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Scalable DICOM 3D-printed phantoms mimicking marine mammal bone and soft tissue

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As charismatic sentinel species, California sea lions (*Zalophus californianus*) are commonly found in professional care settings such as zoos, aquariums, and rehabilitation facilities, in addition to their free-ranging coastal populations. These animals frequently strand due to illness, trauma, or environmental stressors, including toxic algal blooms such as domoic acid poisoning, underscoring the need for innovative tools and training methods to improve diagnostic care, monitoring, and veterinary intervention. This study presents a systematic approach for developing scalable, 3D-printable phantoms of a California sea lion pelvis using DICOM (Digital Imaging and Communications in Medicine) standard images from computed tomography (CT) scans to aid in veterinary blood collection training. The CT image data was processed using Simpleware ScanIP software to create detailed anatomical models, emphasizing the blood collection site at the caudal gluteal region and optimized for 3D printing. Through threshold-based segmentation of the DICOM data, several distinct anatomical layers were modeled separately, including a combined epidermal and dermal compliant skin shell, an adipose-rich blubber layer, a muscular layer derived from lower-density soft tissue regions, and a skeletal structure segmented from high-density bone data. This separation enabled each component to be fabricated independently using materials that closely matched their biological counterparts. Prior to fabrication, a material characterization study was conducted using dynamic mechanical analysis (DMA) to evaluate the compressive viscoelastic properties of multiple Humimic medical gelatin compositions (Gels 0 through 5), each with distinct mechanical profiles. The apparent elastic modulus of each gel under cyclic loading was calculated from stress–strain hysteresis data. Based on these results, individual gel types were selected to best match the mechanical properties of biological tissues, including blubber, skin, muscle, and bone. The quad-layered phantom was then fabricated using a combination of high-resolution stereolithography (SLA), fused deposition modeling (FDM), and gel casting techniques. This process resulted in the successful creation of 3D-printed anatomical phantoms that mimic both the mechanical and anatomical properties of the California sea lion pelvis. The methodology presented here provides a framework for creating engineered medical training models with anatomical fidelity and tunable material properties, offering a scalable alternative to traditional approaches in both veterinary and human health education, and the potential for personalized compatible implant design and biomimetic soft robotics.

Ensuring the health and well-being of animal populations, especially non-domestic species, requires effective training in specialized care techniques. However, traditional methods of veterinary training, particularly in specialized procedures such as blood collection, often present significant challenges due to the morphological diversity across animal species¹. This is particularly true in the case of marine mammals like the California sea lion (*Zalophus californianus*), where anatomical complexities and limited accessibility pose unique obstacles to effective training^{1,2}. Currently, human and veterinary physicians use several tools in their training such as suture kits that simulate skin, virtual surgery simulators, and animals – both alive and deceased^{1,3–5}. Of the former, these tools lack the physical presence that would be provided in a more realistic training experience^{1,4}. One method of introducing tactility into the learning model is to incorporate physical 3D medical models, also regarded to as “phantoms”. Phantoms are models that mimic the structure of anatomical features of interest based on imaging modalities (computed tomography [CT], magnetic resonance imaging [MRI], ultrasound [US]), which are used to simulate realistic clinical scenarios, allowing practitioners to develop procedural skills through tactile and repeatable training^{4–9}.

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This study applies this concept by utilizing medical imaging CT scan data to develop an anatomically accurate representation of a live marine mammal, the California sea lion, for blood collection training purposes. California sea lions are a common species featured in zoos and aquariums across the globe due to their charismatic nature. Additionally, free-ranging California sea lions serve as sentinel species for ocean health, stranding at increasing rates and entering rescue and rehabilitation facilities due to a range of causes including illness, trauma, cancer, and environmental toxins such as domoic acid. As part of comprehensive.

diagnostic and treatment protocols, veterinary professionals routinely collect blood from these marine mammals to monitor systemic health, guide care, and assess environmental exposure¹⁰. At present, veterinary trainees tasked with blood collection from this species often rely on a technique highly dependent on tactile sensation^{2,11}. This method involves the identification and feeling of bony landmarks in the pelvic region to orient and locate the optimal collection site, which is typically a softer tissue region located lateral to the sacral vertebrae, approximately one-third of the distance between the femoral trochanters and the base of the tail². However, this approach is inherently limited by its reliance on subjective tactile sensation, which requires significant time and repeated practice to develop the precision needed for consistent and effective blood collection.

While this study focuses on developing a 3D phantom model for veterinary blood collection training, the workflow of converting DICOM-standard medical images into scalable, engineered 3D models is highly adaptable. Specifically, it can also be applied across various fields, such as soft robotics design, bioinspired engineering, and biocompatible implants for cardiac, orthopedic, or neural augmentation applications and beyond. This study serves as a focused implementation of that broader framework, applying it towards the design and fabrication of an anatomically accurate training phantom. The following sections outline the methodology used to generate this phantom, including the image processing pipeline, materials characterization, and fabrication strategy that together enabled the creation of a biologically representative and functionally relevant training tool.

Methods

DICOM image processing

In order to develop an anatomically accurate model of the California sea lion pelvis, DICOM-standard CT and MRI scan images, provided by the U.S. Navy Marine Mammal Program (MMP), were processed using Synopsys' Simpleware ScanIP software's comprehensive anatomical modeling imaging processing tools for segmentation, mask generation, and mesh optimization, making it well-suited for anatomical modeling. The scans provide an initial volumetric resolution of $512 \times 512 \times 666$ voxels, which undergo several of these image processing methods to isolate and prepare the region of interest (ROI) for 3D printing. Following the initial import of the scans into the software, the images were resampled by reducing the pixel spacing cubically to.

0.7 mm (from the default value of 0.9629 mm), improving the overall clarity for subsequent segmentation. Simpleware employs convolution matrices to analyze the surrounding pixels of interest to produce output pixels using discretized approximations of standard Gaussian distributions. Two-dimensional images are processed individually and then stacked on top of one another to produce a 3D rendering. The Simpleware ScanIP workspace along with the default model from import can be seen in Fig. 1a and b, respectively.

The model comprises of two primary components: the skeletal structure and the soft body exterior. As DICOM images inherently store voxel density information (representing the tissue's radiodensity in Hounsfield units, HU), this allows for model segmentation via greyscale thresholding, where specific density ranges are isolated to differentiate between various biological materials. From the CT scan data, two separate masks were generated by thresholding to isolate bone structures from blubber and other soft tissues based on their unique density values. For the bones, the targeted density values ranged from 230 to 1800 HU, resulting in a relatively clean and contiguous mask after applying the Cavity Fill operation to eliminate gaps. The remainder of the

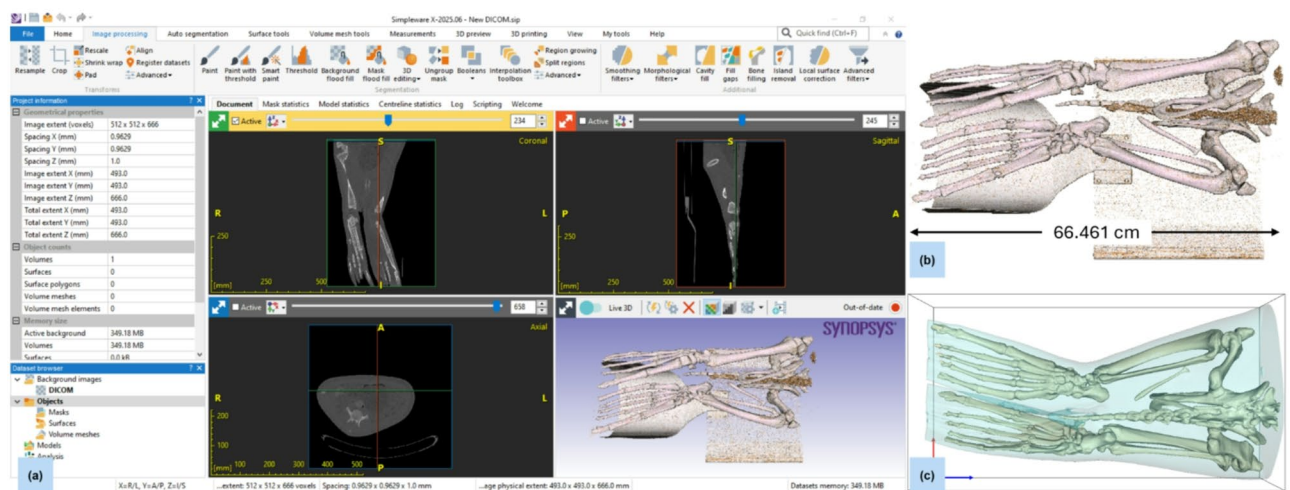


Fig. 1. (a) Simpleware user workspace prior to image processing¹²; (b) 3D render of the raw CT scan of the sea lion's lower body; (c) Processed render of model within workspace with body at 30% opacity.

model required a wider threshold range of -200 to 1800 HU, resulting in an overlaying mask that included superfluous data, such as portions of the imaging machine and bed. The two body models, along with their respective greyscale-HU thresholding histograms can be seen in Fig. 2. Cropping the scans to a tighter ROI reduced some of the extraneous data; however, additional image processing techniques were necessary to fully isolate the body. Larger floating artifacts were removed using the 3D Editing tool, which allowed for the deletion of several portions of the imaging machine bed captured during masking. Further refinement was achieved with the Smart Paint tool, which was used to ‘unpaint’ difficult artifacts closer to the body, as well as the Erode and Dilate tools to ensure disconnection of merged appendages and subsequent restoration of bulk.

Next, both masks were refined through larger-scale operations within the software toolbox. For the skeletal mask, a morphological close operation was applied using a spherical structuring element with a radius of 4 voxels, effectively closing small volumetric gaps. Following this, the Island Removal tool was employed, starting with a threshold of 100 voxels to remove smaller artifacts. The threshold was then iteratively increased to approximately 3000 voxels as additional artifacts were identified, ensuring the removal of all remaining extraneous regions. In a similar manner, the body structure mask was first morphologically closed with a spherical element of a 5 voxel radius. Considering the printability of the structure, subsequent smoothing was applied to both models. Initial smoothing was performed using the Recursive Gaussian tool, with Gaussian sigma values of 5 pixels applied isotopically. To further refine the body structure mask, the Local Surface Correction tool was applied with a search radius of 5 pixels. The result was a significantly more polished and contiguous surface, ideal for subsequent processing and 3D printing as seen in Fig. 1c where the body is rendered at 30% opacity. Additionally, Simpleware’s Split Regions tool enables the segmentation of masks into distinct anatomical components, the skeletal model was divided into three general categories: legs, flippers, and pelvis/spine. This tool provides a means for larger-scale components to be 3D printed separately, which can be later assembled or used to target specific body components for analysis or fabrication.

3D model preparation

The next step in the workflow is to convert the masks into solid models. The bones were exported directly in standard triangle language (STL) files from the Simpleware software, requiring no additional processing. However, the body model required further refinement to prepare it to function as an overall shell to hold the bones and for gel casting, necessitating several additional steps. First, within Simpleware’s 3D Preview context menu, the body model was configured to be exported as an STL with the mask elements decimated to a target of 10,000 max triangles (per part)—allowing for computationally accessible importation into the CAD software.

This resulted in a model of 137,250 elements. The model was then imported into Autodesk’s Fusion 360 software which contains a comprehensive toolset for mesh modification. Within Fusions Design: Mesh interface, the mesh was modified using the Convert Mesh feature. Given the nature of the model, the ‘Organic’ method was selected with High Accuracy and with the Preprocessed Holes option enabled.

With the model now converted into a solid body, Fusion’s design tools can now be employed to edit the model directly. Using the Shell tool, the body was hollowed with a wall thickness of 1.00 mm, forming the negative mold. The mold was then split along a plane at the topmost surface, creating an opening for the bones to be placed and for the gel material to be cast. Several naturally occurring landmarks, such as the caudal vertebrae

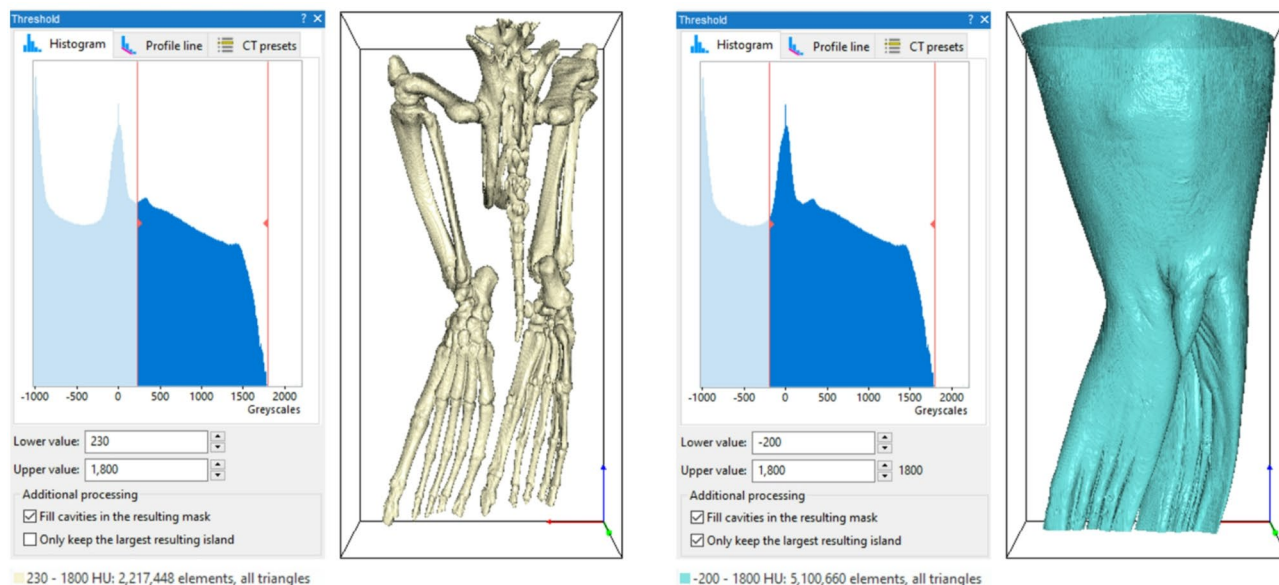


Fig. 2. Threshold histogram of CT voxel greyscale intensity distributions mapped to Hounsfield units used for segmentation, with resulting 3D models; (Left) Bone threshold (230 – 1800 HU); (Right) Soft-tissue threshold (-200 to 1800 HU).

and metatarsal cavities, provide alignment features for later bone placement. With that, the body shell was then exported as an STL for 3D printing. The entire workflow from DICOM import to export can be seen in Fig. 3.

Materials characterization

To identify materials for the anatomical phantom such that its mechanical properties closely mimic those of real sea lion tissue, the materials used were characterized through a series of mechanical tests to achieve optimal material matching. A specialized ballistic gelatin material developed by Humimic Medical™ was selected for this study to simulate the blubber layer of the California sea lions due to its stability, ease of casting, clarity, and the availability of multiple formulations tailored to mimic a range of biological tissues¹³. The gels used in this study are denoted as Humimic Gel 0 through Gel 5. Gel 0, the firmest, is used for dense structures like cartilage or fibrous tissues, while Gel 5, the softest, replicates delicate tissues such as brain matter or blood clots^{14,15}. Intermediate gels, such as Gel 2 and Gel 3, are designed to simulate softer tissues, including fat and muscle, with viscoelastic properties similar to biological counterparts^{16,17}.

The gelatin samples were conventionally cast in 10 cm diameter casting dishes, displayed in Fig. 4 (Left). Each Humimic sample container shown in Fig. 4 (Right) was first melted in an oven at 125 °C for four hours until all visual bubbles dissipated, following manufacturer specifications¹⁸. The cast gels were then allowed to cool at room temperature for 12 h. Samples were cut in circular cross-sections using a hollow punch of 10 mm diameter with a uniform cross-sectional thickness of approximately 5 mm, measured using a digital micrometer. Each sample container, alongside its respective punched specimens, is shown in Fig. 4. Table 1 details corresponding measurements for each gel sample tested.

All mechanical tests were performed using a PerkinElmer Pyris Diamond Dynamic Mechanical Analyzer (DMA), with gel specimens placed in the DMA's isothermal chamber at 20 °C ± 1 °C, ensuring stable temperature conditions across all experiments. The experimental setup can be seen in Fig. 5. Compressive stress-strain hysteresis loading tests were performed on the Humimic gel to 25% strain at 1% strain/minute for three continuous loading cycles. Each gel specimen was compressed by 1 mm at a strain rate of 0.25 mm/min, with a data sampling rate of 1 reading per 5 s (12 samples per minute) over a period of 36 min. A hold of 2 min was applied between cycles to ensure steady-state and zero conditions on the load cell. The linear elastic regions were approximated using a linear fit in OriginLab software with 95% confidence and prediction bands, determining the apparent elastic modulus of each gel and the corresponding goodness-of-fit statistics.

Phantom fabrication

Fabricating a biologically realistic training phantom requires deliberate material selection to replicate the distinct mechanical properties of the materials being modeled. Four distinct components were individually created to capture a quad-layered morphology: the skeletal structure, a compliant skin shell representing the dermis and epidermis, an adipose-rich blubber layer, and an internal muscular layer.

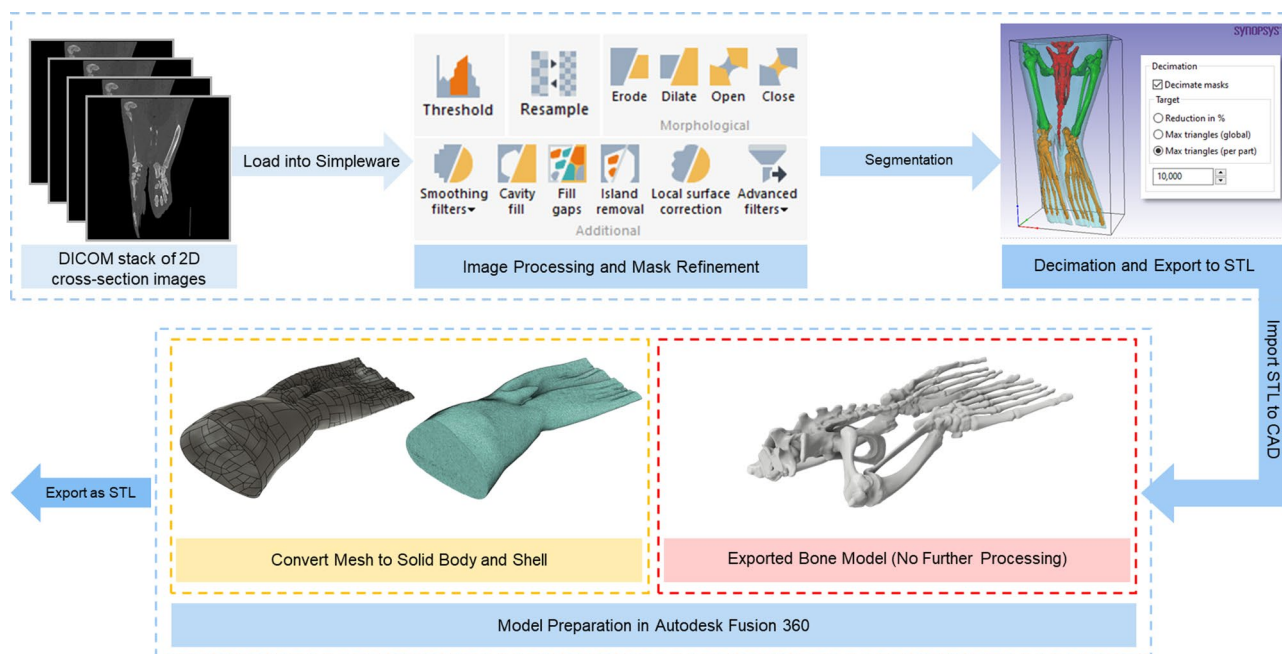


Fig. 3. Workflow for developing multi-material 3D-printed anatomical phantoms from CT imaging data. A DICOM stack of 2D cross-sectional CT images was imported into Synopsis Simpleware ScanIP for image processing, segmentation, and mask refinement. Bone and soft tissue components were segmented separately and exported as STL files following decimation. The bone STL model was imported directly into Autodesk Fusion 360 for print preparation, while the soft tissue shell underwent mesh conversion and surface processing prior to mold generation.

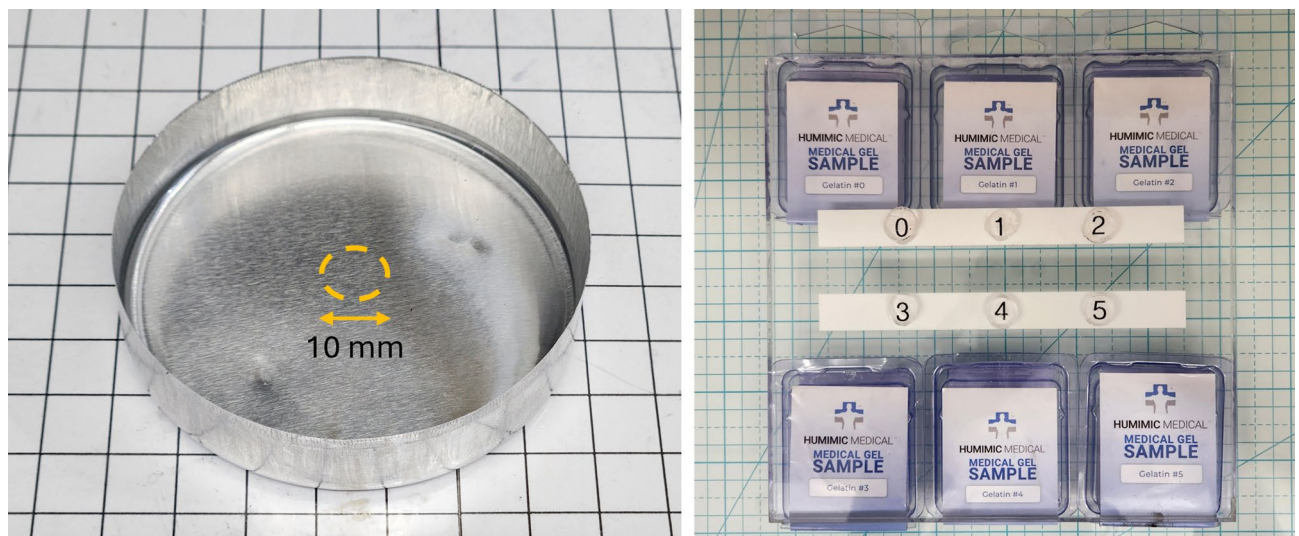


Fig. 4. (Left) Aluminum casting dish (10 cm diameter) with cured gel. Samples were extracted at the circular visual indicator using a 10 mm diameter hollow punch; (Right) Humimic gel samples of formulations #0—#5 tested within the PerkinElmer Pyris Diamond Dynamic Mechanical Analyzer (DMA).

Sample Dimension	Gel 0	Gel 1	Gel 2	Gel 3	Gel 4	Gel 5
d_0 (mm)	9.8 ± 0.5	9.8 ± 0.5	10.01 ± 0.5	9.83 ± 0.5	9 ± 0.5	9.61 ± 0.5
t_0 (mm)	4.45 ± 0.001	4.53 ± 0.001	5.15 ± 0.001	5.38 ± 0.001	6 ± 0.001	4.07 ± 0.001

Table 1. Original thickness (t_0 [mm]) and diameter (d_0 [mm]) measurements of tested Humimic gel samples recorded using a digital micrometer alongside respective dimensional uncertainty.



Fig. 5. Experimental setup for dynamic mechanical analysis (DMA) testing; (Left) PerkinElmer Pyris Diamond DMA system; (Right) Close-up of testing chamber with a Humimic gel sample mounted for compressive testing¹⁹.

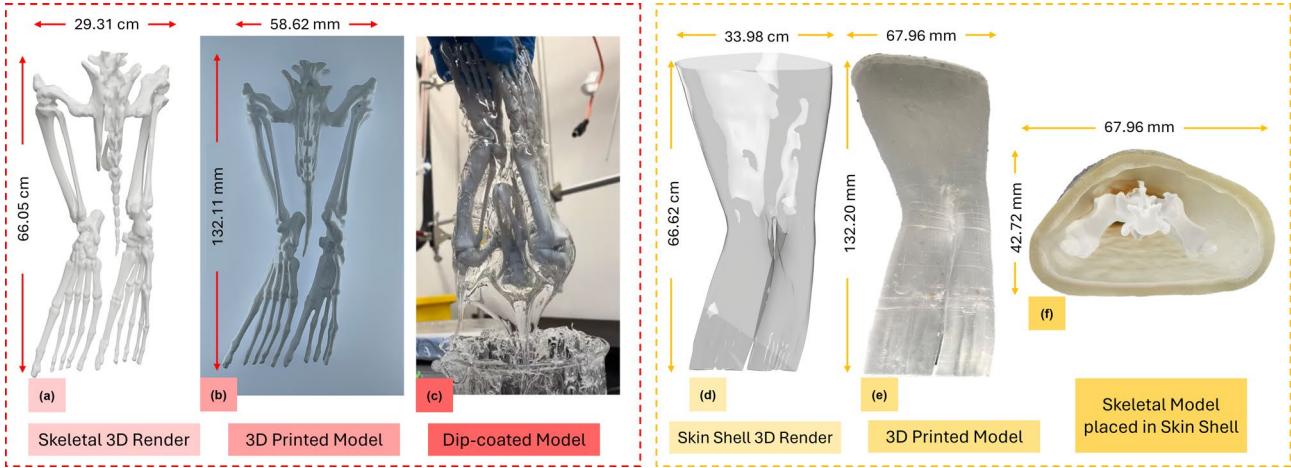


Fig. 6. Phantom model components; (a) Full size skeletal model 3D render; (b) Corresponding 3D-printed bone model at 20% scale; (c) Dip-coating of bone in Humimic Gel 0 to simulate tendon and muscle attachment; (d) Full size 3D render of the compliant skin shell; (e) Final shell printed in Flexible 80A resin at 20% scale; (f) Superior view of staged phantom showing printed skeleton positioned within the compliant skin shell prior to gel cast.

Body Region	Material	20% (mL)	25% (mL)	40% (mL)
Casted Components				
Blubber	Humimic Gel 0	27.5 ± 0.5	53.7 ± 0.5	220.0 ± 0.5
	Humimic Gel 5	86.2 ± 0.5	168.4 ± 1.0	689.6 ± 1.0
3D Printed Components				
Skin	Formlabs Flexible 80A	17.32 ± 0.9	45.9 ± 2.3	138.57 ± 6.9
	Formlabs Draft	29.3 ± 1.5	57.19 ± 2.9	234.2 ± 11.7
Bone				

Table 2. Estimated material volumes for each modeled tissue layer based on Simpleware ScanIP segmentation. Volumes are calculated for 20, 25 and 40% scale models.

The skeletal structures were 3D printed using a Formlabs Form 3 SLA (stereolithography) printer at up to a resolution of 25 μm, producing models at 20, 25 and 40% scale relative to the original CT scan, with 40% being the maximum stable size given the 3D printer build volume. At each respective scale, a variety of Formlabs proprietary photopolymer resins were used across different prototypes, including Rigid 10 K, Tough 1500, and Draft. Once cured, the skeletal models were gradually dip-coated in heated and evacuated Humimic Gel 0 to simulate tendon, ligament, and muscular tissues closely associated with bone. This layer mimics the stiffer properties of soft tissue near joints and attachment points, which aids in force transfer in contrast to the more compliant muscle tissue further from the bone—often referred to as the “belly” of the muscle²⁰. Furthermore, the dip-coating method was motivated by its novelty as a layer-wise fabrication method, resulting from the assumed no-slip condition of the viscous Humimic Gel 0, as well as its thermal sensitivity and insulating properties. Figure 6 shows the final bone print along with the dipping procedure. Considering that the final model is intended for physical handling and training use, the outer shell was fabricated to balance flexibility with structural resilience. This skin shell was also SLA printed using Elastic 50A and Flexible 80A resins to explore differences in compliance under handling without compromising the clarity of internal anatomical structures visible through the surface as seen in Fig. 6. In addition to serving as an external skin analog, the shell also functioned as a negative mold for casting the inner blubber and muscle layers using Humimic gelatin. This dual-purpose design simplified assembly and ensured a cohesive structure with proper alignment between internal and external components.

For the blubber layer, volume calculations were performed using a control volume analysis in Autodesk Fusion 360. The total internal volume of the entire model was determined from the body properties menu of the outer soft tissue mesh, yielding a value of 42.48 m³. This volume was then normalized to the appropriate scale (20, 25 or 40%) and used to calculate the amount of Humimic Gel 0 and Gel 5 required for casting the blubber and muscle layers, respectively. The relative percentages of these soft tissues were measured using Simpleware’s Volume Fraction tool, determining the volume percentage of the blubber and muscle with respect to the total volume of the model. The volumes of the bone and skin shell were directly extracted from the original DICOM-based segmentations and carried forward into the 3D printing workflow. A summary of the calculated volume fractions and estimated material quantities for each anatomical layer is presented in Table 2.

Prior to casting the 20% scale model, 86.2 mL of Humimic Gel 5 and 27.5 mL of Gel 0 was measured in 100 mL graduated cylinders. The samples were heated to 125 °C for 4 h while simultaneously evacuating in a

Napco Model 5831 vacuum oven at approximately -25 inHg. The assembled mold was suspended in an ice bath. Humimic Gel 0 was heated and slowly poured in a spiral pattern along the inner walls of the mold, allowing the highly viscous gel to coat the surface uniformly and settle gently. Once the blubber layer was cast, the skeletal model was inserted and aligned in its anatomically correct position using the naturally occurring alignment features of the mold at the tail and pelvic flippers. The more compliant soft tissue layer, representing muscle, was then cast using heated Humimic Gel 5. This layer was poured until level with the top of the phantom, as shown in Fig. 7a. After curing for 24 h to complete gel cross-linking, heat polishing was selectively applied to the exposed upper surface using a heat gun to smooth imperfections, while avoiding deformation of the skin shell. This process is shown in Fig. 7b. A superior view of the heat-polished phantom can be seen in Fig. 7c along with a color overlay indicating the distinct layers of the model (Fig. 7d).

Results

The following results detail the characterization and validation of materials selected for use in the quad-layered phantom, specifically those of the gels that had undergone dynamic mechanical analysis (DMA) testing to approximate their elastic properties under cyclic loading conditions. This data then informed the selection of materials to mimic biological soft tissues such as blubber and muscle. Additional components, including the skeletal structure and outer shell, were evaluated based on manufacturer-reported mechanical data and relevant literature. The final phantom outcome was assessed for anatomical fidelity and structural integrity to validate the performance of the proposed image-to-phantom workflow.

The apparent elastic moduli of the Humimic gels were approximated using stress–strain data obtained during cyclic compressive loading tests to approximately 25% strain at 1% strain/minute. Mechanical testing involved three continuous loading cycles, and the resulting hysteresis loops were analyzed (Fig. 8 Left). Linear fits were applied to the elastic loading regions of the stress–strain curves, with 95% confidence bands used to ensure statistical robustness (Fig. 8 Right). Due to the viscoelastic nature of the gels, the calculated apparent elastic moduli reflect an approximated stiffness under cyclic loading conditions rather than a static elastic modulus as typically defined. The slopes of these linear fits were recorded for each gel and are presented as effective stiffness values under cyclic loading conditions. These experimental values were then compared to both manufacturer-reported data and the previously published results of Laughlin et al. in Table 3 for validation^{7,19}.

The differences between the reported apparent elastic moduli values may stem from variations in testing methodology, including cyclic loading and viscoelastic contributions. The results highlight the significant differences in viscoelastic properties among the gel types, which align with their intended use cases. Stiffer gels, such as Gel 0 and Gel 1, are better suited for applications requiring higher load-bearing capacities, while softer gels like Gel 4 and Gel 5 more closely mimic the behavior of highly deformable biological tissues. These observations have informed the selection of gels that closely replicate the mechanical characteristics of California sea lion blubber and muscle, where the viscoelastic response plays a key role in energy dissipation.

In addition to the DMA testing of the Humimic gels, other materials used in the phantom such as the skeletal structure and outer shell were selected based on manufacturer-reported mechanical properties and their alignment with literature values for biological materials. Table 4 presents a comparison of elastic and flexural modulus values for blubber, muscle, and bone against potential 3D printing resins and gels used in this study. While Rigid 10 K resin exhibited a modulus range of 7,500–11,000 MPa (closely approximating the mechanical behavior of mammalian bone), Draft resin was ultimately selected due to its improved durability during fabrication. This material provided a practical compromise between mechanical rigidity and fracture resistance, addressing the fragility observed in initial Rigid 10 K prints. For the gels, Humimic Gel 0 and Gel 5 demonstrated approximate stiffness values of approximately 0.0139 MPa and 0.0021 MPa, respectively,

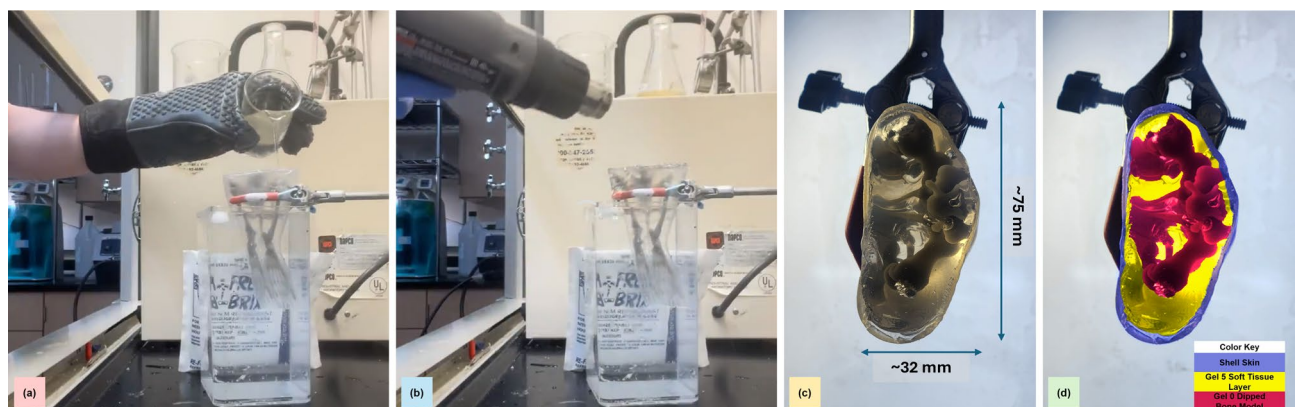


Fig. 7. (a) Casting the final soft tissue layer (20% scale model) using Humimic Gel 5, poured to fill the remaining mold volume; (b) Heat polishing the exposed top layer to smooth surface imperfections without damaging the skin shell; (c) Superior view of phantom model after heat polish; (d) Color overlay of the distinct phantom components. The Gel 0-dip-coated skeletal structure (magenta) is embedded within the Humimic Gel 5 soft-tissue layer (yellow) and enclosed by the compliant outer shell (blue).

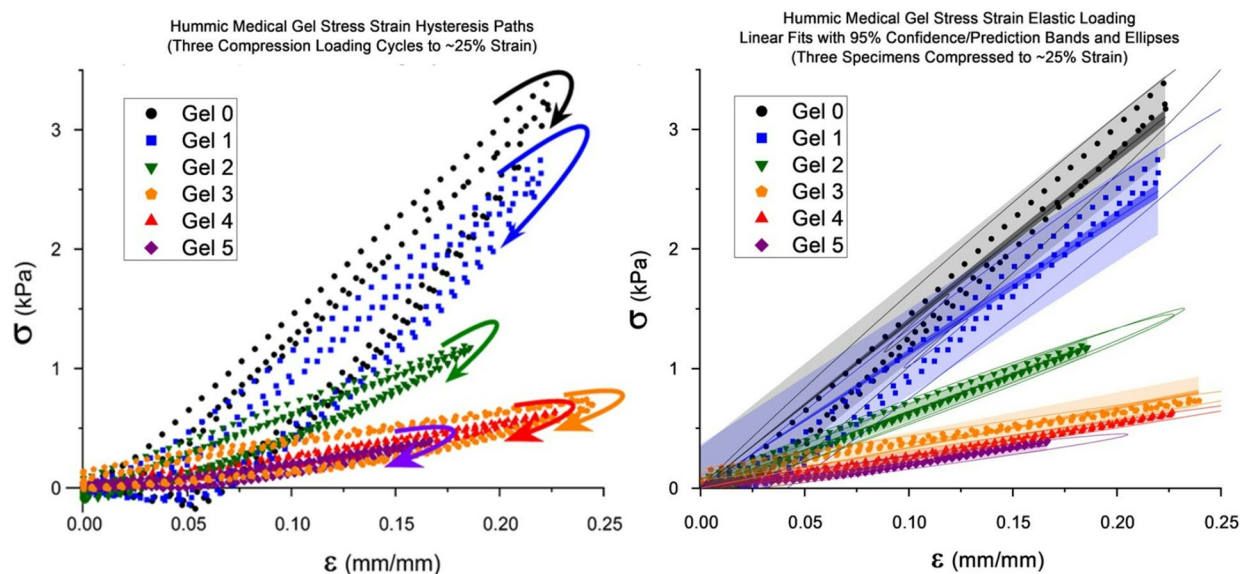


Fig. 8. (Left) Compressive stress–strain hysteresis loops of Humimic Medical Gel to 25% Strain for three continuous loading cycles; (Right) Corresponding linear fit with 95% confidence and prediction bands.

Measurement	Gel 0	Gel 1	Gel 2	Gel 3	Gel 4	Gel 5
<i>E</i> (kPa)	13.9 ± 0.13	11.3 ± 0.14	6.37 ± 0.03	3.35 ± 0.04	2.69 ± 0.01	2.13 ± 0.02
Pearson's <i>r</i>	0.995	0.9992	0.998	0.99	0.999	0.994
Coefficient of Determination (<i>R</i> ²)	0.99	0.985	0.996	0.98	0.997	0.988
Laughlin et al. ⁷ <i>E</i> (kPa)	92.02 ± 16	49.05 ± 5	36.57 ± 7	25.55 ± 5	17.02 ± 7	Not measured
Laughlin et al. ⁷ Reported <i>R</i> ²	0.97	0.96	0.98	0.97	0.91	Not measured
Humimic Reported <i>E</i> (kPa)	570 ¹⁴	370 ²¹	260 ¹⁶	190 ¹⁷	150 ²²	100 ¹⁵

Table 3. Compressive stress–strain elastic loading of Humimic Medical Gel to 25% strain for three continuous loading cycles with linear fit statistics with comparison to reported values.

Biological Component	Sea Lion Value [MPa]	Biomimetic Material	Value [MPa]
Apparent Elastic Modulus			
Blubber	0.2–3.9 ²³	Humimic Gel 0	0.0139
Muscle	0.0212–0.0282 ²⁴	Humimic Gel 5	0.0021
Flexural Modulus			
Bone	10,000–14,000 ²⁵	Formlabs Rigid 10 K	6,000–10,000 ²⁶
		Formlabs Draft	600–2,300 ²⁷
		Formlabs Tough 1500 V2	900–1370 ^{27,28}
Ultimate Tensile Strength			
Skin (Dermis + Epidermis)	7.37–30.26 ²³	Formlabs Elastic 50A V2	3.4 ^{28,29}
		Formlabs Flexible 80A	8.9 ³⁰

Table 4. Comparison of mechanical properties for California sea lion anatomical structures and selected biomimetic materials. Property types include apparent elastic modulus, flexural modulus, and ultimate tensile strength.

approaching the reported ranges for sea lion blubber and muscle tissues^{23,24} and serving as practical, transparent analogs demonstrating 4 distinct layer stiffness’s mimicking nature.

Table 4 additionally summarizes the ultimate tensile strength values for the phantom’s outermost layers, focusing on skin and subdermal structures. Elastic 50A and Flexible 80A resins were evaluated for use in printing the compliant outer shell. Although both materials fall below the full tensile strength range reported for sea lion skin (7.37–30.26 MPa), Flexible 80A demonstrated a higher tensile strength (8.9 MPa) and was

ultimately favored for its balance of compliance, structural integrity, and transparency when compared to the Elastic 50A model.

Based on the results of mechanical testing and material comparisons, a quad-layer phantom of the California sea lion pelvis was successfully fabricated. The final model integrates a rigid skeletal core, a soft tissue gel base, a blubber-analog gel layer, and a flexible outer shell, each constructed from materials selected to match the mechanical behavior of their biological counterparts. Figure 9 displays the completed phantom, demonstrating visual clarity of internal features and anatomical contouring alongside the expected 3D render from Simpleware.

The phantom retained anatomical fidelity throughout the fabrication process and demonstrated structural coherence during physical handling, with no significant delamination or visible distortion between layers. Internal structures remained visible through the outer shell when printed using Flexible 80A, enabling both tactile and visual feedback. These results validate the proposed image-to-phantom workflow as a viable approach for developing multi-material anatomical models for training and bioinspired applications.

Discussion

The development of a scalable anatomical phantom of the California sea lion represents a significant step toward enhancing veterinary training methods for marine mammals. The anatomical fidelity of the 3D-printed model, combined with the viscoelastic properties of the Humimic medical gelatin suggests strong potential for effective use in veterinary training for blood collection. Regarding usage, the 3D-printed phantoms offer several advantages. The clear body of the phantom aids in visualizing the internal structures during practice, enhancing the learning experience by combining tactile feedback with visual cues. Furthermore, unlike with live



Fig. 9. Comparison of (left) original 3D render from Simpleware and (right) the final 20% scale fabricated phantom model. The printed model closely replicates internal skeletal features and anatomical contours with clear visual fidelity.

Material	Per item (pack)	Unit price	20%		25%		40%		100%	
			Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost
Humimic Medical Gel 0	\$42.98 (0.68 kg) ¹⁴	\$0.06321/g	24.2 g	\$1.53	47.3 g	\$2.99	193.6 g	\$12.24	3030 g	\$191.21
Humimic Medical Gel 5	\$42.98 (0.68 kg) ¹⁵	\$0.06321/g	77.4 g	\$4.89	151.17 g	\$9.56	619.2 g	\$39.14	9675 g	\$611.56
Formlabs Flexible 80A Resin	\$209 (1 L) ³⁰	\$0.209/mL	17.32 mL	\$2.22	45.9 mL	\$9.59	138.57 mL	\$28.96	2165.2 mL	\$452.53
Formlabs Draft Resin	\$159 (1 L) ²⁷	\$0.159/mL	29.3 mL	\$4.66	57.19 mL	\$9.09	234.2 mL	\$37.24	3623.69 mL	\$576.17
Total Cost			\$10.82		\$31.23		\$117.58		\$1,831.47	

Table 5. Material amount and cost at four scales (20, 25, 40 and 100%). Unit prices are based on manufacturer pricing. Humimic gel masses were derived from the volumes listed in Table 2 using density values from the material data sheet^{14,15}.

animal training, the phantom allows for repeated practice sessions without ethical concerns, allowing trainees to gain confidence and refine their technique in a controlled, low-pressure environment. Additionally, the scalable nature of the model means it can be adapted to various species and scenarios, further broadening its applicability in veterinary education.

Several remarks can be made regarding the software process and workflow used in developing the phantom. While the accessibility of DICOM-standard medical scans enables precise anatomical modeling, the software process itself can be highly subjective, often relying on the user’s judgment for tasks such as segmentation, mask generation, and morphological operations. This subjectivity introduces variability, making the process as much an art as it is a science. Furthermore, the large file sizes associated with high-resolution scans and detailed models present challenges in terms of storage, processing power, and workflow efficiency. Optimizing the software pipeline to handle these demands more seamlessly could greatly enhance the usability of this approach.

Characterizing viscoelastic materials, such as the Humimic gels used in this study, presents unique challenges due to their time-dependent stress–strain behavior. The apparent elastic moduli reported in this study were approximated from stress–strain data obtained during cyclic compressive loading, where the hysteresis loops depicted the energy loss during loading and unloading cycles. While the apparent elastic modulus values align relatively well with previous studies, they are significantly lower than the manufacturer-reported values^{7,13}. This discrepancy likely arises from differences in testing methodologies, including strain rates, testing instruments, and temperature. Despite these variations, the recent calibration of the DMA and the high goodness-of-fit values for the elastic loading region suggest that the reported results accurately represent the mechanical properties under the specific testing conditions.

Regarding fabrication, the use of a reusable SLA-printed skin shell provided an efficient and effective method for casting the internal layers of the phantom. Acting both as the external anatomical structure and the negative mold, the shell simplified the alignment of the skeletal model and enabled control over wall thickness and gel distribution. Humimic medical gelatin served as the casting material for the blubber and muscle layers, offering excellent clarity, tunable compliance, and reusability well-suited for repeated training use. Formlabs Draft resin was selected for the skeletal structure due to its balance between mechanical strength and durability. The retrieved Simpleware Scan IP volume fractions compared favorably with marine mammal blubber thickness cited in literature. Although typical sea lion blubber varies throughout the body, the measured full scale model blubber thickness of 1.0 ± 0.1 cm was slightly lower than approximated thickness of 1.6 ± 0.1 cm for the pelvic region of the average reported thickness values of fellow members of the Otariidae “eared seal” family, the Steller sea lion (*Eumetopias jubatus*)^{3,31}. Therefore, the difference in pelvic region blubber thickness was reconciled due to species differences between the modeled California sea lion, and the quantitative reference available in the literature being limited to Steller sea lions as the reference species most anatomically similar. However, this can be expected given that the California sea lion can be significantly smaller than the Steller sea lion³².

Some limitations were observed during the fabrication process. The casting process requires precise temperature control and careful handling to prevent defects, such as bubbles or incomplete fills. While Rigid 10 K provided higher stiffness values closer to cortical bone, they were prone to fracturing during fabrication and handling. Draft, by contrast, retained sufficient rigidity both during the fabrication process and in test usage. Despite its successful outcome, the development of this phantom model involved extensive trial-and-error across segmentation, material selection, and fabrication stages, highlighting the iterative and time-intensive nature of translating medical imaging data into functional, anatomically accurate training tools. Future work could explore alternative materials or custom gel formulations to more accurately replicate biological performance.

The scalability of the presented fabrication workflow is an important aspect of its utility for training applications. In principle, the process can be implemented at any size, with the primary theoretical limitation being the build volume of the 3D printer and the practical limitations arising from material cost and shipping logistics. A full-scale model, corresponding to an adult California sea lion, which can reach lengths of up to 1.8 m to 2.4 m for females and males, respectively, would provide the most accurate anatomical training experience. However, smaller-scale models may be preferable when portability, material efficiency, or cost are key considerations. The same digital workflow can be readily scaled to either context, offering flexibility to institutions with varying resources or instructional goals.

Beyond fabrication feasibility, scalability also impacts material use and associated cost. Table 5 outlines estimated material requirements and total costs for different size scales, illustrating how larger models, while offering greater anatomical fidelity, increase material demand proportionally.

Anatomical variability among sea lions, such as differences in age, sex, and body condition, primarily influences overall body dimensions and soft-tissue thickness rather than the relative positioning of vascular landmarks used in blood collection. As such, the presented model captures the essential anatomical features necessary for procedural training across a representative range of adult morphologies. Future work may incorporate morphometric data from multiple individuals to expand this approach into a scalable model library, supporting a wider range of training scenarios and species-specific variations.

Beyond its immediate application in veterinary training, the workflow presented here of converting DICOM-standard medical images into scalable, engineered 3D models has broader relevance across multiple disciplines. Similar imaging-based modeling frameworks can support soft robotics design, bioinspired engineering, and the development of biocompatible implants for cardiac, orthopedic, or neural applications. Recent advances in soft materials and electroactive systems have shown that image-driven fabrication pipelines can bridge biological form and functional engineering design^{33–35}. In this context, the phantom fabrication process described here not only serves as a case study in species-specific model development but also as a scalable approach for reproducing complex biological architectures for diverse research and training purposes.

Conclusion

In this study, a phantom model of a California sea lion pelvis was successfully fabricated for blood collection training. Using the described workflow, DICOM-standard medical images were converted into 3D models through Simpleware ScanIP software, enabling the fabrication of an anatomically accurate engineered model with material properties that closely resemble their biological counterparts. Dynamic mechanical analysis (DMA) was employed to characterize the material stiffness of the Humimic gelatin material at the caudal gluteal blood collection site, emphasizing the purpose to material match in order to simulate the tactile response trainees would expect on the live animal. With a fabrication time of approximately three days, the phantom model demonstrates adaptability for a wide range of anatomical training purposes – provided relevant medical images are available.

Future research will focus on enhancing the functionality of the phantom model. Viscosity testing of artificial blood using a viscometer will ensure that the simulated fluid dynamics closely mimic those of real blood, further improving the training experience. In addition, incorporating smart materials for sensing feedback can be seamlessly integrated into the structure of the model, allowing real-time monitoring of trainee performance. The compatibility between these smart materials and medical gels will also be investigated to address challenges in integration.

The future direction of this research will be toward integrating compliant electroactive materials into the phantom. Electroactive polymers (EAPs) such as polyvinyl chloride (PVC) gels, and hydrogels with additive conductors (carbon nanotubes, polyaniline, etc.) and ionic polymer-metal composites (IPMCs) are novel candidates for phantom electroactive platforms^{36–40}. Inspired by Hunt et al.'s incorporation of coiled polymer actuators into a biomimetic harbor porpoise pectoral flipper, similar methodologies using Simpleware ScanIP data may be applied to further electroactive polymer biomimicry⁴¹. These advancements will contribute to developing versatile medical phantom models, broadening their applications in training and soft robotics. By combining innovative material science with computational modeling, this research lays the groundwork for a new generation of customizable and responsive training tools.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

N.M. and D.F. conceived the experiments(s), N.M. processed and modeled the CT scan data, D.F. fabricated the models and conducted materials testing, N.M., D.F., and K.J.K. analyzed the results, A.M. provided the CT scan data, initial concept, and advised on California sea lion biology and blood collection procedure, K.J.K. is the supervisor of D.F. and N.M., All authors reviewed the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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