Research Square

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Evaluation of 3D Printed Materials for Surgical Education in Orthopaedic and Trauma Surgery: A Focus on Osteotomy and Osteosynthesis

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Abstract

Introduction:

Three-dimensional (3D) printing enables the creation of anatomically accurate and customizable bone models for surgical training. However, limited evidence exists regarding which stereolithography (SLA) materials most realistically replicate bone behavior during osteotomy and osteosynthesis. This study systematically compared eight SLA resins to identify optimal materials for orthopaedic and trauma surgery simulation.

Methods

Distal fibula models were fabricated from eight Formlabs resins (Grey Pro, High Temp, Tough 1500, Tough 2000, Durable, Rigid 4K normal cure, Rigid 4K cure without heat [cwh], and Rigid 10K) using SLA printing. All models were filled with rigid polyurethane foam (150 g/cm³) to simulate trabecular bone. Six trauma surgeons evaluated each model on a six-point Likert scale for visual appearance, drilling, sawing, screwing, and splitting behavior. Statistical comparisons were performed using one-way ANOVAs followed by Tukey's post-hoc test for multiple comparisons.

Results

Significant differences between-material were observed for appearance ($p = 0.013$), screwing ($p = 0.025$), splitting ($p < 0.001$), and training adequacy ($p < 0.001$). Rigid 4K (cwh) achieved the highest overall realism rating (4.3 ± 0.8) and unanimous suitability for surgical training (100%). It outperformed high-stiffness resins such as Rigid 10K ($p = 0.009$) and heat-cured Rigid 4K ($p < 0.001$), which tended to fracture abruptly and lacked realistic splintering. Tough 1500, Tough 2000, and Durable also demonstrated favorable handling and fracture characteristics, providing cost-effective alternatives for specific training tasks.

Conclusion

Among eight SLA resins tested, Rigid 4K (cure without heat) most closely replicated the tactile and mechanical properties of human bone. The combination of a rigid outer shell and polyurethane foam core provided lifelike feedback during drilling, sawing, and fixation, supporting its use in structured orthopaedic and trauma curricula. The findings establish empirical material benchmarks for developing standardized, reproducible 3D-printed training models in surgical education.

Introduction

High-quality surgical education remains a cornerstone of safe and effective patient care, especially in orthopaedic and trauma surgery. However, traditional training opportunities — such as cadaveric dissection or intraoperative learning — are increasingly constrained by ethical, logistical, and financial limitations [1,2]. These constraints disproportionately affect junior trainees who require repeated exposure and guided repetition to acquire technical proficiency [3–5].

Hands-on simulation training has emerged as a critical component of modern surgical education. Physical models allow learners to develop psychomotor skills, spatial understanding, and procedural confidence in a risk-free environment [1,5,6]. Commercially available anatomical models (e.g., Sawbones®) are widely used, but they often suffer from high costs, limited fracture realism, and fixed anatomical configurations that hinder scenario individualization [2,7,8].

Additive manufacturing, commonly referred to as 3D printing, offers a promising solution to these challenges. It enables the cost-effective production of anatomically accurate, customizable, and repeatable training models [5,7,9,10]. Moreover, 3D printing allows for the incorporation of patient-specific anatomy and fracture morphologies—features that are particularly relevant in trauma surgery [10–14]. In surgical education, 3D-printed models have been shown to improve procedural understanding, technical confidence, and overall learner satisfaction [1,6,15–17].

Among the various 3D printing technologies, fused deposition modeling (FDM) and stereolithography (SLA) are the most accessible and commonly used in clinical and educational settings [10,18]. FDM is widely available and inexpensive but tends to produce lower surface resolution and inferior detail fidelity. SLA, on the other hand, enables higher resolution, smoother surfaces, and more complex internal geometries—qualities that may better replicate the tactile and visual properties of human bone [10,19–21].

Recent comparative studies suggest that SLA-printed models outperform FDM-based models in terms of anatomical realism, surface resolution, and material homogeneity, especially for tasks involving fine motor skills like drilling or sawing [21,22]. However, SLA printers are more costly and require stricter post-processing, although ongoing advances in affordability and usability have increased their integration into orthopaedic education [10,21–23].

Despite the growing interest in 3D printing for surgical education, there is a lack of systematic evaluations comparing different SLA materials regarding their suitability for simulating osteotomy and osteosynthesis procedures. Many studies focus on visual appearance or qualitative feedback, while few offer structured, comparative evaluations of different materials under realistic surgical conditions [22–24].

The primary aim of this study was to systematically evaluate the educational and mechanical fidelity of eight different SLA-compatible resins when used to produce 3D-printed distal fibula fracture models for surgical training. Specifically, we investigated whether material-specific differences influence the subjective perception of realism during simulated osteotomy and osteosynthesis procedures. Therefore, the research question was: Which of the tested SLA resins provides the highest tactile and functional

similarity to human bone in the context of orthopaedic trauma education? We hypothesized that at least one of the tested SLA materials would offer sufficient haptic fidelity and procedural stability to serve as a realistic and reproducible alternative to commercially available training models.

Methods

Model generation and design

A high-resolution CT scan of the distal fibula of a healthy adult female was retrieved from the institutional PACS system, anonymized, and exported in DICOM format. Segmentation was performed using Mimics Medical v24 (Materialise, Leuven, Belgium), and the mesh was further refined in Meshmixer (Autodesk, San Rafael, USA) (Fig. 1). To facilitate internal foam filling and achieve standardized mechanical properties, the model was digitally hollowed to a uniform wall thickness of 2 mm. An apical vent hole was added at the distal tip to allow air displacement during polyurethane injection.

3D printing and materials

Eight different versions of the fractured fibula model were fabricated using stereolithography (SLA) on a Formlabs Form 3B printer (Fig. 1). Each material was selected to represent a distinct range of mechanical and haptic behaviors (Table 1). Prints were generated using a 0.1 mm layer height with material-specific PreForm (Formlabs) profiles. All models were post-processed according to the manufacturer's recommendations. One material, Rigid 4K, was tested in two curing protocols: standard UV post-curing with heat, and light-only post-curing (cure without heat) to investigate differences in ductility and fracture behavior.

Table 1
Mechanical and thermal properties of the eight SLA resins used for fibula model fabrication (nc: normal curing, cwh: cure without heat).

Material	Tensile Modulus (GPa)	Elongation at Break (%)	Flexural Modulus (GPa)	HDT @ 0.45 MPa (°C)	Notable Characteristics
Grey Pro	2.6	13	2.2	78	Balanced stiffness and moderate flexibility
High Temp	2.9	2.4	2.6	238	Exceptional heat resistance, low ductility
Tough 1500	1.5	51	1.4	66	Spring-back behavior, PP-like mechanical profile
Tough 2000	2.2	48	1.9	63	High strength, ABS-like behavior
Rigid 4K (nc)	4.1	5.3	3.4	77	Glass-filled, high stiffness, post-cured with heat
Rigid 4K (cwh)†	~ 3.5	~ 6.0	~ 3.0	~ 60	Same resin, light-only curing (lower stiffness)
Rigid 10K	11.0	1.7	9.9	238	Ultra-rigid, highly glass-filled composite
Durable	1.0	55	0.66	< 41	High impact strength, PE-like ductility

Data derived from Formlabs Technical Data Sheets (accessed October 2025)

† Rigid 4K (CWH) represents the same resin as Rigid 4K, but cured without thermal post-curing (light-only curing). This modification reduces crosslinking density and yields slightly lower stiffness (~ 3 GPa vs. 4 GPa) and higher elongation (~ 6–7%), resulting in a more bone-like tactile behavior compared with the fully cured state.

Following printing, all models were internally filled with rigid polyurethane foam (density: 150 g/cm³; BEIL Kunststoffprodukte GmbH, Peine, Germany), simulating trabecular bone structure (Fig. 1). This density aligns with values reported for the distal fibula based on high-resolution peripheral quantitative CT (HR-pQCT) analysis by Schlickewei et al. (2021), ensuring anatomical and mechanical relevance for simulation [25].

Evaluation protocol and questionnaire

Model evaluation was performed under standardized conditions by eight board-certified trauma surgeons, each with at least three years of operative experience in fracture fixation (Fig. 2). Each rater

assessed all models in randomized order and was blinded to the material identity. None of the participants were involved in the development or printing of the models.

A structured evaluation instrument was adapted from McMillan et al. (2020)[19], consisting of a six-point Likert scale grouped into five domains reflecting critical surgical handling parameters (Table 2):

Table 2

Structured evaluation framework adapted from McMillan et al. (2020)[19], showing all domains and items used for subjective material assessment on 6-point Likert scales or binary response formats

Domain	Item	Scale
Appearance	- Visual similarity to real bone	Likert (1–6)
Drilling	- Resistance during drilling - Debris (powder) formation - Change in resistance over time	Likert (1–6) each
Sawing	- Resistance during sawing - Debris formation - Change in saw speed over time	Likert (1–6) each
Screwing	- Screw resistance during insertion - Endpoint behavior ("screw stop")	Likert (1–6) each
Splitting	- Splinter behavior under overload	Likert (1–6)
Total	- Global subjective realism score (overall impression of material)	Likert (1–6)
Alternative	- Is this material a viable alternative for surgical training?	Dichotomous (1 = Yes, 2 = No)
Training adequacy	- Is this material an adequate substitute for bone in surgical training?	Likert (1–6)

- Appearance – resemblance of surface and color to cortical bone
- Drilling – resistance and chip behavior during drilling
- Sawing – resistance and particle dispersion during oscillating saw use
- Screwing – tactile feedback during screw insertion and terminal torque
- Splitting – fracture and fragmentation response to mechanical overload (simulated using blunt probe pressure)

Each category was scored from 1 (very dissimilar to bone) to 6 (highly similar to bone). Additional parameters included:

- A global realism score (“Total”)
- A binary suitability rating (1 = suitable for simulation, 2 = not suitable)
- A training adequacy rating (1 = not suitable at all, 6 = fully suitable replacement)

This structure allowed quantitative assessment of both individual material properties and their educational utility for orthopaedic simulation. Similar category-based frameworks for material realism have been used in recent validation studies of 3D-printed training models in orthopaedic and cranio-maxillofacial surgery [11,22,26,27].

Reporting follows key elements of the SQUIRE 2.0 framework for quality improvement studies in medical 3D printing.

Ethics

This study was reviewed by the local institutional ethics board, which confirmed that it does not fall under the jurisdiction of the ethics committee, as it does not involve human subjects or patient data (Reference: 2024-300559-WF).

Statistical analysis

All Likert scores were aggregated by material and rater. Descriptive statistics (mean ± standard deviation) were calculated for each of the five core evaluation categories and global ratings. Differences across materials were assessed using a one-way analysis of variance (ANOVA). When the ANOVA indicated significant differences, post hoc pairwise comparisons were performed using Tukey's post-hoc test. Statistical significance was defined as $p < 0.05$. Analyses were conducted using IBM SPSS Statistics (Version 29, IBM Corp.).

Results

Descriptive ratings and comparative analysis

Mean Likert ratings for all domains are summarized in Table 3 and shown in Fig. 3. Across materials, Rigid 4K (cure without heat), Tough 2000, Tough 1500, and Durable consistently achieved the highest scores for overall realism, while High Temp and Rigid 10K received the lowest ratings across multiple domains.

Table 3
Descriptive ratings (mean ± SD) and one-way ANOVA results for eight SLA 3D-printed materials (NC: cormal curing; CWH: cure without heat); bold print indicates significant values

Category	Grey Pro	High Temp	Tough 1500	Tough 2000	Rigid 4K (nc)	Rigid 4K (cwh)	Rigid 10K	Durable	*p*-value
Appearance	3.7 ± 1.1	4.0 ± 1.0	3.7 ± 0.7	3.2 ± 0.7	4.4 ± 1.1	4.8 ± 1.3	4.7 ± 1.0	3.8 ± 1.6	**0.013**
Drilling	3.4 ± 0.9	3.7 ± 1.0	3.4 ± 0.7	3.6 ± 1.1	3.6 ± 1.4	4.2 ± 0.7	4.3 ± 1.4	3.5 ± 0.5	0.702
Sawing	3.5 ± 0.9	3.2 ± 1.7	3.4 ± 0.9	3.8 ± 0.7	3.7 ± 0.7	4.3 ± 0.6	3.9 ± 1.2	3.5 ± 1.4	0.837
Screwing	2.8 ± 0.8	1.7 ± 0.6	4.2 ± 1.1	3.3 ± 0.7	3.3 ± 1.2	3.8 ± 1.6	2.6 ± 0.7	3.3 ± 1.5	**0.025**
Splitting	3.0 ± 1.0	1.5 ± 0.5	4.8 ± 1.2	3.0 ± 1.2	3.6 ± 1.1	4.3 ± 1.4	2.0 ± 0.6	5.2 ± 0.8	**< 0.001**
Total	3.6 ± 0.6	3.2 ± 0.7	4.0 ± 0.7	3.5 ± 0.5	4.0 ± 1.0	4.3 ± 0.8	3.9 ± 0.8	4.1 ± 1.2	0.520
Training adequacy	3.2 ± 0.8	1.7 ± 0.5	3.3 ± 1.4	4.0 ± 1.1	3.3 ± 0.9	4.5 ± 0.5	3.4 ± 0.7	3.7 ± 1.0	**< 0.001**

One-way ANOVA demonstrated significant between-material differences for appearance ($p = 0.013$), screwing behavior ($p = 0.025$), splitting behavior ($p < 0.001$), and training adequacy ($p < 0.001$). No significant differences were observed for drilling ($p = 0.702$), sawing ($p = 0.837$), or total realism ($p = 0.520$).

Post-hoc analysis

Tukey's post-hoc testing further differentiated material performance across the evaluated domains (Table 3). For appearance, no pairwise comparison reached statistical significance, although trends were observed between Tough 1500 and Rigid 4K (cure without heat) ($p = 0.058$) as well as between Tough 2000 and Rigid 10K ($p = 0.095$). Regarding screwing behavior, Tough 1500 was rated significantly superior to High Temp ($p = 0.020$), while non-significant tendencies favored both Tough 2000 ($p = 0.067$) and Rigid 4K (cure without heat) ($p = 0.088$) over High Temp.

In terms of training adequacy, High Temp consistently ranked lowest, performing significantly worse than Tough 2000 ($p = 0.003$), Rigid 4K (cure without heat) ($p < 0.001$), and Durable ($p = 0.021$). Moreover, Rigid 4K (cure without heat) outperformed Rigid 10K ($p = 0.009$).

The most pronounced differences emerged for splitting behavior. Tough 1500 achieved significantly higher ratings than High Temp ($p < 0.001$), Rigid 4K (normal cure) ($p = 0.049$), and Rigid 10K ($p = 0.001$).

Similarly, Tough 2000 outperformed High Temp ($p = 0.001$) and Rigid 10K ($p = 0.012$). Rigid 4K (cure without heat) was also rated superior to High Temp ($p = 0.001$). Finally, Durable demonstrated the broadest advantage, receiving significantly higher scores than Grey Pro ($p = 0.025$), High Temp ($p < 0.001$), Rigid 4K (normal cure) ($p = 0.012$), and Rigid 10K ($p < 0.001$).

Binary suitability ratings are presented in Table 4 and Fig. 4. Rigid 4K (cure without heat) achieved unanimous approval, with all raters (100%) considering it suitable for surgical training. High suitability was also reported for Tough 2000 (83.3%), Tough 1500 (66.7%), and Durable (66.7%). In contrast, High Temp and Rigid 10K were judged suitable by only 16.7% of raters, and Rigid 4K (normal cure) by 33.3%. A chi-square test confirmed significant differences across materials (χ^2, $p = 0.027$).

Table 4
Percentage of raters judging each SLA material as suitable for surgical training (χ^2 test, $p = 0.027$)

Material	Suitable (%)
Rigid 4K (cure w/o heat)	100.0%
Tough 2000	83.3%
Tough 1500	66.7%
Durable	66.7%
Grey Pro	50.0%
Rigid 4K (normal cure)	33.3%
High Temp	16.7%
Rigid 10K	16.7%
Chi² test (overall)	p = 0.027

Discussion

This study systematically evaluated eight stereolithography (SLA) resins to identify materials that most accurately reproduce the tactile and mechanical properties of human bone for orthopaedic and trauma surgery training. Among all tested materials, Formlabs Rigid 4K (cure without heat) achieved the highest overall realism ratings across all evaluated domains. The resin was consistently perceived as the most bone-like material by participating surgeons, particularly for drilling resistance, sawing feedback, and screw purchase. Materials such as Tough 1500, Tough 2000, and Durable also demonstrated favorable characteristics and comparably high mean Likert scores, suggesting that their haptic behavior and tool response were still judged to be clinically acceptable. This implies that, while Rigid 4K (cwh) represents the preferred standard for bone realism, the other three resins offer viable, cost-effective alternatives for training models depending on the desired balance between stiffness and ductility.

From a biomechanical perspective, the superior performance of Rigid 4K (cwh) can be attributed to its balance of stiffness and controlled brittleness, which produced realistic fracture propagation and tactile resistance during osteosynthesis simulation. While its tensile and flexural moduli (approximately 3–4 GPa) are below the values reported for cortical bone (typically 7–20 GPa), this modest compliance may actually enhance perceived realism by allowing micro-yielding and splintering rather than abrupt brittle failure. In contrast, the heat-cured variant of Rigid 4K exhibited noticeably higher ductility, which reduced tactile similarity to bone — an observation aligning with manufacturer data showing that additional thermal curing increases elongation and decreases brittleness. When compared to the even stiffer Rigid 10K resin (flexural modulus ≈ 11 GPa), the difference in tactile realism becomes more apparent: although Rigid 10K generated excellent drilling resistance, it tended to fracture abruptly and lacked the nuanced splintering behavior that surgeons associated with real bone. This finding reinforces that absolute stiffness alone does not ensure biomechanical authenticity; rather, a material must replicate the controlled yielding and progressive crack propagation characteristic of human cortical bone[28]. These results are consistent with prior experimental work on human cortical bone, including fibular specimens, showing that real bone exhibits high but finite stiffness and gradual microfracture propagation under load before failure, with stiffness and toughness varying with age and tissue maturity [29–31]. Dissanayaka et al. likewise emphasized that deviations in material behavior — whether excessive brittleness, melting, or continuous shavings — diminish the realism of drilling and fragmentation patterns [22]. Similar trade-offs between stiffness and realism have been observed in comparative studies of 3D-printed skull and vertebral models, where a moderate modulus and layered architecture provided the most authentic tactile feedback [32–34].

Beyond orthopaedics, convergent findings from neurosurgery, cranio-maxillofacial (CMF), and spinal training further demonstrate that realism arises from balancing stiffness and toughness and, critically, on reproducing bone's layered architecture. In neurosurgical simulation, burr-hole and craniotomy models consistently show that single-material prints at either extreme — overly stiff and brittle or too soft and thermally unstable — undermine drilling realism and debris formation, while intermediate-stiffness polymers that differentiate the outer table, diploë, and inner table yield more authentic cutting resistance and bone-dust-like particulate behavior [22,32]. Comparable results have been reported in CMF applications, where hybrid skull or mandibular models combining rigid outer shells with porous or foam-filled cores improved drill and saw feedback and reduced both glassy fracture and "gummy" shavings [23,27].

Spine studies reinforce this trade-off. Dual-material or lattice-core vertebral models that mimic cortical and cancellous bone achieve superior tactile feedback during pedicle probing and screw placement compared with homogeneous blocks, while excessively stiff constructs tend to fail abruptly under load [33,34]. This mirrors the impressions of our raters: Rigid 4K (cwh) produced crisp cutting and realistic chip formation yet allowed controlled fracture propagation, whereas the higher-modulus Rigid 10K felt overly brittle and less physiologic. The strong secondary performance of Tough 1500/2000 and Durable further supports that materials with modest ductility can still deliver credible splintering and screw-purchase

behavior. Collectively, these cross-disciplinary insights and our present findings confirm that a moderate elastic modulus and layered structure—not maximum stiffness—are key to achieving mechanical and haptic authenticity in 3D-printed bone models.

Beyond biomechanical authenticity, these findings carry significant implications for surgical education. High-fidelity haptic feedback has been repeatedly shown to enhance psychomotor skill acquisition, spatial understanding, and procedural confidence among medical students and junior trainees [5,15]. Traditional synthetic bone models, such as commercial polyurethane “Sawbones”, offer standardized geometry and uniform stiffness but fail to reproduce the variability, anisotropy, and fracture propagation behavior of real bone [2,35,36]. In contrast, 3D printing enables generation of anatomically accurate, patient-specific structures with digitally defined fracture lines and internal textures, allowing reproducible yet realistic simulations of osteosynthesis — as implemented in the present study.

Such task-specific models provide immediate visual and tactile feedback, aligning with constructivist principles of experiential learning and the “Peyton’s four-step approach” widely adopted in procedural training [37]. Their integration into structured curricula could facilitate progressive skills development—from basic drilling and screw placement to complex osteotomy planning—without reliance on cadaveric tissue [38]. Moreover, the low cost and scalability of stereolithographic printing make these models feasible for large-scale undergraduate and postgraduate training programs, particularly in trauma and orthopaedic education. Comparable initiatives in neurosurgical and maxillofacial training have already demonstrated that haptically realistic 3D-printed simulators improve performance metrics, shorten learning curves, and increase user satisfaction relative to conventional teaching tools [23,39].

From a broader perspective, this study underscores the expanding role of additive manufacturing as a translational interface between digital surgical planning and physical simulation. Recent developments in spine, cranial, and maxillofacial surgery illustrate how 3D-printed bone models have evolved from visual aids to fully functional training platforms that allow residents to rehearse screw trajectories, craniotomies, osteotomies, and plate contouring on anatomically faithful and mechanically representative structures [22,23,34,38,39]. Similar progress is evident in orthopaedic traumatology, where patient-specific fracture models are increasingly used to teach reduction maneuvers, implant positioning, and fixation strategies with reproducible, CT-derived accuracy [14,35,40,41].

By systematically identifying which commercially available resins most effectively balance stiffness, brittleness, and tactile realism, the present work helps define a material basis for standardized, reproducible educational models across institutions. Such benchmarks are essential to harmonize training quality and to facilitate integration of 3D-printed simulation tools into curricula for trauma and orthopaedic education. Looking ahead, combining validated resins such as Rigid 4K with digital fracture modeling and multimaterial printing may further close the gap between simulated and operative bone handling, ultimately linking preoperative planning, intraoperative rehearsal, and skills assessment within a unified additive-manufacturing framework.

Some limitations should be acknowledged. The assessment relied on subjective expert ratings rather than quantitative mechanical measurements. Although surgeon perception is ultimately decisive for educational realism, future studies should complement subjective scores with force and torque measurements during drilling or sawing to provide objective validation. In addition, only six trauma surgeons participated in the evaluation, limiting statistical power and generalizability. Expanding future trials to include residents and medical students would provide valuable insights into the models' didactic effectiveness. Moreover, all prints were single-material constructs; real bone's hierarchical architecture — with dense cortical layers surrounding trabecular cores — could be more accurately represented by multi-material or gradient-print approaches. Finally, temperature effects, tool wear, and long-term durability were not assessed, though these may influence the sustainability of printed simulators for repeated training.

Conclusion

This study identifies Formlabs Rigid 4K (cure without heat) as the most realistic stereolithographic resin for simulating bone behavior in surgical education, with Tough 1500, Tough 2000, and Durable also providing credible tactile performance for selected applications. The combination of a rigid outer shell and polyurethane foam core reproduced the visual appearance and haptic response of human bone with high fidelity, supporting its use as a reproducible and cost-effective tool in undergraduate and postgraduate orthopaedic training.

By offering empirically derived material guidance, this work contributes to the standardization of 3D-printed training simulators in medical education. Future research should focus on integrating validated bone analogues into structured curricula and quantitatively assessing their impact on learning outcomes, skill retention, and procedural proficiency. With ongoing advances in multi-material printing, bio-composite resins, and curriculum-based simulation design, high-fidelity, patient-specific bone replicas are likely to become an essential component of surgical training and preoperative rehearsal across multiple disciplines.

Abbreviations

3D
Three-dimensional
3DP
Three-dimensional printing
SLA
Stereolithography
CWH
Cure without heat
NP
Normal post-curing

PU
Polyurethane
CT
Computed tomography
CAD
Computer-aided design
CMF
Cranio-maxillofacial
ANOVA
Analysis of variance
SD
Standard deviation
χ^2
Chi-square test
GPa
Gigapascal
HV
Vickers hardness
MPa
Megapascal.

Declarations

Ethical approval

The local ethics committee confirmed that this project does not constitute human subjects research (Ref. 2024-300559-WF)

Competing interests

The authors declare that they have no conflict of interest.

Consent for publication

Not applicable

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Author Contribution

TD, JEH, CC, JK, and KHF contributed to the conception and design of the study. TD, JEH, and JK were responsible for model fabrication, data acquisition, and experimental testing. TMB, AS, and DD performed the statistical analysis and data interpretation. TD and CC drafted the manuscript. JK and KHF provided critical revision and supervision of the final version. All authors read and approved the final manuscript.

Data Availability

All data generated or analyzed during this study are available from the corresponding author on reasonable request.

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Figures

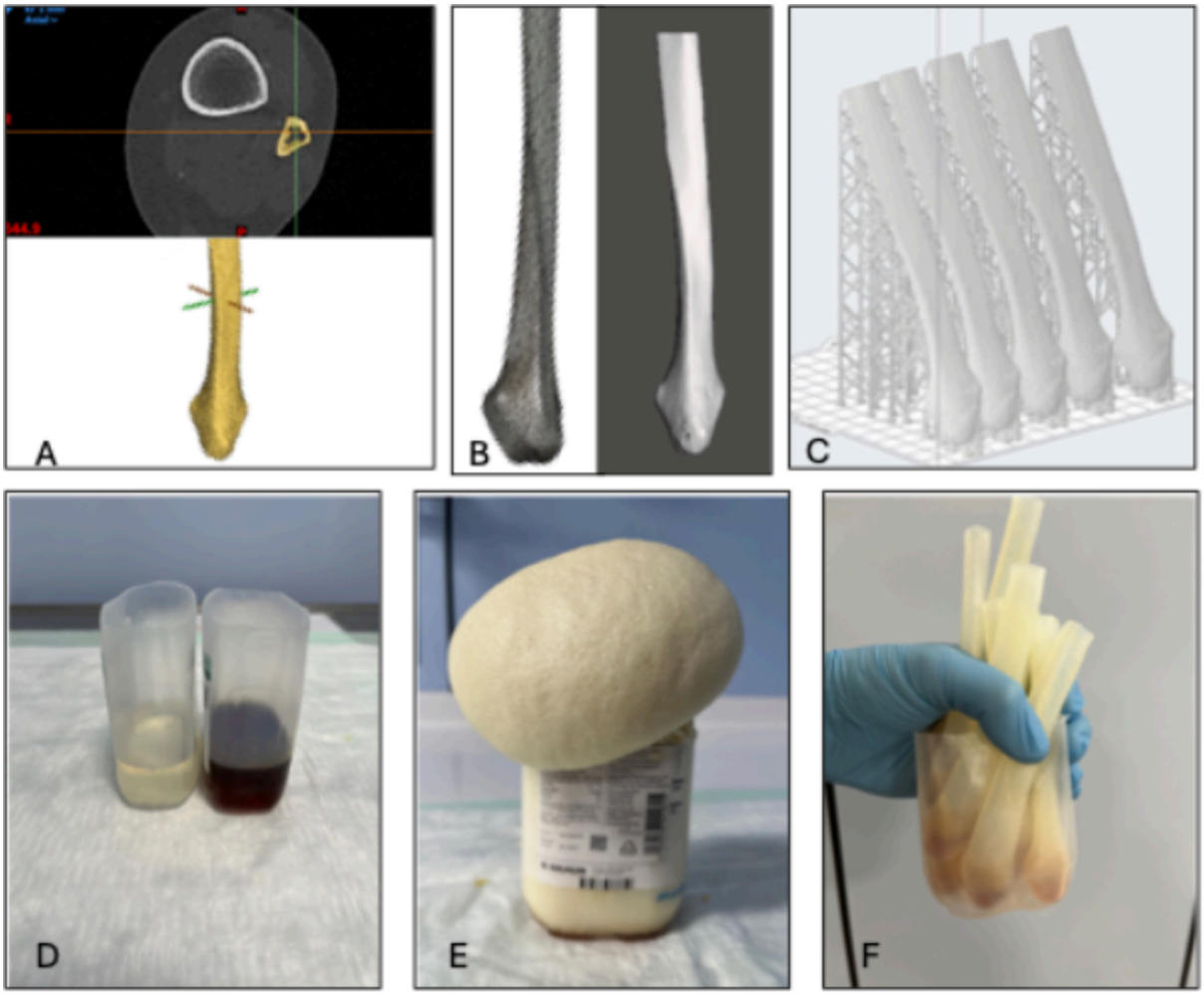


Figure 1

Workflow from CT segmentation to polyurethane-filled 3D-printed fibula models

(A) Segmentation of the distal fibula in Mimics v24 (Materialise, Leuven, Belgium) based on CT data (upper panel) and corresponding 3D preview (lower panel), (B) Digital model refinement and preparation in Fusion 360 (Autodesk Inc., San Rafael, CA, USA; left) and Meshmixer (Autodesk Inc., San Rafael, CA, USA; right), (C) Printing setup in PreForm software (Formlabs Inc., Somerville, MA, USA) for a Form 3B stereolithography printer, (D) Two-component polyurethane foam system (Beil GmbH, Peine, Germany), consisting of a hardener and rigid foam, mixed in a 1:1 ratio from two base foams (100 g/cm³ and 200 g/cm³) to achieve a target density of 150 g/cm³, (E) Demonstration of foam expansion in a plastic cup: the mixture expands beyond the indicated blue fill line, illustrating volumetric expansion and expansion force, (F) Fibula models immediately after filling with liquid polyurethane prior to expansion.

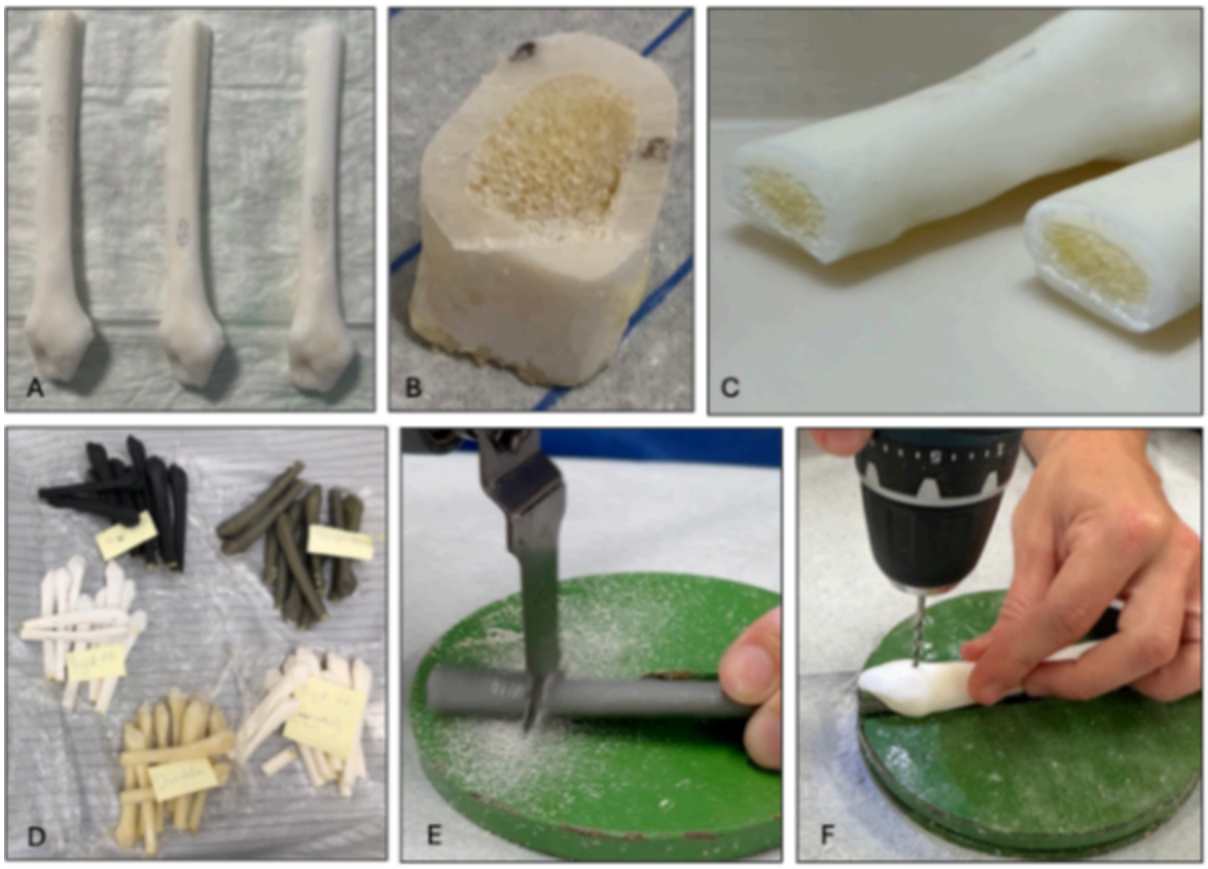


Figure 2

Final polyurethane-filled fibula models and experimental testing workflow

(A) Three completed 3D-printed fibula models filled with polyurethane foam (150 g/cm³) to simulate trabecular bone. (B) Cross-section of a fibular shaft demonstrating the internal polyurethane foam core. (C) Two osteotomized fibula models showing the spongiosa-like polyurethane foam structure at the osteotomy site. (D) Overview of multiple printed fibulae made from different SLA materials prepared for evaluation. (E) Osteotomy of a fibula model using an oscillating saw, illustrating cutting resistance and chip formation. (F) Drilling procedure performed on a 3D-printed fibula model during material testing.

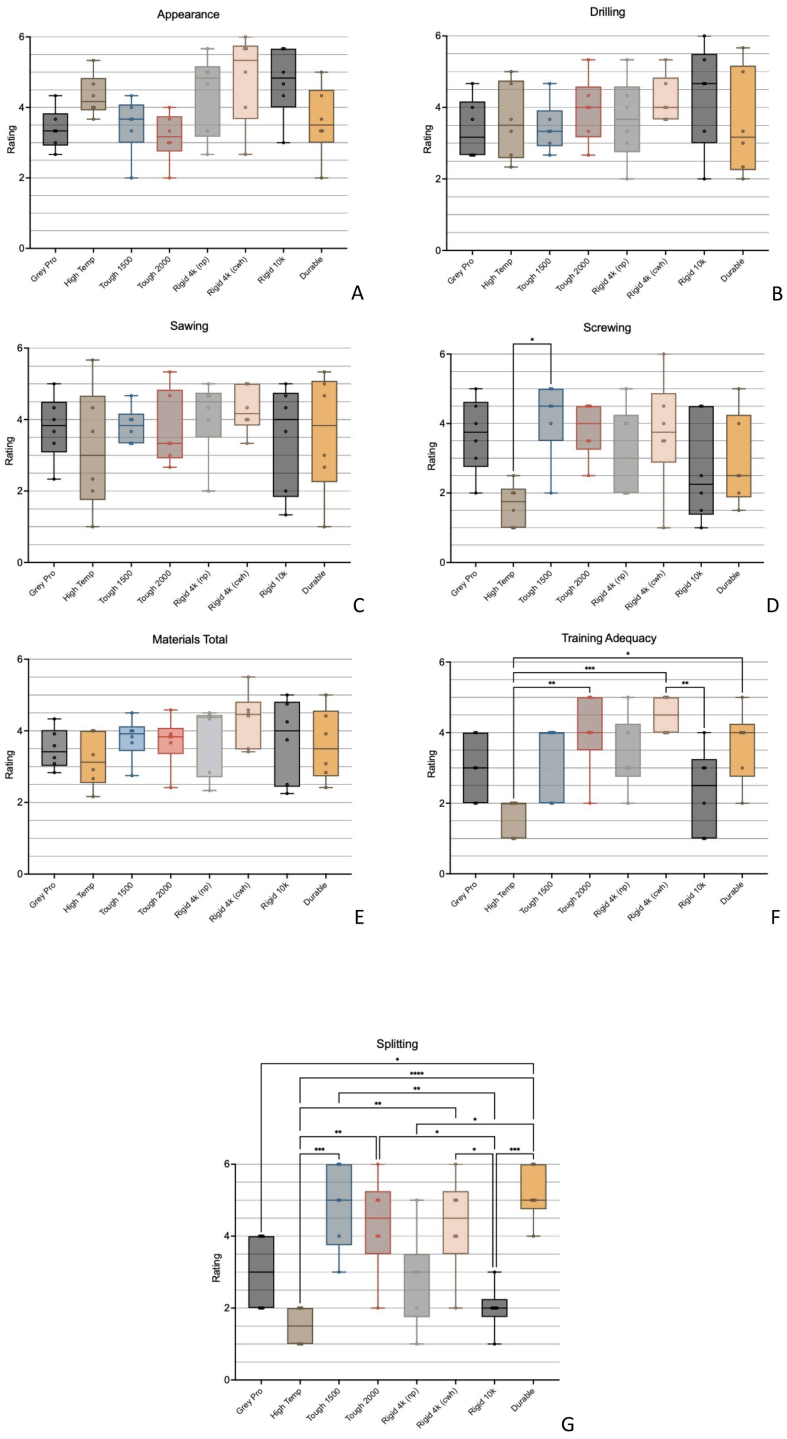


Figure 3

Box-and-whisker plots showing surgeon ratings across all evaluation domains for the tested SLA materials.

(A) Appearance, (B) Drilling, (C) Sawing, (D) Screwing, (E) Material Total, (F) Training Adequacy, and (G) Splitting; Rigid 4K (np) = Rigid 4K normal post-curing and Rigid 4K (cwh) = Rigid 4K cured without heat

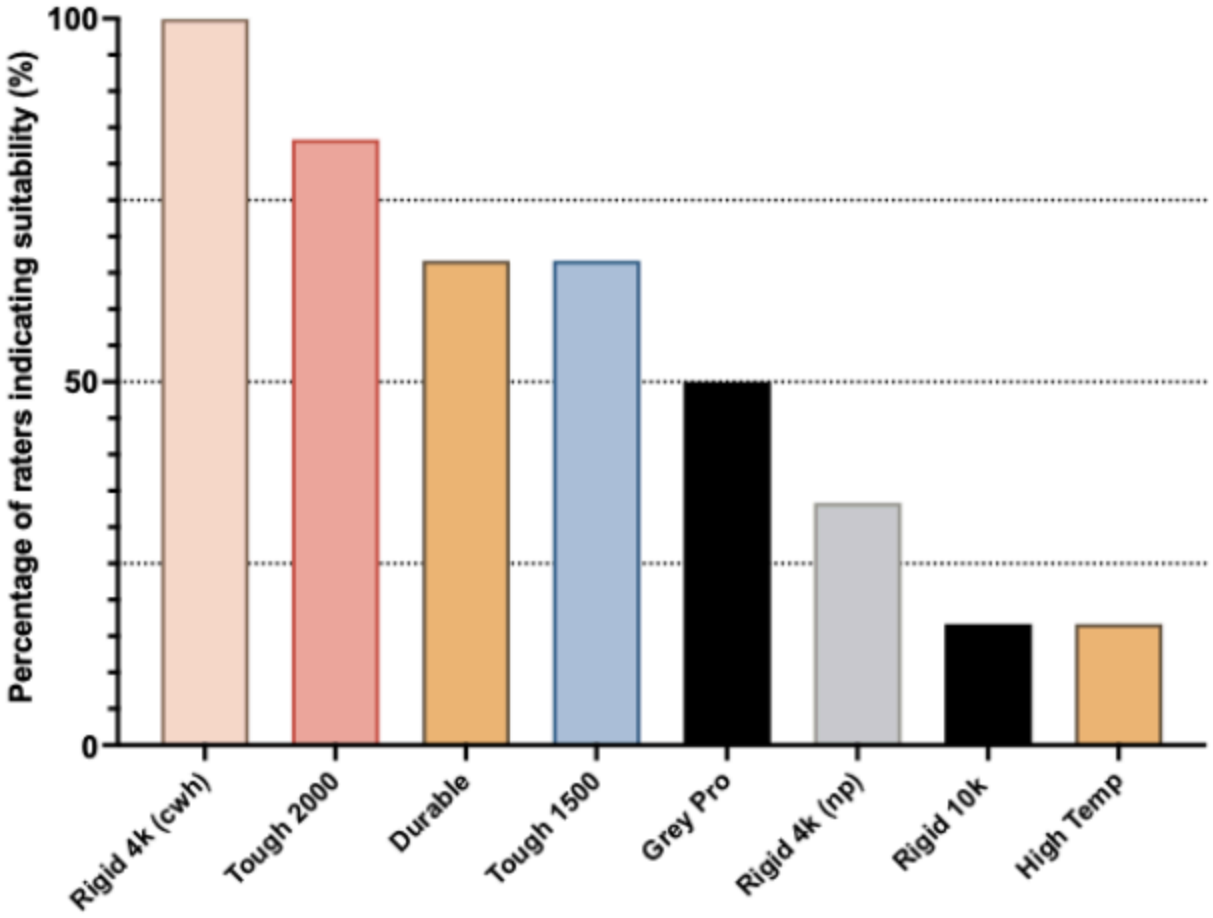


Figure 4

Surgeon-rated suitability of SLA resins for surgical training. Bars show the percentage of raters indicating suitability (%). χ^2 test across materials: $p = 0.027$. *Rigid 4K (np) = Rigid 4K normal post-curing; Rigid 4K (cwh) = Rigid 4K cured without heat.*