Published in final edited form as:

J Hand Surg Am. 2013 March ; 38(3): 583–587. doi:10.1016/j.jhsa.2012.12.005.

The Emerging Utility of Composite Bone Models in Biomechanical Studies of the Hand and Upper Extremity

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HISTORICAL BACKGROUND

Composite bone models—synthetic renditions of human bones made from plastics and epoxies—have been manufactured by several companies over the last few decades, including Sawbones (Pacific Research Laboratories, Vashon, WA), Synbone (CH-7208, Malans, Switzerland), and Promedica (43–190, Mikołów ul. Brzozkwinowa 11, Poland). High-fidelity composite bone models are of particular interest to investigators studying the biomechanics and failure properties of fracture fixation constructs, a field that has traditionally relied on cadaver specimens for experimentation. Cadaver samples are suboptimal for a variety of reasons, including high cost, tenuous availability, handling and storage challenges, and a remarkable degree of inter-specimen variability that reportedly exceeds 100% of the mean in some metrics.¹

Sawbones and Synbone brand models have received the most consideration in the biomechanics and fracture fixation construct literature, although the Sawbones product is particularly well validated in comparisons with cadaver specimens and is considerably better represented in the hand and upper extremity biomechanics research.

CONSTRUCTION AND MECHANICAL PROPERTIES

Sawbones composite models, currently in their fourth generation of production, consist of an epoxy resin cortical component, which encircles a porous foam core designed to replicate cancellous bone. The earliest first-generation composites, introduced in the 1980s, consisted of a rigid polyurethane foam core with a rudimentary fiberglass overlay. Second-generation composite bone models, introduced in the early 1990s, were constructed from layers of woven fiberglass matting embedded in a pressure-injected epoxy resin, all around a polyurethane foam core.² These so-called fiberglass-fabric-reinforced epoxy resin models had no intramedullary canal and required manual craftsmanship to layer sheets of fiber-glass (A. Johnson, Pacific Research Laboratories, personal communication, March 29, 2012).³ This process was implemented with the goal of closely mirroring the diaphyseal flexural stiffness of organic human bone, and in this regard, second-generation composite models

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No benefits in any form have been received or will be received related directly or indirectly to the subject of this article.

excelled. Investigators found no statistical difference between second-generation Sawbones composites and their cadaver analogs in the domain of lateral bending stiffness, and further, they noted the composites to have a 15-fold reduced standard deviation in this parameter.¹

Although second-generation composites achieved physiologic lateral bending stiffness values, the 45° oblique orientation of the glass fibers in these models' fiberglass-fabric-reinforced matrix produced accentuated torsional stiffness—nearly double that established for cadaver bone.¹ Given the importance of stiffness in the rotational axis to the integrity of fixation constructs and stability of fracture geometries, this aberrancy represented a notable detraction from the generalizability of these models to the clinical setting.

By the late 1990s, short-glass-fiber-reinforced epoxy replaced the fiberglass-fabric-reinforced cortical material of the second-generation models.³ This third-generation material was conducive to injection molding around the polyurethane foam core, streamlining the manufacturing process and producing a more geometrically consistent result (A. Johnson, Pacific Research Laboratories, personal communication, March 29, 2012).^{3,4} Because injection molding of the epoxy resin aligns glass fibers parallel with the long axis of the bone in the diaphyseal region, but more randomly at the metaphysis, torsional stiffness values approached that of cadaver bone, and the already excellent lateral bending stiffness property was preserved (A. Johnson, Pacific Research Laboratories, personal communication, March 29, 2012).^{1,5}

The injection-molded short-glass-fiber-reinforced epoxy construction of third-generation composites also further improved the definition of cortical anatomic detail, as well as consistency of these topographical features between specimens. Heiner and Brown⁶ reported vastly improved consistency of fit in preformed axial and torsional testing molds of third-generation, compared to second-generation, composite tibiae and femurs, while also noting the more anatomically correct eccentric cross-sectional profile and inclusion of linea aspera in third-generation versus second-generation composite femurs. Finally, third-generation models were the first to include a hollow intramedullary canal at the center of the rigid polyurethane foam core (A. Johnson, Pacific Research Laboratories, personal communication, August 22, 2012).⁴

Fourth-generation Sawbones composite models, introduced most recently, are also constructed of short- glass-fiber-reinforced epoxy using the same injection molding process used to produce third-generation models. Accordingly, these modern versions retain the same level of cortical anatomic detail as the previous iteration, but benefit from optimized glass fiber and epoxy resin components (A. Johnson, Pacific Research Laboratories, personal communication, August 22, 2012). Fourth-generation composites further improve on replicating the flexural and torsional stiffness reported for cadaveric bone and also demonstrate 48% improved fracture toughness, nearly 300% improved fatigability, and better thermal stability when tested in a normal saline bath at 37°C.^{3,5,7,8} Finally, fourth-generation composites have demonstrated ultimate failure characteristics similar to those of human bone (Fig. 1).⁷ Currently, only fourth-generation Sawbones are available for purchase from Pacific Research Laboratories; however, less biomechanically correct polyurethane

foam models are available for use in surgical education (A. Johnson, Pacific Research Laboratories, personal communication, August 22, 2012).

Although rigorous biomechanical validation of composite lower extremity long bones has been accomplished in the literature, examples of similar comparisons in the upper extremity are less frequent. A notable exception is work from Dunlap and colleagues⁹ that compares third-generation and fourth-generation composite humeri, as well as cadaveric humeri, in the domains of flexural rigidity and torsional stiffness. Outcomes were similar to those for the lower extremity models, in that fourth-generation composite humeri are a superior approximation of cadaveric bone in all dimensions of strain compared to third-generation models.⁹ Similarly, interspecimen variability of the fourth-generation models was found⁹ to not exceed 10.0%.

FRACTURE FIXATION CONSTRUCTS IN THE UPPER EXTREMITY

Despite the observation that the majority of composite bone model validation studies have used femurs and tibiae, there exists a large and growing body of literature trialing third-generation and fourth-generation upper extremity Sawbones models. Investigators have used composite metacarpal, scaphoid, radius, ulna, and humerus models to study the fixation of common fracture patterns in the hand, wrist, and forearm.

Sohn and colleagues¹⁰ evaluated lateral bending stiffness and load to failure of multiple plating constructs in a transverse metacarpal fracture model using fourth-generation Sawbones composites, ultimately demonstrating the superior load to failure and stiffness characteristics of a shorter, 3-dimensional plate construct as opposed to more standard linear plates. Similarly, Gajendran and colleagues¹¹ tested a variety of screw and plate constructs in a comminuted metacarpal shaft fracture model using fourth-generation composite Sawbones (Fig. 2). The authors found that a 3-dimensional nonlocking plate construct offered superior load to failure in both cantilever dorsal apex bending stress and torsional stress when compared with a 3-dimensional locking plate and more standard linear plates.

Composites have also been innovatively adapted to replicate osteoporotic bone through engineered decreases in foam core density. Sokol and colleagues¹² trialed volar plating constructs in a comminuted distal radius fracture model by creating a dorsal wedge osteotomy in the distal metaphysis of fourth-generation Sawbones radii. The investigators applied either an all-locking screw volar plate construct or a hybrid configuration of locking and nonlocking screws to 3 different conditions of bone quality, including the normal-density composite model, a low-density osteoporotic model, and an over-drilled osteoporotic model simulating decreased screw purchase. Under these conditions, equivalency was demonstrated between the 2 volar plating constructs within a given bone quality group with regard to load at failure under axial compression (Fig. 3).¹²

Authors have developed creative ways to study fracture fixation in the small and peculiarly shaped bones of the wrist, as demonstrated by Gokce and colleagues' investigation¹³ of scaphoid waist fracture fixation using fourth-generation Sawbones models. Fourth-generation composite scaphoids were bedded into an epoxy resin for application of an axial

compressive force, then trialed with various geometries of 2-Kirschner wire fixation in 3 fracture patterns, including transverse, dorsal oblique, and volar oblique. The 20° crossed Kirschner wire fixation was most robust for transverse and volar oblique fractures, whereas a 25° oblique Kirschner wire orientation resisted axial compression best for dorsal oblique fractures.¹³

The most recent, fourth generation of composite bone models have come the furthest yet in terms of approximating the lateral bending, torsional, and axial compressive stiffness, as well as loads to failure, of cadaveric bone. Still, investigators need to be aware of the limitations of these composites.

First, although they have similar geometries as human bones and their structural properties are closer to cadaver samples than those from previous generations, no biomechanical studies have recorded average values that are identical to that of human specimens for even the fourth-generation composites in all pertinent metrics. The matter is complicated further by the ongoing debate regarding the significance of achieving those values in the first place, given the sometimes extreme interspecimen variability in cadaveric bones.

Second, most composite models offer a bone-only substrate for study, lacking the periosteum, ligaments, and other soft tissues found *in situ* that may help stabilize fixation constructs, or contrarily, perhaps even de stabilize the construct by interfering with optimal component placement. Manufacturers have begun to address this, notably with the recent introduction of a Sawbones soft-tissue complete lumbar spine—including all ligaments, discs, and facet capsules—that is reported to replicate the range of motion of the cadaver lumbar spine (A. Johnson, Pacific Research Laboratories, personal communication, August 22, 2012).

Composite bone models continue to evolve to better achieve the complex physical properties of organic human bone, and they represent an increasingly relevant option for biomechanical studies. Lower extremity long bones have been well validated against cadaveric specimens, although much of this work remains to be attempted in the upper extremity. In addition to replicating the biomechanical properties of human bone, composites handle and are instrumented in a manner reminiscent of their biological counterparts, are radiopaque, and have achieved accurate reproduction of anatomic detail.^{1,14} Currently available composite models are an appropriate replacement for cadaver specimens in a variety of biomechanical studies involving torsional, axial compressive, and lateral bending stresses; however, many authors opt to perform small sample cadaver validation studies in parallel with composites when previously unvalidated Sawbones are tested.

Acknowledgments

The authors would like to thank Amy Johnson, MS, Engineer Associate with Sawbones, Pacific Research Laboratories, Inc., Vashon, WA, for her clarification of the manufacturing processes and construction of Sawbones composite models across production generations.

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FIGURE 1.

Under the same loading conditions, composite models demonstrate failure modes similar to human bones. In the pictured fourth-generation composite femur model, **A** torsional stress produces a spiral fracture in the diaphysis, **B** compressive axial stress produces a transverse fracture, and **C** lateral bending stress produces a butterfly fragment. Adapted with permission from Springer and Gardner MP, Chong ACM, Pollock AG, et al. Mechanical evaluation of large-size fourth-generation composite femur and tibia models. *Ann Biomed Eng.* 2010;38(3):613–620.⁷ With kind permission from Springer Science and Business Media.

FIGURE 2.

Metacarpal shaft plating constructs in a comminuted fracture model. **A** Torsional stress to failure of the 3-dimensional locking plate; **B** failure of the linear nonlocking plate under cantilever bending; and **C** (top to bottom) linear nonlocking plate, 3-dimensional nonlocking plate, and 3-dimensional locking plate. Adapted with permission from Gajendran VK, Szabo RM, Myo GK, et al. Biomechanical comparison of double-row locking plates versus single and double-row nonlocking plates in a comminuted metacarpal fracture model. *J Hand Surg Am.* 2009;34(10):1851–1858.¹¹ With permission from Elsevier.

FIGURE 3.

Volar plating constructs in a comminuted distal radius fracture model by dorsal wedge osteotomy. **A** (Top) the volar plate is elevated off the surface of the bone model in the all-locking screw construct, versus **A** (bottom) the plate-bone contact achieved by first placing nonlocking screws in the hybrid construct. **B** The hybrid construct being tested in an axial compression jig. Adapted with permission from Sokol SC, Amanatullah DF, Curtiss S, et al. Biomechanical properties of volar hybrid and locked plate fixation in distal radius fractures. *J Hand Surg Am.* 2011;36(4):591–597.¹² With permission from Elsevier.