Mechanical Properties of 3D Printed Clavicles are Closer to Cadaveric Bones than 4th Generation Sawbones

Kathryn S. Strand, BS
Elizabeth Silvestro, MS
Iman Naqvi
Michael W. Hast, PhD

McKay Orthopaedic Research Lab,
Department of Orthopaedic Surgery,
University of Pennsylvania,
Philadelphia, PA

Introduction

Synthetic bone models have increasing utility in experimental research and education.[1] Their benefits include lower costs, less variability than cadaveric bone, no institutional oversight, and no ethical considerations. Commercially available synthetic bones (4th Generation Sawbones) are created with injection molding techniques and have been validated to be equivalent to human bones in a variety of way.[2,3] The rise in additive manufacturing (AM) presents an opportunity for synthetic bone models to be custom-made for mechanical testing purposes. Little is known about the efficacy of these custom 3D printed models. Prior studies have examined the mechanical properties of AM bones, but they only tested small segments of bone and did not evaluate 3D prints under varied loading conditions.[4,5] The clavicle is an attractive testbed for such testing for several reasons. First, clavicular fractures are difficult to repair surgically, and implant design testing could benefit from an improved model. Second, the clavicle is the only horizontal long bone and undergoes a wide variety of loading paradigms during activities of daily living.[6] Applying different and physiologically relevant loading paradigms allows for a thorough analysis. Thus, the purpose of this study was to directly compare the mechanical properties of 3D printed, commercially available, and human cadaveric clavicles under variable loading scenarios. We hypothesized that 3D printed clavicles would better mimic the human condition in axial compression and bending, but not in torsion due to the layered structure of the AM specimens.

Methods

Four different experimental groups ($n = 6$) were analyzed for this study; fresh-frozen human cadaveric clavicles (3 left, 3 right, from 3 donors, 2 M, 1F, aged between 65-68 years), two groups of 3D printed clavicles printed in Verowhite (VW) and a composite of TissueMatrix and BoneMatrix (TB), and commercially available 4th generation Sawbones (SB) composite clavicles (Model 3408-1; Pacific Research Laboratories, Vashon, WA). Custom models were fabricated with a Stratasys (Eden Prairie, MN) J850 Digital Anatomy Printer. All samples were oriented to print layers along the long axis of the bone. Mechanical tests included nondestructive 4-point bending, torsion, and axial compression in a randomized order, followed by a final compressive test to failure. Testing protocols were based on previous studies and utilized triangular waveforms.[7] All specimens were potted in poly(methyl methacrylate) (PMMA) and loaded on a universal test frame (Electroforce 3550, TA Instruments, Eden Prairie, MN) with a 15 kN load cell. For 4-point bending, the upper anvils were displaced a total of 1 mm at 0.25 Hz for 10 cycles [7]. Bending was applied in both the anterior-posterior (AP) and superior-inferior (SI) directions and bending rigidity was calculated. For compressive and torsional testing, specimens were oriented vertically with the lateral end positioned upwards. Compressive testing loaded specimens between 10 and 315 N for 10 cycles 8. Torsional testing rotated specimens to ±3° at 0.25 Hz for 500 cycles, and torsional rigidity was averaged across cycles 10, 100, 200, 300, 400, and 500 for anterior and posterior rotation of the sternal end [8]. For compressive testing to failure, specimens were compressed at a rate of 0.63 mm/sec.[9] Significant differences between groups were tested with a one-way ANOVA with Holm-Sidak post-hoc tests ($p < 0.05$). When tests for normality and equal variances failed ($p < 0.05$), Kruskal-Wallis tests with a Dunn's post-hoc was used.

Results

Results from torsional testing indicated that the SB group was significantly stiffer than Cadaveric and TB groups, respectively (Figure 1). Bending tests also showed that the SB group had higher bending rigidity than all groups in the SI direction (Figure 2A), but these findings were not as clear in AP bending. Notably, cadaveric samples had higher bending rigidity than the TB group during both bend tests, and higher bending rigidity

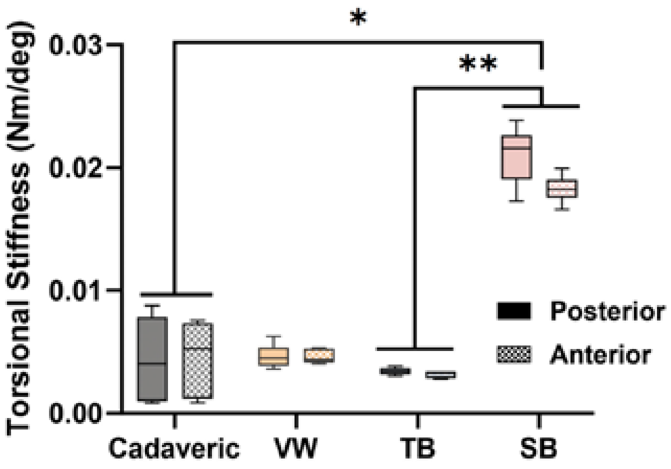

Figure 1. Average torsional stiffness **p<0.01.

than the VW group in the SI bend tests (Figure 2A&B). The axial stiffness of the SB group was significantly higher than the Cadaveric, VW, and TB groups, but there were no differences between the cadaveric specimens and either 3D printed group (Figure 3A). The compressive failure loads for Cadaveric, SB, VW, and TB groups were 3350 ± 1999 N, 4670 ± 969 N, 2611 ± 321 N, and 1883 ± 282 N, respectively, with significant differences between SB and TB groups (Figure 3B).

Discussion

We observed no differences between the Cadaveric and VW groups in any testing condition except for SI 4-point bending. Additionally, the SB group was significantly different from the cadaveric specimens in every outcome measure except for AP 4-point bending. These results demonstrate that commercially available synthetic models may be too rigid to accurately emulate the mechanical behavior of cadaveric clavicles. These findings partially disprove our original hypothesis that the layered materials in AM specimens would fail easily in torsional testing. As expected, the cadaveric group had the most variability across all outcome measures. However, the variances within the 3D oriented groups (TB and VW) were much lower, demonstrating consistency within this printing method which may lead to less noisy mechanical testing outcomes. Taken together, these results demonstrate that AM bone models can effectively mimic the mechanical behavior of human bones under a variety of physiological conditions. In particular, our findings suggest that the VW materials and printing protocol may be an attractive option for 3D printed complete synthetic bone models in both torsion and axial/transverse loading conditions.

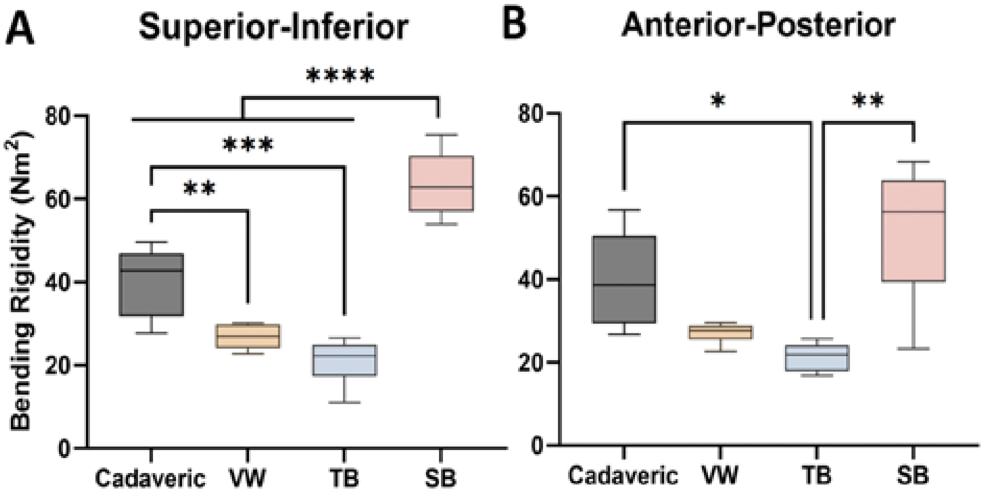

Figure 2. Average bending rigidity across 10 cycles in the **(A)** SI and **(B)** AP directions. *p<0.05, **p<0.01, ***p<0.001, ****p<0.0001.

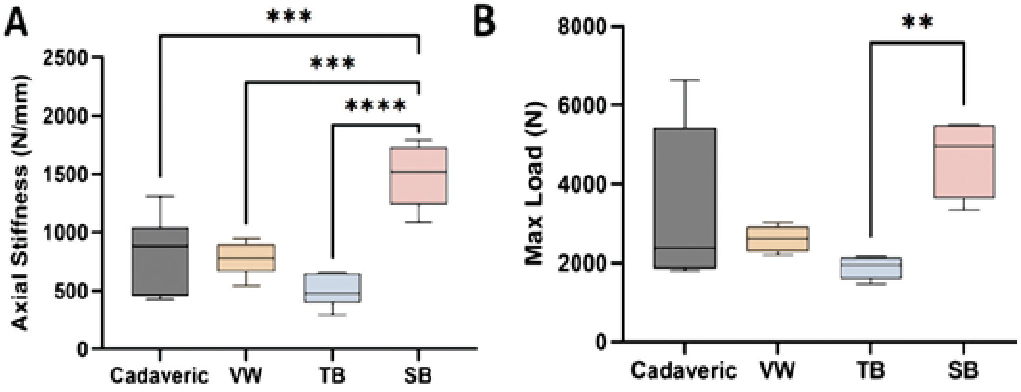

Figure 3. Axial compression testing results. **(A)** Average axial stiffness across 10 cycles; **(B)** Maximum loads during compressive failure tests. **p<0.01, ***p<0.001, ****p<0.0001.

Significance/Clinical Relevance

The results of this study suggest that AM specimens created with VW material are the most comparable to human cadaveric tissues under varied mechanical loading conditions. These findings present AM bone models as an accessible and physiologically relevant option, opening doors to utilize AM in developing patient-specific bone models for more wholistic and clinically relevant mechanical testing applications.

References

1. **Elfar J, Stanbury S, Menorca RMG, *et al.*** Composite Bone Models in Orthopaedic Surgery Research and Education. J Am Acad Orthop Surg. 2014;22(2):111-120.
2. **Chong ACM, Miller F, Buxton M, *et al.*** Fracture Toughness and Fatigue Crack Propagation Rate of Short Fiber Reinforced Epoxy Composites for Analogue Cortical Bone. J Biomech Eng. 2007;129(4):487-493.
3. **Chong ACM, Friis EA, Ballard GP, *et al.*** Fatigue Performance of Composite Analogue Femur Constructs under High Activity Loading. Ann Biomed Eng. 2007;35(7):1196-1205.
4. **Husemoglu RB, Baysan G, Ertugruloglu P, *et al.*** The Mechanical Comparison of Artificial Bone and 3D Printed Bone Segments. J Med Innov Technol. 2020;2(2):127-130.
5. **Nägl K, Reisinger A, Pahr DH.** The biomechanical behavior of 3D printed human femoral bones based on generic and patient-specific geometries. 3D Print Med. 2022;8(1):35.
6. **Iannolo M, Werner FW, Sutton LG, *et al.*** Forces across the middle of the intact clavicle during shoulder motion. J Shoulder Elbow Surg. 2010;19(7):1013-1017.
7. **Schmidt EC, Dear KA, Hendow C, *et al.*** Examining the novel use of continuous compression implants in clavicle reconstruction: A biomechanical study. *Clin Biomech.* 2021;88:105437.
8. **Uzer G, Yildiz F, Batar S, *et al.*** Biomechanical comparison of three different plate configurations for comminuted clavicle midshaft fracture fixation. *J Shoulder Elbow Surg.* 2017;26(12):2200-2205.
9. **Sánchez-Molina D, García-Vilana S, Velázquez-Ameijide J, *et al.*** Probabilistic assessment for clavicle fracture under compression loading: rate-dependent behavior. *Biomed Eng Appl Basis Commun.* 2020;32(05):2050040.