Application of 3D Printing and Design in Healthcare: A Focus on Undergraduate Research to Attract Students to Bioengineering and Related Disciplines

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***Abstract*—This research-to-practice paper describes developing and analyzing state-of-the-art smart boots created by combining CAD technology and advanced 3D printing techniques to attract students in bio-engineering and related fields. The primary objective of this innovative immobilization boot is to expedite fracture recovery phases through an ergonomic design to ensure optimal patient comfort during its use. Technological solutions are crucial in aiding the rehabilitation process for fractures caused by falls, heavy lifting, or rotational trauma. However, cost and comfort-related issues persist, underscoring the need for alternative approaches. This research addresses these challenges and delves into the broader implications of fracture treatment, catalyzing future projects and investigations in bioengineering. Additionally, this study serves as an educational tool that sparks the interest of high school and engineering students, promoting multidisciplinary collaboration in innovation. By involving students in specialized courses covering 3D design, human bone anatomy, biology, and materials science, this initiative empowers them to deepen their knowledge and develop new technologies to address bone injury problems. Material analyses include evaluating the type of material depending on the fracture site, such as PLA for printing and cotton and silicone gel for the midsection between the splint and the body. This research aims to advance our understanding of the type of fracture, the methods associated with their treatment, and tissue repair processes during bone callus formation. To summarize, this multidisciplinary approach drives advancements in bio-engineering and related fields, aiming to enhance patient outcomes and inspire students to pursue further research in bio-engineering and related fields. As part of this endeavor, a list of university-level courses based on the experience of the University of Puerto Rico at Mayaguez (UPRM), such as biology, biomaterials, 3D design, and 3D printing, will be suggested to foster the development of practical skills and improve each student's proficiency.**

***Index Terms*—3D Printer, CAD Design, Immobilization Boot, Ankle Fracture, Bioengineering Education.**

I. Introduction

In the United States, the hospitalization rate for ankle fractures is estimated to be 4.22 per ten thousand people per year [1], and 25% of these cases require surgical intervention [2]. These fractures can occur due to multiple factors, either directly or indirectly; depending on the cause, they can be stable or unstable, based on the number of malleoli affected, such as the medial, lateral, or posterior malleolus of the tibia [3]. X-rays from different angles or magnetic resonance imaging [4] are performed in the affected ankle area to determine the specific details of the fracture. There are different classifications that analyze the shape of ankle fractures, such as Danis-Weber, Lauge-Hansen, or AO [5]. Patients who have had a Danis-Weber type B or C fracture are more likely to suffer from deltoid ligament injury, lateral ankle instability, and chronic pain compared to other classifications [6]. Therefore, the treatment for these patients must be comprehensive, evaluating their weight-bearing capacity [7], the risk of increased blood clotting [8], and swelling in the entire area. If treated surgically, patients should maintain immobilization as part of their recovery. Thus, a practical solution is the use of immobilization boots, which are more effective for patients with stable Danis-Weber fractures, improving pain relief and preventing fracture displacement [9].

Unlike casts, boots can be removed at any time, allowing the area to be cleaned, massaged to improve circulation, and iced to reduce swelling during the first few weeks. In addition to all these advantages, if the patient is able to walk, the boot can be a useful tool to prevent further injuries, such as the pressure and force exerted by the foot with each step, and it also provides stability and support during any movement. A study conducted over six years showed that middle-aged patients who used boots responded better than patients who used casts, even when walking without crutches, with no loss of reduction or pseudoarthrosis [10].

An undergraduate or high school student could design an immobilization boot based on existing market designs and research conducted to optimize them. The boot can be divided into two parts: the inner structure, which could be made of polyester, serving as the interface between the skin, and the external structure, which could be the boot's plastic. In this research, the student is expected to focus on the design of the external structure of the boot, which should feature characteristics that relate to the anatomical design in each profile of the foot (front, top, back, bottom, isometric) and previous studies on bone and ligament behavior during the recovery from an ankle fracture, as mentioned earlier.

The student should also evaluate the height of the boot, as short boots are practical for foot and ankle fractures in this analysis. Current studies show that short immobilization boots offer more advantages, in addition to being easily removable [11]. This is because the fasteners on the front of the foot and leg reduce the load on the ankle joint with a mechanism similar to that of a patellar tendon support orthosis; these fasteners complement the curved and anatomical design of the foot.

The student should focus on designing an immobilization boot that conforms to the anatomy of each individual, providing comfort during the recovery process. An important part of the design is that the internal base of the boot should have space for the heel area, elevation in the tarsus, and slight elevation in the phalanges area. The external sole of the boot should have a curvature, as this minimizes the rolling movement of the foot at the metatarsophalangeal joint, which also helps reduce the load when bearing weight while protected by the boot [10]. However, the degree of load will depend on the type of fracture, type of surgery, age, height, weight, postoperative time, and other factors. Depending on the degree of load the patient requires, the design of the boot's external sole will change, modifying its height and curvature radius. All these anatomical details and types of fractures help to obtain an improved 3D design of an orthopedic boot.

Once the base design is obtained, work on the physical product begins. Because of the need to enable rapid prototyping of various designs, 3D printers were utilized to construct the boot. Modern 3D printers and 3D printing techniques vary depending on the intended application. In medical applications, the ability to produce detailed, accurate, and biocompatible parts is a valued feature [12]. Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM) are the techniques that are most compatible with the development of a boot, SLS is used in customized prosthetics and orthotics while FDM is used in prosthetics and medical device prototypes. The materials used in these prototypes range from nylon, thermoplastic polyurethane (TPU), acrylonitrile butadiene styrene (ABS), and polylactic acid (PLA).

II. System Design

A. Methodology

Students must conduct a literature review as a starting point on commercially available immobilization boots. Based on this review, they should design and make adaptations grounded in previous research on immobilization boots, taking into account the Danis-Weber fracture classification. The design presented in this work was developed using Fusion360 (a software with a free version for students with an academic email) and customized to fit the following measurements for a patient's foot, considering post-fracture swelling (Fig. 1): width in the metatarsal area (AA'), width in the cuboid area (BB'), foot length (CC'), height between the base and the talus area (DD'), height between the base and the navicular area (EE'), toe height (FF'), and the curvature height in the cuboid area (GG').

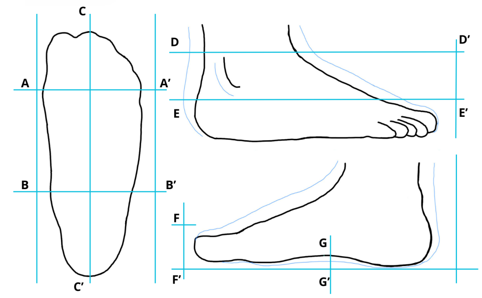

Fig. 1. Foot measurements considering swelling (blue line).

Once the measurements are taken, the design process in the 3D program begins, starting with the sole, which is sketched on the XY plane, beginning with the CC' line that indicates the length of the design. The remaining lines are then added to form the curves and complete the sole (Fig. 2).

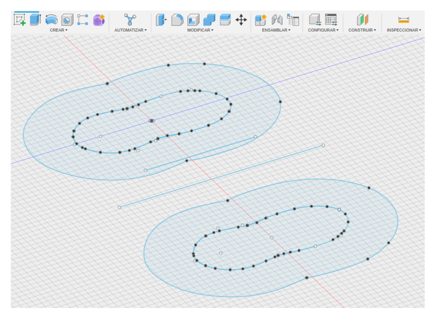

Fig. 2. Base design of the boot in Fusion 360.

After completing the base, it is extruded to create a 3D body in the Z-axis direction. The curved design for the thickness perpendicular to the ED area is then added to this body. This second sketch must account for the heel's curve and the boot's height when creating the body that shapes the boot. Next, holes are made to serve as anchors for the foot adjusters, placed on parallel planes in three areas: The first should extend beyond the main base design, and the adjustment areas near the ankle and leg should be located in the main part of the boot to provide better support. Finally, the base is reviewed to add an internal curve based on the GG' height and an external curve that spans between the CC' ends, resulting in the completed design (Fig. 3).

Once the design was completed, it was printed using various filament printers, employing PLA with an extrusion temperature of 190-220°C and a heated bed at approximately 50°C. The printers used were: Creality K1, Ender 3-Neo, and Prusa. The highest quality print was achieved with the Creality printer due to its ability to generate the necessary curved details. Finally, additional adjustments were made, such as adding elastic straps with adjustable closures and absorbent microfiber insoles in the sole and contours (Fig. 4). Students can adapt other types of thicker fabric to their boot design for better patient comfort. Mobility, support, and anatomical fit tests were conducted, evaluating the adjustability of the support (Fig. 5), ensuring the base was at the same height as the other foot, and that the weight was centered on the sole, thus preventing the ankle area from bearing all the weight. Despite this, the range of motion maintained its rigidity with the surface, and there was no breakage of the boot while the person walked. These fit tests were carried out in different positions (standing, lying down at 45°, 90°, and 180°), with no internal instability issues observed. The base maintained its friction on smooth surfaces, and the sole was slightly larger than the foot to ensure that the gel area under the heel allowed the toes not to protrude beyond the platform. The platform of the boot supported the person's weight, 60 kg.

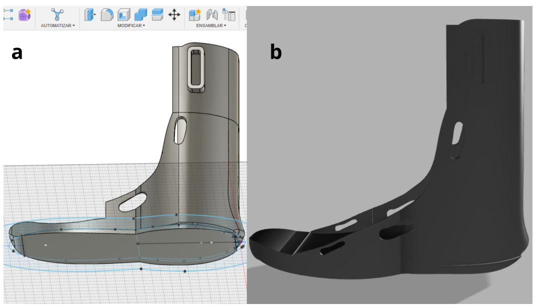

Fig. 3. Finalized 3D Design of the Immobilization Boot in Fusion 360: (a) Initial design explained earlier. (b) Additional adjustments to the design.

Fig. 4. Printed boot along with its supports.

III. Challenges

To create an immobilizing boot using a 3D printer, two points need to be considered: the 3D design and the 3D printing. For the design, open-source or free software like Fusion360 or SOLIDWORKS can be employed to design in X-Y, X-Z, and Y-Z planes. However, care needs to be taken when analyzing the planes since any future modification will affect all of them.

Fig. 5. Printed boot test inside the laboratory.

Regarding 3D printing, three types of printers were evaluated: the Ender 3-Neo, the Prusa, and the Creality K1 models. These 3D Printers utilized the same type of filament, a PLA with a nozzle temperature of 190-220 °C and a bed temperature between 30-60 °C. PLA was chosen because it is a biodegradable thermoplastic, it has high-temperature resistance, low thermal expansion, and high tensile strength which makes it appropriate for an immobilizing boot [13].

The Prusa and the Ender 3-Neo 3D printers took twenty hours to finish the printing process. However, the Creality K1 3D printer finished printing the design in five hours. The Ender 3-Neo and Prusa 3D printers have a range of issues that have been identified when using PLA. [14] It was found that printer configuration, parameters, and geometry significantly affect the mechanical properties of PLA. Additionally, the Creality K1 printer did not require the addition of a supporting frame when performing the printing job.

An important detail to consider is the cost comparison between a commercial boot on the market and one made by oneself. As shown in Table 1, these are the prices of some printers that can print the part and the commercial boots, and Table 2 shows the prices of different brands of PLA filaments found on Amazon in August 2024.

Adding the cost of a printer and the filament is much higher than buying a commercial immobilization boot. However, it should be noted that the student can print multiple prints and use different designs with the printer. In the short term, purchasing a commercial immobilization boot is recommended, but investing in a 3D printer is the best option in the long term.

IV. Didactic Evaluation Suggestions

For didactic evaluation in the design and printing of immobilizing boots, it is recommended that instructors consider the following questions when teaching their students:

1. What is a fracture and how is it identified?
2. Why is it important for a patient with an ankle fracture to use an immobilizing boot?

TABLE I
COST COMPARISON

Printer	Price (USD)	Commercial Boots	Price (USD)
Creality Ender 3	169.00	Medibot	34.96
Anycubic Kobra 2	289.99	Air Walking Boot	39.15
AnkerMake M5C	299.99	Ossur Formit Walker Boot	54.99
Creality K1	444.11	GHORTHOUD Walking Boot	56.99
Original Prusa MK4	949.00	United Ortho USA16115	62.95

TABLE II
COST PLA FILAMENTS

PLA Filaments (1Kg)	Price (USD)
SILK PLA	6.99
ANYCUBIC PLA	9.87
SUNLU PLA	11.99
FLASHFORGE PLA	11.19
OVERTURE PLA	17.49

3. What processes should be followed to design and print an immobilizing boot?
4. What are the fundamental criteria to consider during the design and printing of an immobilizing boot?
5. How does the type of fracture affect the design of the immobilizing boot?
6. What materials can be used in the manufacture of an immobilizing boot?
7. How can the functionality and fit of the immobilizing boot be assessed once printed?
8. What aspects of the 3D printing process should be considered to ensure the quality of the final product?

These questions can help guide students in gaining a comprehensive understanding of the topic and applying their knowledge practically in the design and manufacture of orthopedic boots.

V. Professional Skill Development

The students can develop a variety of skills during this research project. The University of Puerto Rico uses internal and external programs as tools for participants to develop new skills that will help them become more competitive candidates in the industry after graduation. These experiences are essential in bridging the gap between the theory discussed in courses and the real-world practice that enables professionals to apply their knowledge and understand nuances. Some of the vital professional skills learned by the participants were:

- Ability to develop organizational skills, group decisions, and critical thinking.
- Ability to organize oral and poster presentations for professional events and recruitment
- Identify learning gaps in colleagues and provide support
- Create technical reports for the team and people outside the research
- Ability to identify, formulate, and solve engineering problems using techniques learned in previous courses.
- Learning to design and simulate possible solutions for mechanical and electrical systems
- Adapting engineering problem-solving skills to ethical problems in bio-engineering

The UPRM's Bio-Engineering Graduate program focuses on training students in computational bioengineering and biomedical engineering research. The program offers interdisciplinary research opportunities to enable students to work in state-of-the-art research alongside the faculty. Additionally, the program prepares graduates to be aware of the ethical and social responsibilities associated with problems in bioengineering. The IEEE Engineering in Medicine and Biology Society (EMBS) student chapter at UPRM is similarly focused on promoting interdisciplinary research at all student levels, collaborating with industry professionals to share their experiences in the field and bring their perspectives on becoming Biomedical or Bio Engineers.

VI. Suggested Courses

For this research project, students are expected to take several courses beforehand. Table III lists some of the courses that students should have taken before engaging in the research project. The courses are coded by ”U” for undergraduate students, ”G” for graduate students, and ”U/G” courses can be taken by either group. Because this project is multidisciplinary, the table will have courses from different majors. Some of these courses have been suggested for other undergraduate research experiences at UPRM [15] - [17].

VII. Conclusion

This project focuses on developing students' skills in designing and manufacturing immobilization boots, which are essential for providing support during fracture recovery within the field of bioengineering. The suggested courses and the evaluation of the type of fracture are key aspects that the student must master before designing and printing the boot. Additionally, taking precise measurements in specific areas of the foot allows for greater accuracy in the design, ensuring comfort and firmness during the patient's mobility tests.

Upon completion of the project, the student is expected to have gained comprehensive knowledge of fractures, human anatomy, 3D modeling and design applied to the human body, 3D printing, and biomaterials. To deepen these concepts, it is

TABLE III
EXAMPLE OF SUGGESTED COURSES [17]

Course	Description
INGE 3809 Creative Design (U)	Introduction to the underlying principles and methodologies of engineering graphics communications. Fundamentals of graphic visualization, sketching, PC-based Computer-Aided Design (CAD), and technical presentations.
INME 4108 Material Science (U)	Study of the relationship of the mechanical properties of materials at the micro and macro structure levels emphasizing the application of materials in the fields of engineering
INME 4210 System Design (U)	Modeling, simulation, and analysis of dynamic systems with and without basic control actions in mechanical engineering within time, complex, and frequency domains.
BIOL 4505 Human Physiology (U)	A study of the structure and function of man with emphasis on the physiological principles
BIOL 4761-62 Human Anatomy (U)	Human Anatomy, including neuroanatomy and osteology of the head, the neck, and the extremities. Additionally includes the great body cavities (thoracic, abdominal, pelvic) and their parieties.
INEL 5208 Biomedical Instrumentation (U/G)	Theoretical and practical aspects of the methods used to measure physiological events with emphasis in the cardiovascular, pulmonary, and nervous systems.
INME 6065 Biomedical Engineering (G)	Application of engineering principles and quantitative methods in biology to analyze and describe complex biological systems.
INME 6115 Biomaterials (G)	Study of advanced materials as applied to biomedical systems. Integration of materials science and engineering concepts with biology for interfaces between living cells and organic and inorganic materials.
INME 6135 Tissue Engineering (G)	Study of tissue engineering applied to biomedical systems with emphasis on quantitative cell and tissue biology, cell and tissue characterization, engineering methods and design, and clinical applications.
BING 6002 Molecular and Cellular Biology (G)	Study of the biology of cells, emphasizing examples relevant to bioengineering. Topics such as protein structure and function, cellular membranes and organelles, cell growth and oncogenic transformation, the extracellular matrix, and cell movement will be included.
BING 6016 Ergonomics for Biomedical Engineers (G)	Study of anatomical and physiological concepts that describe and predict human motor capabilities, with particular emphasis on the evaluation and design of manual activities in diverse occupations.

recommended that students study the basics of tissue engineering, the mechanical properties of materials, and cell biology. This will allow them to better understand the bone regeneration process and optimize the design of immobilization boots.

A future educational proposal would be to implement a laboratory course or educational module that offers a hands-on experience in manufacturing. In this setting, students could apply their knowledge of 3D design and printing to address real health problems by manufacturing functional low-cost prototypes. This practical approach would allow them to make continuous improvements to boot designs, focusing on enhancing comfort and functionality for the end-users.

ACKNOWLEDGMENT

The authors thank the University of Puerto Rico-Mayaguez (UPRM), the UPRM's Industrial Affiliates Program, the UPRM's Minds2CREATE Research Team, and the Consortium for Hybrid Resilient Energy Systems (CHRES) DE-NA-0003982 for their support in this work.

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