Knee joint dynamics: an experiment to introduce the concept of torque to biomedical and life sciences students

Classical dynamics results a fundamental pillar of any general physics course. The presentation often starts by showing Newton´s three laws and their applications to static and dynamic scenarios, treating objects as particles that can be displaced but not rotated. Common examples include a mass sliding over an inclined plane[1, 2] or a bullet shot at a determined angle with the floor[3]. In all those cases, macroscopic objects are considered as point-like and the problems can be solved by applying Newton´s laws to the center of mass of the objects. On the other hand, by allowing the object to rotate adds another degree of freedom to the system. In this case, torque made by a force with respect to a rotation axis tends to produce rotation. Torque, $\vec{\tau}$, is defined as

$$\vec{\tau} = \vec{r} \times \vec{F}\ , \tag{1}$$

where $\vec{r}$ is the vector that joins the rotation axis and the point at which the force is applied, $\times$ denotes vector product, and $\vec{F}$ is the force (Figure 1). As can be observed, the torque is a vector magnitude obtained by applying a vector product. It is perpendicular to the plane formed by $\vec{r}$ and $\vec{F}$, and its direction determines the rotation sense, given by the *right-hand rule*. The modulus of the torque can be obtained as

$$|\vec{\tau}| = |\vec{F}||\vec{r}|\sin\theta\,, \tag{2}$$

where $l = |\vec{r}|\sin\theta$ is commonly called the *lever arm*. Students often find the concept of torque challenging, and the teaching of torque has drawn much attention[4].

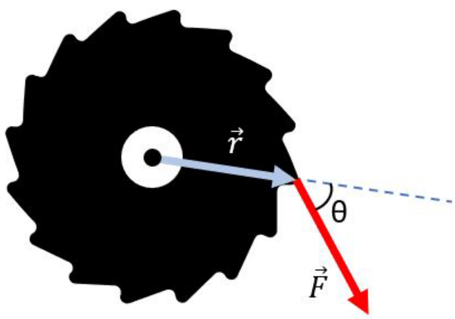

Figure 1.- Rotating saw showing the parameters involved in calculating the torque of the force.

As can be deduced, torque is a measure of the ability that a force has to rotate an object with respect to a fixed axis. In general physics books, many of the examples and problems related to torque involve levers, discs, and so on. Such “academic” examples and problems may not be motivating for students in biomedical or life science degrees. In this work, we show an experiment in which torque is explained based on a simplified model of the knee joint dynamics, which might interest this kind of student. In addition, the experiment demonstrates the importance of the kneecap (patella) for the proper functioning of the knee joint and the ability to walk[5]. The torque made by the muscles can also be analyzed in other body joints[6] but this experiment is particularly visual and easy to perform.

Let us illustrate a simplified model of the knee joint with (Figure 2a-b) and without kneecap (Figure 2c-d). Obviously, the illustrations are mere approximations to the real knee joint that we will use to carry out our experiment in a similar way as it is done in Ref. [6]. The tibia goes up by the action of the quadriceps muscle, which pulls it through a couple of tendons that join the quadriceps with the kneecap and the kneecap with the tibia. The rotation axis is approximately plotted as a black circle in Figure 2 although the femur does not strictly rotate around a fixed point. The force exerted by the muscle is plotted in red and the force transmitted to the tibia is plotted in green. Here, the most important magnitude is the capacity of the quadriceps to rotate the tibia around the black circle and this magnitude is the torque produced by the force. The question to pose to the students is: assuming that the whole force made by the muscle is transmitted to the tibia, which of the two cases shown in Figure 2 has higher torque?

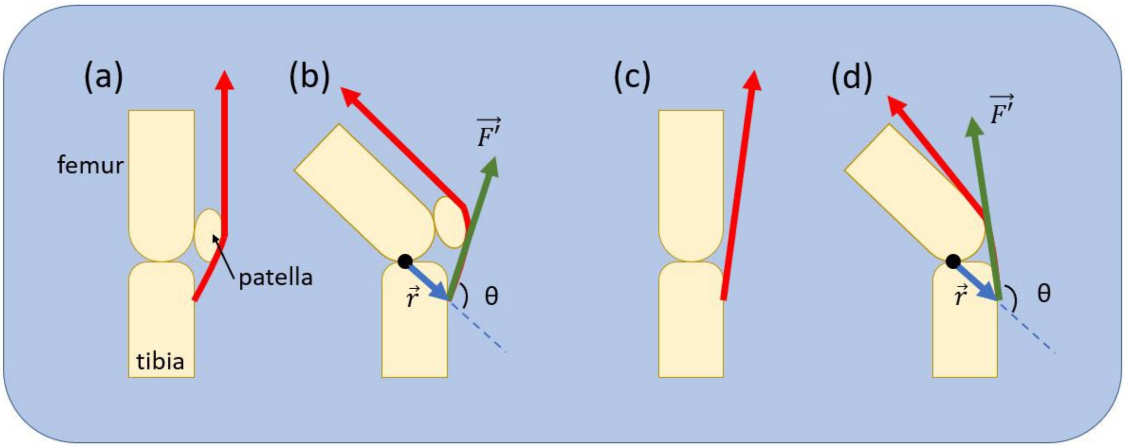

Figure 2.- Illustration of the knee joint. (a-b) Without kneecap and (c-d) with kneecap.

Only the force component that is perpendicular to the vector $\vec{r}$ (see Figure 2) will have the ability to rotate the object, the tibia in our case. Therefore, it is clear that the case shown in Figure 2b has more rotation capacity than the case shown in Figure 2d. The modulus of the vector $\vec{r}$ and the modulus of the force $\vec{F}'$ are equal in both cases but the angle θ is not. Therefore, following Equation (2), the torque is bigger for the case with the kneecap. Assuming that the torque necessary to elevate the tibia is a given one, the force needed will be smaller in the case with the kneecap, and this is what we will demonstrate experimentally with a simplified model of the knee joint.

Once we have deduced the importance of the kneecap for the efficient functioning of the knee joint (minimizing the force needed from the quadriceps to pull up the tibia), we may demonstrate it experimentally by manufacturing the simplified set-up shown in Figure 3. The procedure is the following: take two wood strips and join them with a hinge to simulate the femur and the tibia with the knee joint, Figure 3(a, b); affix a stud to the tibia and fasten a slightly elastic tape to it to simulate the pair of tendons, Figure 3(c, d); withhold or insert a small piece of wood to act as the kneecap (we have carved a simulated patella from a bottle cork), and use a dynamometer to estimate the force that the quadriceps would have to exert to extend the knee, Figure 3(e, f). This simplified model differs from the real knee joint, in which both tendons, the patellar tendon and the quadriceps tendon, are joined to the kneecap, below and above, respectively. Anyway, it serves properly for the purpose of the example.

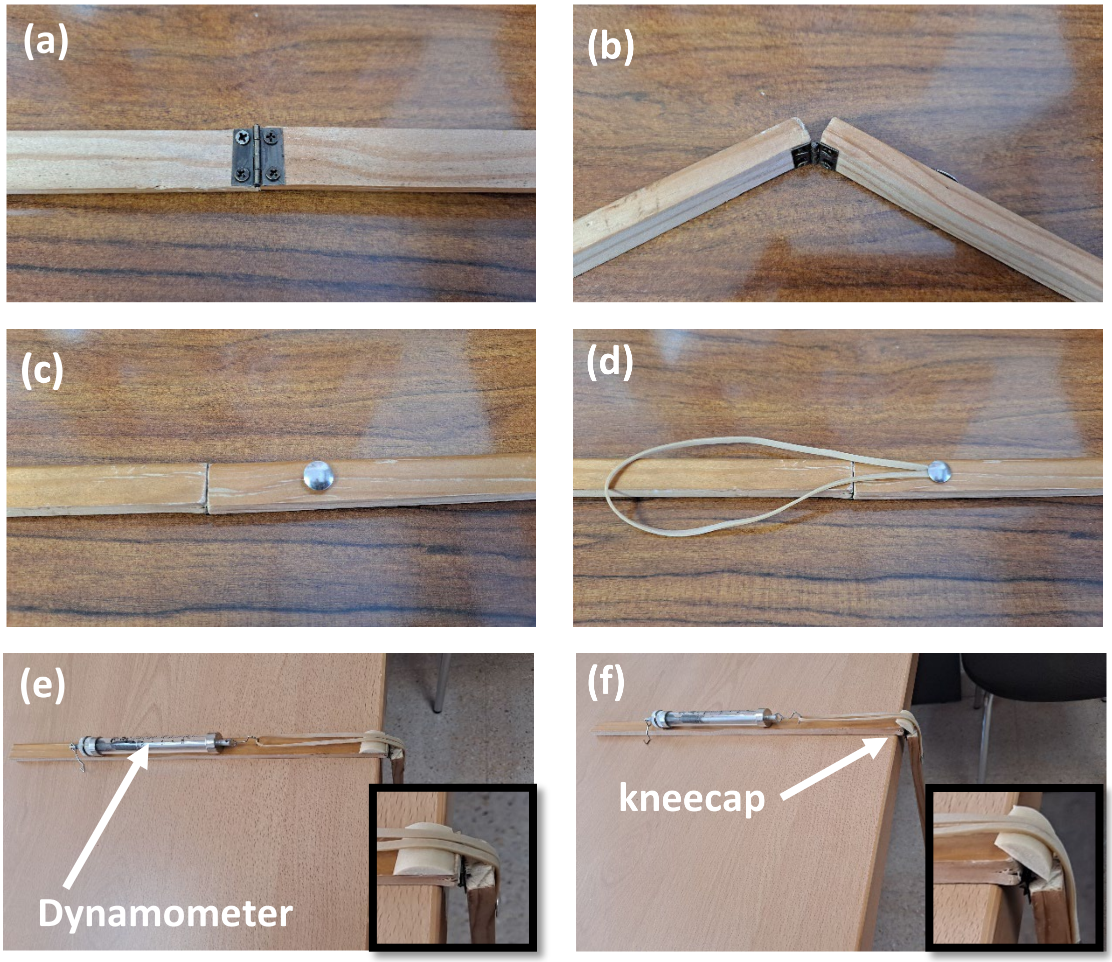

Figure 3.- (a)-(d) Manufacturing process of the simulated knee-joint. Experimental set-up used to simulate the knee joint: (e) similar as without kneecap and (f) with kneecap. Subfigures (e) and (f) have zoom on the patella to see its position.

The experiment consists of pulling the elastic tape horizontally and measuring the force exerted at the moment in which the simulated tibia starts to move up. The experiment must be performed with and without kneecap. The resulting dynamometer measurements are shown in Table 1. The necessary force is clearly smaller when the kneecap is used around the right place, as was deduced before. The maximum force which is able to be measured by the dynamometer is 3 N, so we do not know exactly the force needed to pull up the tibia without the kneecap. What is clear is that this force is bigger than the force with the kneecap.

Table 1. Necessary forces to pull up the "tibia" in our experimental set-up.

	Without kneecap	With kneecap
Force (N)	>3	0.8±0.05

Here, we must mention that another effect might be involved in the results: the friction of the elastic tape around the edge, given by the Capstan equation. In the case without a kneecap, the tape touches the tibia at a sharp edge, and in the case with a kneecap, this contact is smoothed. So, the difference in force could be due to both effects: friction and the angle of the force. However, since this friction effect would also be present in vivo, the difference in force measured in the experiment faithfully models the difference in force that would be present in vivo. Anyway, to minimize the friction difference, we have performed the experiment with the piece of cork in both cases. The first one with the piece of cork on the femur (zoom in Figure 3e), and the second one with the piece of cork approximately in the place in which the patella should be (zoom in Figure 3f).

In summary, in this work we present a simple experiment in which the concept of torque is introduced. This experiment is appropriate for biomedical and life sciences students, for whom "academic" examples may not be directly applicable to their professional careers. The experiment consists of a simplified analysis of the knee joint dynamics, revealing the importance of the kneecap in its functioning, and explaining the torque concept as the ability of a force to produce rotation. Obviously, this experiment could also be useful for university students with diverse backgrounds, or even for high school students, to introduce the concept of torque.

Acknowledgments:

References:

[1] J. C. Licini, "A Tilted-Axes Tool for Introductory Mechanics and Mathematics Courses," Phys. Teach. 56, 528 (2018).

[2] H. Y. Chen, H. M. Nieh, and S. W. Ko, "Acceleration Measurement Using Arduino and a Smartphone for the Motion of Objects on an Inclined Plane," Phys. Teach. 60, 351 (2022).

[3] Ch. Hanna, "Determining the speed on an air rifle bullet," Phys. Teach. 19, 184 (1981).

[4] R. W. Bird, "Pictorial representation of torque and rotational inertia," Phys. Teach. 36, 492 (1998).

[5] I.P. Herman, Physics of the Human Body, 2nd edition (Springer 2016), p. 108.

[6] V. Pagonis, *et al.*, "Modeling forces on the human body," Phys. Teach. 37, 469 (1999).