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DESIGNING A 3D PRINTED BONE SIMULANT FOR WIRE NAVIGATION TRAINING

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ABSTRACT

Medical simulation has risen in popularity as a method of improving surgical outcomes for less experienced practitioners. In orthopedic surgery, haptic feedback is an essential element of simulation. In the case of Kirschner wire navigation, for example, a steel pin is drilled through cortical bone and into cancellous bone. Currently, many orthopedic simulations use Sawbones polyurethane foam surrogates as a bone simulant (Sawbones, Vashon Island, WA). When designing a simulator, however, creating or modifying an existing mold for cast parts is costly, which can be a critical limitation. A relatively low-cost alternative is 3D printing prototype bone surrogates.

In this experiment, three rapid-prototyped bone samples were printed from light-weight polylactic acid, each with different material densities based on their printing temperature. In a blind test, orthopedic surgeons were asked to drill a Kirschner wire into four bone simulants: three made from polylactic acid, each prepared with different printing temperatures, and a Sawbones control. The surgeons rated their experience with the surface engagement, drill feel, and ability to redirect their wire. The survey found that the densest sample, printed at the lowest temperature, received the highest surgeon rating, with an average score of 13.5/15 ± 2.60; the Sawbones control received the worst rating: 6.5/15 ± 2.96.

Keywords: 3D printing, bone simulation, haptic feedback

1. INTRODUCTION

Recent advances in 3D printing technology have produced a high-strength polymer mixed with a heat-activated expanding agent. This material, produced and distributed by colorFabb (colorFabb, Belfield, Netherlands), is a lightweight polylactic acid, or LW-PLA, with regular PLA being a commonly used printing material. The heat-activated expansion creates a closed cell foam structure that reduces density and hardness, which can approximate the structure of cortical bone. Currently, Sawbones polyurethane foam cortical shell models are the most commonly used bone simulants. These models are often sufficient for low fidelity exercises, but when designing new simulation activities, unique bone models/anatomy shapes are often required. Developing a new Sawbones model can be a time-consuming and costly process. However, 3D printing offers a low-cost intermediate for testing and validating simulators before large-scale production. This study examines if surgeons find the 3D printing materials an acceptable substitute for a full-scale production of a Sawbones model.

2. MATERIALS AND METHODS

2.1 Creation of specimens

Four different test specimens were prepared for the survey: three were 3D printed from LW-PLA model SKU:030011, and one was prepared from a Sawbones product. The variety of Sawbones model used for this study was the foam cortical shell material, as that is the type commonly used at simulation and training courses. The Sawbones model was taken from an adult femur model SKU:1130-21-33. It was cut in half along the anterior-posterior plane, and the pink cancellous bone foam core was scraped out until none remained below the drilling surface.

The 3D printed models were semi-cylindrical with fixation holes on the bottom plane. They had an outer radius of 25.4mm and an inner radius of 21.4mm. The cortical thickness of 4mm was chosen to be similar to the Sawbones samples, which ranged between 3-5mm. Three types of testing specimens were created from the solid model. They were printed on an Ender 3 printer (Creality 3D, Shenzhen, China) with a 1mm nozzle. Table 1 displays the printer parameters for each model, varied to account for the difference in expansion between temperatures. For each temperature setting, flow rate, layer height, and printing speed were adjusted until a specimen could be printed with consistent surface texture and color on the drilling face. All specimens were eventually printed at a speed of 40mm/s.

TABLE 1: Printing parameters for polylactic acid samples

Temperature (˚C)	Layer Height (mm)	Flow Rate (%)
210	0.5	63.75
220	0.6	40.00
230	0.7	35.00

The four samples from each set were weighed, and their volume was measured with a water displacement test to find the density. These and other relevant densities are shown in Table 2. The table compares the density of the printed samples with the density of Sawbones cortical material (Porro, 2020) and the cortical bone density reported in the study “Quantitative Ultrasound Assessment of Cortical Bone Properties Beyond Bone Mineral Density” (Grimal et al., 2019).

TABLE 2: Density of the test specimens and human bone.

Sample	Sawbones	Polylactic Acid Print Temperature (˚C)			Human Bone
		230	220	210	
Density (g/cm^3)	0.29-0.35	0.73	0.96	1.40	1.6-2.0

2.2 Testing apparatus

A small box was constructed to house the 4 test specimens. The specimens were screwed down in a random order and given labels A-D (A=230˚C, B=210˚C, C=Sawbones, D=220˚C). Beneath each specimen was a piece of black packing foam, which acted as a transition material to provide resistance once the drill penetrated the specimen, to prevent drilling into the box floor. The lid of the box contained 4 holes covered with a thin piece of opaque silicone to prevent identification of the specimens (Figure 1).

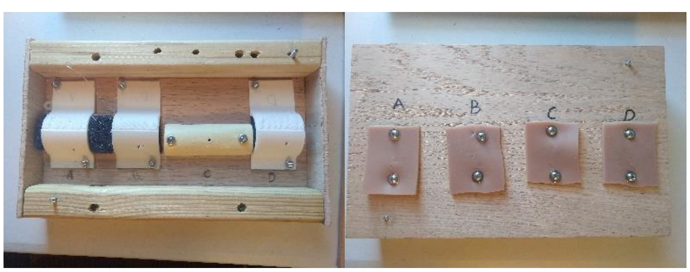

FIGURE 1: (Left) Specimens secured into the testing box. The specimens were bolted down so that drilling only occurred on the smooth face, as the other half of the rounded surface had an irregular texture due to low flow at the beginning of each layer. (Right) The box was presented to participants with a lid placed to obscure vision of the specimens.

2.3 Participants

Orthopedic surgery residents and faculty were invited to participate in the study, with the exception of first-year residents, who lack experience in the operating room. The surgeons were presented with the box of specimens, a surgical drill, and a Kirschner wire. They were asked to drill through one of the specimens and then given a three-question survey about that specimen. The questions asked if the wire surface engagement, drill feel, and ability to redirect the wire were similar to that of healthy cortical bone. The surgeons circled an answer on the scale of strongly disagree to strongly agree, assigned a numerical score from 0-5, with 5 being strongly agree. They would repeat this process for all 4 specimens. Each surgeon was given a different order in which to test the specimens in accordance with a Latin square design. After a surgeon finished all the specimens, the pieces were switched out away from view, and the next surgeon was surveyed.

3. RESULTS

In total, 4 orthopedic surgeons were surveyed, 3 faculty and 1 third-year resident. Once their survey responses were recorded, the data were tabulated (Figures 2 through 5). Surgeons are labeled as rater A, B, C, and D in each of the survey figures.

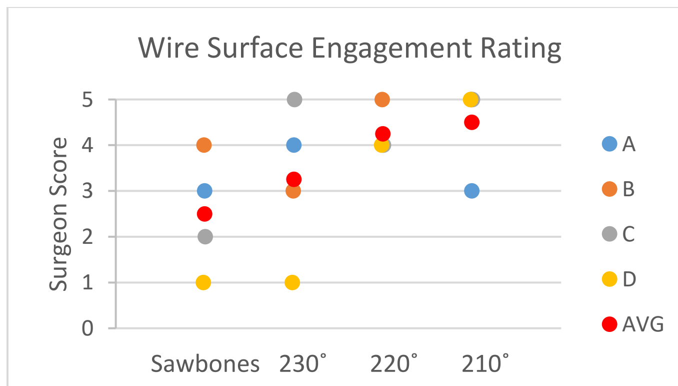

FIGURE 2: Question 1 asked if the Kirschner wire engaged with the surface the same as cortical bone. Samples are displayed in order of increasing density.

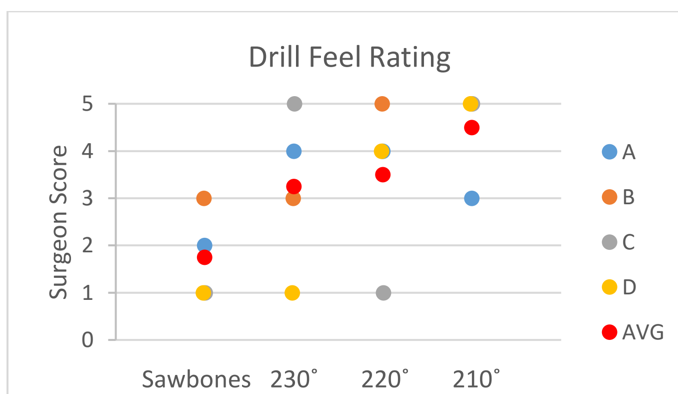

FIGURE 3: Question 2 asked if drilling into the material felt the same as typical cortical bone.

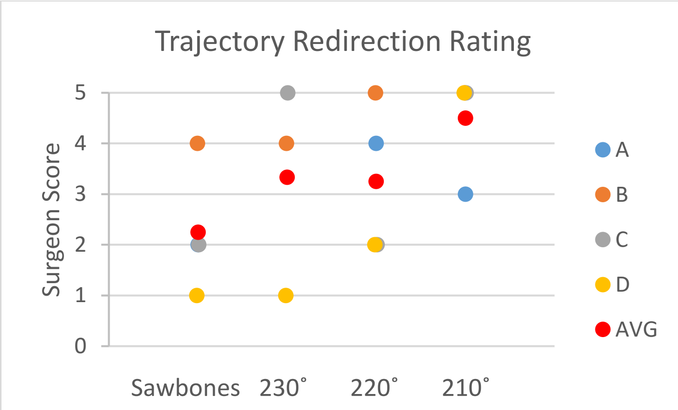

FIGURE 4: Question 3 asked if the feeling of redirecting the wire once through the cortex layer was similar to healthy bone. For this question, surgeon A did not fill out a response for the 230 ˚C specimen.

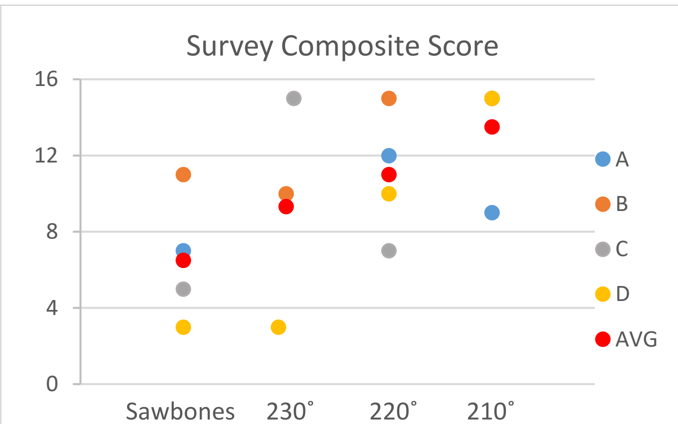

FIGURE 5: Composite scores were created by totaling the scores for each question. For the 230˚C specimen, surgeon A did not fully fill out the questions, but the response to the questions they did fill out were in 4 out of 5 and they commented that it was one of the top two favorites.

4. DISCUSSION

While we surveyed multiple questions, the central hypothesis was essentially "can 3D printed materials approximate the feel of an industry standard Sawbones product." This study shows that not only do the surgeons find the 3D printed material to be acceptable, but that they prefer it over the Sawbones product. When looking at the composite score, the lowest rated sample was the hollowed Sawbones cortex, with an average score of 6.5±2.96. The 230˚C sample had the next highest composite score, although the composite scores ranged from 3 to 15, suggesting that the surgeons had a large variability in bone property preferences. For instance, one surgeon commented that it felt soft, another stated it was close to second place. The highest rated material specimen was the 210˚C bone LW-PLA piece, with an average score of 13.5±2.60. The 210˚C had the highest average score for each question, however in question 1 the 220˚C sample had a very close average score, only 0.25 points less. Question 1, wire-surface engagement, had the smallest spread of ratings between the surgeons, with the lowest and highest average score between samples having only a difference of 2. This may indicate that density has less impact on the surface finish than it does on other mechanical properties of the material. While the 3D printed samples are meant to simulate real cortical bone, in an actual surgery the periosteum covering the bone influences the feel of wire placement. The collagen and elastin weave of the periosteum covers almost all bone surfaces, and its strain stiffening properties allow surgeons to easily set their trajectory without slipping on the hard, bony surface (Tate et al., 2016). It is possible that use of a secondary material to represent the periosteum would improve the surface engagement score of all the bone simulants.

When asked to choose a favorite sample from the set, 2 surgeons picked 210˚C, 1 picked 220˚C, and one surgeon could not choose between 220˚C and 230˚C. Based on their ratings across all questions, Surgeon A preferred samples of intermediate density, but showed no preference for the highest density sample. Surgeons B and D highly preferred the highest density sample, but greatly disliked the lowest density samples. Surgeon B showed no difference in scoring between the 210˚C and 220˚C samples. Surgeon C gave both the 210˚C and 230˚C samples full points but gave low scores to the 220˚C sample for both drill feel and trajectory redirection. Their only commentary was that, "[the 210˚C sample] felt very realistic."

The results from Table 2 and Figures 2 through 5 indicate that increasing the density of a bone simulant improves the surgeons' experience via more realistic haptic feedback. The samples made from LW-PLA in this study did not reach the density of real cortical bone, so it is possible that a denser material than that used in this study would receive similar approval by the surgeons. While the Sawbones model was shaped like the shaft of a femur, the printed models were all perfect half circles, yet they all received higher ratings for surface engagement. This demonstrates that the hardness of a bone sample can outweigh the feel of bony surface irregularities when it comes to a surgeon's sense of touch. Rapid prototyping simple models without exact anatomy could be an effective way to create early simulations.

While the Sawbones sample was consistently given the lowest average rating, it is possible that the removal of the non-cortical material impacted the overall feel. A follow up study would keep the Sawbones interior intact and similarly dense foam would be used to support the 3D printed samples. The same questions would be used to see if the cancellous support changes the surgeons' opinions.

5. CONCLUSION

Sawbones remains the top choice for mass manufacture of skeletal anatomy models, but in terms of simulation practice, there remains room for improvement. The data demonstrate that a denser, harder bone simulant garners a more favorable response from orthopedic surgeons. 3D printed bones made from porous LW-PLA, while not economical in the long-term, offers a prototyping alternative that provides realistic haptic feedback.

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