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STUDY REGARDING THE USAGE OF 3D PRINTED SPECIMENS FOR VALIDATING BIOENGINEERING EXPERIMENTAL REASEARCHES

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Abstract: *This study is focused upon highlighting the usage of 3D-printed specimens to pre-validate experimental research on bone structures, an approach which offers several advantages. These models enable precise replication of complex anatomical geometries, allowing for controlled testing conditions and repeatability. They reduce the reliance on cadaveric or animal bones, lowering ethical concerns and costs. Additionally, 3D printing facilitates rapid prototyping and customization, making it ideal for simulating specific pathologies or implant scenarios. This approach enhances the reliability and efficiency of biomechanical studies before proceeding to clinical or in vivo phases.*

Key words: *3D printing, FDM, SLA, bioengineering experiment, bone structure*

1. INTRODUCTION

The experimental study within the research is one of the most challenging stages within the bioengineering field, due to the high perishability of the specimens and their lack of consistency.

Although within the market, specific replicas or specimens replacements can be found, due to the lack of homogeneity in the bone structure, the obtained results might not be as close to reality as they should be, therefor, for a valid approach of the problematic, researchers tend to use within the studies real bone specimens, either cadaveric human-sourced, or based on the comparative anatomy similarities, the specimens could also be sourced from bovine, ovine or even porcine [1], [2].

As well known, obtaining human or animal-sourced specimens is a thorough process and consists in plenty of documentation and ethical procedures, therefore, scraping a real bone specimen is highly undesirable.

During the experimental research setup, several important parameters must be strictly determined, a process which implies using specimens that will probably get scraped.

3D printing bones for experimental validation offers a powerful and cost-effective method to simulate human skeletal structures in biomechanical research [3], [4], [5]. By using CT scans of real bones and printing them researchers can replicate anatomical geometry and internal architecture with remarkable fidelity [6], [7]. These printed replicas allow for controlled testing of mechanical properties under various loading conditions [8], [9].

This study's main objective is to present the advantages of using 3D printed specimens within the setup validation of biomechanical experiments on real bone structures, describing the whole process, starting with the printing of the specimens using adequate parameters, post-processing the obtained parts and finally using them within the experimental setup.

2. MATERIALS AND METHODS

Bone specimens are characterized by the high complexity of the shapes and internal structure, based on the lack of homogeneity of the bone tissue, therefore, conventional manufacturing such as milling or turning of the bone replicas require sophisticated 5 axis machine tools for the outer surfaces and in some cases conventional manufacturing could also be impossible.

For the inner structure, although, obtaining different structures within the same part, by conventional manufacturing is not approachable.

One of the manufacturing means which can satisfy the stated objectives is the 3D printing method. Through this approach, cheap parts with high inner structure and outer surface complexity could be rapidly obtained.

It is important pointing out that on the market there are currently some specialized composite alternatives that can be used for studying the behavior of the bone structures, such as the Sawbone specimens (Pacific Research Laboratories, Vashon, WA), approached within a number of studies and the obtained results were relevant for the field, but such specimens are quite expensive [10].

For this specific study, two of the 3D printing methods have been focused on: the Fused Deposition Modeling (FDM hereinafter) and Stereolithography (SLA hereinafter) methods, both being previously consecrated as adequate rapid prototyping methods.

Within the next couple paragraphs, each method will be presented, focusing on their particularities.

2.1 3D printing of bone specimens through the FDM method

The FDM 3D printing method is characterized by the advantage of being capable of producing high complexity parts, rapidly and with low expenses. The downfall of the method consists in the appearance of the staircase effect of the outer surfaces of the part. In our case, for presenting this method, we used a 1.75mm Acrylonitrile Butadiene Styrene (ABS hereinafter) wire and the UP Plus 2 3D printer.

The first step consisted in importing the 3D models of the parts (in *.stl formats) within the 3D printer specialized software – UP Studio v2.4 and positioning them into the workspace. Through successive translations and rotations of the models it is aimed that the contact surfaces of the parts to be as simple as possible, for easy post-processing of the support structures, as presented in Figure 1.

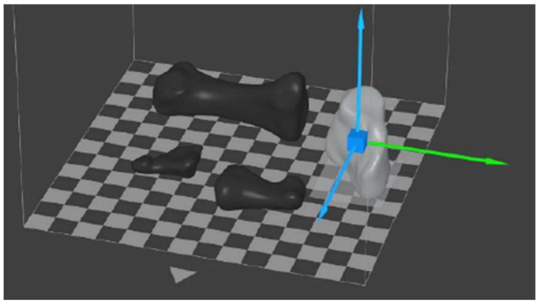
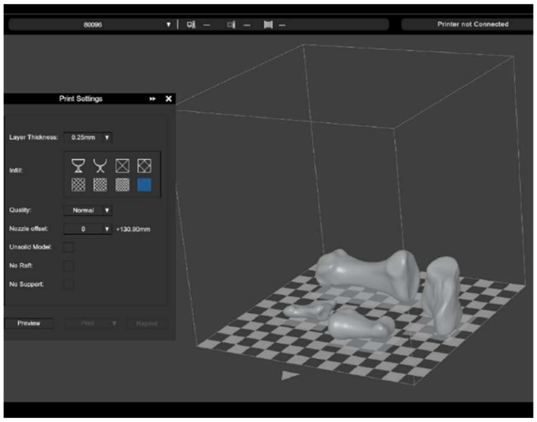


Fig. 1. Positioning the parts into the workspace.

The printing parameters were as following: 99% infill, layer thickness – 0.25mm, 240°C temperature, nozzle size: Ø0.2mm, 3-layer side wall, deposition strategy: zig-zag and slow deposition speed, parameters presented in Figure 2.



Layer Thickness: 0.25mm

Quality: Normal

Nozzle offset: 0 +130.90mm

Unsolid Model: ☐

No Raft: ☐

No Support: ☐

Fig. 2. 3D printing parameters setup.

Fig. 3. Staircase effect on the 3D printed parts.

The printing time was around 2.2 hours and based on the selected 3D printing setup, several defects resulted, mainly the staircase effect, presented in Figure 3.

2.2 3D printing of bone specimens through the SLA method

For obtaining closer to reality 3D printed bone replicas, the SLA method is the suitable approach. Due to the usage of resins as raw materials and the process itself, smoother outer surfaces can be obtained, lacking the staircase effect. Within this current study, the SLA 3D printer was the Form 3+ one, and the resin was FormLabs RS-F2-GPGR-04, raw material which assures the development of high precision prototypes. Following the same steps as the previous approach, the parts were imported as .stl files into the PreForm software, they were places into the workspace in the adequate positions and the suitable printing parameters were selected. The printing process lasted around 3hrs, having 381 layers and using circa 50mL of material, data presented in Figure 4.

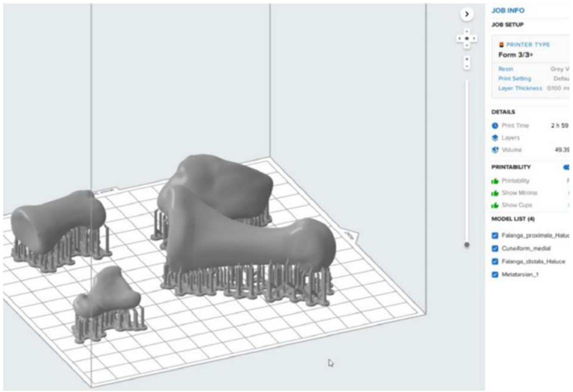


Fig. 4. Simulation of the SLA 3D printing of the bone replicas within the PreForm software.

Finally, after the removal of the support structures, the bone replicas obtained through the SLA method require a 60-minute UV-type post-curing process, for reaching the suitable mechanical characteristics. [14]

The final replicas obtained after treatment are of a significantly higher quality than those obtained using ABS, as shown in Figure 5.

Fig. 5. Resulted bone replicas by using the SLA 3D printing method.

Although the results obtained using the second method were of higher quality, the cost of the raw material (resin) was considerably higher, and the processing time was approximately 25% longer.

After analyzing the two methods, we concluded that the FDM method is suitable and useful for conducting the preliminary experiment to validate the tests we will perform in achieving our experimental objectives.

3. VALIDATION OF THE EXPERIMENTAL METHODOLOGY PROCESS

The experimental setup approached consisted in simulating one of the most frequent Hallux Valgus deviation surgical correction interventions – the first metatarsal opening-wedge osteotomy. This particular surgical method consists of three main phases upon the first metatarsal:

1. creating the slot on the posterior side of the first metatarsal (drilling and milling)
2. opening the wedge up to the desired angle of correction
3. fixation of the corrected configuration of the bone through a special plate.

3.1 Design and development of the clamping device

In order to execute the necessary steps under fair precision conditions, a special device has been designed and developed, starting from the imposed particularities of the clamping systems on the CNC and the tensile strength testing machine, alongside with the geometries of the specimens, rather 3D printed or real bone.

First of all, the clamping system has been designed to be able to clamp the specific bone, in our case the first metatarsal, taking into account the fact that the real bone specimens might have slightly different outer configuration, therefore, for an accurate position, five M6 holes/screws have been disposed on both sides of the device, one M8 was placed for the longitudinal positioning and finally, on the lower side, another M6 was placed for angular positioning of the specimen/bone, features presented in Figure 6.

The clamping of the specimen/bone is done through the upper brackets.

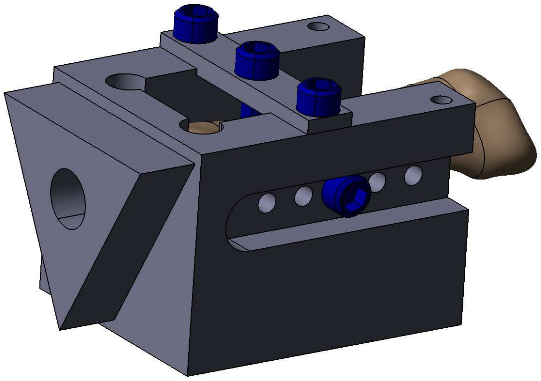


Fig. 6. Specimen clamping device.

Furthermore, the device had a triangle-section area for clamping on the CNC's chuck jaws and finally, for clamping on the tensile strength testing machine a L-shaped part was designed, the whole assembly being presented in Figure 7.

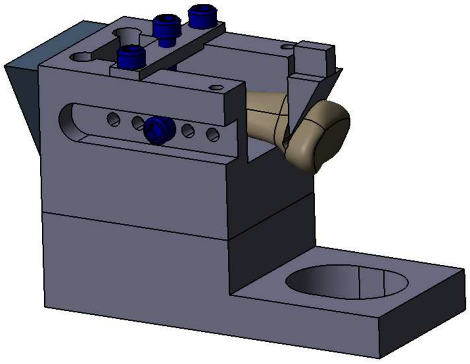


Fig. 7. Device assembly.

The resulting device is presented with a 3D printed specimen in Figure 8.

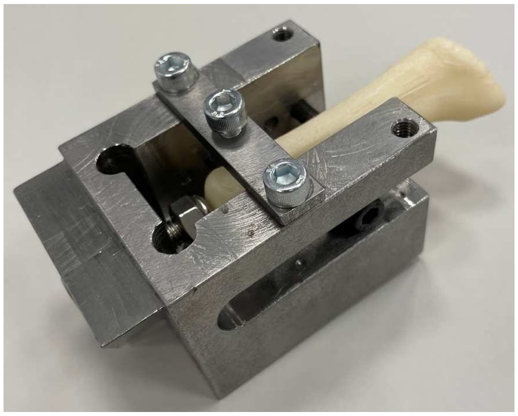


Fig. 8. Device and 3D printed specimen.

Having such a device assures the precision conditions required and allows us to carry on with the experimental validation of the setup.

3.2 Experimental methodology validation

The presented experiment had the focus of determining the maximum value of the wedge up to the apparition of the first micro fissures in the slot for different positions of the slot, therefore, in order to carry on to the experiment on the real bones, it was mandatory to pre-validate the whole experimental setup.

As presented in the walkthrough of the surgical intervention, upon the 3D printed specimen has been machined the slot. After fixing the specimen into the clamping device (Figure 9), the reference coordinate system of the part has been set up, as in Figure 10.

Fig. 9. Device clamped in the chuck jaws.

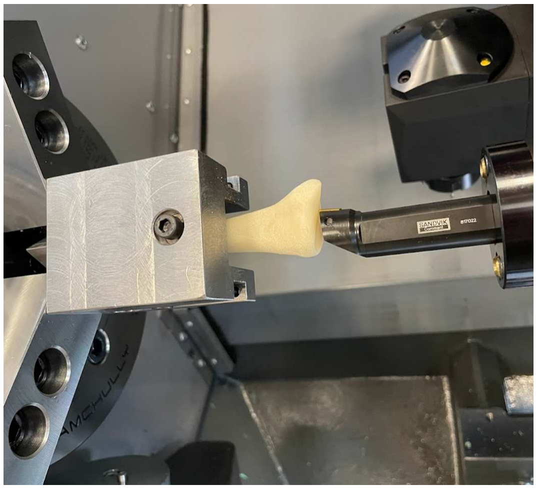


Fig. 10. Reference coordinate system set up.

The first manufacturing phase consisted of drilling a Ø3mm hole, associated with the center of rotation of angulation during the wedge-opening process, as presented in Figure 11.

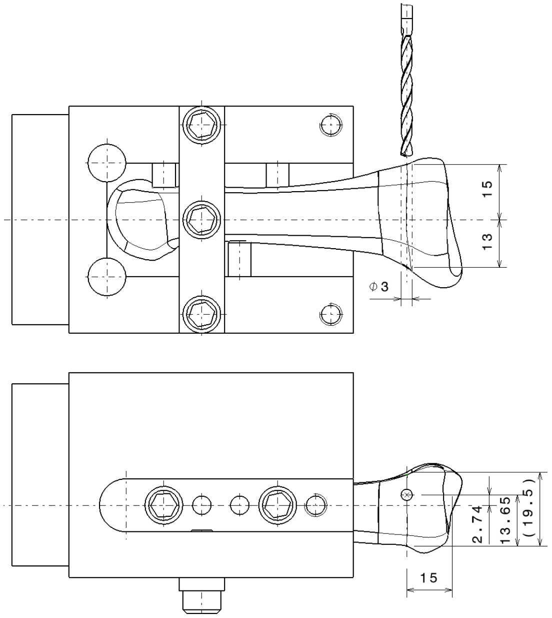


Fig. 11. Drilling a Ø3mm hole on the specimen.

After positioning the drill on the desired position (as in the sketch) the drilling operation can be executed, assuring that the manufactured hole is through and the tool holder does not get to clash with the specimen clamping device. The drill prepositioning is presented in Figure 12.

Fig. 12. Positioning of the Ø3mm drill.

Finally, Figure 13 illustrates the specimen after the drilling phase, carrying on to the milling of the slot.

Fig. 13. Specimen after the drilling.

As presented, the next phase consisted of creating the slot for the wedging process, illustrated in Figures 14, 15 and 16, walking through a similar path as the previously presented drilling phase.

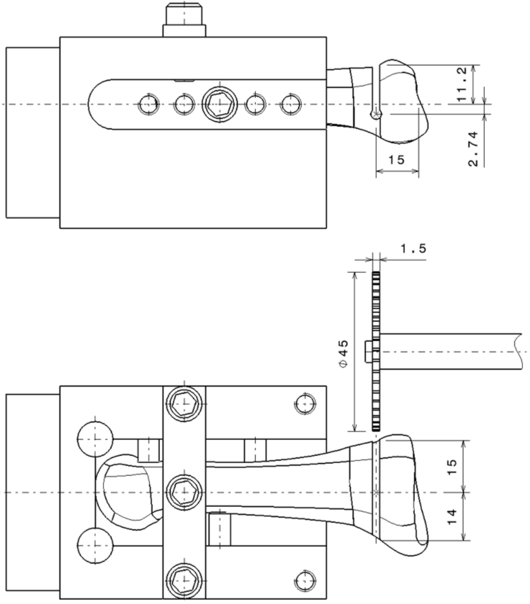


Fig. 14. Milling a 1.5 mm slot on the specimen.

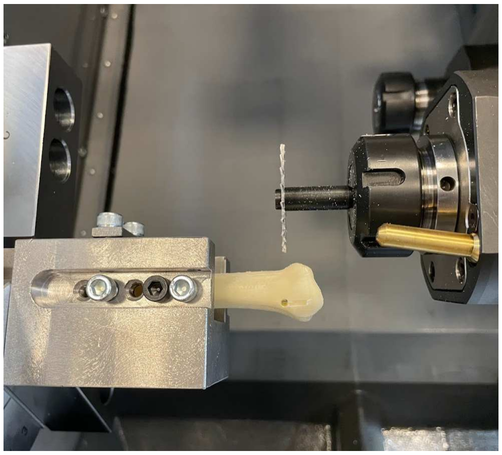


Fig. 15. Positioning of the 1.5mm mill.

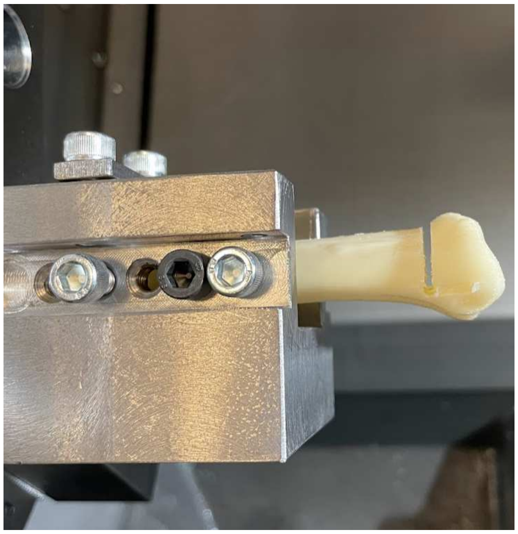


Fig. 16. Specimen after the slotting.

The next step in the process requires the specimen to be brought into the anatomical position by wedge-opening the previously done slot. By using the same clamping device, without removing the part from it, the whole system was placed on a tensile strength testing machine in order to simulate the wedge opening, setup presented in Figure 17.

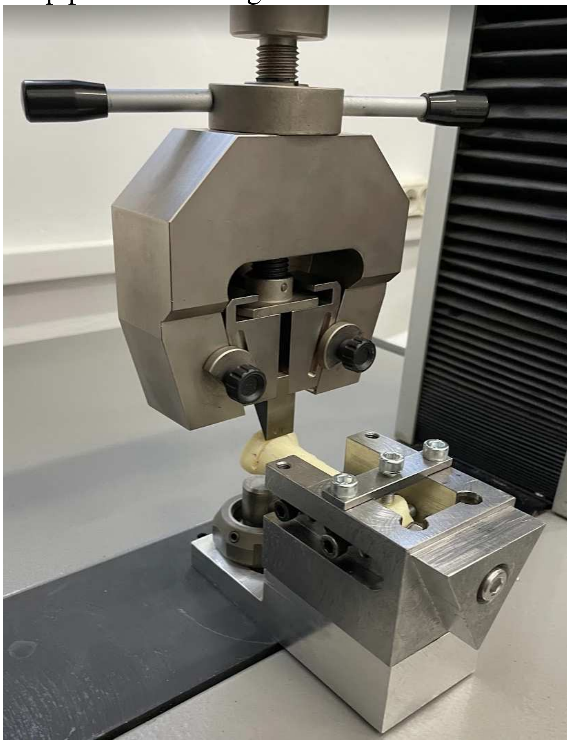


Fig. 17. Device fixed on the tensile strength testing machine for wedge-opening.

The upper punch was set up to translate on the Z- axis up to a designated position, associated with the maximum wedge-opening, resulting in the configuration as Figure 18.

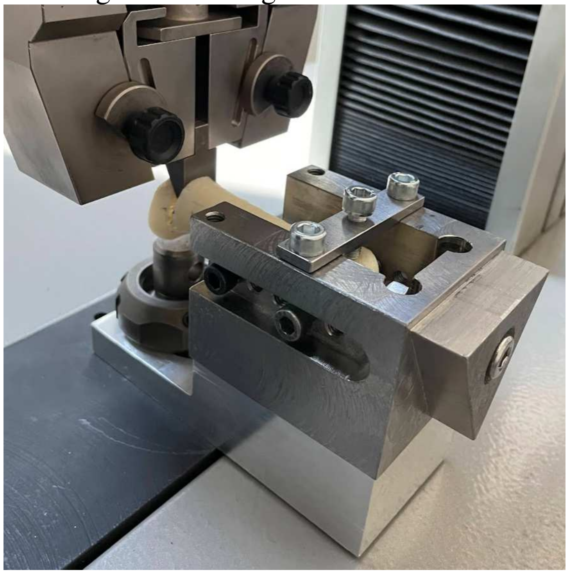


Fig. 18. Final punch position

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Figure 19 presents the final position of the punch, focusing on the appearance of the fissures within the specimen.

Fig. 19. Detailed view of the specimen.

The resulting force-displacement graph is presented in Figure 20, illustrating the growth of the force alongside with the displacement, up to the fissuring of the specimen.

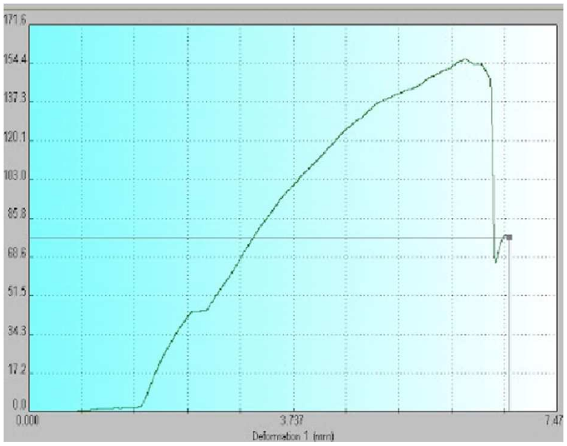

Fig. 20. Force-displacement graph.

The values extracted from the graph are concluding, very close to the expected results, therefore the experimental setup can be validated, and it can be carried on to the real bone experiment.

4. CONCLUSIONS

The use of 3D printed bone specimens has emerged as a transformative approach for validating experimental setups in biomechanical research. These synthetic models offer a high degree of reproducibility and customization, allowing researchers to replicate complex anatomical geometries and internal structures with remarkable precision. Unlike natural bone, which varies significantly between individuals in terms of density, morphology, and mechanical properties, 3D printed specimens provide a controlled baseline for testing. Moreover, additive manufacturing enables the integration of specific defects, implants, or geometrical modifications to simulate pathological conditions or surgical interventions, enhancing the relevance of the experimental setup.

In addition to their structural fidelity, 3D printed bones facilitate cost-effective and ethical experimentation, especially in early-stage validation where the use of cadaveric or animal specimens may be impractical or restricted. Researchers can iterate designs rapidly, adjusting parameters such as porosity, infill patterns, or material composition to mimic the mechanical behavior of cortical and trabecular bone. This flexibility supports the refinement of testing protocols before transitioning to biological specimens, minimizing waste and improving experimental efficiency. Ultimately, the strategic use of 3D printed bone models bridges the gap between computational simulations and in-vivo studies, ensuring that experimental setups are both robust and clinically relevant.

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Studiu privind utilizarea replicilor osoase printate 3D pentru validarea cercetărilor experimentale în domeniul bioingineriei

Acest studiu se concentrează pe punerea în evidență a utilizării replicilor osoase printate 3D pentru validarea preliminară a cercetărilor experimentale privind structurile osoase, o abordare care oferă mai multe avantaje. Aceste modele permit reproducerea precisă a geometriilor anatomice complexe, oferind condiții de testare controlate și repetabilitate. Ele permit reducerea utilizării oaselor provenite de la cadavre sau animale, diminuând preocupările de natură etică și costurile. În mod suplimentar, printarea 3D facilitează prototiparea rapidă și personalizarea, fiind ideală pentru simularea unor patologii specifice sau scenarii de implantare. Această abordare îmbunătățește fiabilitatea și eficiența studiilor biomecanice înainte de a se trece la fazele clinice sau in vivo.

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