and top is the same) and rolling motion (velocity of the point at the top is $2\omega R$) [13].

Velocity at the Bottom of the Cylinder

Mashood and Singh carried out an experiment that showed a wheel rolling down an incline without slipping; students were required to deduce velocities at characteristic points on the wheel [14]. Most students wrongly applied the rotational motion model to the rolling wheel. They reasoned that the centre of mass is stationary and points at bottom and top have velocities of equal magnitude. Mixing up rotational and rolling motion is a common error regarding rolling motion [15]. Students also argued that, in addition to angular velocity and radius, the linear velocities of points on the wheel circumference depend on the angle of the incline [12]. The request for students to reason about how slipping influences the velocities of characteristic points on a wheel revealed another example of misconception, viz. regarding the linear velocities of all points on the wheel, which, according to the students, decreases when slipping occurs. This can be attributed to students' lack of experience with numerical problems related to rolling with some slipping and consequently, probably attempting to apply non-formal, intuitive mental models. Following the introduction of visual analogies the experimental group students' mental models were more compatible with scientifically accepted knowledge of rolling motion [12].

Relationship between Rolling Motion and Friction

Students' reasoning on the role of friction for the motion of a cylinder down an incline again was an example of limited understanding. Specifically, students were asked to reason about a cylinder that was placed on an incline whose angle could be changed, where the coefficient of static friction between cylinder and incline was zero. The most common wrong answer reflected the misconception that a cylinder would roll down the incline (without slipping) for all angles of the incline [12][15].

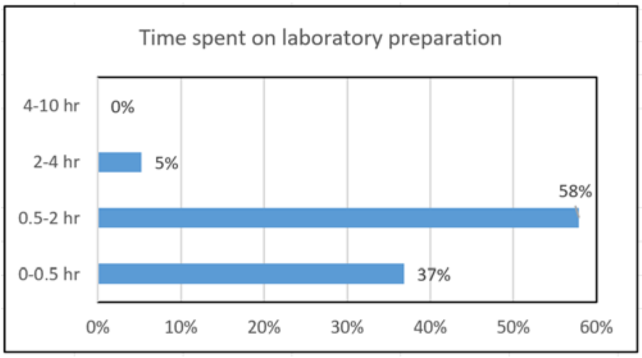
METHODOLOGY

The results presented in this paper were based on two surveys carried out on in the course, Dynamics of Rigid Bodies, offered in year three, semester one of the BEng mechanical engineering programme at the University of Botswana. The course was delivered through a blended mode consisting of traditional lectures, tutorials and laboratories. The Blackboard virtual learning and learning management system was applied to all elements of teaching, including provision of teaching material and communication with students. It was also used by the students to submit their continuous assessments (assignments, projects and laboratory reports). The experiment on rolling motion was conducted by students in groups of four; students used their own smartphones. Students were not coached on the laboratory material. Rolling motion on an incline, although generally introduced in the course, was mainly left for students' own study, as part of the attempt to fulfil the learning outcome *independent learning ability*.

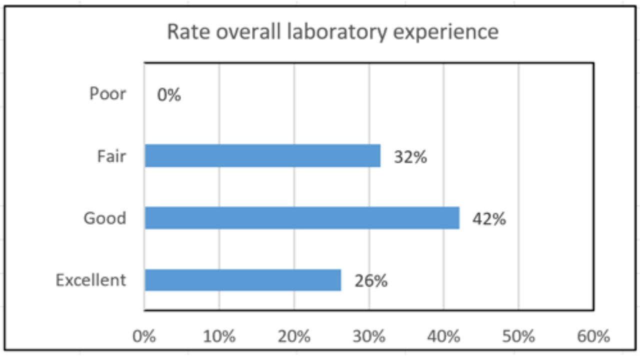
A survey of the students' experience with the particular laboratory session consisted of six multiple-choice questions and the allowance of open-ended comments. All 19 students responded, i.e. a 100% response rate. A test on the theory of rolling motion was multiple-choice with five questions. The test was done immediately prior and after the laboratory session. Out of 19 students registered for the course, 15 participated in the tests (an 83% submission rate).

RESULTS AND DISCUSSION

The survey on the general experience of students with respect to the laboratory showed highly positive results; all 19 students would recommend the laboratory to fellow students. The students mostly spent less than two hours to prepare for the laboratory session, many spent less than half an hour, and only a few spent more than two hours (Figure 4a). The students rated the overall laboratory experience highly, with 68% assessing it as either good or excellent (Figure 4b). They also considered themselves mainly as *active participants* (53% - Figure 4c), which was as expected. Students used their own phone to download the application. The phone was mounted on the cylinder and the recorded data were then transferred to the computer. The majority claimed (94% either agreed or strongly agreed) that the laboratory session improved their understanding of the theory (Figure 4d).



a)



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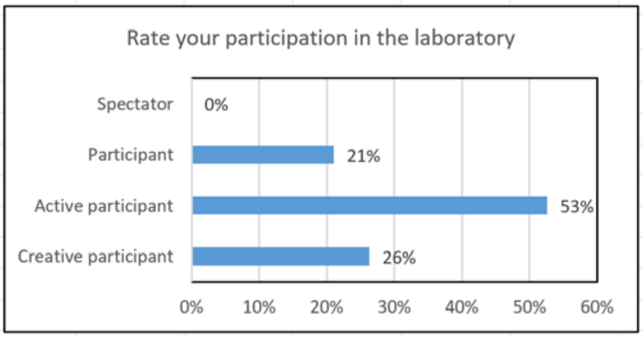

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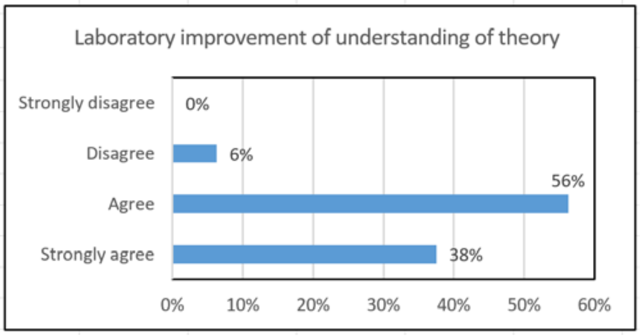


d)

Figure 4: Students' ratings of the laboratory experience.

In the open-ended question requesting students to comment on the laboratory experience, their positive comments on the laboratory experiment included:

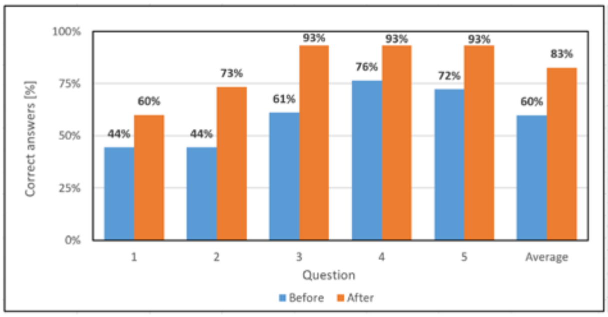
- *new and quite interesting;*
- *the experiment was interesting and required our own input, normally we just go to the laboratory to collect data and not really learn anything;*
- *the laboratory was at least interesting and we had to use* […] *own equipment, which was a novelty;*
- *the laboratory was simple and easy to understand.*

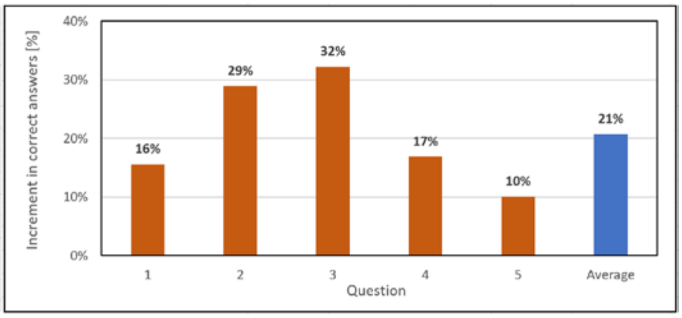
However, students also made several negative comments, solely on the time allocated to the laboratory session:

- *we had a serious time constraint;*
- *laboratory hours should be extended;*
- *we rushed the experiment as we did not have enough time to verify the results obtained.*

The test required students to answer five questions, testing them on their knowledge of issues related to rolling motion. In particular, the questions dealt with changes in angular and linear acceleration and velocity of the rolling cylinder, the velocity of the point of contact between the cylinder and the inclined surface (the instantaneous centre of rotation), and the rolling motion related to friction between the cylinder and the surface.

There was a general improvement in the students' results in the survey questions (Figure 5a). However, the results of the survey generally were disappointing, with only 60% of positive answers (on average) before the laboratory, which increased to 83% (again, on average), after the laboratory; an increment of 23%. The detailed results showing the increase in positive answers are shown in Figure 5b.





a) b)

Figure 5: Comparison of questions answered correct before and after the laboratory session.

The biggest improvement was achieved with questions related to the changes in the angular acceleration of the cylinder when rolling for a particular angle of incline, and the velocity of the point of contact between the cylinder and the inclined surface. Also encouraging was the fact that conducting the laboratory increased the percentage of correct answers for all questions above the 50% mark.

CONCLUSIONS

The difficulties and misconceptions experienced by students related to rolling motion have been widely documented. Despite that, teaching of the topic has not improved. The traditional approach to teaching based on the use of mathematical representations is not successful. The report in this article was an attempt to develop students' understanding of rolling motion, based on an experiment. In the experiment motion data were recorded by mobile phone and an attempt was made to make the investigation of rolling motion more attractive and interesting for the students.

Surveys showed that the students enjoyed the experiment and judged it to be both easy and fun. They also considered themselves active participants and would recommend the experiment to fellow students. The experiment moderately improved the students' understanding of rolling motion. The instructors were not happy with the performance of the students regarding the topic, even after the experiment, but there was still a noticeable improvement in the students' understanding. There may be a need to improve the experiment in terms of learning material and increase the time for the laboratory, but it is appropriate to invest efforts in continuing this alternative approach to teaching this complex topic.

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BIOGRAPHIES

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