

MERGING PHYSICS AND ANATOMY: INNOVATIONS IN TEACHING HUMAN BODY MECHANICS

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Abstract

This study delves into a novel approach that combines animation with a 3D-printed leg prototype, serving as an innovative tool for teaching mechanics in a multidisciplinary course, *Mechanics and the Human Body*. This course is created to serve students from physical therapy, exercise science, occupational therapy, and pre-medicine students. While biomechanics textbooks offer theoretical problems, they lack interactive animations. Moreover, physics educators frequently face a deficiency of demonstrations directly related to the human body. Our approach fills these gaps by integrating a physical prototype and dynamic animation to vividly illustrate core concepts such as torque, rotational motion, and static equilibrium, focusing on examining tendon force as a function of external force. The methodology involved 3D-printing a leg prototype and applying external forces to the ankle to simulate leg extension exercises. A string representing the tendon was attached to the leg and routed over the "kneecap" to a fixed Newton meter. This setup allowed for precise measurements of tendon force as external forces varied. The data collected provided students hands-on experience analyzing mechanical forces, further reinforced through an interactive Python animation. The animation allowed the manipulation of variables and visualization of outcomes real-time. Although the prototype restricted the length of the leg and its weight, through the animation, students were encouraged to change those key factors and check how the force on the tendon changes as a function of an external force. To evaluate the benefits of this teaching method, we compared student understanding and engagement with and without the use of the prototype and animation. Assessment results show significant improvement in the student's understanding of mechanical concepts and ability to apply them to human body mechanics. Feedback from students further emphasized the importance of the hands-on approach in making theoretical concepts more relatable to their major. In conclusion, we report our new approach to teaching the Mechanics and Human Body Course. The combined use of animation and 3D-prototype enhanced the learning experience of our students by providing a practical, multidisciplinary perspective on mechanics. The combo deepened the understanding and fostered a greater appreciation for the connection between mechanics and the human body. It holds promise for improving physics and health sciences education, benefiting many students, and reassuring educators of its practicality and effectiveness.

Keywords: *Tendon force, mechanics and human body, physics pedagogy, physics and leg extension.*

1. Introduction

Visual learning has consistently enhanced student understanding in STEM education, with research highlighting the benefits of animations, demonstrations, videos, and simulations across disciplines (Mayer, 2009). However, while some fields have ample visual learning aids, others suffer from inadequate resources. We have recognized one such area as studying Mechanics in the Human Body, where straightforward yet practical demonstrations can bridge the gap between physics and anatomy. The course focuses more on Newtonian mechanics and its applications, concentrating on the various movements in the Human Body. We have already initiated the development of life-sized physical prototypes accompanied by simulations for the Mechanics and the Human Body courses taught at our institution (Mohottala et al. 2024). This study focuses on a recent model we designed to examine the force exerted on the patellar tendon during leg extension exercises. Our objective is to create an educational tool that can enhance students understanding in complex physics concepts by linking them to familiar anatomical structures.

2. Background and motivation

Students enrolled in courses that combine human anatomy and mechanics often have a strong background in human physiology but limited exposure to physics and algebra. As a result, abstract physical concepts—such as torque, force distribution, and moments—can be challenging for them to grasp. Studies have shown that using physical models improves comprehension in biomechanics education by allowing students to interact with representations of forces and motion (Hall et al., 2021). By designing a physical prototype that mirrors the anatomy of the lower leg, we aim to create an intuitive learning experience where students can directly visualize and interact with the forces at play. This approach allows them to apply their anatomical knowledge in a way that makes physics concepts more accessible and meaningful.

2.1. Challenges in modeling the lower leg

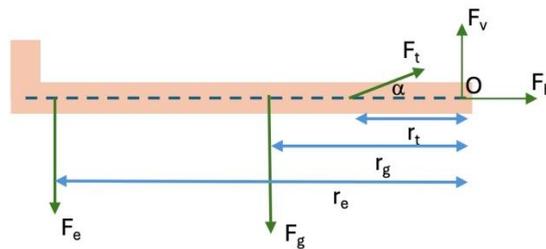
Developing an accurate prototype of the lower leg for modeling motion presented several challenges. One significant complexity arose in replicating the movement of the patella (kneecap). Unlike simple hinge joints, the patella does not follow a straightforward linear or rotational path; its motion is dictated by intricate interactions with surrounding tendons and muscles (Van Eijden et al., 1986). Misrepresenting this motion in a prototype could lead to an inaccurate understanding of force distribution during leg extensions. To address this, we 3D printed the lower leg using thermoplastic polyurethane (TPU) for flexibility, allowing for realistic articulation. To obtain a reasonable weight for the leg, we filled the leg with silicone. Additionally, we created multiple variations of the patella using polylactic acid (PLA) to explore different constraints and movement patterns. By iterating through these designs, we worked to refine a model that accurately represents how forces are transferred through the tibia during exercise.

The below discussion includes prototype design and 3D printing, the choice of printing material to mimic the natural elasticity of tendons and ligaments (Bertsch et al., 2022) and using PLA for the patella to evaluate its impact on the patellar tendon force distribution. Tendon force measurements during leg extension exercises and comparing force data with theoretical physics models are made at the end of the manuscript.

2.2. Physics behind

The main objective of this research, as stated in the introduction, is to help students grasp the fundamental physics involved in the motion of the human body. Specifically, this study focuses on the static equilibrium of forces in the lower leg around the kneecap. To achieve that, we began examining the forces acting on the leg. Figure 1 illustrates all the forces at work on the lower leg when it is subjected to an external pulling force at the ankle. Since we are considering static equilibrium, the distances from the pivot point are also indicated.

Figure 1. The force diagram of the leg where F_t , F_g and F_e are the force on patellar tendon, weight of the leg, and external force respectively and r_t , r_g and r_e are the corresponding distances from the kneecap to each force. The force acting on the patella is given in its vertical and horizontal components as F_v and F_h respectively.



Static equilibrium gives, that the net torque (τ) around point “O” equals to zero, leading to the below equation.

$$\begin{aligned}\Sigma \tau &= 0 \\ F_t r_t \sin \alpha &= F_g r_g + F_e r_e \\ F_t &= \frac{F_g r_g + F_e r_e}{r_t \sin \alpha} \\ F_t &= \frac{r_e}{r_t \sin \alpha} F_e + \frac{r_g F_g}{r_t \sin \alpha}\end{aligned}$$

$$y = mx + C \text{ type}$$

The graph of F_t vs. F_e shows a linear relationship, $y = mx + C$ type. Since we are dealing with the human body, there are limitations that applies on the upper limit of the external force (F_e). Within the boundaries, we applied forces on the ankle and recorded the F_t values and the complete discussions are given below.

3. Methodology

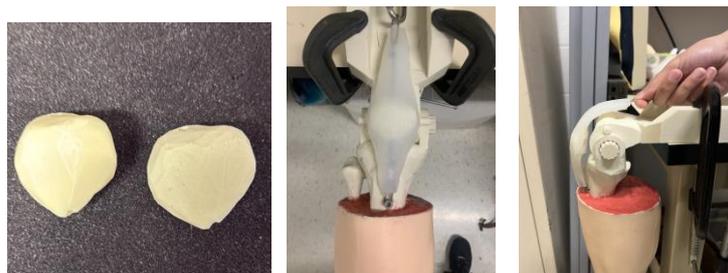
Precise measurements are essential to create a realistic and anatomically accurate 3D-printed leg model. This model measures the forces exerted on the patellar tendon when external forces are applied to the ankle during full leg extension. Initially, a life-size skeleton was used to determine accurate dimensions of the bones and identify key anatomical components such as the femoral head, condyles, tibial plateau, and malleoli. As shown in Figure 2 a volunteer from the group performed a leg flexion exercise to assess the patellar angles at various flexion positions. During full leg extension, it was recorded that the patellar angle is at 19.9° to the horizontal.

Figure 2. Leg flexion was done to assess the patellar angles at various flexion positions.



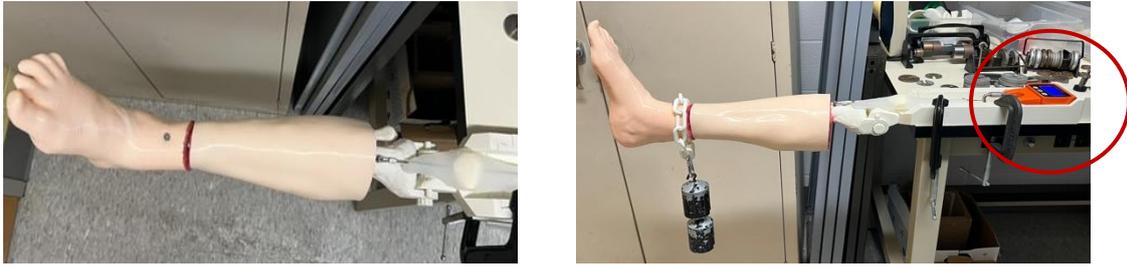
Following this, Fusion 360 was utilized to design the model based on the collected data. The components—including the Newton meter holder, femur holder, shin and foot skin shells, and the patella—were printed using the 3D Bambu Lab X1 printer. Since we needed solid parts for the Newton meter holder, femur holder, and patella, they were constructed from PLA synthetic filament as shown in Figure 3. However, the skin shells for the shin and foot were made from TPU synthetic filament leaving some room to stretch.

Figure 3. (a) shows two different size patellae printed using PLA. (b) shows the patella encapsulated in a silicon patella tendon and (c), the side view of the knee joint.



After all parts were printed, the model was assembled, and the skin shell was filled with silicone, resulting in a total mass of 3.86 kg. The completed model was securely fastened to the lab bench. The patella was encased in a silicone mold to simulate the patellar tendon. One end of the patellar tendon was connected to a pin located in the tibial tuberosity (the tendon attachment site), while the other end was secured to the Newton meter in the holder (Newton meter was used to read the tendon force), which was firmly attached to the bench with clamps.

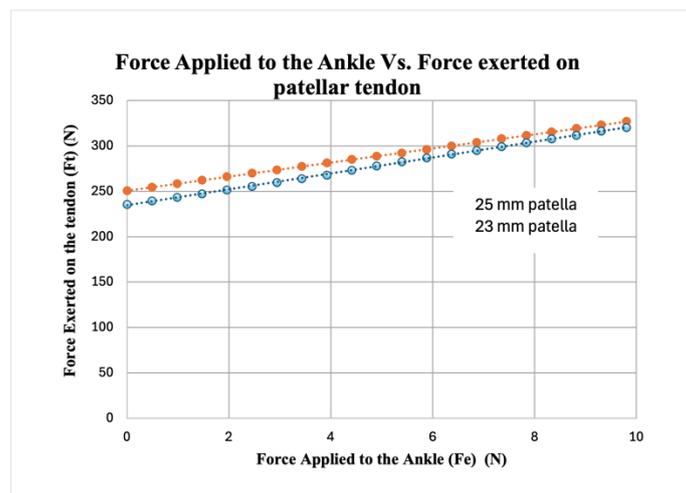
Figure 4. (Left) The prototype of the completed leg attached to the clamp top view. (Right) The side view of the leg, the weight is hung at the ankle. Within the circled area, the orange meter is the Newton meter that we used to record the F_t data.



4. Discussion

Various masses, ranging from 50 grams to 1 kilogram, were hung around the ankle, and the resulting forces exerted on the tendon were recorded as a function of the forces applied at the ankle. Figure 5 shows the graph of tendon force (F_t) versus the externally applied force F_e . In this experiment we used two patellae that was 23 mm and 25 mm thick. The graph clearly shows the linear behaviors as predicted by the theory in equation (1). Also, the size differences make subtle changes in the actual F_t values as it slightly changes the length of the lever arm ($r_t \sin \alpha$).

Figure 5. The graph of applied force (F_e) versus the measured patellar tendon force (F_t).



Initially, this setup was used as an in-class demonstration to spark curiosity and introduce the concept. Students were then grouped and tasked with collecting data using different masses. They recorded their findings and compared them with theoretical predictions. In most cases, their experimental results matched the theoretical values within a 5% margin of error.

This hands-on experience boosted students' confidence, particularly among those who typically struggled with problem-solving. Encouraged by their progress, many students repeated the experiment—refining their measurements and comparing them with calculated values. This iterative process not only deepened understanding but also significantly improved engagement and retention in the class.

4.1. Conclusion and future directions

This study represents a step toward integrating physical prototypes and simulations into Human Body and Mechanics education. By providing students with tangible, interactive models, we enhance their ability to grasp fundamental physics concepts within an anatomical framework. Research indicates that hands-on engagement with physical models improves conceptual understanding and retention in STEM fields (Freeman et al., 2014). Future work will involve refining the model further, incorporating additional biomechanical factors such as muscle tension and external resistance, and expanding the use of simulations for in-depth analysis.

By continuing to develop these educational tools, we aim to foster a more comprehensive and engaging learning experience for students navigating the intersection of physics and human anatomy.

Acknowledgement

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