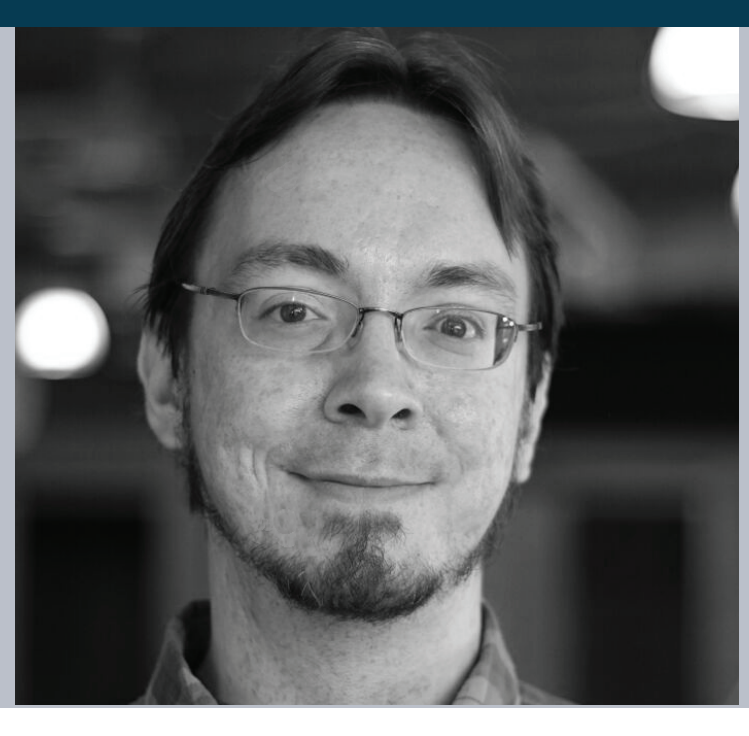
Revenants

3D printed, multimodal, biomimetic medical phantoms

Gregory Phillips



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Medical phantoms and model aids are expensive and laborious to produce. As readymades, their uses are modally constrained and their properties inflexible. Using open-source 3D printing, experimental materials, and streamlined data conversion workflows, a proof of concept is presented to address market needs: Revenants are fully customizable anthropomorphic medical models that are derived from real patient scan data, are produced rapidly and inexpensively, and have the potential to function across diagnostic modalities with relevance to many preclinical and clinical contexts, including quality assurance, training, and treatment delivery. The prototypes demonstrate promising features analogous to hard and soft tissues found in human long bones.

In medicine, *phantoms* are devices that represent the human body. Conceived alongside the invention of radiography and fluoroscopy at the turn of the 20th century, early phantoms were made from blocks of wax, wood, or tanks of water; they were used to determine safe radiation dosages. Phantoms continue to play a critical role in testing treatment protocols and evaluating the performance of CT, MRI, ultrasound, and other medical diagnostic systems. Phantoms provide a standardized baseline for testing, eliminate the need for donor tissues and the exposure of patients to unnecessary risk.

A *revenant* is a ghost or animated corpse that has returned from the grave to haunt a specific person, herein signifying the proposal of a new kind of phantom: Revenants utilize digital manufacturing to meet growing market needs for cost savings, versatility, and mass customization.

Raising the ghost

How can medical models be improved to meet the needs of today's physicians and researchers?

Phantoms must possess known and reproducible attributes that are difficult to maintain using conventional manufacturing methods. As a result, phantoms are typically designed for narrowly defined purposes: to calibrate a specific type of diagnostic machine or to represent an anatomical average. As readymades, phantoms are static and unalterable; they are materially isotropic and cannot effectively mimic biological processes such as vascular perfusion or tissue degradation. The need to preserve these expensive models often involves toxic chemicals that make handling problematic.

As medical treatment protocols become more sophisticated, so must the models used to design them. Trends include multimodal screening, where two or more imaging modalities are used; and patient-specific medicine such as customized implants, orthotics, and drug cocktails.

3D printing allows for the precise reproduction of medical models free from typical economies of scale. Printed models can be made-to-order at price points competitive with mass-produced alternatives. Open-source hardware and software make sophisticated automation accessible to smaller firms, streamlining data conversion and fabrication workflows. Experimental printing materials and the capacity for 'open-source materials' with custom additives, owing to small batch filament extrusion devices, provide the potential for infinite variability and versatility.

Materials and methods

This project used CT datasets of the humerus from the Laboratory of Human Anatomy and Embryology, University of Brussels; and pelvic region CT datasets from the Visible Human Project, courtesy of the Carver College of Medicine, University of Iowa.

Rapid patient-specific modelling

Image segmentation of hard and soft tissue (Fig. 1) was achieved automatically via InVesalius (level set method) and semi-automatically using ITK-SNAP (live contour), while 3D mesh editing, filtering and repair was achieved via Meshmixer and Meshlab; all free software programs. Licensed programs Mudbox and Simplify3D were used to enhance model surfaces and to generate complex 3D printing toolpaths (Fig. 2), respectively.

Open-source 3D printing, customizable materials

Complex, multi-material anthropomorphic prototypes were printed via fused filament fabrication (FFF) using acrylonitrile butadiene styrene (ABS) and Porolay, an experimental mixture of thermoplastic polyurethane (TPU) and polyvinyl alcohol (PVA) developed by Kai Parthy (Fig 2). After printing as a rigid plastic, the Porolay is soaked in water. The PVA dissolves, leaving behind a soft gel, foam, or felt-like flexible and non-toxic material.

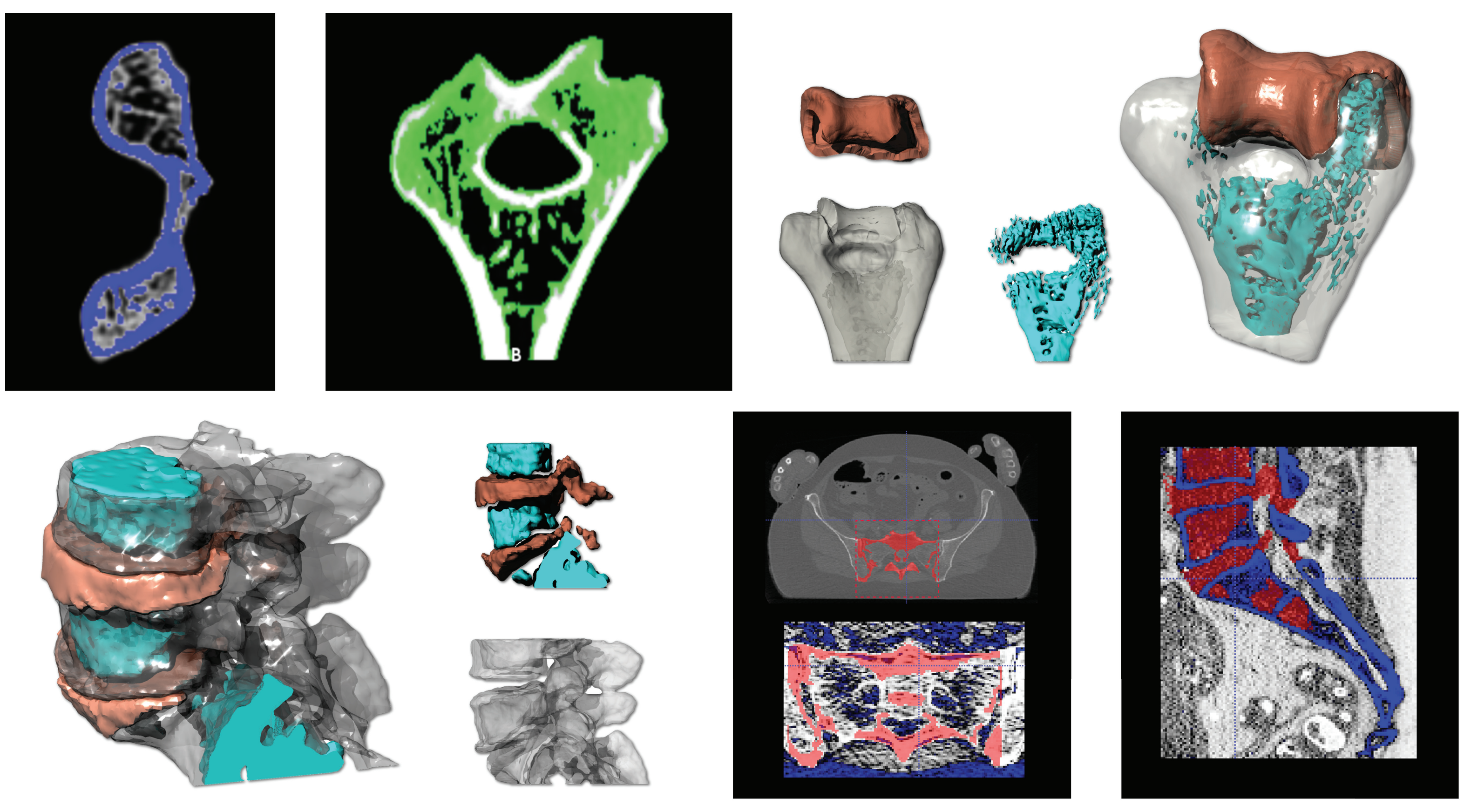

Figure 1. Clockwise from top left: Automatic segmentation of humeral epiphysis CT (cortical and spongial bone) using InVesalius; 3D surface reconstruction of humerus and lumbar region using Meshlab, Meshmixer, and Mudbox; Semi-automatic segmentation of pelvic region CT using ITK-SNAP.

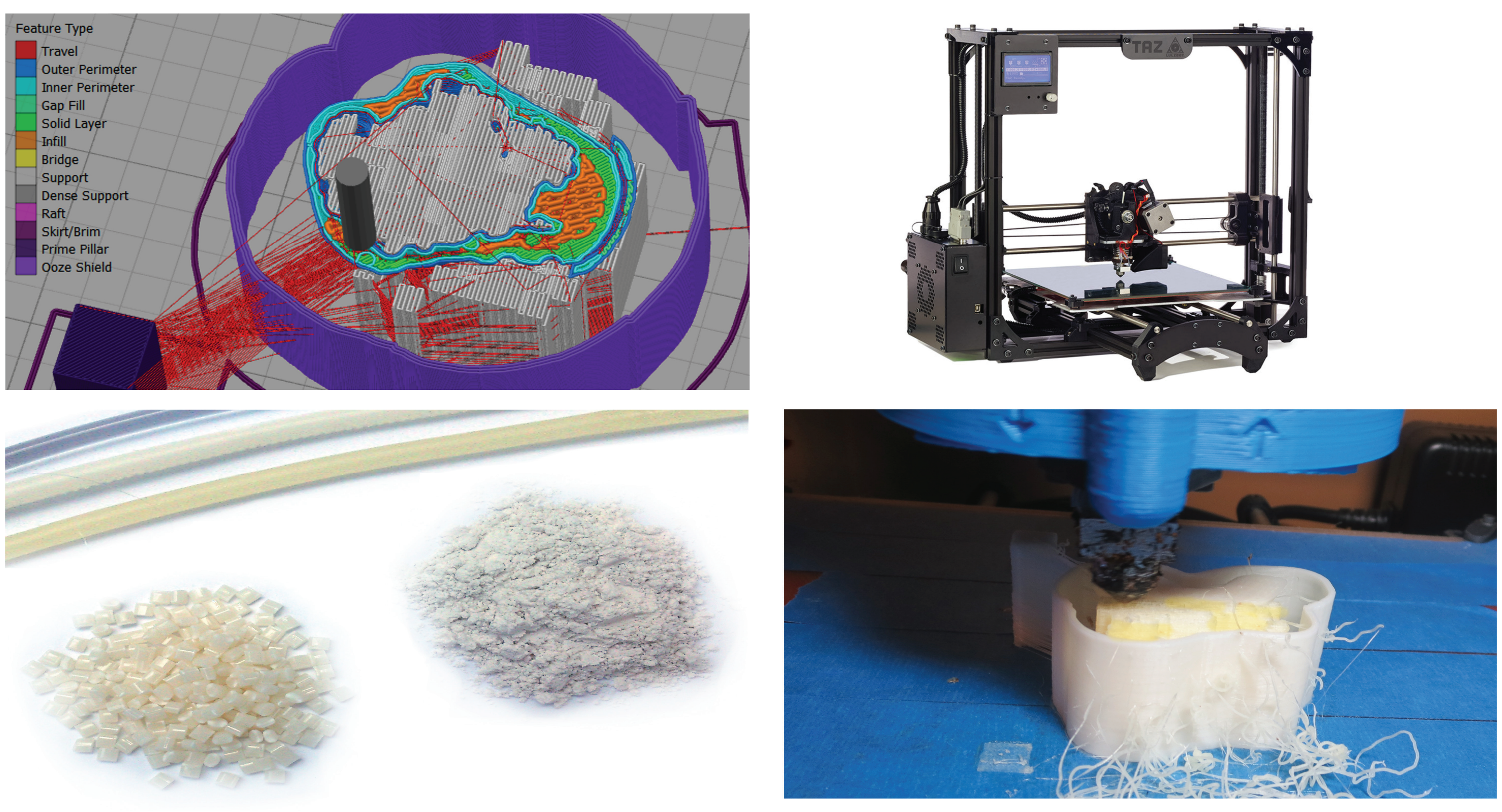

Figure 2. Clockwise from top left: Toolpath generation and strategy visualization using Simplify3D; Taz 5 desktop 3D printer (Photo by Aleph Objects Inc.); experimental filaments and custom masterbatch samples (ABS, silica); multi-material print in progress with ooze shield and prime pillar.

A filament extruder was constructed based on the Filastruder v1.6 plans and kit developed by and with assistance from Tim Elmore (Fig. 7). Built from off-the-shelf and printed components, the extruder was used to produce small batches of customized anisotropic FFF printer filament, including ABS with additives intended to more closely mimic cortical bone properties.

3D printing was accomplished using a Lulzbot Taz 5 desktop printer with dual extrusion modification. While the Taz 5 is capable of 0.1 mm resolution, prints were constrained to 0.3 mm to improve speed and to better approximate real world scenarios where dataset resolution rarely exceeds 1.0 mm. For added efficiency, auto-generated support material was used to simulate soft or spongial tissue.

Results and next steps

Revenant prototypes (Fig. 3-6) show promising biomimetic attributes, including porous microstructures and water absorption (pending tests). Multiple tissue analogues are executed in the same print. Automatic segmentation and print speeds of approx. 40 mm/hr (for diaphysis) represent significant reductions in production time and labour. Open-source hardware and software can reduce costs by up to 90% when compared to enterprise-oriented alternatives.

Forthcoming development may include proprietary material patents and steps toward Class II medical device approval. The accompanying project paper details plans for low-cost bioprinting using hydrogels suitable for cell culture.

Gregory Phillips is an artist, designer, and educator hybridizing traditional material arts with new media, including advanced computer-aided design, direct digital manufacturing, and data visualization. A graduate of George Brown College's Jewellery Arts program and OCADU's Material Art & Design program (Bdes.), Gregory enjoys pushing the limits of new materials and the tools used to shape them. In addition to teaching 3D modelling and rapid prototyping at Durham College, Gregory is a researcher with Neurovent Research Inc., designing novel methods of ventilating newborns without injury; and the CIVDDD-funded Surgical Fetus Project, an initiative to develop anatomically accurate fetus models for high-risk, patient-specific in utero surgical training.

Figure 3. Multi-material slices of humeral epiphysis printed at different lengths, infill percentages and patterns. Infill material (yellow) may represent spongial bone, marrow, or connective tissue.

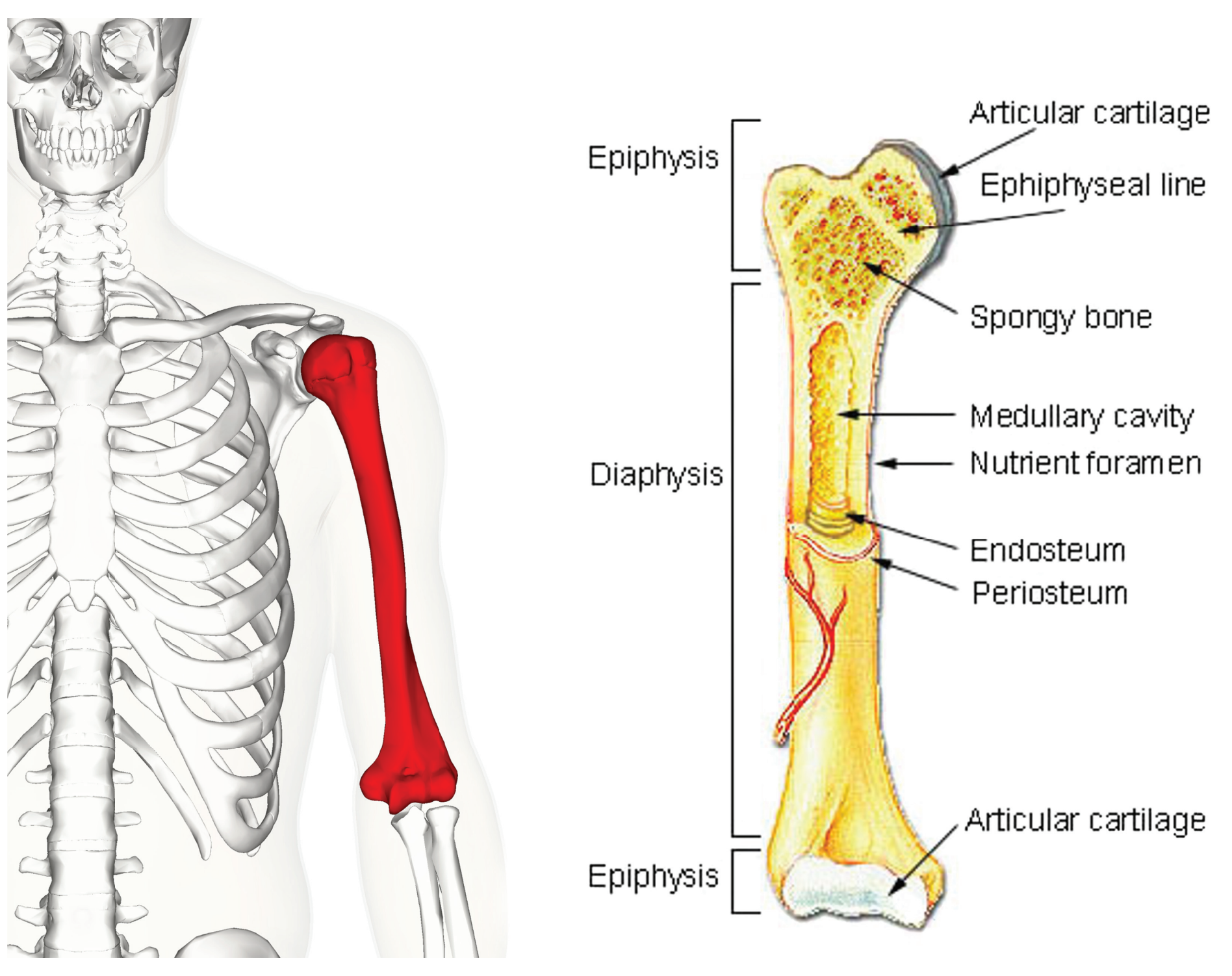

Figure 4. Anatomy of the humerus identifying regions of interest. Adapted from BodyParts3D, © The Database Center for Life Science licensed under CC Attribution-Share Alike 2.1 Japan.

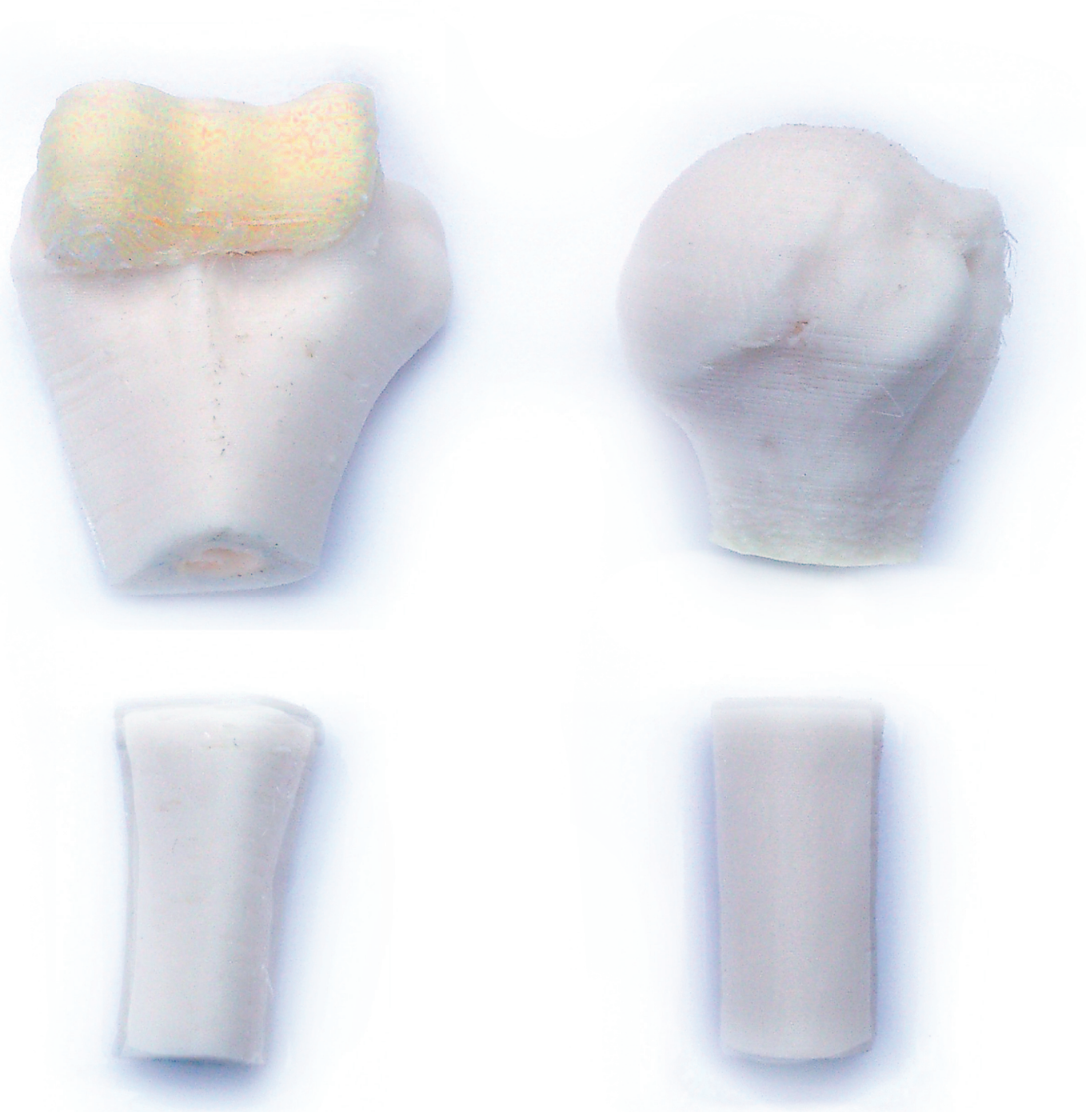

Figure 5. 3D printed prototype phantoms. Top row: Distal (left) and proximal epiphysis with bone, cartilage, and marrow analogues. Bottom row: Corresponding sections of diaphysis.

Figure 6. Fibrous printed material demonstrating liquid absorption.

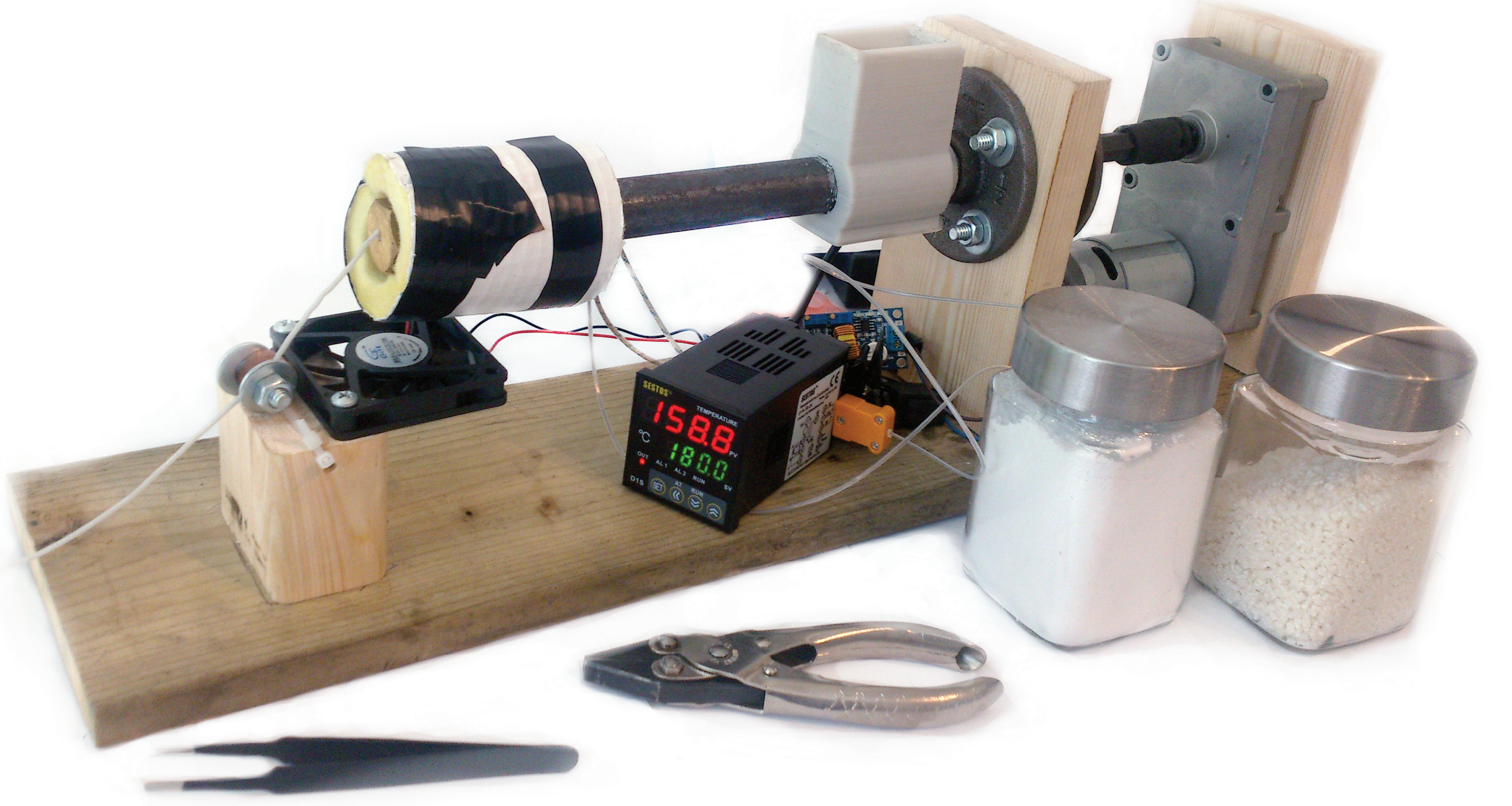

Figure 7. Custom filament extrusion apparatus in operation. Based on the Filastruder v1.6 by Tim Elmore.

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