TED ANKARA COLLEGE FOUNDATION HIGH SCHOOL

INTERNATIONAL BACCALAUREATE

PHYSICS EXTENDED ESSAY

THE INVESTIGATION OF TORQUE CAUSED BY THE FRICTIONAL FORCE (FRICTIONAL TORQUE)

Name of the candidate: Umut Servan ALDATMAZ

Candidate number: D1129003

Name of supervisor: Mine GÖKÇE ŞAHİN

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Umut Servan Aldatmaz
D1129003

ABSTRACT

The objective of this essay, is to analyse what factors are affecting on the friction torque. In this essay, I tried to reach the friction torque values from different methods and unique experiments. This experiment is conducted to investigate the factors affecting torque of frictional force on a rotating object. By this purpose, a falling mass is used in order to create a constant torque on a rotating disc. The mass is tied at one of the ends of a rope whose other end is fixed to the disc and then released. During the experiment, initial height of the object, the radius of the pulley which is fixed to the disc and the mass of the object is changed in order to outline the factors affecting on friction torque.

At the end of the experiment, it was clear that when the theoretical value of torque is increased the friction torque also increased. Change in mass, initial height and moment arm is affected both the change in potential energy and the friction torque. Therefore, it could be conducted as the effect of friction on a system is changing due to some factors.

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CONTENT

A. LITERATURE REVIEW

Almost everybody hear the term torque in daily life. With the improving technology we see lots of new cars or vehicles in the street everyday. And the term torque is generally used for describing the properties of a vehicle. But lots of people do not know what torque really means.

1. WHAT IS TORQUE?

"Torque is the tendency of a force to cause a rotation of the body on which it acts"[1]*.* Briefly, we can define the torque like that. This pattern is related with the magnitude and the direction of the force. The object rotates on an axis.

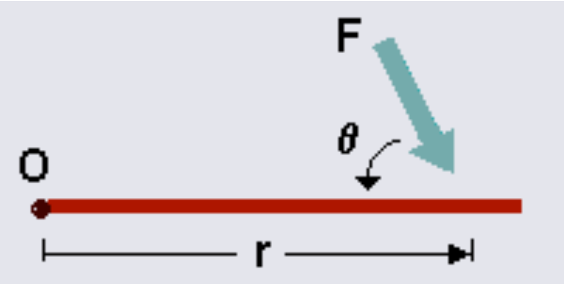


Figure 1: The force acts on a body and creates torque on the object.

In the Figure 1 "F" is the force acting on the object, "r" is the moment arm, and □ is the angle between force and the rotation axis.

τ = r x F sin□.

As seen instead of using in cars we use the torque in every part of our daily life. To give a basic example when we turn a screw with a screw wrench we use our force to turn something therefore we create a torque.

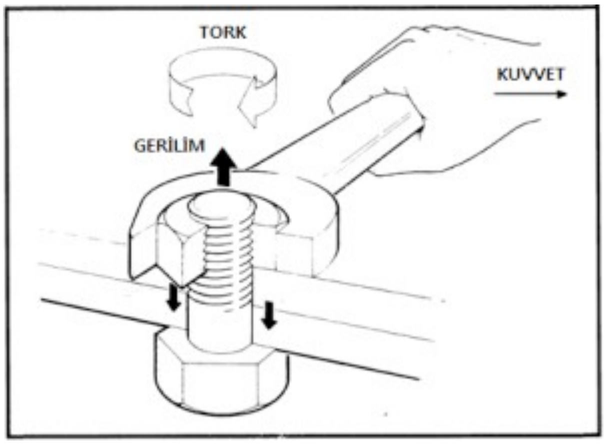


Figure 2: Turning the screw with wrench could be an example for torque concept.

2. FRICTION FORCE

In lots of physics problems we neglect the force of friction. Friction is an against force which acts on a body. *"When two bodies interact with direct contact (touching) of their surfaces the interaction forces are called contact forces."* On a free body diagram of an object *"the perpendicular component is the normal force and the component which is parallel to surface is called the friction force"*[2]

- *Friction always opposes the motion or attempted motion of one surface across another surface.*
- *Friction is dependent on the texture of both surfaces.*
- *Friction is also dependent on the amount of contact force pushing the two surfaces together (normal force)*[3]

3. CONSERVATION OF ENERGY

"Energy in a system may take on various forms (e.g. kinetic, potential, heat, light)".[4] Conservation of energy law says that energy is not created or destroyed in a system. Therefore, the sum of all the energies in an isolated system is constant. So we can say that, according to the law of energy conservation the total energy in a system will not change. However as it is said before the friction force is generally neglected while solving a problem.

So, because of the friction force is an against force, the total energy in a system with friction will not be constant it will change.

For instance, if there were no friction the total energy acting on the pendulum below will not be changed and the pendulum will swing forever. The total mechanical energy acting on this pendulum is the sum of potential energy and kinetic energy. The potential energy turns into kinetic energy and the pendulum swings. However, some of the energy is lost because of the air friction while the potential energy turning into the kinetic energy.

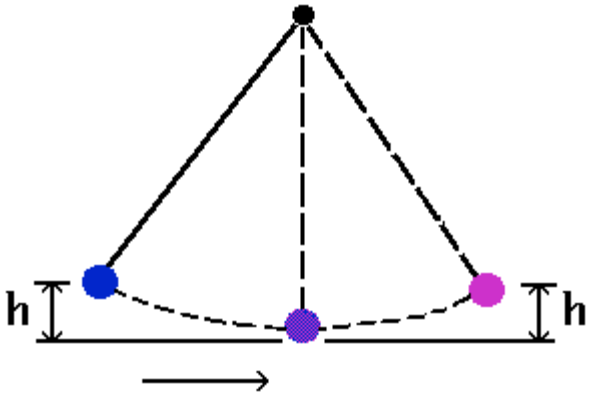


Figure 3: The pendulum is swinging.

4. TORQUE IN REAL LIFE

As mentioned torque is important when designing a machine or an engine. The measurement of torque is also important in automotive engineering, being concerned with the transmission of power from the engine through the drive train to the wheels of a vehicle. Torque (and power output) can be measured with a dynamometer.

A screw wrench is used where the tightness of screws and bolts is very critic. "*Torque is also the easiest way to explain mechanical advantage in just about every simple machine.*"

Also if we divide the real life applications of torque into two; it will be the usage in complex machines and in simple machines. The best examples for simple machines are the wrenchs and the seesaws. Engines and electric motors could be an example for the real life application of torque in complex machines.

As mentioned before we are using the torque in everywhere in our daily life. And when we are calculating the Torque we are neglecting the force of friction. This force of friction acts on the body and creates a negative work. And when this friction force is acted on a rotating object it causes a negative torque value which is called the friction torque. For instance, when we turn a compass rose it will stop after a few seconds.

This experiment is conducted to investigate the factors affecting torque of frictional force on a rotating object. By this purpose, a falling mass is used in order to create a constant torque on a rotating disc. The mass is tied at one of the ends of a rope whose other end is fixed to the disc and then released. When the mass is going downwards by the effect of gravitational force, this force makes work on that object. Some of the potential energy which the object lose, turns into the kinetic energy and the object accelerates. The other potential energy turns into the rotational kinetic energy and the disc starts to turn and the angular speed of the disc increases. When the velocity become maximum (the object comes to the bottom). The potential energy will be;

$$mgh = ½ \times m \times v_{max}^2 + ½ \times I \times w_{max}^2$$

from the conservation of energy. When the mass is at the bottom, the disc continues to turn because of the kinetic energy which it already has. The fixed pulley starts to round the rope therefore the object starts to go upwards. In this case garavitational force make work nagatively, therefore the object slows down and the disc is also slows down. If there is no friction force acting on the system, the mass will go up to its initial height(where we let it to fall). However, if there is a friction force affecting the system (and in earth it must be) some of the total mechanical energy will be lost so there will be difference between the initial and final height. Using this height difference the difference between the potential energies and the friction torque values will be found at the end of the experiment.

B. DEVELOPING THE EXPERIMENT

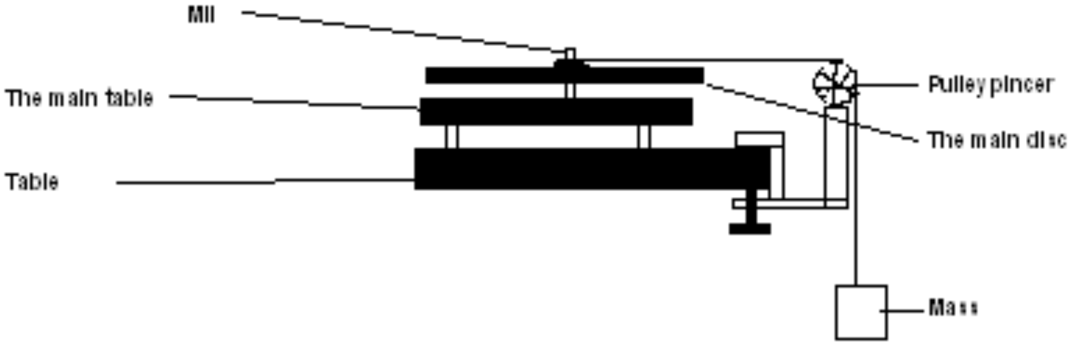


Figure 4: It is the side view of the experiment which is set up.

1. Materials

- A main disc with a mass of 991,2 g ± 0,1 g and radius of 12,7 cm ± 0,1 cm (a disc with a hole at center in order to place the mil)
- Three pulleys which are fixed to the main disc and have the radius of 1,5cm, 2,0cm and 2,5 cm ± 0,1 cm
- A rope with height of 1,5 m ± 0,1 cm
- A pulleypincer
- A mass hanger (5g ± 0,1 g)
- Masses (10g, 20g and 100g ± 0,1 g)
- Another pulley to make rope parallel to the table.
- A table which has a hole on it
- Ruler ± 0,1 cm

2. The key variables

2.a. Dependent variable:

- The friction torque affecting on the main disc.

2.b. Controlled variables (for each experiment):

- The radius of the main disk
- The length of the rope used in each experiment.
- The initial height of the mass from ground (h0)

2.c. Independent variables:

- The height which the masses are let to free fall (h1)
- The mass of the object used in the experiments.
- The radii of the pulleys used in the experiments.

NOTE: The experiment consists of three parts (1, 2, 3) in each part the radius of the main disc, radius of the pulleys used, length of the rope and initial height of the mass from ground is constant. However, in the overall experiment the radii of the pulleys used are changed to observe the changes in friction torque.

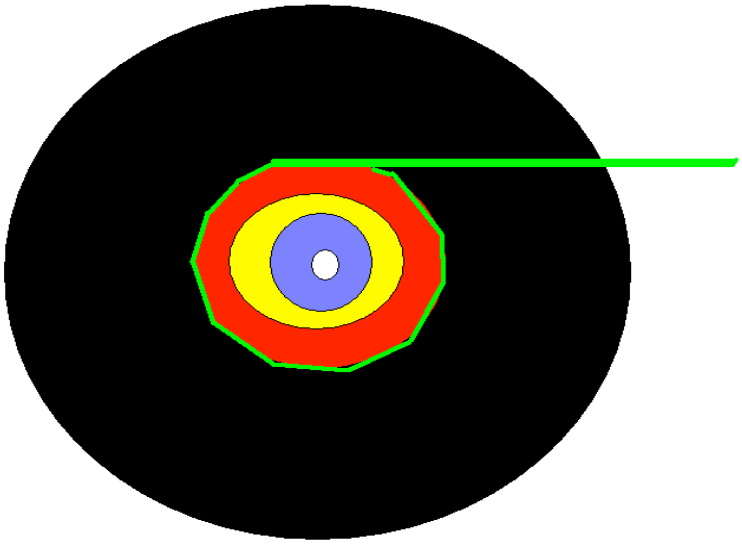


Figure 5 : The top view of the apparatus. In the picture; red, yellow and the blue parts are the pulleys with radius of 1,5cm, 2,0cm and 2,5cm. The green part is the rope and the white thing is the mil.

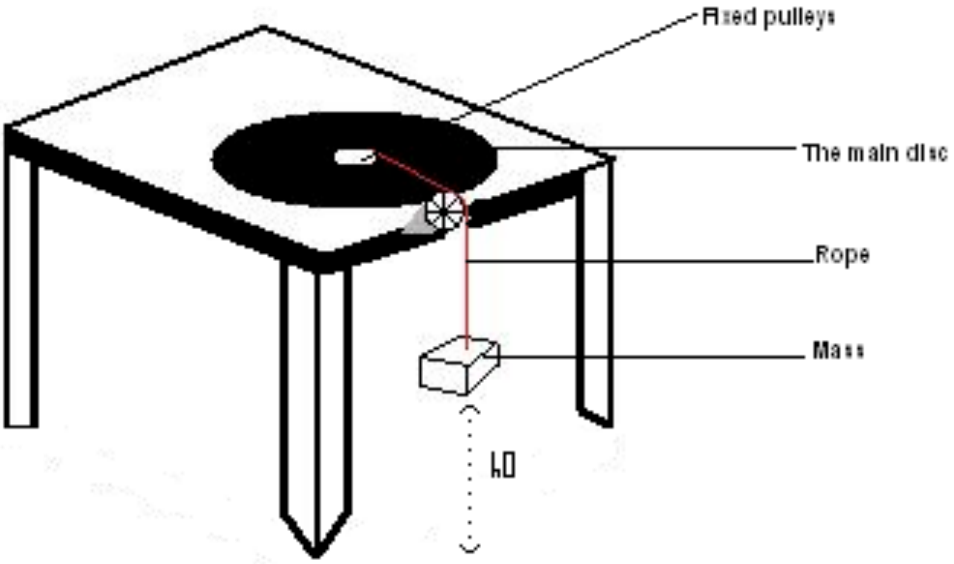


Figure 6: The side view of the set up could be seen. And the initial height of the mass (h0) is seen.

3. METHOD

3.a. Part 1:

1. The 1,50 m rope is binded to the first pulley(with radius 1,50 cm)
2. The masshanger is tied to the rope.
3. A 20g mass is put in to the mass hanger.
4. The mil is fixed with the hole of the main disc and the main disc is binded with the table.
5. Another pulley is fixed to the table with the help of pulley pincer. As seen on the figure 4.
6. The rope should be parallel to the surfaceof the table.
7. The height of the object from ground is measured when the rope is not rounded to pulley.
8. The data is saved as h0.
9. The rope is rounded to the pulley and when the height becomes 25,00 cm(h1) the object is released.
10. It is seen that the disc is turning wait until the object goes up and stops.

11. When the object stopped immediately the disc is stopped manually. For this step it will be better to work as a pair because it is hard to measure the height while holding the disc.
12. The height where object stops is saved as "h2".
13. These steps are repeated three times. Three h2 values should be measured for each mass and h1 value.
14. After that, h1 is changed as 37,5 cm, 50 cm, 62,5 cm, 75 cm and 87,5 cm.
15. For each height three h2 values is measured to get a more accurate data.
16. All these steps are repeated for different masses.
17. Masses to consider; 30g, 40g, 60g, 80g, 100g.

3.b. Part 2

In part two, the only change during whole experiment is made in the radius of the fixed pulley used. This part of the experiment is conducted to see how the change in the moment arm affects the torque caused by friction.

3.c Part 3

In part three, the only change during whole experiment is made in the radius of the fixed pulley used. This part of the experiment is conducted to see how the change in the moment arm affects the torque caused by friction.

WARNING: The mass of mass hanger is regarded during the calculation. The table of raw data is presented in Appendix A.

C. DATA PROCESSING

1. Frictional Torque Calculation

The data processing consists of following calculations; the average h2 values, the angular speed of the rotating object, the loss (change) in potential energy and the total distance covered by the object.

At first, the potential energyof the object is found by the following expression;

$$\square PE = mg\,(h1-h2).$$

Where h1 is the initial height of the object and h2 is the final height of the object.(when the disc stops rotating.)

The acceleration of free fall is 9,78 ms^{-2} in Ankara.

The total distance covered by the object during one trip was found in order to find the value of friction torque.

$$d = [(h1 - h0) + (h2 - h0)] = h1 + h2 - 2h0$$

Where h0 is the

In order to find the angular speed of the rotating disc, the distance which object travelled per round of the pulley needed to be calculated.

$q = d / r$ where “r” is the radius of the pulley in each experiment.

We know that the change in energy is the work done by the acting force. And if we divide the change in potential energy to the angular speed of the object; this gives us the the work done by the frictional force per rotation of the disc. This value equals to the frictional torque. Therefore;

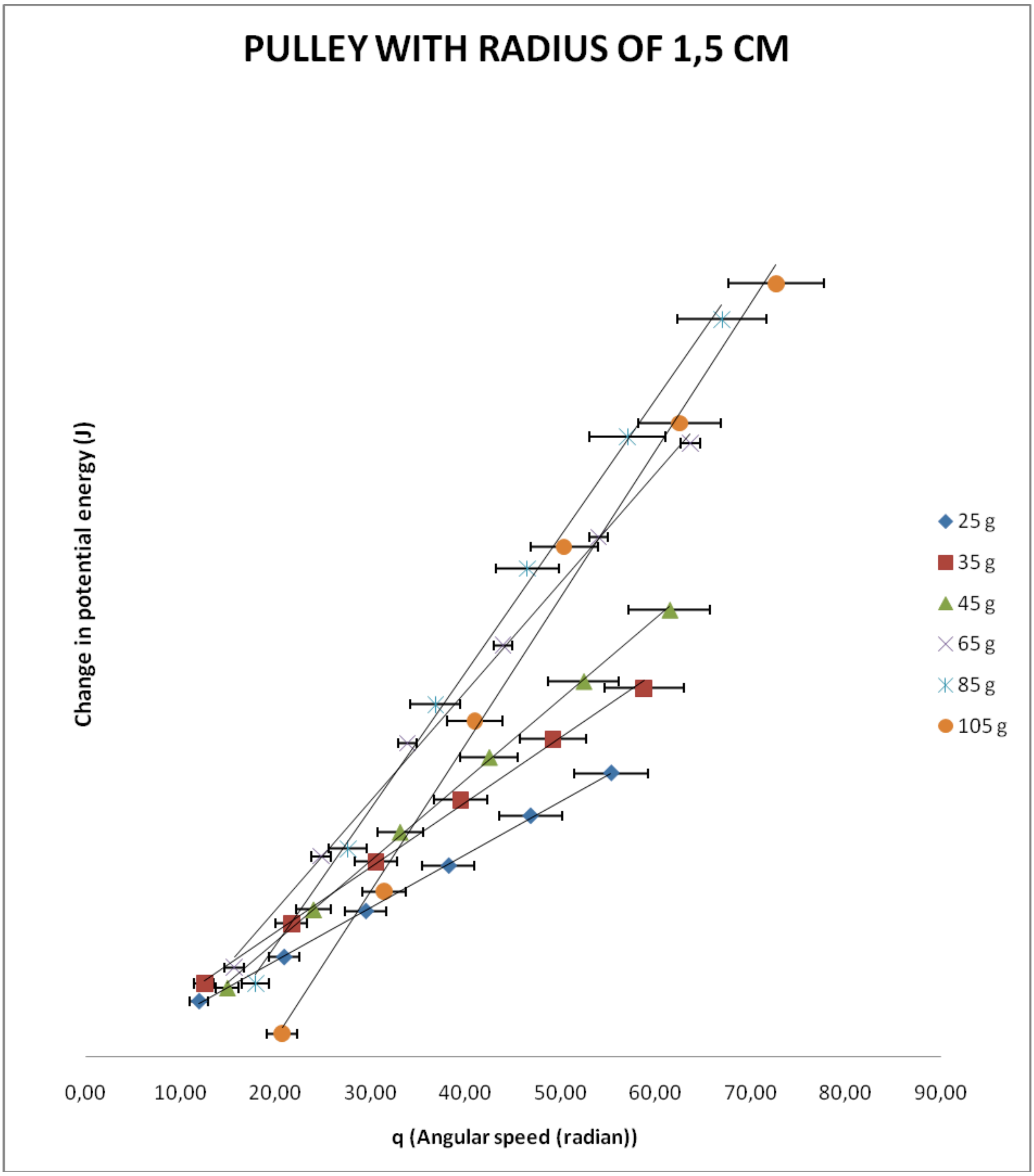
$$\tau_f = \square PE / q$$

Note: the uncertainties of the variables are calculated as below;
Given;

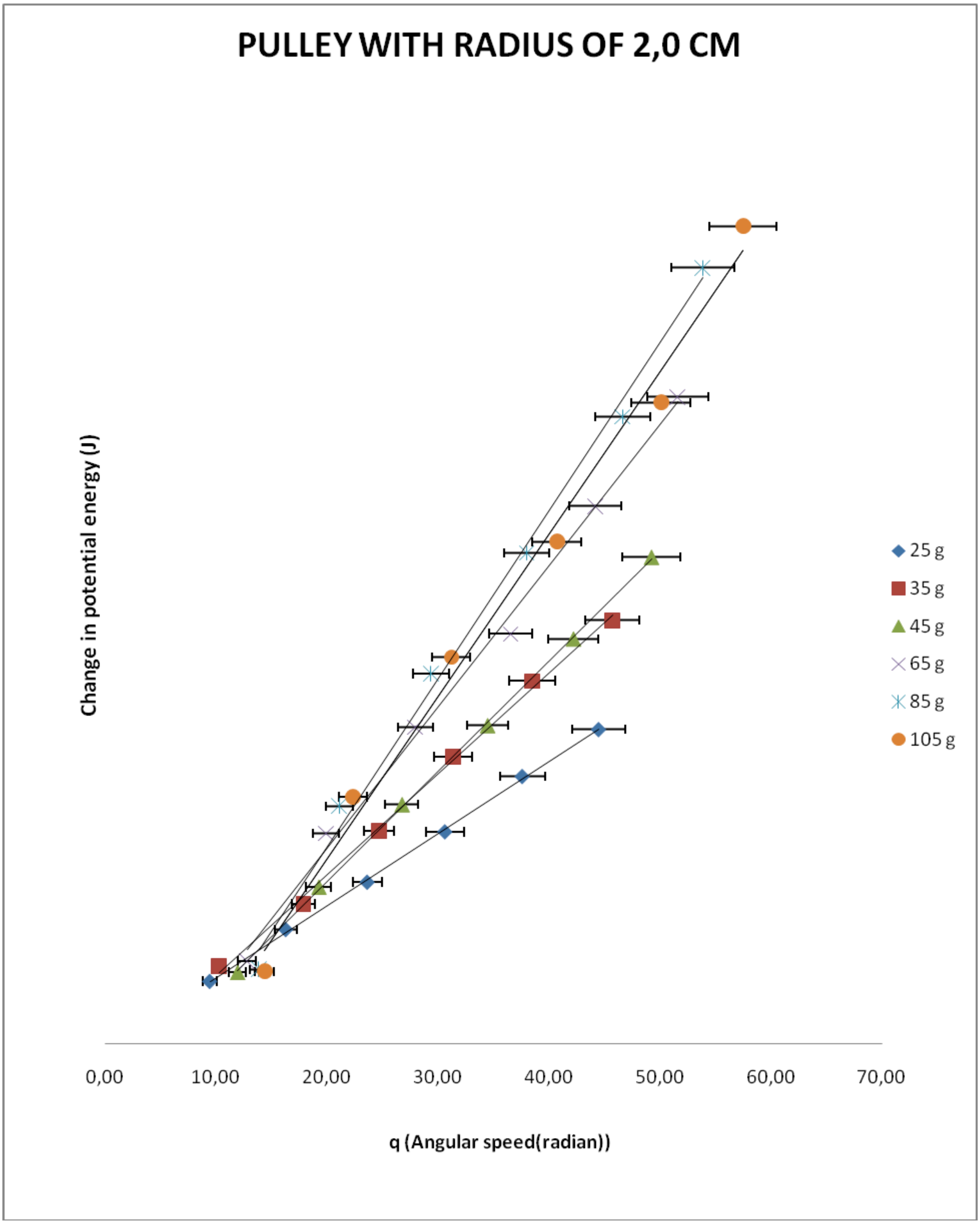
- $X \pm \square X$
- $Y \pm \square Y$

Then, $X*Y = X*Y \pm \left(\frac{\Delta X}{X} + \frac{\Delta Y}{Y}\right) * X*Y$ OR $X/Y = X/Y \pm \left(\frac{\Delta X}{X} + \frac{\Delta Y}{Y}\right) * X/Y$

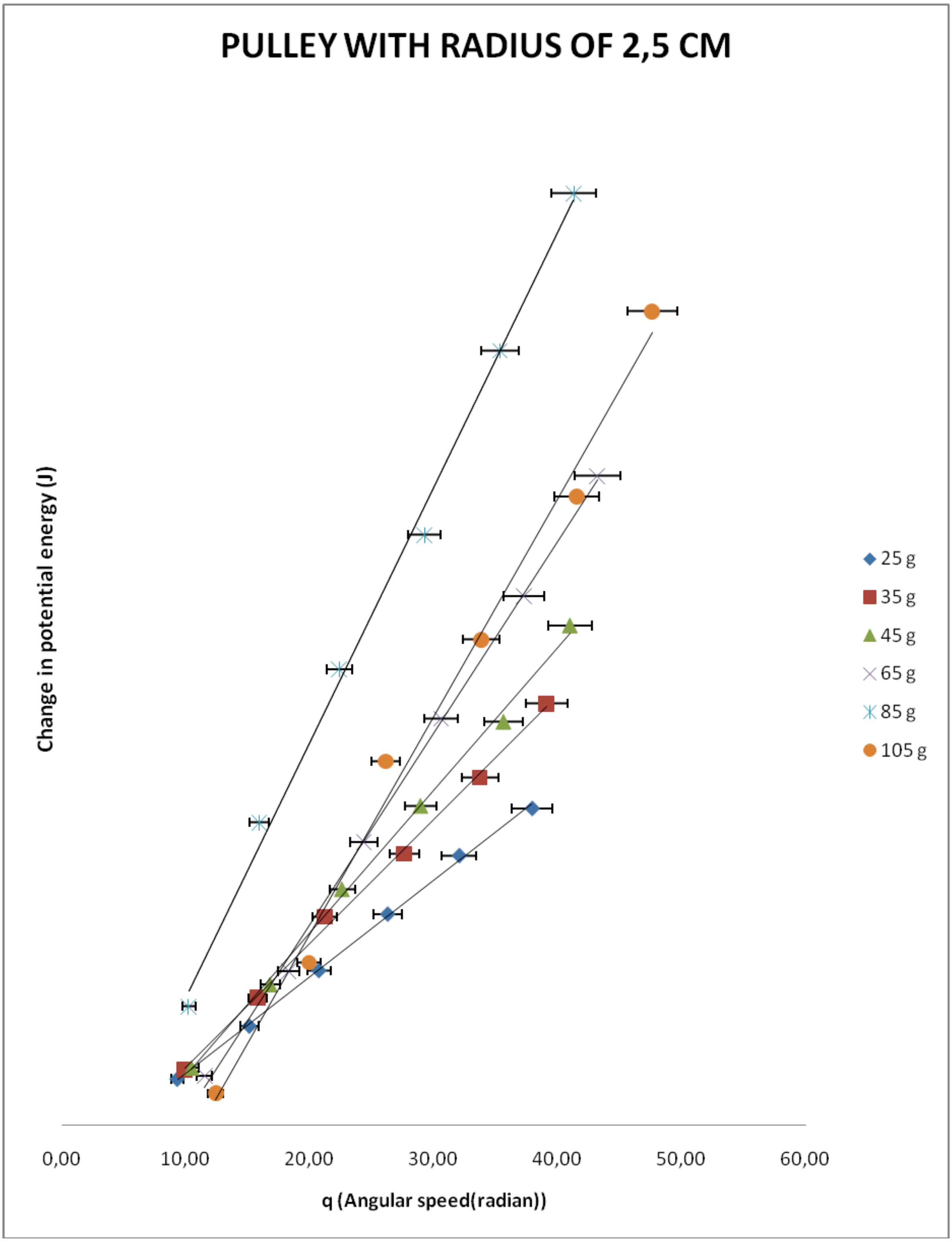
In order to calculate the friction torque, ΔPE vs q graphs were plotted for different pulleys and masses;



Graph 1 : Angular speed vs the change in potential energy when a pulley with 1,5 cm is used. The relationship between change in potential energy and angular speed for different masses could be seen in this graph.



Graph 2: Angular speed vs the change in potential energy when a pulley with 1,5 cm is used. The relationship between change in potential energy and angular speed for different masses could be seen in this graph.



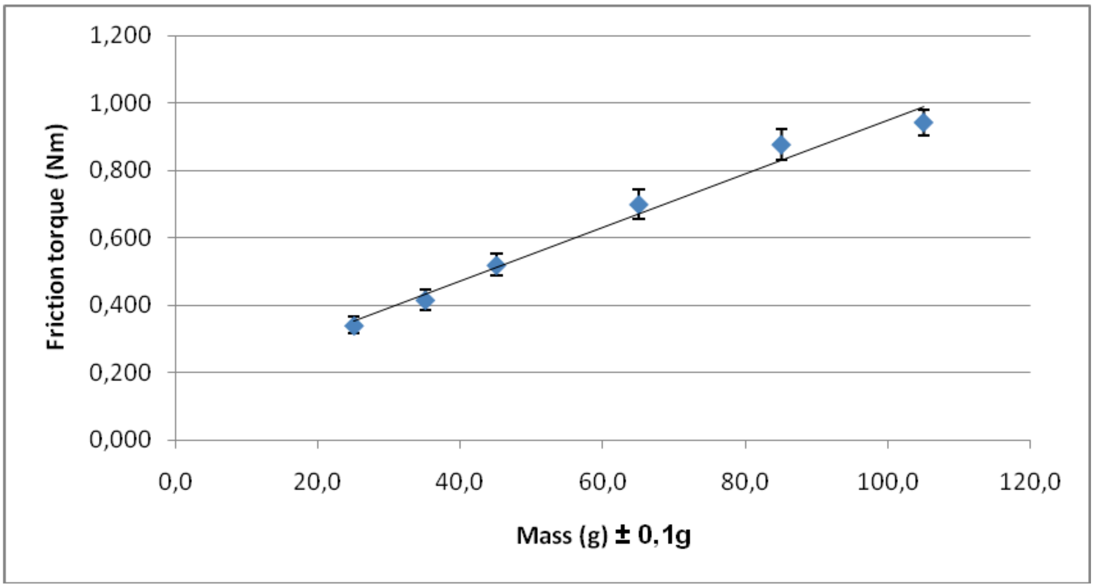
Graph 3: Angular speed vs the change in potential energy when a pulley with 1,5 cm is used. The relationship between change in potential energy and angular speed for different masses could be seen in this graph.

2. Relation between mass and the Friction Torque

The values for each friction torque is found by the slopes of the graphs above;

Mass (g) ± 0,1 g	Friction torque (Nm)
25,0	0,341 ± 0,025
35,0	0,416 ± 0,032
45,0	0,520 ± 0,033
65,0	0,699 ± 0,044
85,0	0,877 ± 0,045
105,0	0,942 ± 0,039

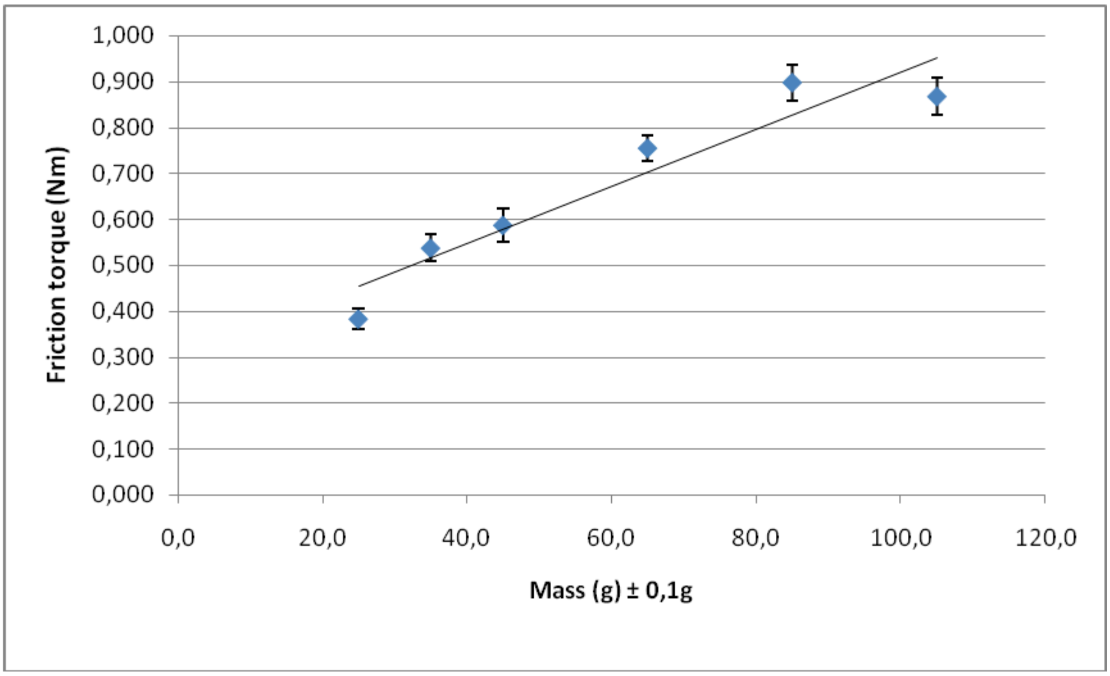
Table 1: Mass and frictional torque table when the radius of pulley is 1,5 cm.



Graph 4: The relationship between friction torque and mass when the radius of the pulley is 1,5 cm.

Mass (g) ± 0,1 g	Friction torque (Nm)
25,0	0,384 ± 0,023
35,0	0,538 ± 0,029
45,0	0,588 ± 0,036
65,0	0,755 ± 0,029
85,0	0,897 ± 0,040
105,0	0,867 ± 0,040

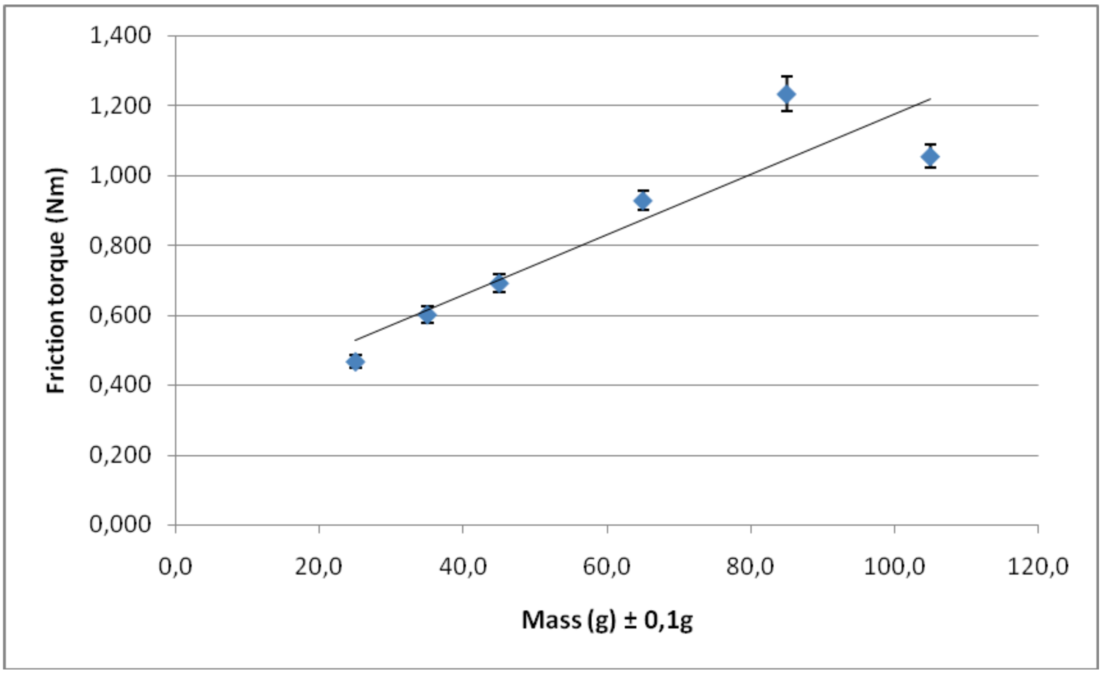
Table 2: Mass and frictional torque table when the radius of pulley is 2,0 cm.



Graph 5: The relationship between friction torque and mass when the radius of the pulley is 2,0 cm.

Mass (g) ± 0,1 g	Friction torque (Nm)
25,0	0,467 ± 0,018
35,0	0,602 ± 0,023
45,0	0,692 ± 0,025
65,0	0,929 ± 0,029
85,0	1,234 ± 0,050
105,0	1,055 ± 0,033

Table 3: Mass and frictional torque table when the radius of pulley is 2,5 cm.



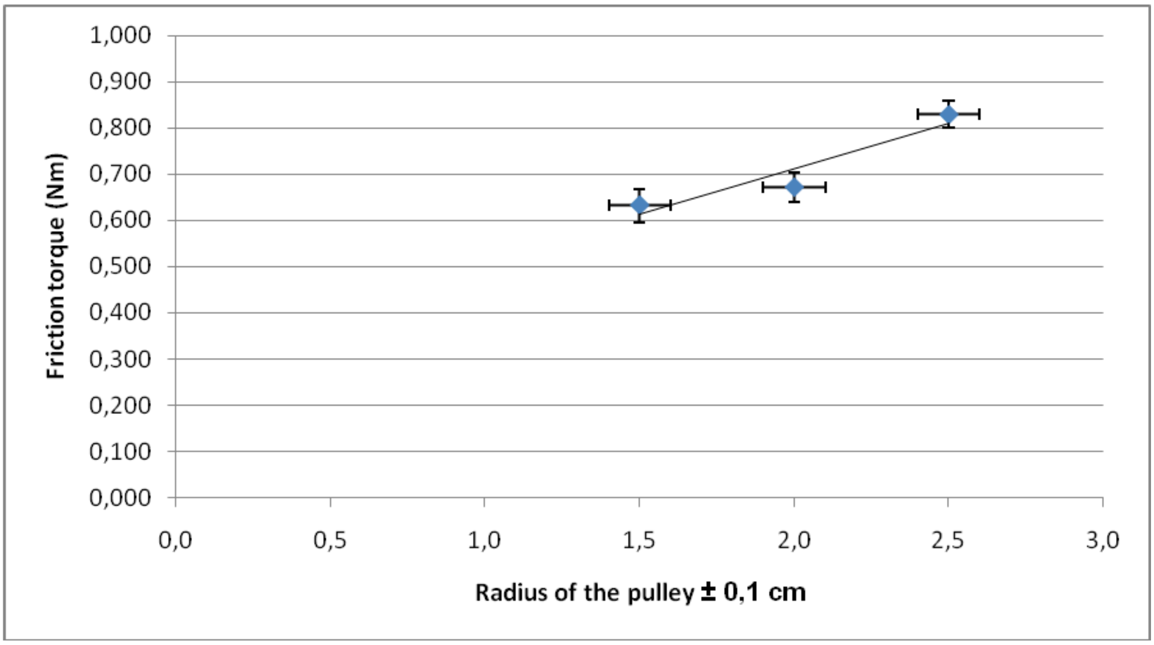
Graph 6: The relationship between friction torque and mass when the radius of the pulley is 2,5 cm.

3. Relation between the radii of pulleys and the friction torque

In order to find the relation between the radii of pulleys and the friction torque; the average value for friction torque is calculated for each part of the experiment.

Radius of the pulley (cm) ± 0,1 cm	Friction torque (Nm)
1,5	0,632 ± 0,036
2,0	0,671 ± 0,032
2,5	0,830 ± 0,029

Table 4: Average torque for each pulley is calculated and shown above.



Graph 7: The relationship between the friction torque and the moment arm is shown.

As it is mentioned before, the slopes of graphs gives the values of frictional torque which affects the rotating disc. It could be seen that there are some differences between the values of frictional torque which are measured by using different masses. Whan the mass of object used in each trial is increased, the value for frictional torque is also increased.

Also as it is seen from the average values of friction torque when the distance between the points; axis of rotation (the mil) and the point where the force acts is increased, the frictional torque in the system is also increased.

D. CONCLUSION

1. SUMMARY OF THE RESEARCH

According to the basic physics laws (i.e. Newton's laws) force of friction is an against force which makes an object lose energy. Because of friction the total energy could not be conserved. The same process is acceptable for the torque as well. When a force applied on an object to rotate it, if there is a friction force a friction torque is occured. In my work I made some experiments to see how this friction torque changes via using a basic system. The change in potential energy is used to calculate the friction torque.

2. COMPARING THE CHANGE IN POTENTIAL ENERGIES

The experiment is carried into three parts. Each of which are performed with different pulleys. When the change in potential energies in each part of the experiment is outlined, it could be easily seen that the change in potential energy is decreasing when the pulley radius is increased. The data tables show that, when the mass kept constant the change in potential energy decreases with the increase in moment arm. For instance, in part 1, when the mass is 25 g the change in potential energy is 18,21 J. However, in part 2, when the used mass is again 25g the change in potential energy is 16,76 J. Lastly,in part 3 with the same mass the loss in potential energy is 15,34 J. Therefore, it could be conducted as; when the moment arm increases the loss in potential energy is decreasing. So, friction is less effective on the system when the disc rotates with a large moment arm.

3. COMPARING THE FRICTION TORQUE VALUES AND THE GRAPHS

The change in potential energy vs q graphs' slope gives us the friction torque. And when we look the graphs we can see that the slope increases in each experiment with the increase of mass of the object used. For example, in graph 1 the slopes (friction torque's) are like; 0.340, 0.415, 0.519, 0.699, 0.876 and 0.942 with the increasing masses. So it could be said that, the mass of the object used (F) in the experiment and the friction torque is directly proportional. Also, when we look the average friction torque values at the end of each experiment (look at analysis of the graphs part) we can easily realize that when the moment arm (radius of the pulley) increased the value of friction torque is increased too. Therefore, we could not say that the friction torque is constant. It has some changes with the differences of the pulley's radius used in my experiment and the mass of the object ("F" in theory).

4. WHAT IS THE UNEXPECTED RESULT?

Another dependent variable in the experiment was the initial height of the mass. It is strange that friction torque changes due to the change in initial height because in theory, torque is only dependent to the force. However, in the research the mass of the object did not changed, only the initial height is changed. And after collecting all data and making all calculations, I saw that the distance taken by the object is decreasing with the decrease of the initial height. Because, when the initial height is lower the object has lower initial potential energy.

First of all from the formula τ = r*F we know that the Torque should increase when the moment arm (radius of the pulley) is increased. Also when the weight of mass used in experiments increased the friction torque is increased. It could be seen again in the formula above. However, in my research I used one extra variable which is the initial height of the object. When we look the datas collected, it is clear that there is a big change occured when I changed the initial height of the object. Firstly, in the literature formula of Torque there is nothing about the initial energy or height. However, I observed that when the initial energy of the object decreased the height that object went up again (h2) decreased as well and that affected the loss in potential energy. In real life we could not make any comments on the effect of initial potential energy to the Torque because we neglect the frictional torque. As a conclusion, it could be said that, the initial energy of the object is effective only when the frictional Torque is considered because frictional force is a negative force which makes an object lose energy. We can only consider the energy change when friction is effective on the system.

5. ERROR SOURCES IN THE EXPERIMENT

- First of all, when the initial height (h1) and the second height (h2) of the object is measured, ruler is used and the data is taken manually. It is an error source because the object is tied to a rope and it was very hard to see the right place. There could be some mistakes which are reflected to the research.
- Also, when the object was going down the disc speeded and when the object started to go up again the disc started to slow down. The disc is needed to stop when its speed was exactly zero. For a human being, it is very hard to do that. It caused some small mistakes in measuring the second height (h2) of the object.

- I used another pulley to minimize the friction between rope and the table however even I minimize it there are still a small amount of friction which can cause an error when calculating the friction torque.

6. WHAT SHOULD BE DONE TO CORRECT THESE ERRORS?

- To correct the first error an electronic device could be used to measure the heights such as a laser-meter.
- The experiment can be done as a grop. For instance, two people this will minimize the error but of course it would not be enough to get rid of this error.
- The pulley could be oiled in order to decrease its friction coefficient.

Lastly, I can say that in our daily life we use torque in everywhere. Even opening a door is the use of the term torque. However we forgot that there is another force which is independent from us called "friction force". Friction force is also doing a negative work when we are opening the door. In my experiments and research I tried to figure out how this friction torque changes and is it constant? I decided an experiment system to work on it and in this work I give some calculations with my reflections.

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F. APPENDICES

1. Appendix A (Raw data collection)

Pulley 1 (r = 1,5 cm)

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	1,50	25,00	8,75	87,50	12,75	13,00	13,25
2	1,50	25,00	8,75	75,50	12,25	12,00	12,50
3	1,50	25,00	8,75	62,50	12,25	12,25	12,50
4	1,50	25,00	8,75	50,00	12,00	12,00	11,25
5	1,50	25,00	8,75	37,50	11,75	11,25	11,00
6	1,50	25,00	8,75	25,00	10,50	10,50	10,25

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	1,50	35,00	8,75	87,50	18,00	18,50	18,25
2	1,50	35,00	8,75	75,50	16,75	15,75	15,00
3	1,50	35,00	8,75	62,50	15,00	14,75	13,00
4	1,50	35,00	8,75	50,00	14,75	12,75	12,50
5	1,50	35,00	8,75	37,50	12,25	12,50	12,75
6	1,50	35,00	8,75	25,00	11,50	11,00	11,25

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	1,50	45,00	8,75	87,50	22,50	22,00	22,25
2	1,50	45,00	8,75	75,50	20,50	20,50	21,00
3	1,50	45,00	8,75	62,50	18,75	19,00	18,50
4	1,50	45,00	8,75	50,00	17,25	17,00	17,25
5	1,50	45,00	8,75	37,50	16,25	16,00	15,75
6	1,50	45,00	8,75	25,00	15,00	14,75	15,00

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	1,50	65,00	8,75	87,50	25,50	24,75	26,25
2	1,50	65,00	8,75	75,50	22,75	23,25	23,00
3	1,50	65,00	8,75	62,50	21,25	20,75	20,75
4	1,50	65,00	8,75	50,00	18,75	18,25	18,00
5	1,50	65,00	8,75	37,50	17,50	17,25	17,00
6	1,50	65,00	8,75	25,00	16,25	16,00	15,75

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	1,50	85,00	8,75	87,50	30,25	30,50	30,75
2	1,50	85,00	8,75	75,50	28,00	27,25	27,50
3	1,50	85,00	8,75	62,50	24,50	24,75	25,00
4	1,50	85,00	8,75	50,00	22,75	23,00	22,50
5	1,50	85,00	8,75	37,50	22,00	21,50	20,75
6	1,50	85,00	8,75	25,00	18,75	19,75	19,50

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	1,50	105,00	8,75	87,50	38,50	39,00	39,75
2	1,50	105,00	8,75	75,50	36,25	35,75	35,50
3	1,50	105,00	8,75	62,50	31,25	30,25	30,25
4	1,50	105,00	8,75	50,00	31,00	30,75	25,25
5	1,50	105,00	8,75	37,50	30,00	27,75	23,75
6	1,50	105,00	8,75	25,00	24,50	23,75	22,50

PULLEY 2 (radius of 2,0 cm)

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,00	25,00	8,75	87,50	18,75	18,50	19,50
2	2,00	25,00	8,75	75,50	17,50	16,50	17,50
3	2,00	25,00	8,75	62,50	17,75	15,00	16,00
4	2,00	25,00	8,75	50,00	13,75	15,25	15,25
5	2,00	25,00	8,75	37,50	12,75	12,50	12,50
6	2,00	25,00	8,75	25,00	12,25	11,25	10,75

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,00	35,00	8,75	87,50	22,00	21,00	21,25
2	2,00	35,00	8,75	75,50	18,25	19,00	19,50
3	2,00	35,00	8,75	62,50	17,75	18,00	17,50
4	2,00	35,00	8,75	50,00	16,25	17,00	17,25
5	2,00	35,00	8,75	37,50	15,50	15,75	16,00
6	2,00	35,00	8,75	25,00	12,75	13,00	13,25
	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,00	45,00	8,75	87,50	30,75	27,25	27,50
2	2,00	45,00	8,75	75,50	26,25	26,25	26,75
3	2,00	45,00	8,75	62,50	24,25	23,75	23,75
4	2,00	45,00	8,75	50,00	21,25	21,00	20,75
5	2,00	45,00	8,75	37,50	18,25	18,50	18,75
6	2,00	45,00	8,75	25,00	17,25	16,00	15,75

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,00	65,00	8,75	87,50	33,75	33,00	32,75
2	2,00	65,00	8,75	75,50	30,75	30,25	30,00
3	2,00	65,00	8,75	62,50	27,75	28,00	28,50
4	2,00	65,00	8,75	50,00	23,00	23,25	24,00
5	2,00	65,00	8,75	37,50	19,75	19,50	20,25
6	2,00	65,00	8,75	25,00	18,00	17,75	18,50

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,00	85,00	8,75	87,50	37,75	37,25	38,00
2	2,00	85,00	8,75	75,50	35,75	35,50	34,50
3	2,00	85,00	8,75	62,50	31,25	31,00	30,75
4	2,00	85,00	8,75	50,00	26,25	26,50	26,00
5	2,00	85,00	8,75	37,50	22,00	22,50	22,25
6	2,00	85,00	8,75	25,00	20,50	20,00	20,25

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,00	105,00	8,75	87,50	45,00	45,25	44,75
2	2,00	105,00	8,75	75,50	42,50	42,25	41,75
3	2,00	105,00	8,75	62,50	36,25	36,75	36,25
4	2,00	105,00	8,75	50,00	29,75	30,25	29,75
5	2,00	105,00	8,75	37,50	24,75	25,00	24,25
6	2,00	105,00	8,75	25,00	21,50	21,25	21,00

PULLEY 3 (radius of 2,5 cm)

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,50	25,00	8,75	87,50	25,00	24,75	24,50
2	2,50	25,00	8,75	75,50	22,00	22,25	22,00
3	2,50	25,00	8,75	62,50	20,25	20,75	21,00
4	2,50	25,00	8,75	50,00	19,75	19,50	18,75
5	2,50	25,00	8,75	37,50	18,25	17,75	17,50
6	2,50	25,00	8,75	25,00	15,75	16,25	15,50

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,50	35,00	8,75	87,50	28,00	27,75	27,50
2	2,50	35,00	8,75	75,50	26,25	26,50	26,00
3	2,50	35,00	8,75	62,50	24,50	24,00	23,75
4	2,50	35,00	8,75	50,00	20,25	20,50	20,75
5	2,50	35,00	8,75	37,50	19,75	19,50	19,25
6	2,50	35,00	8,75	25,00	17,25	17,00	17,50

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,50	45,00	8,75	87,50	32,25	32,50	32,75
2	2,50	45,00	8,75	75,50	31,00	31,25	31,00
3	2,50	45,00	8,75	62,50	27,75	27,25	27,00
4	2,50	45,00	8,75	50,00	23,00	24,50	24,50
5	2,50	45,00	8,75	37,50	22,25	22,00	21,75
6	2,50	45,00	8,75	25,00	19,00	18,75	18,25

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,50	65,00	8,75	87,50	38,25	38,00	37,75
2	2,50	65,00	8,75	75,50	35,50	35,25	34,75
3	2,50	65,00	8,75	62,50	31,25	31,50	31,75
4	2,50	65,00	8,75	50,00	28,00	29,00	28,25
5	2,50	65,00	8,75	37,50	25,75	25,50	26,00
6	2,50	65,00	8,75	25,00	21,25	21,00	21,50

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,50	85,00	8,75	87,50	33,75	33,00	32,75
2	2,50	85,00	8,75	75,50	30,75	30,25	30,00
3	2,50	85,00	8,75	62,50	27,75	28,00	28,50
4	2,50	85,00	8,75	50,00	23,00	23,25	24,00
5	2,50	85,00	8,75	37,50	19,75	19,50	20,25
6	2,50	85,00	8,75	25,00	18,00	17,75	18,50

	r (cm)	m (g)	h0 (cm)	h1 (cm)	h2 (cm)	h2 (cm)	h2 (cm)
1	2,50	105,00	8,75	87,50	48,00	49,50	49,75
2	2,50	105,00	8,75	75,50	45,75	46,00	45,75
3	2,50	105,00	8,75	62,50	39,75	40,00	39,00
4	2,50	105,00	8,75	50,00	32,75	33,00	32,75
5	2,50	105,00	8,75	37,50	30,00	29,75	29,75
6	2,50	105,00	8,75	25,00	27,50	27,25	25,75

2. APPENDIX B (ANALYZED DATA)

PART 1

r = 1,5 cm

Table 1: m = 25 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
13,00	18,21525	83,00	55,33
12,25	15,46463	70,25	46,83
12,33	12,26575	57,33	38,22
11,75	9,35213	44,25	29,50
11,33	6,39775	31,33	20,89
10,42	3,56563	17,92	11,94

Table 2: m = 35 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
18,25	23,70428	88,25	58,83
15,83	20,42390	73,83	49,22
14,25	16,51598	59,25	39,50
13,33	12,55100	45,83	30,56
12,50	8,55750	32,50	21,67
11,25	4,70663	18,75	12,50

Table 3 :m = 45 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
22,25	28,71653	92,25	61,50
20,67	24,13215	78,67	52,44
18,75	19,25438	63,75	42,50

17,17	14,44995	49,67	33,11
16,00	9,46215	36,00	24,00
14,92	4,43768	22,42	14,94

Table 4: m = 65 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
25,50	39,41340	95,50	63,67
23,00	33,37425	81,00	54,00
20,92	26,43453	65,92	43,94
18,33	20,13050	50,83	33,89
17,25	12,87293	37,25	24,83
16,00	5,72130	23,50	15,67

Table 5: m = 85 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
30,50	47,38410	100,50	67,00
27,58	39,83313	85,58	57,06
24,75	31,38158	69,75	46,50
22,75	22,65293	55,25	36,83
21,42	13,37008	41,42	27,61
19,33	4,71070	26,83	17,89

Table 6: m = 105 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
39,08	49,71908	109,08	72,72
35,83	40,73370	93,83	62,56
30,58	32,77523	75,58	50,39

29,00	21,56490	61,50	41,00
27,17	10,61130	47,17	31,44
23,58	1,45478	31,08	20,72

EXPERIMENT 2

r = 2,0 cm

Table 1:m = 25 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
18,92	16,76863	88,92	44,46
17,17	14,26250	75,17	37,58
16,25	11,30813	61,25	30,63
14,75	8,61863	47,25	23,63
12,58	6,09213	32,58	16,29
11,42	3,32113	18,92	9,46

Table 2: m = 35 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
21,42	22,62033	91,42	45,71
18,92	19,36848	76,92	38,46
17,75	15,31793	62,75	31,38
16,83	11,35295	49,33	24,67
15,75	7,44503	35,75	17,88
13,00	4,10760	20,50	10,25

Table 3: m = 45 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
28,50	25,96590	98,50	49,25
26,42	21,60158	84,42	42,21
23,92	16,98053	68,92	34,46
21,00	12,76290	53,50	26,75
18,50	8,36190	38,50	19,25
16,33	3,81420	23,83	11,92

Table 4: m = 65 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
33,17	34,53970	103,17	51,58
30,33	28,71245	88,33	44,17
28,08	21,87868	73,08	36,54
23,42	16,89903	55,92	27,96
19,83	11,23070	39,83	19,92
18,08	4,39693	25,58	12,79

Table 5: m = 85 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
37,67	41,42645	107,67	53,83
35,25	33,45983	93,25	46,63
31,00	26,18595	76,00	38,00
26,25	19,74338	58,75	29,38
22,25	12,67733	42,25	21,13
20,25	3,94868	27,75	13,88

Table 6: m = 105 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
45,00	43,64325	115,00	57,50
42,17	34,23000	100,17	50,08
36,42	26,78498	81,42	40,71
29,92	20,62358	62,42	31,21
24,67	13,17855	44,67	22,33
21,25	3,85088	28,75	14,38

r = 2,5 cm

Table 1: m = 25 cm

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
24,75	15,34238	94,75	37,90
22,08	13,06038	80,08	32,03
20,67	10,22825	65,67	26,27
19,33	7,49800	51,83	20,73
17,83	4,80850	37,83	15,13
15,83	2,24125	23,33	9,33

Table 2: m = 35 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
27,75	20,45243	97,75	39,10
26,25	16,85828	84,25	33,70
24,08	13,15003	69,08	27,63
20,50	10,09785	53,00	21,20
19,50	6,16140	39,50	15,80
17,25	2,65283	24,75	9,90

Table 3: m = 45 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
32,50	24,0550	102,50	41,00
31,08	19,54778	89,08	35,63
27,33	15,47685	72,33	28,93
24,00	11,44260	56,50	22,60
22,00	6,82155	42,00	16,80
18,67	2,78730	26,17	10,47

Table 4: m = 65 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
38,00	31,46715	108,00	43,20
35,17	25,63990	93,17	37,27
31,50	19,70670	76,50	30,60
28,42	13,72053	60,92	24,37
25,75	7,46948	45,75	18,30
21,25	2,38388	28,75	11,50

Table 5: m = 85 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
33,17	45,16730	103,17	41,27
30,33	37,54705	88,33	35,33
28,08	28,61058	73,08	29,23
23,42	22,09873	55,92	22,37
19,83	14,68630	39,83	15,93
18,08	5,74983	25,58	10,23

Table 6: m = 105 g

h2 average (cm)	Δ potential energy (J)	Distance (cm)	q(radian)
49,08	39,45008	119,08	47,63
45,83	30,46470	103,83	41,53
39,58	23,53313	84,58	33,83
32,83	17,62845	65,33	26,13
29,83	7,87290	49,83	19,93
23,50	1,54035	31,00	12,40