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3D Printing in Medicine

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Utilization of 3D printing modeling techniques in the simulation instruction of ultrasound-guided puncture procedures on scoliotic spines of spinal muscular atrophy

Di Xia[1], Fangliang Xing[2], Jiao Zhang[1], Jiaxin Lang[1], Gang Tan[1] and Xulei Cui[1*]

Abstract

Background Puncture training with simulation models has emerged as a critical method for transmitting puncture skills, improving success rates, and minimizing injuries. Yet, obstacles such as proper material for ultrasound guidance, restricted options of 3D printing resources, and available substances to simulate human skin and muscle still hinder the production of simulation models that closely replicate clinical practice. This study aimed to develop a selective laser melting (SLM), 3D-printed simulation model that replicated the spine and skin contours of patients with spinal scoliosis.

Methods The 3D models of the scoliotic spines were developed from 3D reconstructions of high-resolution, computed tomography images from patients with spinal scoliosis, while the models of the skin to the bone structure were constructed based on the 3D reconstructions of the skin contours. SLM technology was used to print 3D models of the patients' spines. Gelatin casting was implemented to simulate the patients' skin and muscle tissues and to meet ultrasound anatomical requirements. Practical puncture training, which closely resembles clinical puncture practice, was then carried out to validate the effectiveness of the model. Improvements in proficiency and confidence in performing ultrasound-guided punctures after the simulation-model training were evaluated using the paired sample *t* test.

Results This research utilized 3D digital modeling, SLM 3D printing technology, and gelatin casting to establish simulation models of patients' spines and skin contours impacted by spinal scoliosis. The use of medical grade stainless steel material for modeling the spine and gelatin for skin and muscle tissues ensured the model had superior ultrasound anatomical properties. After the simulation training session, participants' proficiency and confidence in both ultrasound-assisted positioning and real-time guided puncture showed significant improvement, demonstrating the effectiveness of the simulation training model.

Conclusions The simulation model closely mimicked real clinical situations and was an effective training tool for medical professionals. Furthermore, these findings demonstrated the potential of 3D printing technology in

*Correspondence:
Xulei Cui
cuixulei10685@pumch.cn

Full list of author information is available at the end of the article

developing simulation models that closely replicate real-world clinical scenarios and may have significant implications for medical education and training.

Keywords Selective laser melting (SLM), 3D printing, Gelatin casting, Puncture training, Simulation models, Spinal muscular atrophy

Background

Puncture training is essential for equipping healthcare professionals with the skills required for safe and precise procedures [1]. This is particularly crucial for patients with spinal muscular atrophy (SMA), whose spinal deformities make punctures challenging even for experienced practitioners [2]. Mastery of these procedures demands extensive practice, especially given the unique complexities of SMA cases [3]. However, due to the rarity of SMA, patient numbers are limited [4]. The intricate nature of puncture procedures and the associated risks make acquiring sufficient hands-on experience difficult in real-world clinical settings. As a result, developing effective training methodologies for puncturing complex spinal deformities in SMA patients remains a significant challenge [5]. Addressing these challenges is critical for advancing medical education and ensuring healthcare professionals' proficiency in managing such cases.

In recent years, simulation models have become essential for practical training [6, 7]. Key challenges in their development include selecting materials with suitable acoustic properties for ultrasound guidance, replicating human skin and muscle anatomy, and ensuring a realistic tactile response to puncture needles.

Advancements in digital modeling and 3D printing have improved simulation model development [8, 9]. However, limitations in printing materials and difficulties in replicating complex anatomical structures remain significant obstacles. Patients with spinal deformities, such as those with SMA, often exhibit not only spinal abnormalities but also soft tissue and skin deformations, complicating probe placement and puncture path planning. While 3D-printed spinal models based on real patients have been reported [10, 11], they fail to accurately simulate soft tissue and skin, limiting their effectiveness in providing realistic training experiences.

To meet the needs of the profession for this highly specialist medical training, particularly in patients with SMA and the associated spinal deformities, we developed an innovative simulation model that meticulously replicates the spine and skin contours of patients with spinal scoliosis.

Methods

Digital modeling and 3D printing for accurate scoliosis simulation

Patient-specific data acquisition and processing

The process begins with high-resolution CT (HRCT) scans to capture the structural features of scoliotic spines. Scans were performed using a Siemens CT machine at Peking Union Medical College Hospital (Beijing, China) with the following parameters: Modality—CT; Station Name—CTAWP73555; Study Description—Spine_CTM_Customized (Adult); Implementation Version—CENTRICITY_3.0; Slice Thickness—0.6 mm; Pixel Spacing—0.6934 mm.

The resulting 3D reconstruction (Fig. 1) represents the scoliotic spine from the thoracic to sacral vertebrae. For lumbar puncture training, we focus on the T12 to S1 segment. To isolate this region, a volume slicer GUI (Fig. 2) is used to precisely extract the relevant HRCT data. This selective modeling approach optimizes computational efficiency while preserving essential anatomical structures for training.

Advanced digital modeling

Our approach focuses on precise digital modeling of both the scoliotic spine and the overlying skin. Using computer-aided design (CAD) software, we create a 3D virtual model that accurately replicates the complex spinal geometry, including vertebral bodies, pedicles, and articular processes.

Additionally, we model the patient's skin, emphasizing its spatial relationship with the deformed spine (Fig. 3). To facilitate puncture simulation, designated skin areas are strategically left open, exposing only the scoliotic spine. This innovative design allows for the integration of multiple materials to simulate various tissue layers, significantly enhancing model realism.

Innovative 3D printing techniques

To achieve high anatomical accuracy, we employ two advanced 3D printing technologies:

a. Stereolithography (SLA) for Skin Surface.

Using an M6 industrial-grade SLA printer, we produce a high-resolution skin model with the following parameters:

- Layer thickness: 0.05 mm.

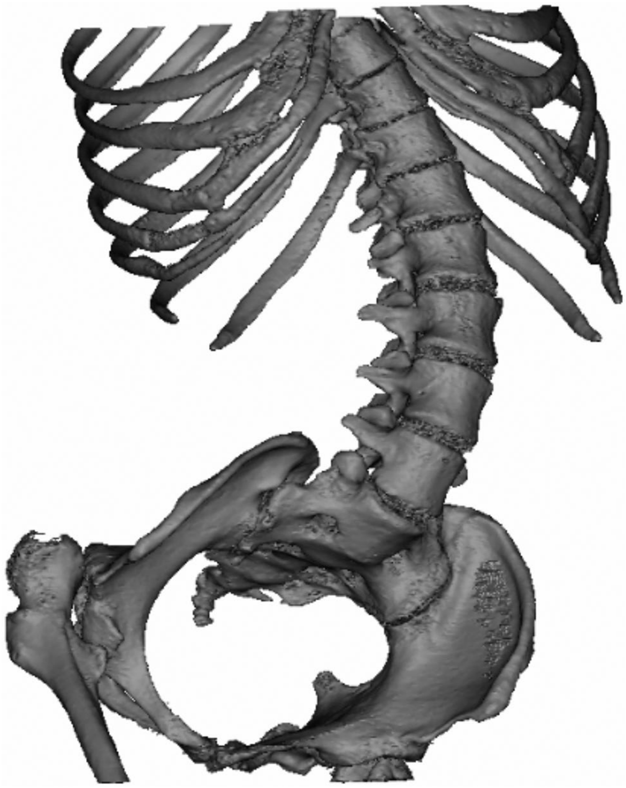

Fig. 1 3D spinal reconstruction of scoliosis

- Laser power: 250 mW.
- Scanning speed: 3000 mm/s.
- Resin type: Biocompatible clear resin (USP Class VI certified).

This ensures an anatomically precise skin surface while maintaining spatial alignment with the underlying spine.

b. Selective laser melting (SLM) for spine structure.

The spine is printed using SLM technology with medical-grade stainless steel (316 L), chosen for its ability to replicate the acoustic properties of bone. The optimized SLM parameters include:

- Layer thickness: 30 microns.
- Laser power: 200 W.
- Scanning speed: 900 mm/s.
- Hatch spacing: 0.1 mm.
- Oxygen level in build chamber: <0.1%.

These settings ensure accurate mechanical properties, structural integrity, and ultrasound compatibility.

Precision and post-processing

The final printed spine model (Fig. 4) maintains an error margin of less than 0.02 mm at a 1:1 scale, achieved through:

- High-precision SLM calibration.
- Optimized build orientation to minimize distortion.
- Post-processing steps, including stress relief heat treatment and precision machining.

Further processing includes:

- Stress relief heat treatment (300 °C for 2 h) to reduce residual stress.
- Wire EDM cutting to detach the model from the build plate.
- Bead blasting for improved surface finish and ultrasound properties.
- High-resolution CT scanning and ultrasound testing to verify structural and acoustic accuracy.

Model assembly and tissue simulation

To enable realistic lumbar puncture training, the area between the vertebral body and skin is filled with flexible materials simulating soft tissues. The selected filling material must:

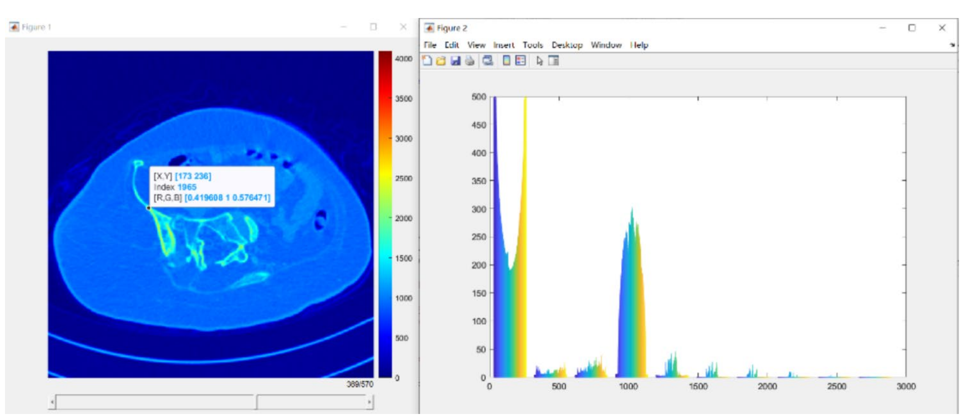

Fig. 2 3D volume reconstruction and intensity distribution of a scoliotic spine

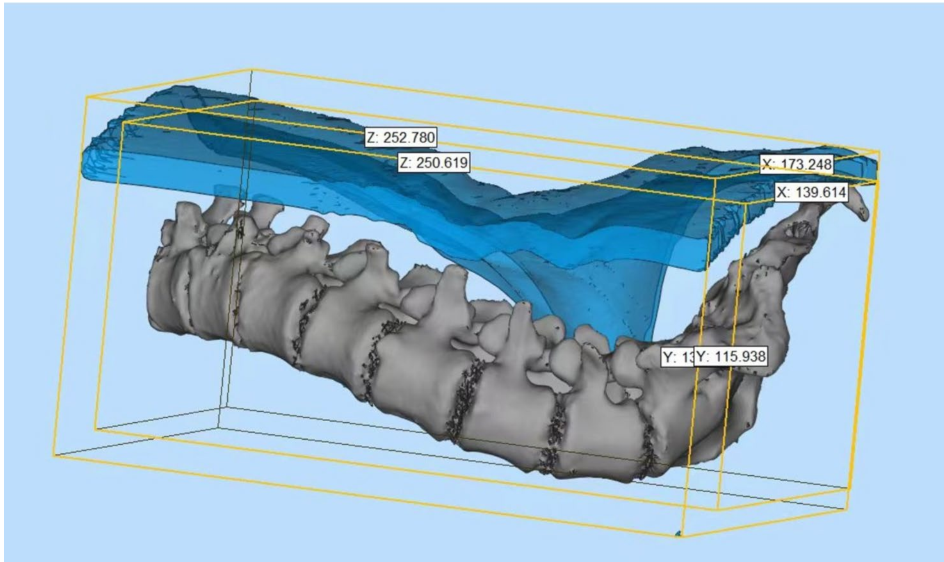

Fig. 3 Digital modelling graphics with epidermal structures

Fig. 4 3D printed part of the digital model

1. Mimic the softness of human skin and muscle.
2. Differ in ultrasound properties from the spine.
3. Provide realistic needle feedback.
4. Be durable and reusable.

Soft gelatin (Shore hardness A0) was identified as the optimal material after extensive testing.

The gelatin was poured in a controlled process:

1. A hollow section served as a mold, with a separately printed skin component acting as a barrier.
2. The gelatin was mixed with a curing agent (1:1 ratio), ensuring homogeneity and air bubble elimination.
3. The mixture was poured through a small reserved hole and left to set for 12 h.

The final model (Fig. 5) includes a silicone rubber layer, while ultrasound imaging (Fig. 6) confirms excellent ultrasound-guided performance. A customized base further stabilizes the model for training, aligning with the patient's anatomical features for enhanced accuracy.

Verification of the model's effectiveness

To assess the effectiveness of the training model, 33 anesthesiologists and neurologists participated in ultrasound-guided lumbar puncture training. The training consisted of three components:

- Theoretical Instruction– A lecture on positioning and real-time ultrasound guidance for lumbar puncture.
- Case Demonstration– Practical demonstrations of lumbar puncture procedures under ultrasound guidance.
- Hands-on Practice– Simulation-based training, allowing participants to perform ultrasound-guided lumbar puncture.

Fig. 5 Simulated model for lumbar puncture training filled with gelatin casting

Participants' confidence and proficiency were evaluated through pre- and post-training questionnaires (Appendix 1), while overall training quality was assessed via a satisfaction survey. The effectiveness of the simulation tools was statistically analyzed using a paired sample t-test. This study was reviewed and approved by the Ethics Committee of Peking Union Medical College Hospital.

Results

Utilizing SLM 3D printing technology, we developed a simulation model that closely replicates the anatomy of patients with spinal scoliosis. This model offers a realistic depiction of bone structure for training, and its ultrasound performance is enhanced by using gelatin to simulate skin and muscle tissues (Figs. 5 and 6).

Evaluated as clinically applicable, the model provides lifelike skin and muscle textures along with an authentic needle insertion experience, making it ideal for training clinicians in complex lumbar puncture procedures.

Table 1 summarizes assessment scores, which indicate that participants significantly improved their proficiency and confidence in both ultrasound-assisted positioning and real-time guided puncture after the training sessions and simulation exercises.

Discussion

Our research addresses a key challenge in medical education: developing accurate simulation models for lumbar puncture training, particularly in patients with scoliosis. Traditional methods struggle to replicate the complex spatial relationships between a deformed spine and the skin surface, limiting training effectiveness. To overcome these limitations, we leverage advanced 3D printing technology.

Our study demonstrates that a lifelike lumbar puncture training model significantly enhances learning outcomes. The model is created using selective laser melting (SLM) 3D printing combined with sophisticated gelatin casting techniques. High-resolution CT (HRCT) scans provide the foundation for precise 3D reconstruction of the scoliotic spine, with medical grade stainless steel chosen for its compatibility with imaging modalities. Gelatin, which mimics the properties of human skin and muscle, ensures a realistic tactile experience. This approach offers a more precise representation of intricate anatomy, particularly in complex puncture scenarios associated with severe spinal scoliosis. By faithfully replicating clinical conditions, trainees can refine their skills and better prepare for real-world procedures [12, 13].

The strategic employment of these materials in our model not only facilitates a realistic representation of the human anatomy, but also enhances the educational efficacy of the simulation. This combination of medical grade stainless steel and gelatin also ensures that our model possesses ultrasound anatomical properties. The model's fidelity in ultrasound imaging and tactile feedback offers a immersive training experience, bridging the gap between theoretical knowledge and practical clinical skills. Practice of ultrasound-assisted positioning is particularly relevant as ultrasound guidance becomes increasingly prevalent in puncture procedures [14–17]. Having a model that accurately reflects this technology can notably improve the training outcomes and ensure medical professionals can be more confident in handling clinical complexities [18].

The application of 3D printing in spinal puncture training is well-supported in the literature, yet significant challenges remain in teaching puncture techniques for spinal muscular atrophy (SMA) patients. (1) These patients exhibit not only spinal deformities but also soft tissue and skin irregularities, making accurate puncture path selection highly dependent on clinical experience. (2) SMA is a rare disease with considerable anatomical variability among patients, limiting hands-on training opportunities. Our study integrates 3D-printed spinal deformity models with gelatin-based soft tissue replicas,

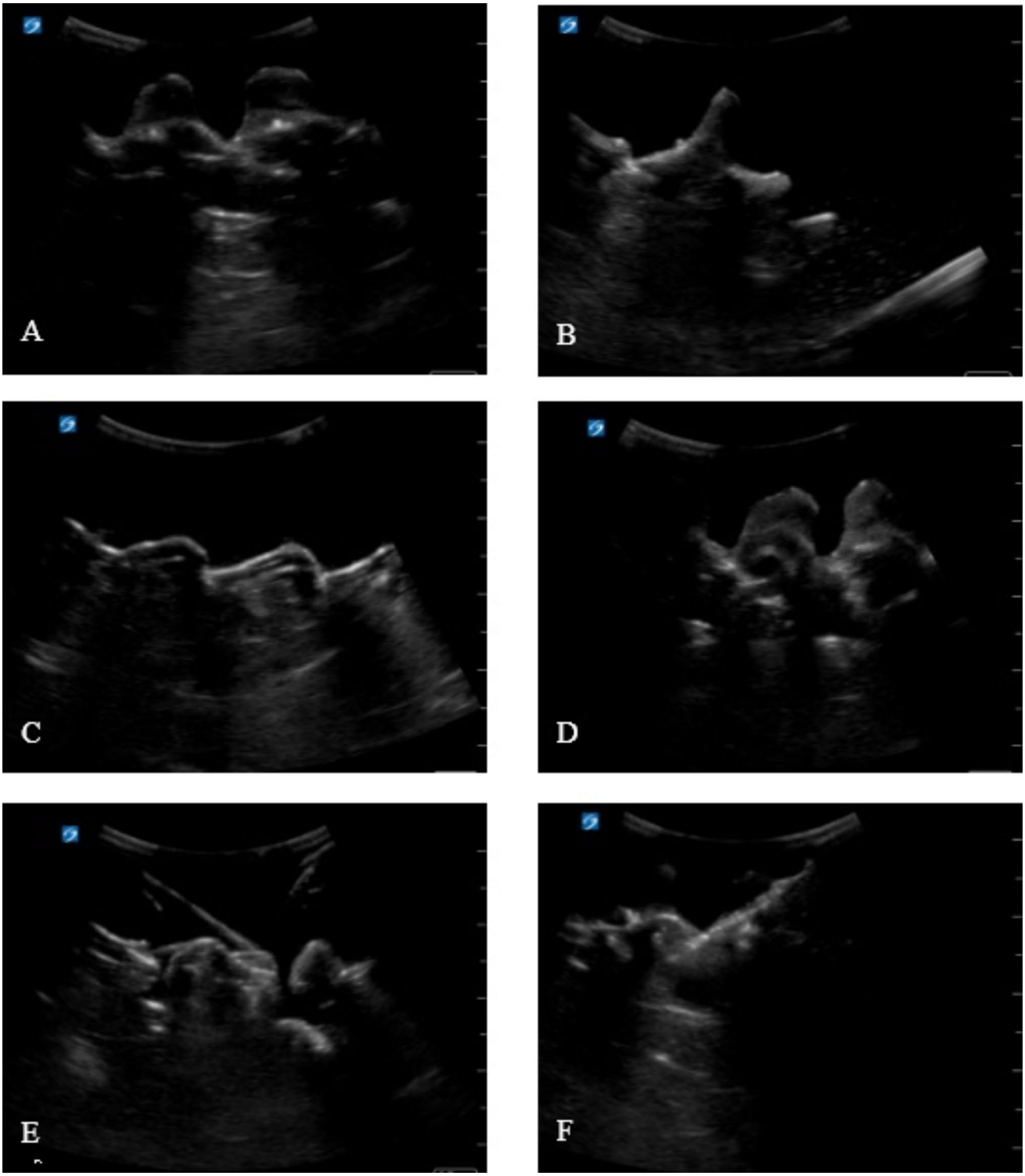

Fig. 6 Ultrasound image of a typical puncture plane of the model. Pictures A and B show coronal ultrasound images of the spine; Pictures C and D show sagittal ultrasound images of the spine; Pictures E and F show the ultrasound images of paravertebral puncture

accurately simulating the appearance, texture, and tactile properties of SMA patients' back tissues. This approach enables realistic simulation, localization, and procedural practice, addressing key challenges and offering new perspectives for spinal puncture training.

Digital modeling technology played a crucial role in our study, allowing for the precise design and physical replication of the training model. This controlled environment enables trainees to develop competence before performing procedures on actual patients [19].

Table 1 Participants' confidence and proficiency in ultrasound-guided lumbar puncture

Questionnaire	Before training	After training	Difference	*p* value
How confident are you that you can successfully perform a successful lumbar puncture maneuver on a patient with a normal spinal structure?	7.76 ± 2.15	9.33 ± 1.33	1.57 ± 1.48	<0.001
How confident are you that you can successfully identify and localize the spinous processes and the puncture space when performing a lumbar puncture with ultrasound-assisted localization in a patient with normal spinal structures?	4.52 ± 2.65	8.73 ± 1.55	4.21 ± 2.31	<0.001
How confident are you in successfully identifying the ventral and dorsal unions and locating the depth of puncture when performing a lumbar puncture with ultrasound-assisted localization in a patient with normal spinal structures?	4.12 ± 2.63	8.82 ± 1.36	4.70 ± 2.20	<0.001
What is your level of confidence in performing real-time ultrasound-guided lumbar punctures in the intervertebral space in patients with normal spinal structures?	4.61 ± 2.79	8.48 ± 1.46	3.88 ± 2.11	<0.001
What is your level of confidence in performing real-time ultrasound-guided lumbar puncture in a patient with normal spinal structure to successfully visualize and identify the ventral and dorsal unions through the intervertebral space?	4.15 ± 2.65	8.64 ± 1.45	4.49 ± 2.14	<0.001
How confident are you in performing a successful lumbar puncture maneuver on a patient with SMA with a spinal deformity?	4.12 ± 2.56	7.64 ± 1.80	3.52 ± 2.39	<0.001
How confident are you at being able to successfully identify and localize the spinous processes and puncture space when performing an ultrasound-assisted localization of a lumbar puncture in a patient with SMA with a spinal deformity?	3.45 ± 2.53	7.79 ± 1.98	4.33 ± 2.40	<0.001
How confident are you in performing an ultrasound-assisted localization of a sublumbar puncture in a patient with SMA with a spinal deformity and being able to successfully visualize and identify the ventral and dorsal unions and locate the depth of the puncture?	3.27 ± 2.65	7.45 ± 1.91	4.18 ± 2.49	<0.001
How confident are you at being able to successfully identify and localize the intervertebral space when performing a real-time ultrasound-guided lumbar puncture in a patient with SMA with a spinal deformity?	3.30 ± 2.65	7.36 ± 1.83	4.06 ± 2.59	<0.001
How confident are you in performing real-time ultrasound-guided lumbar puncture maneuvers for patients with SMA with spinal deformities and successfully visualize and identify the ventral and dorsal unions via the intervertebral plate space?	3.18 ± 2.69	7.18 ± 1.93	4.00 ± 2.55	<0.001

SMA = spinal muscular atrophy

Despite its advantages, the lumbar puncture model has areas for improvement. Refining the puncture needle to minimize interface resistance with gelatin is necessary. Additionally, integrating mixed-reality technology for procedural guidance is in progress and expected to enhance training efficacy. Beyond education, this technology facilitates the replication of patient-specific spine and soft tissue models, allowing anesthesiologists to pre-plan and adjust puncture paths during procedures. This transition from training to clinical application has the potential to enhance patient care quality.

In summary, the use of SLM 3D printing and gelatin casting in developing a realistic lumbar puncture training model holds significant promise for clinical education. This approach offers an accurate, customizable solution that could revolutionize puncture training. While challenges remain, its potential benefits make it an exciting prospect for the future of medical training.

Conclusions

This study illustrates a unique method for constructing simulation models of spines and skin contours of patients with spinal scoliosis using SLM 3D printing technology. By employing gelatin to emulate real muscle and skin tissues, a simulation model was created that closely mirrored actual clinical scenarios. Practical training with this model resulted in substantial enhancements in puncture training effectiveness.

The use of SLM 3D printing technology has yielded a model that aligns closely with the anatomy of patients with spinal scoliosis, thereby improving the precision of needle insertion during puncture procedures. Furthermore, the anatomical properties of the model met the requirements for ultrasound guidance, making it ideal for use in training for ultrasound-assisted positioning. The model's authentic texture, resembling skin and muscle tissues, coupled with its lifelike needle insertion experience, marks it as a valuable tool for training medical professionals in complex lumbar puncture scenarios.

Creating training models that emulate the tactile feel of actual punctures is crucial in the development of medical training models. These models have the potential to significantly improve patient outcomes and decrease the clinical risks associated with puncture procedures. The findings of this study underscore the potential of 3D printing technology in the creation of simulation models that faithfully replicate real-life clinical scenarios, and carry profound implications for the future of medical education and training.

Abbreviations

HRCT	High-resolution computed tomography
SLM	Selective laser melting
SMA	Spinal muscular atrophy

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s41205-025-00266-x.

Supplementary Material 1

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Author contributions

Di Xia, Fangliang Xing and Xulei Cui conceived, designed, and implemented this study. Di Xia, Jiao Zhang and Jiaxin Lang collected the data. Di Xia completed the statistical analysis and interpreted the data. Di Xia drafted the manuscript. Xulei Cui and Gang Tan revised it critically. All authors have approved the manuscript for publication and there is no conflict of interest in this submission.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

The institutional review board of Peking Union Medical College Hospital reviewed our study protocol (I-23ZM0027). It classified our study as "exempt" because this study utilized legally obtained existing anonymous data, did not interfere with public behavior, did not cause harm to the human body, did not involve sensitive information, and did not touch upon commercial interests. The requirement of written informed consent was also waived by the institutional review board.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Anesthesiology, Peking Union Medical College Hospital, Beijing, China

[2]Beijing Intelligent Entropy Science & Technology Co Ltd, Beijing, China

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