Students’ understanding level of friction force direction concept on rolling object

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Abstract. Students’ understanding is the students’ ability to representing the concept correctly. Understanding and illustrating the direction of friction is very important in solving dynamic motion problems. The general idea that the direction of friction force is opposite to the direction of objects motion. This research aim was to describe students’ understanding level of friction force direction on rolling object without slipping in the horizontal plane. This research used survey method by using descriptive qualitative. The sample used consists of 28 students who were selected by purposive sampling in the academic year 2017/2018 of Physics Education, Universitas PGRI Madiun. Data collected from three-tier diagnostic test about the direction of friction force. A test was given to 28 students who had obtained the friction force topic in the lecture. The result is 10.7% students can understand and explain the friction force direction on the spool caused by the external force. 3.57% of the students can explain the friction force direction on the sphere with the external force at the center and the edge of the sphere and 3.57% can explain the friction force direction on each bicycle wheel. The friction force direction is not always opposed to the object’s motion. The friction force direction acting on the rolling object can be pointed in the opposite direction or in the same direction of an external force. This research in further can be used to improve the learning process of friction force.

1. Introduction
Force is the basic concept of Newtonian mechanics. The friction force is a force that occurs because all surfaces are rather rough and the two surfaces stick or interlock at various points [1]. When learning the friction force, it is necessary to also understand the direction of friction force. The direction of friction force is one of the topic that need to be understood. Understanding the direction of frictional force can make it easier for students to represent a force in free body diagrams. The idea is that friction forces direction is opposite to the motion of the object [2],[3], [4]. However, not all objects moving in the horizontal plane have the same direction as the movement. Rolling objects have a friction force in the same direction of object motion, opposite to the object motion, or no friction [5]. Salazar et al give examples in some cases which show that the friction force has the same direction as the center of mass velocity [2].

There are several articles that discuss students’ understanding of force concept. The study has shown that students have the misconception on force concept [6]. Students have not understood the concept of friction force in rolling motion [7], [8] and pre-service teachers have difficulty understanding the concept of rolling friction coefficients [9]. When students study systems of particles, some students are
confused about the friction force direction because the direction of static or kinetic frictional force can be opposite or in the same direction as the center of mass velocity [3]. Moreover, students cannot show the friction force direction on rolling objects such as bicycle wheels [10]. Understanding the force concept such as the direction of frictional force should be emphasized in the learning so that students can understand the overall material friction force.

Students’ conceptual can develop from their daily experiences. However, there is the intuitive understanding of around them which does not agree with the scientific concepts explanation. Level of understanding generally consists of several categories namely no understanding, partial understanding, misconception and understanding [11]. According to Akbas, the classification of the understanding levels: understanding, limited understanding, misunderstanding and irresponsiveness [12]. Misconceptions cases or something that is known and believed but not match with what is known to be true scientifically [13]. Initial conceptual understanding of students before learning will affect the understanding of student concepts after learning. Identify students' understanding is very important to be able to teach physics effectively [14]. In addition, knowing the students' concept of understanding is important to evaluate progress in learning [15]. To know the level of understanding can be done in various ways, one of them is through the three-tier diagnostic test. The advantage of the three-tier test is that it can distinguish between lack of knowledge and misconception [16]. The survey in this study was conducted to find out the students understanding level about the direction of friction force on the rolling object without slipping on the horizontal plane. This hope that teachers can take the first step to improve learning, after knowing the student’s misconceptions.

2. Experimental Methods

Survey method using descriptive qualitative analysis was used in this research. Survey research in education knows to discover current conditions. It is to describe the conditions or to explain it. One of the data collection in the survey method is the test. The data is collated and presented in tables with explanatory comments [17]. The sample used consists of 28 students who were selected by purposive sampling in the academic year 2017/2018 of Physics Education, Universitas PGRI Madiun. Data collected from three-tier diagnostic test about the direction of friction force. The first tier is multiple choice consists of 5 options. The second tier includes the reason of students choose the first tier, and the third tier is confidence index (if the students are sure to answer). A test consist of three item, each item has been validated by an expert in physics education.

The test is given to 28 students who have obtained the topic of friction in the lecture. Students understanding categories were analyzed based on three-tier test analysis [18], shown in Table 1.

| Categories       | Response Types                                    |
|------------------|---------------------------------------------------|
| Scientific Knowledge | correct response + scientific explanation + sure |
| Lack of Knowledge          | incorrect response + scientific explanation + not sure |
|                          | correct response + unscientific explanation + not sure |
| Error                      | incorrect response + scientific explanation + sure |
| Misconception             | incorrect response + unscientific explanation + sure |

Students who have scientific knowledge means understanding and lacking knowledge means lack of understanding. Students who have an error answer (incorrect response + scientific explanation + sure) are included in the misconception category [19]. Based on Abraham, students included in the category of not understanding if repeat question, irrelevant or unclear response. The level of students' understanding in this study is understanding (scientific knowledge), limited understanding (lack of knowledge), misconception, and no understanding.
3. Result and Discussion
The test consists of three-item. The three item test was applied to the students to determine their opinion about friction for direction. The analysis of student answers is shown in Table 2.

| Levels of Understanding | First Question (Q1) | Second Question (Q2) | Third Question (Q3) |
|-------------------------|---------------------|----------------------|---------------------|
|                         | total student (%)   | total student (%)   | total student (%)   |
| - Understanding         | 3 10.7              | 1 3.57              | 1 3.57              |
| (scientific knowledge)  |                     |                     |                     |
| - Limited understanding  | 8 28.6              | 4 14.3              | 9 32.1              |
| (lack of knowledge)     |                     |                     |                     |
| - Misconception         | 12 42.9             | 21 75.0             | 12 42.9             |
| - No understanding      | 5 17.9              | 2 7.14              | 6 21.4              |

Table 2. Analysis of student answer according to levels of understanding

Q1 is a question of the friction force direction on the rolling spool without slipping due to an external force \( F \). Q2 is the difference of friction force direction on a rolling sphere without slipping because of an external force \( F \) at the edge and center of the sphere. Q3 is friction force direction on the bicycle wheel.

3.1. The Direction of Friction Force on the Rolling Spool without Slipping in the Horizontal Plane.
Q1. An object has mass \( m \). It can roll away because of a force \( F \) parallel to the horizontal plane, see Figure 1. It is two wheels with radius \( R \) connect to a cylinder with radius \( r \). Please find the friction force direction \( f \) between the object and the horizontal plane when \( r > \frac{I}{mR} \). \( I \) is the moment of inertia of an object.

![Figure 1. Spool in the horizontal plane](image)

The result from Q1, 10.7% students answered in the category of understanding (if a student answered both the first and the second tier correctly, and sure in the third tier). 28.6% of them answered in the category of limited understanding (if it is incorrect on one of a tier and not sure in third-tier; the first and the second tier is correct or incorrect, and the third tier is not sure). 42.9% students answered in the category misconception (correct-incorrect-sure; incorrect-correct-sure; and incorrect-incorrect-sure). The most important misconception of the students is the idea that friction force direction on the rolling spool is opposite to the direction of spool motion because it is always opposite to the rotational motion or translational motion. In addition, the misconception students that the friction force has the same direction and opposite to the spool motion.

Some students can answer the question of multiple choice correctly but have not explained the reason. Example of misconception at the second tier is shown in Figure 2. At the first level, students can answer correctly that the friction force has the same direction as the spool motion. But based on Figure 2, students have reasoned that the direction of friction force is always opposite to the direction of object motion. The object motion according to Figure 2 is the motion of the rotation of the object.
Figure 2. Example of incorrect response

Based on student misconception, some students argued the friction force direction on the rolling object is opposite to the translational motion. According to the student, determines the direction of friction force on a rolling object equal to a block moving on a horizontal plane. Students also argued the friction force can decrease the linear acceleration of an object. If the spool is rolling to the right then it has the direction of the friction force to the left. A misconception of other students is friction force direction on the object is opposite to the rotation motion, and friction force can decrease the angular acceleration. For example: If an object rotates clockwise, it has the friction force direction counterclockwise.

Based on Carvalho [5], determined the direction of friction force ($f$), it can be known through the translation motion equation $a = \frac{\sum F}{m}$ and rotation motion $(f = \frac{\text{mom}}{l})$ on the object. It is assumed that the friction force direction has the same direction as the external force. The equation of translation motion is

$$F + f = ma \tag{1}$$

The acceleration of rotation motion is

$$f = \frac{Fr - fR}{l} - \frac{R^2}{l} \tag{2}$$

Substitute equation (1) into equation (2) to obtain the frictional force equation.

$$F + f = m \left( \frac{Fr - fR^2}{l} \right)$$

$$Fl + fr = Fmr - fmr^2$$

$$f = \frac{Fmr - f}{I + mR^2} \tag{3}$$

$I$ is the inertia moment of the spool. Equation (3) is the equation of friction force on the spool. Determine the direction of the frictional force depends on three situations:

1. $r > \frac{l}{mR}$, the friction force is positive. So, the friction force in the same direction with spool motion.

2. $r = \frac{l}{mR}$, the frictional force is zero.

3. $r < \frac{l}{mR}$, the frictional force is negative so that the friction force is in opposite direction with its motion.

The friction force on the rolling spool has a different direction (not always opposite to spool motion). The direction of the frictional force depends on the radius $r$. Based on Q1, the radius is $r > \frac{l}{mR}$ so the friction force has the same direction as the motion of the object.
3.2. The Direction of Friction Force on Sphere Rolling without Slipping in the Horizontal Plane.

Q2. The two solid sphere rolling in the horizontal plane. Sphere 1 is given an external force $F$ to the right spaced $R$ from the center of the sphere and the sphere 2 is given $F$ right at the center of the sphere, Figure 3. If the sphere moment of inertia is $\frac{2}{5} mR^2$, where does the frictional direction indicated by both sphere?

![Figure 3. A sphere is given an external force at the (a) edge (b) center](image)

The result from Q2, 3.57% students answered in the category of understanding. 14.3% of them answered in the category of limited understanding. 75.0% students answered in the category misconception. The maximum misconception was seen in this question. It can be thought that students do not have the right ideas about friction force direction on the rolling sphere. The student’s misconception: friction force direction of the two-sphere to the left as opposed to the direction of translational motion, friction force direction on both sphere to the right as opposed to the rotational motion, and friction force direction of the sphere 1 to the left and the sphere 2 to the right. Some students do not notice external forces at different points. Some students have difficulty determining the friction force direction of rolling objects caused by external forces, same as research by Ambrosis [8]. Examples of students’ answers with the wrong response, is shown in Figure 4.

![Figure 4. Examples of incorrect response](image)

Since an object can move when the direction of the friction force is opposite to the force applied to the object, either on a given force at the center of the object or not.

Students have different of conceptual understanding. Based on Figure 4, the students’ misconception is friction force direction on the rolling objects always opposite to the object motion without considering the position of the external force. Some students argued the friction force direction opposite the translation motion. The sphere has an acceleration to the right so that the direction of friction force to the left. Other students had the opinion, the frictional force against the rotation of objects. The sphere is rotating clockwise so that the friction force direction is counter-clockwise. The student's misconception, the direction of the frictional force opposite the object motion. It will be difficult in determining the friction force direction on the rolling object. Another misconception i.e. the sphere, which is given an external force on the edge, will accelerate the rotation motion. So, it has a direction of friction force to the left. The sphere, which is given an external force in the middle, it will accelerate the translation motion. So, it has a friction force to the right.

The theory can be explained in Figure 5 by Pinto and Salazar [2], [3]. A homogenous object has mass $m$ and radius $R$ in a horizontal plane, example a sphere, a cylinder. The external force ($F$) is applied to an object at height ($y$), as shown in Figure 5. There is a friction force ($f$) from the contact point between the cylinders and the horizontal plane.

![Figure 5. Examples of incorrect response](image)
Figure 5. The object on the horizontal plane is given the force \((F)\) at the height \((y)\) and the friction force \((f)\) (presented to the right). Normal and weight force are equal in magnitude and have opposite directions, not shown in the figure.

According to Figure 5, the condition rolling without slipping when 
\[
R v/R g < 0.32
\]
The rolling object has translation and rotation motion. The equation of translational motion according to equation (1), assumed direction of friction force in the direction of an external force. The equation of rotation motion is:
\[
F(y-R) - fR = Ia
\]
\[
F(y-R) - fR = \beta m R^2 \frac{a}{R}
\]
\[
f = \frac{R}{R} \left( \frac{1 - \beta}{1 + \beta} \right)
\]
Equation (4) is a frictional force when a homogenous object rolls with the influence of an external force \((F)\) at a height \((y)\) of the horizontal surface. \(\beta\) is a mass distribution factor owned by homogenous objects. Suppose the moment of inertia in the solid sphere is \(2/5 m R^2\) so \(\beta = \frac{2}{5}\). The direction of the frictional forces will vary when the external force \((F)\) is given at different height \((y)\).

1. When \(y = (1 + \beta) R\), so \(f = 0\). This means that objects will roll without slipping and no friction force arises between objects and surfaces.
2. When \(y < (1 + \beta) R\), so \(f\) is negative. The direction of the friction force is opposite to the direction of the force \((F)\)
3. When \(y > (1 + \beta) R\), so \(f\) is positive. The resultant of force \(F + f\). It means that the friction force shows the same direction as the external force.

Based on Q2, the sphere has a moment of inertia \(2/5 m R^2\) so \(\beta = \frac{2}{5}\). Sphere 1 is given the external force of the edge of the sphere so that it has \(y = 2R\). It means that \(y > (1 + \beta) R\), so the friction force shows the same direction as the external force direction (to the right). Sphere 2 is given an external force in the center, so \(y = R\). It means that \(y < (1 + \beta) R\), the frictional force indicates the direction opposite to the direction of its external force (to the left).

3.3 The Direction Of Friction Force in Bicycles’ Wheels

Q3. A child pedals a bicycle toward the x-negative direction, see Figure 6. He predicts the direction of the frictional force on the bicycle wheel. The correct prediction of the direction of the frictional force on each wheel is...

Figure 6 Bicycle
The result from Q3, 3.57% students answered in the category of understanding. 32.1% of them answered in the category of limited understanding. 42.9% students answered in the category misconception, and 21.4% students were no understanding. Some students predicted the friction force direction on all wheel to the negative x-axis. The students’ misconception is the friction force direction on the front wheels and rear wheels as opposed to the rotation motion of wheels. According to them, both wheels are rotated counter-clockwise so that the friction force direction is to clockwise or to the negative x-axis. Another prediction is friction force direction on all wheels to the positive x-axis. The students’ misconception is friction force direction on the front wheels and rear wheels as opposed to the translation motion of wheels. This result is the same as the research by Calvalho, Prasitpong and Wulandari [5],[7],[10]. Example of the incorrect response is shown in Figure 7.

![Figure 7. Examples of the incorrect response](image)

In general, the rear wheel of a bicycle is rotated by a rider (not a machine). The rear wheel can rotate due to a chain. This is similar to the rotation of a motorcycle wheel or a car wheel that is rotated by a machine. The bicycle's front wheel is not connected to a machine and is free to rotate. The direction of friction on the front wheel is different from the rear wheel.

The rear wheel can move because of the torque on the wheels. The bicycle has an acceleration of the negative x-axis. The fundamental equation for translational acceleration, \( a = \frac{\sum F}{m} \). Based on the translation equation, there is one force acting on the rear wheel to cause acceleration to the negative x-axis. That force is the friction force. If the friction force on the rear wheel does not exist, the wheel cannot be accelerated in the direction of motion. The direction of acceleration is to the negative x-axis, then the friction force direction on the rear wheel \( f_b \) to the negative x-axis.

Figure 8 is free body diagram of the bicycle with wheel mass is \( m_a \) and \( m_b \), connected by a rigid bar. A rigid bar mass is \( m_c \).

![Figure 8. Free body diagram on the wheels of the bicycle](image)

The front wheel gets a force from a rigid bar that acts on the axles. So, it can move translations. The front wheels have translation motion to the left. As a result, the frictional force on the front wheel \( f_a \) has a direction to the right. The translation motion of the front wheel is caused by the force from a rigid bar that acts on the axles. While the rotation motion of the front wheel is caused by the friction between the wheels and the ground. If the front wheel does not touch the ground, so it will not rotate. Finally, both bicycle wheels can rotate in the same direction but the friction force direction on each wheel is
opposite. Friction force direction is not always opposed to the object’s motion. The friction force direction is determined by the cause of moving objects, not the direction of the object motion.

The bicycle has translation and rotation motion. Considering the moment of inertia $I$ to be the same for both wheels, and the bike mass is $m_a + m_b + m_c$. The linear acceleration on the bicycle is $a = \frac{\Sigma F}{m}$. A bicycle can move when the friction force on the rear wheel is larger than the front wheel. Linear acceleration of on bicycle can be written

$$a = \frac{f_b - f_a}{m_a + m_b + m_c} > 0$$

This result is important for students because it shows a conceptual understanding of the concept of the friction force direction. It is estimated that it is very important to investigate this conception. In addition, it can be used to improve the learning process about the direction of friction force. It is advisable to improve the learning process on the friction force direction in accordance with the technique by Calvalho and Prasitpong[7],[5]. This is to improve students' conceptual understanding about the direction of friction force.

4. Conclusion

This result is very important because it has shown students' conceptual understanding of the friction force direction. 10.7% students can understand and explain the friction force direction on the spool caused by the external force. 3.57% of the students can explain the friction force direction on the sphere with the external force at the center and the edge of the sphere, and 3.57% can explain the friction force direction on each bicycle wheel. The students' misconception is the incorrect idea that friction force direction on the rolling object is opposite to the direction of object motion. The friction force direction on the rolling spool has a different direction (not always opposite to spool motion). The direction of friction forces on a rolling homogeneous object, which is given an external force, is not always opposite direction with an external force. In addition, bicycle wheels can rotate in the same direction but the friction force direction on each wheel is opposite. The friction force direction is determined by the cause of moving objects, not the direction of the object motion. Furthermore, it is suggested to do other research about students' conceptual understanding of the different topic, it is will make a contribution to the teaching of the subject.

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6. Reference

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