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Visualization of Tendon Force by Combining 3D Printing and Interactive Simulations in Physics Education

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Abstract

We present an innovative teaching approach for discussing mechanics and the motion of the Human Body in introductory-level physics courses. In this research, we built a 3D-printed leg prototype and created an interactive animation to teach "Mechanics and the Human Body", a physics course tailored for students in physical therapy, exercise science, occupational therapy, and other related fields. Both tools help address a gap in biomechanics education: the lack of dynamic demonstrations and visual aids related to the human body. These tools also involve students in creating an active teaching-learning environment, instilling important hands-on learning skills that we want our students to have in an era where artificial intelligence plays a significant role in every field. We designed and created a 3D-printed, average-sized human leg prototype to demonstrate leg extension exercises and measure tendon force as a function of external forces applied at the ankle. To address natural limitations of the physical model, such as changes in length or weight of the leg, we designed a Python-based animation to allow various adjustments within the well-defined physical constraints and obtain real-time changes in tendon force. The focus of the demonstration was to solidify students' understanding of the mechanics of the leg's motion under an external force. The interactive animation was used to guide students in problem-solving strategies and to restrict them from using AI tools for problem-solving without a proper understanding. The year-end students' feedback supported our efforts and emphasized the effectiveness of visual and hands-on learning in making abstract physics concepts more understandable. We conclude that our demonstration and the animation converted passive listeners into active participants, and that both tools could be a potential replacement for AI as they provide a real-time, hands-on experience for users that AI is not capable of providing.

Keywords

Tendon Force, Mechanics and Human Body, Physics Pedagogy, Physics and Leg Extension, Replacing AI in Physics Education

1. Introduction

Visual learning has consistently been shown to improve students' grasping of novel materials and understanding of complex concepts in STEM education, with research highlighting the benefits of animations, demonstrations, videos, simulations, and physical representations across disciplines (Bertsch et al., 2022; Chi, 2009). While high-quality visual learning tools effectively support some fields, other fields remain underserved. One such underserved area in physics is *Mechanics in the Human Body*, where clear, practical demonstrations are essential for bridging the gap between physics and anatomy (De Jong & Van Joolingen, 1998; Freeman et al., 2014). This course emphasizes Newtonian mechanics and its applications, focusing on the forces, torques, and moments underlying human movement (Goldick, 2000; Hake, 1998). To address this gap, we have initiated the development of life-sized physical prototypes, accompanied by simulations, for the *Mechanics and Human Body* courses taught at our institution (Hall et al., 2021). Prior work in physics and engineering education also has shown that combining physical models with computational simulations improves conceptual understanding (Mayer, 2009; McGinnis, 2005).

Despite efforts to keep Artificial Intelligence (AI) out of the lecture room, modern students have increasingly become accustomed to using AI from an early age. AI plays an integral part in their academic development. Educators across all levels, including K-12 through college, are working to integrate AI into their curricula, placing greater emphasis on hands-on activities. In alignment with these efforts, our work focuses on achieving two additional objectives: expanding the limited demonstrations available for the aforementioned course and introducing new hands-on activities that enhance students' independent critical-thinking abilities and help them understand complex physics concepts specific to their disciplines. This research centers on a recently developed 3D model designed to examine the force exerted on the patellar tendon during leg-extension exercises by linking it to familiar anatomical structures, taking an approach consistent with embodied and interactive learning frameworks (Mohottala & Lothamer, 2025).

2. Background

Students enrolled in a course that combines human anatomy and physics often have a strong background in human physiology but limited exposure to physics and algebra. As a result, abstract physics concepts related to motion or static equilibrium, such as torque, force distribution, momentum, and even the laws of conservation challenge them. Studies have shown that the combined use of physical models and demonstrations improves comprehension in biomechanics education, especially when students are allowed to interact with them (Mohottala et al., 2026). By designing a physical prototype that replicates the anatomy of the lower leg, we aim to create an intuitive learning experience in which students can apply their anatomical knowledge to make physics concepts more accessible and meaningful.

Developing a nearly accurate model of a physical lower-leg prototype for its motion presented several challenges. One significant complexity arose when replicating the kneecap (patella) movement. 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, as explained in the references (Prince, 2004; Redish, 2003). To address this, we 3D-printed the lower leg in thermoplastic polyurethane (TPU) to provide some flexibility and realistic articulation. To obtain a reasonable weight for the leg, we filled the leg with silicone. Additionally, we created multiple patellae 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. Having said that, our model may not be used in an anatomy lab, because the interior mechanism of a human leg is more complex than the model we developed.

The following sections cover the details of the prototype design and 3D printing, the choice of printing material to mimic the natural elasticity of tendons and ligaments (Van Eijden et al., 1986) and the use of PLA for the patella to evaluate its impact on patellar tendon force distribution. Tendon force measurements during leg extension exercises and comparisons of force data with theoretical physics models are presented at the end of the manuscript.

Equilibrium and Mechanics

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 examining the static equilibrium of forces in the lower leg around the kneecap. **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.

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

$$\sigma\tau = 0$$

$$F_t r_t sin\alpha = F_g r_g \, sin + F_e r_e \, sin$$

$$F_t = \frac{\left(F_g r_g + F_e r_e\right) sin}{r_t sin\alpha}$$

$$F_t = \frac{r_e \, sin}{r_t sin\alpha} F_e + \frac{r_g F_g \, sin}{r_t sin\alpha} \quad (1)$$

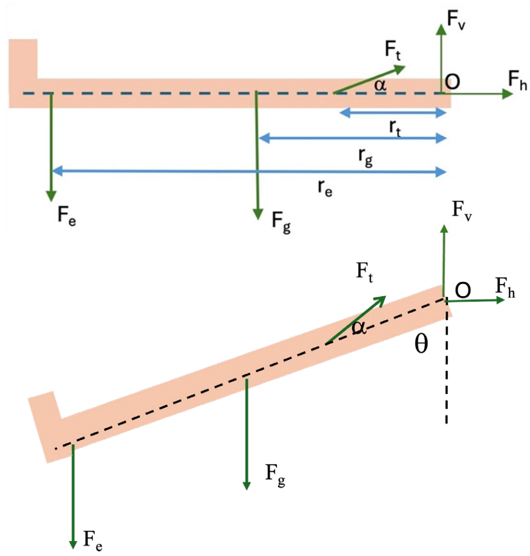


Figure 1. The force diagram of the leg where F_t, F_g and F_e are the force on patellar tendon, weight of the leg, and external force respectively and r_t, r_g and r_e are the corresponding distances from the kneecap to each force. The force acting on the patella is given in its vertical and horizontal components as F_v and F_h respectively (above). The lower diagram shows the rotation of the leg. The q represents the angle between the leg and the vertical. The distances are not separately shown but are the same as in the diagram above.

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 apply 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

We used Fusion 360 to design an accurate human-sized leg model and print a 3D prototype to systematically measure forces transmitted through the tibia when the leg is loaded at the ankle during extension. In this research, we conducted the experiment at three different angles q measured with respect to the vertical axis (the -y-axis): 90˚, 65˚, and 75˚. Building a realistic, anatomically accurate 3D-printed leg model was crucial for replicating physiological loading conditions.

A life-sized anatomical skeleton was initially used to measure bone dimensions and identify key landmarks, including the distal femoral head, condyles, tibia plateau, and malleoli. Then, a team member was asked to perform controlled flexion-extension movements of the lower limb to determine patellar tendon alignment (α-angle), analogous to the q angle at various knee flexion angles. During full leg extension, it was recorded that the patellar angle is at 19.9˚ to the horizontal. The patellar-tendon angle was used as a design parameter for the prototype and simulation setup, not as a population-derived anatomical average. We compared the measured configuration with published biomechanical models of the knee, including the work (Zajac, 1989; Zheng et al., 1998) to confirm it fell within physiologically plausible bounds before adopting it for our mechanical design.

Based on the collected data, we designed the model and printed the components including the Newton meter holder, femur holder, shin and foot skin shells, and patella on the 3D Bambu Lab X1 printer. The Newton meter holder, femur holder, and patella were made from PLA synthetic filament for solidity. The skin shells for the shins and feet were made from TPU synthetic filament to allow some stretch. The patella casing was molded from a block and filled with silica, as shown in **Figure 2** (the white, transparent material).

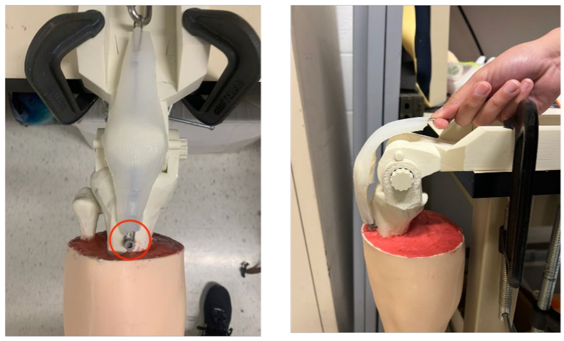


Figure 2. Shows a patella encapsulated in a silicon patella tendon, both front and the side views of the knee joint. The red circle shows the tibial tuberosity.

Following the printing of all components, the model was assembled, and the skin shell was filled with silicone, resulting in a total mass of 3.86 kg. The assembled model was then securely fastened to the laboratory bench. The patella was encased in a silicone mold to simulate the patellar tendon. One end of the simulated patellar tendon was connected to a pin at the tibial tuberosity, representing the tendon attachment site, while the other end was secured to the Newton meter in the holder. The Newton meter, which was firmly attached to the bench with clamps, was used to measure the tendon force, as illustrated in **Figure 3**. *Note*: The Newton meter was calibrated with known masses prior to the experiment.

Figure 3. (Left) The side view of the leg at horizontal position (where $q = 90^\circ$), 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, (Right) the side view at an angle $q = 75^\circ$ with the vertical.

4. Python Based Simulation

A Python-based leg force simulation was developed to provide a user-friendly platform for visualizing the forces acting on the lower limb model under various conditions. For example, lower leg mass, shin length, exercise weight and joint angles are set to vary within reasonable limits. This simulation was not specifically designed for electrophysiological or motor unit analyses; instead, it focuses on allowing users to intuitively explore the relationships between force and torque in real time. The simulation operates on the basic principle of having an input signal, a target system, and an output signal. In this context, the input signals consist of user-defined parameters that can be adjusted using graphical sliders. The target system is a three-dimensional leg model, which includes representations of the thigh and shin, and is displayed using the Visualization Toolkit (VTK). The output signals provide computed values for tibia force (F_t). Figure 4 shows the animation interface for the leg.

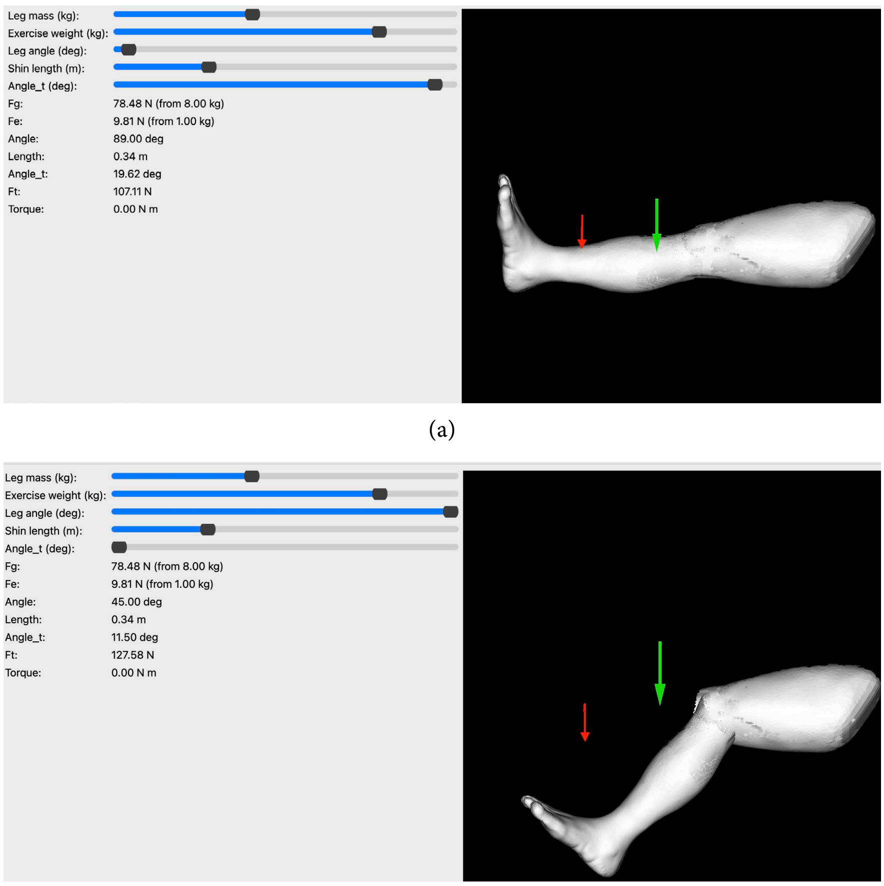


Figure 4. An example of the simulation interface. The sliders are used to change the values of leg mass, length of the shin, leg angle with the vertical, and the patellar-tendon angle (a). The net torque remains to be zero and all the values that the user picked appear below the sliders. The calculated value of the tendon force, Ft, is given. (a) shows the leg at horizontal position ($q \sim 90^{\circ}$) and (b) shows the leg at $q = 45^{\circ}$.

Functionality of the Simulation

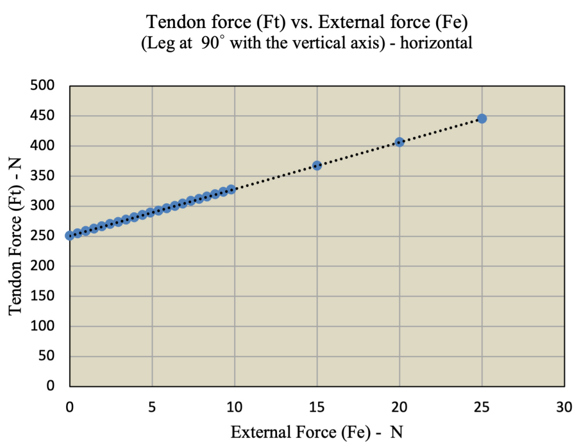
The simulation operates entirely through a graphical user interface (GUI). When launched, the user sees a main window, which includes five sliders to specify key physical parameters. These sliders allow the user to adjust leg mass, exercise weight, leg angle, shin length, and an additional variable labeled "Angle t." Angle t represents a angle in Equation (1) between the tendon and the leg axis (a value was measured using the prototype). As users move the sliders, the program gets updated and the calculated values are displayed on the screen instantly in the text fields, the 3D animated leg model reorients to reflect the new angle values. The red and green arrows show the external force magnitude and the tendon force magnitude respectively, and direct to the insertion points. The length of the arrow changes with the inserted external force values and corresponding angles. For instance, increasing the exercise weight slider, as shown in **Figure 4(a)**, applies a larger external force to the shin, causing the red arrow in the VTK window to grow longer. Similarly, increasing the leg angle slider, illustrated in **Figure 4(b)**, rotates the shin around the knee pivot, and both the on-screen measurements and the rendered force arrows update accordingly.

Users can freely adjust the parameters in real time to explore changing biomechanical relationships. This design emphasizes a cohesive GUI for model setup, simulation execution, and output display.

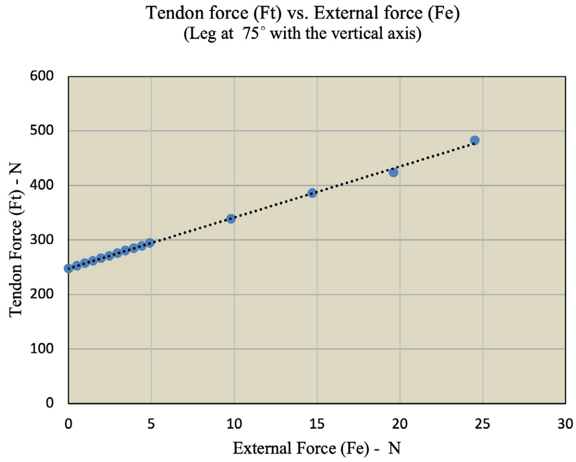
5. Results and Discussion

Here we discuss and compare the data from both the prototype and the simulation. As noted, the prototype is restricted to the chosen values for the length of the leg and weight. Although, the simulation has the capability of changing the lengths and the weights in addition to other variables, here we compare the data gathered from both the prototype and the simulation for some chosen angles.

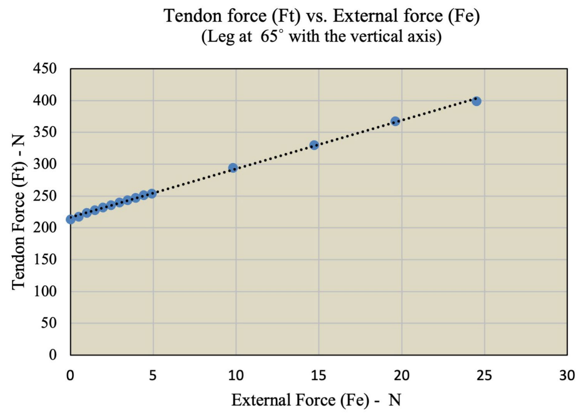
Various masses, ranging from 50 g to 2.5 kg, were hung around the ankle, and the resulting forces exerted on the tendon were recorded as a function of the forces applied at the ankle. **Figure 5** shows the graph of tendon force (Ft) versus the externally applied force Fe. In this experiment we used two patellae that were 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 ($r_t \sin a$).



(a)



(b)



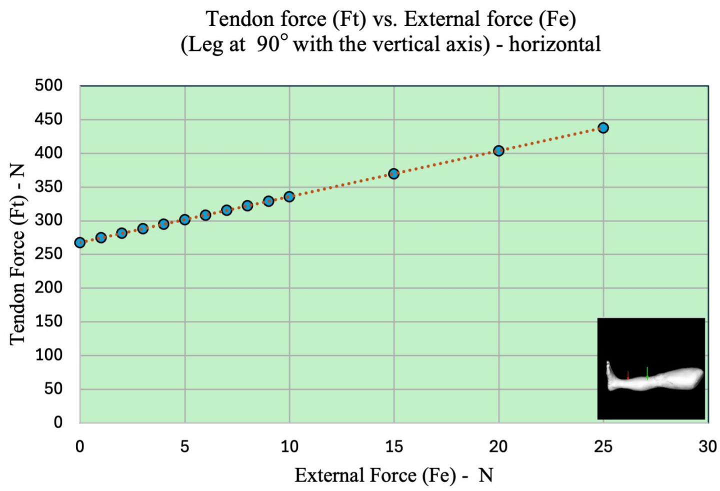
(c)

Figure 5. The graphs show how the tendon force (Ft) changes as a function of the applied force (F_e). The data is from the actual experiments from the prototype. As the labels show the angle of the leg with the vertical, changes from 90˚ to 65˚ (from left to right).

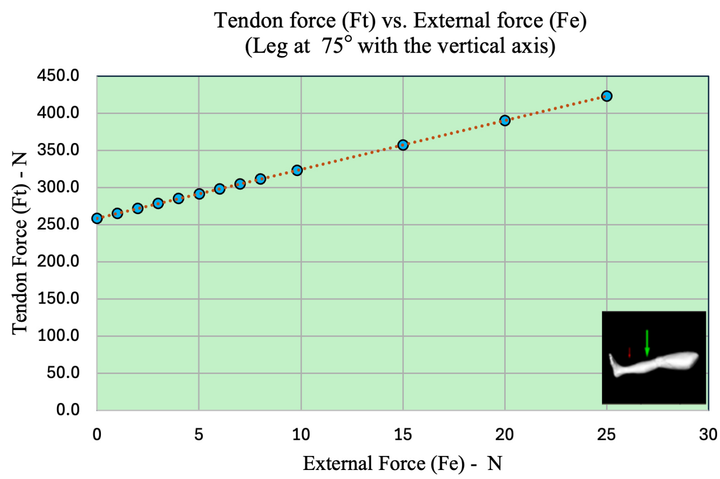
Initially, this setup was used as an in-class demonstration to spark curiosity and introduce the concepts of torque and equilibrium. Students were then grouped and tasked with collecting data using the model with different masses hanging at the ankle. They recorded their readings for the Tibia force on the Newton meter, did the calculations within the group, and compared them with the calculations. In most cases, their experimental results matched the theoretical calculations within a 5% - 10% margin of error as calculated by the formula,

$$\%\ error = \frac{|calculated - experimental|}{\text{calculated}} * 100$$

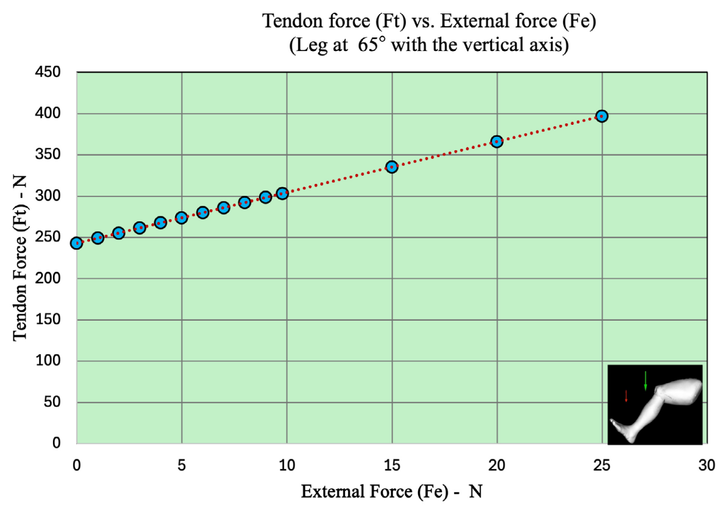
One of the questions raised by the students was about how to interpret data when comparing individuals of different heights and weights. To address this, the students were introduced to the simulation. The data presented in Figure 6 were collected using the same weights and dimensions in the simulation to ensure consistent results. However, it is essential to note that the simulation lacked the capability to utilize two different patellae. As shown in Figure 6, all graphs show



(a)



(b)



(c)

Figure 6. The graphs show how the Tendon force (Ft) changes as a function of the externally applied Force (Ft) for the data acquired from the simulation. As the labels show the angle of the leg with the vertical, changes from 90˚ to 65˚ (from left to right). The insets show the orientation of the leg as appears in the animation.

a linear behavior as expected and discussed in Equation (1). The results align with the prototype data, and the minor deviations could be attributed to the fact that the simulation overlooks all possible resistive forces. In contrast, unavoidable resistive forces are present in the actual prototype.

As mentioned earlier, our aim was to engage students from physical therapy, prosthetics, pre-med, and sports medicine in learning about mechanics and its relation to the human body. Although our prototype and animation can't be fully compared to actual human leg function due to the complexities of human anatomy, both teaching tools effectively explained the mechanics of equilibrium during leg extension exercises. Both **Figure 5** and **Figure 6** show linear behavior that aligns with the theory discussed in Section 2, equation (1).

The prototype allowed them to vary the applied weight, measure the force on the tendon, change the leg's angle relative to the vertical axis, and repeat the exercise. The simulation enabled them to evaluate the setup for individuals with different biometric measurements. Encouraged by their progress, many students repeated the experiment, refined their measurements, and compared them with calculated values. They also used the simulation to examine how tendon force depends on leg length and weight.

Student Assessments and background information:

In general, we offer several types of introductory-level physics courses. Some are designed for STEM majors and include calculus, while others are algebra-based. The course selected for this study, Mechanics and the Human Body, is algebra-based. Introductory classes are typically capped at 24 students, although some sections exceeded this limit. Usually, two sections are offered each semester, resulting in approximately 50 students per term. Over three years, nearly 150 students participated in this teaching model. Each cohort included students from the same disciplines described above. In each iteration, one section served as the control group. Student assessment focused on quizzes and exam questions addressing the rotational motion of the human body. We compared class averages between the experimental and control groups. Classes utilizing the instructional tools consistently achieved higher averages than the control group. Over time, students' problem-solving approaches improved. Notably, students who used the model often justified their solutions and identified possible sources of error when their answers were not physically meaningful, rather than leaving incorrect responses unexplained.

6. Conclusion

In conclusion, our findings indicate that both the simulation and the prototype improved students' understanding of mechanics and the human body. Also, the combination significantly boosted students' confidence, especially among those who had difficulty visualizing and relating concepts to problem-solving and who relied heavily on AI for this reasoning. We don't plan to share success in quantitative statistics but rather qualitative findings due to the small sample sizes in both the control and experimental groups. We can affirm observing a clear improvement in students' attitudes toward learning principles of mechanics and applying them to the motion of the human body over the past two years.

With rapid advancements in 3D printing, anyone who needs a classroom leg model for demonstration can follow our strategy and use our designs for instruction. Providing students with interactive models improves their understanding of fundamental physics concepts in an anatomical context.

Acknowledgments

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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