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Evaluating the efficacy of a cost-effective, fully three-dimensional-printed vertebra model for endoscopic spine surgery training for neurosurgical residents

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Study Design: A fused deposition modeling three-dimensional (3D)-printed model of the L4–5 vertebra for lumbar discectomy was designed. The model included separately printed dura mater, spinal cord, ligamentum flavum, intervertebral disc (from thermoplastic polyurethane), and bony structures (from polylactic acid), and the material cost approximately US$ 1 per model. A simple plumbing endoscope was used for visualization. Dura mater injury was assessed by painting two layers on the dura mater, which peeled off with trauma.

Purpose: Endoscopic spine surgery is a subject of high interest in neurosurgery given its minimally invasive nature; however, it has a steep learning curve. This study evaluated the effectiveness of a cost-efficient 3D-printed model when teaching this technique to neurosurgery residents.

Overview of Literature: Only a few studies have investigated the efficacy of such a model.

Methods: Eight residents with >2 years of training participated. Residents performed the procedure bilaterally and twice at 1-week intervals.

Results: From the 32 surgeries, four were excluded because of facet removal (as it widened the surgical corridor), leaving 28 surgeries for analysis. Initial surgeries demonstrated a mean operation time of 21 minutes 18 seconds (standard deviation [SD], 2 minutes 32 seconds), which improved to a mean of 6 minutes 45 seconds (SD, 37 seconds) in the fourth surgery (F(3, 17)=19.18, p<0.0001), demonstrating a significant reduction in surgical time over successive surgeries. The median area with the paint removed decreased, from 161.80 (85.55–217.83) to 95.13 mm^2 (12.62–160.54), (F(2.072, Inf)=2.04, p=0.128); however, this was not significant. Resident feedback indicated high satisfaction with the educational value of the model.

Conclusions: The developed fully 3D-printed model provides a viable and scalable option for neurosurgical training programs, enhancing the learning experience while maintaining low costs. This model may be an excellent stepping stone for learning lumbar spine endoscopy, acclimating to the two-dimensional view, progressing to cadaver models, and, eventually, independent surgery.

Keywords: Endoscopes; Residency; Minimally invasive surgical procedures; 3D printing; Simulation training

Introduction

In recent years, endoscopic spine surgery has gained notable interest, specifically in the lumbar region, because of its minimally invasive characteristics. This procedure is associated with reduced operative time, diminished blood loss, shorter hospital stays, and faster overall patient recovery in comparison with typical open surgeries [1-5]. Despite these advantages, the transition to endoscopic techniques presents a significant challenge because of its steep learning curve. The issue stems from the need to adapt to a two-dimensional view, which contrasts with the three-dimensional (3D) perspective in open surgery. In addition, the restricted working space and specialized instrument skills further increase the difficulty, so inexperienced surgeons may easily make mistakes that could lead to serious complications, such as root injury or dural tear [6-10].

Given the difficulties involved, training in models is essential to obtain the requisite skills and confidence in endoscopic spine surgery. Conventional training techniques, including using cadaveric dissections, provide excellent practical knowledge and accurate anatomical representation of actual surgical situations. However, these methods have their limitations. Cadaveric teaching is often expensive, and the difficulties in obtaining and preserving cadaver specimens might restrict their availability, particularly in resource-limited settings. This constraint presents a substantial obstacle to universal training.

Furthermore, the lack of bleeding in cadaveric tissue may result in a misleading perception of the surgical environment, potentially instilling a false sense of confidence in trainees. This discrepancy between cadaveric training and live surgery can result in a gap in the surgeon's preparedness, as the critical skill of managing intraoperative bleeding is not adequately accomplished.

In response to these challenges, cost-effective alternatives such as 3D-printed models have emerged as viable solutions for surgical training [11-15]. These models can be produced at a fraction of the cost of cadaveric specimens, providing consistent and controlled environments for repeated practice. Furthermore, these simulators can be customized to replicate specific surgical situations, enabling safe training. However, the cost of these simulators may render them unusable on a wide scale in low-resource settings.

By utilizing a simple plumbing endoscope and a fully fused deposition modeling (FDM) 3D-printed model of the L4–5 vertebra, a highly accessible and semi-realistic training setup was developed for neurosurgery residents. This study of the efficacy of the developed model aimed to close the divide between theoretical knowledge and practical abilities by offering basic training for residents to safely enhance their proficiency in lumbar endoscopic spine surgery before progressing to more complex training tools.

Materials and Methods

Ethical standards and participant consent

This study adhered to the principles outlined in the Declaration of Helsinki. Ethical approval was obtained from the Ege University Medical Research Ethics Committee (decision no., 24-4.1T/17; April 25, 2024), ensuring that all research involving human subjects was conducted in accordance with internationally recognized ethical standards. Informed consent was obtained from all participating neurosurgery residents before their involvement in the study.

Model preparation

Using lumbar spine model files that were licensed under Creative Commons Attribution 4.0 International provided by Espinoza Orias et al. [16], a model of the L4–5 level, complete with dura mater and roots and separate ligamentum flavum and intervertebral disc, was created.

Meshmixer ver. 35.0 (Autodesk, San Francisco, CA, USA) was used to separate the lamina from the pedicles and add anchoring points to secure the lamina back to the vertebral body. Changing only the lamina and soft tissue parts between trainees reduced costs, printing times, and carbon footprint.

3D Slicer was used to create a dura mater and nerve root model that would fit into the model [17]. Autodesk Fusion ver. 2.0.x (Autodesk) was used to create a flavum model that would attach to the anchor points, as well as the rigid box and the skin made from thermoplastic polyurethane (TPU) that would house the model and provide a dark chamber.

The files were then printed using a FDM 3D printer Ender-3 S1 (Creality, Shenzen, China). Polylactic acid (PLA) was used to print the rigid parts (enclosure, pedicles, and lamina), whereas TPU was used to print the soft tissue parts. The printing settings and relevant files are available in our repository (https://github.com/AkbulutBB/3DEndoscopeModel).

The models of the dura mater and roots were first dyed with red acrylic paint, followed by a second coat

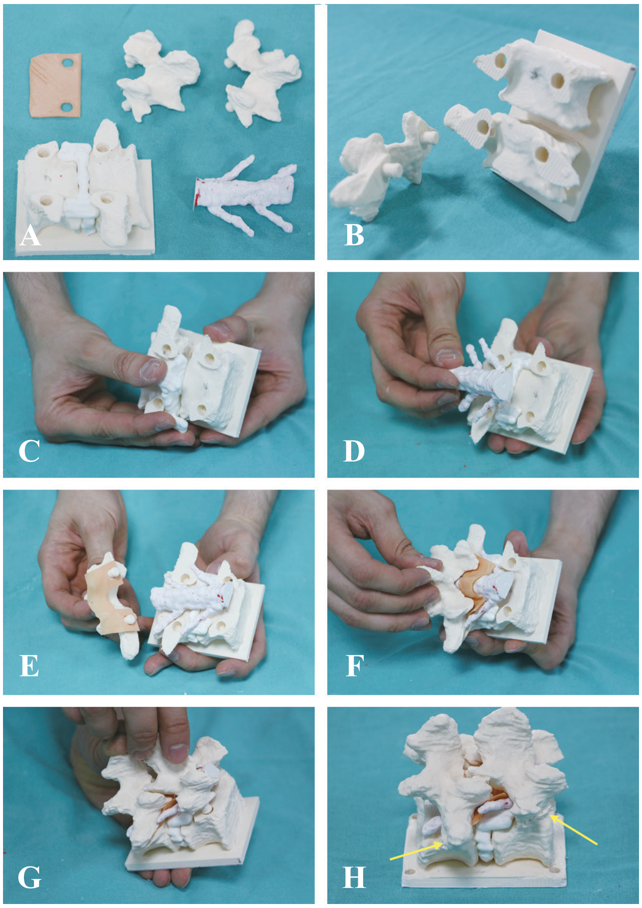

Fig. 1. The assembly process requires the ligamentum flavum, the L4 lamina, the L5 lamina, the vertebral bodies attached to a base, the intervertebral disc, and the painted dura mater with roots **(A)**. The attachment base and laminas have pins for precise placement and durability **(B)**. The first step is to insert the intervertebral disc into its place **(C)**. Then the dura mater with roots is placed in its position **(D)**. Ligamentum flavum, now attached to the L5 pins **(E)**, is inserted into its place **(F)**. The L4 lamina is inserted into its pins **(G)**, and both laminas are welded with a three-dimensional pen (yellow arrows) **(H)**.

of white paint that came off. This allowed us to assess the amount of trauma the trainee did to the dura mater and roots as the paint peeled off during the manipulation of tools.

A 3D pen was used to weld the lamina to the pedicles in an easily removable manner. It was also durable enough to resist removal by the Kerrison rongeurs. Fig. 1 shows the assembly process and the model. The chamber was then assembled using readily available 2-mm screws and nuts and attached to a plywood board to provide stability (Fig. 2). The box was then covered with a black sheet to provide a dark chamber and ensure that the residents worked using only the endoscopic footage (Fig. 3).

Moreover, 67.43 g of PLA filament (approximately US$ 0.74) was used during the production of the body and pedicles, which were used for eight surgeries with some deformation but could be used possibly more. The dura mater, roots, and flavum required 13.96 g of TPU filament (US$ 0.42), and the lamina required 45.63 g of PLA filament (US$ 0.50). The model costs approximately US$ 1.013 per training session. The assembly and disassembly of the model took 30 minutes, and the total printing time was 10 hours before each session. Fortunately, the printing process is autonomous and requires minimal monitoring.

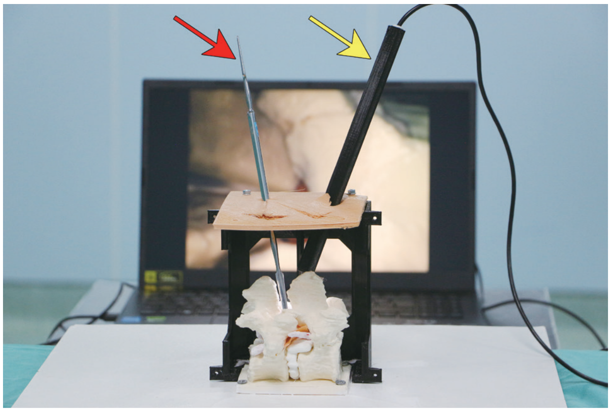

Fig. 2. The finished model with its one side removed. A dura separator (red arrow) and our simulator endoscope (yellow arrow) are inserted through the thermoplastic polyurethane-based skin. A laptop computer is used for visualization of the endoscopic view.

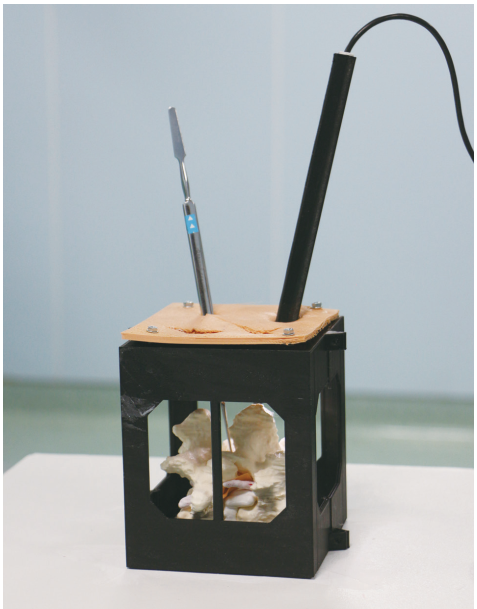

Fig. 3. Assembled version of the model. A black cardboard wrap held with long tail clips was used in our study to force the trainee to use the endoscopic view, but surgical sheets may also be used.

Subject selection and the procedure

Residents in their second postgraduate year were deemed capable of being on-call and performing emergency procedures at Department of Neurosurgery, Ege University Faculty of Medicine (Izmir, Turkey).Thus, eight residents who had >2 years of training were enrolled. Out of the total, four residents had previously conducted microscopic lumbar discectomy, whereas the remaining four only provided assistance during the procedure. None of the residents previously performed or assisted endoscopic lumbar discectomy. All residents were right-hand dominant.

The residents were provided with a Midas Rex drill (Medtronic, Dublin, Ireland), disk forceps, Kerrison rongeur, and a dura mater separator. For visualization, an affordable plumbing endoscope (Kebidumei, Dongguan, China) was utilized. It cost US$ 20 and had a 3D-printed PLA handle to ensure rigidity. Irrigation was provided by affixing a saline intravenous line to the drill handle using tape.

After a presentation on lumbar discectomy utilizing the unilateral biportal endoscopic approach, the model was presented to the residents, who allowed to examine the model using the endoscope. Once the trainees gained sufficient confidence in using the endoscope, they were instructed to thin the lamina using the high-speed drill, remove it with Kerrison rongeurs to allow for discectomy, and then release the ligamentum flavum from the superior border of the lamina and remove it using forceps. After that, they were asked to identify the root and neural foramen. The procedure was considered complete after the residents successfully placed a dissector into the disk space. In each session, the residents first performed the procedure on the right side of the model (simulating a unilateral approach), and the instructor provided feedback. Then, they performed the procedure on the left side of the model, receiving additional feedback to conclude the session.

All training sessions were conducted after working hours (between 18:00 and 20:00) to minimize interruptions and enhance standardization. After the surgical procedure, the residents were instructed to complete a Likert scale questionnaire regarding the training session (Supplement 1), details of which are provided in Fig. 4.

Assessment of the surgery

During the surgical procedure, the residents received instructions in the initial session, and questions thrown in the subsequent sessions were responded accordingly. The surgical time, facet injury, and root injury were documented.

After surgery, the lamina was carefully removed using pliers. The amount of paint that peeled from the dura mater, which indicated trauma, was assessed by two blinded raters using a scale of 1–4 (Fig. 5). This scale considered the extent of paint removal, ranging from no damage, where neither the white nor the red paint layers were peeled, to severe damage, where the underlying TPU-based dura mater model was damaged directly. The median of the two raters' assessments was used for the final score. The surface area with the paint removed was also assessed with ImageJ (National In-

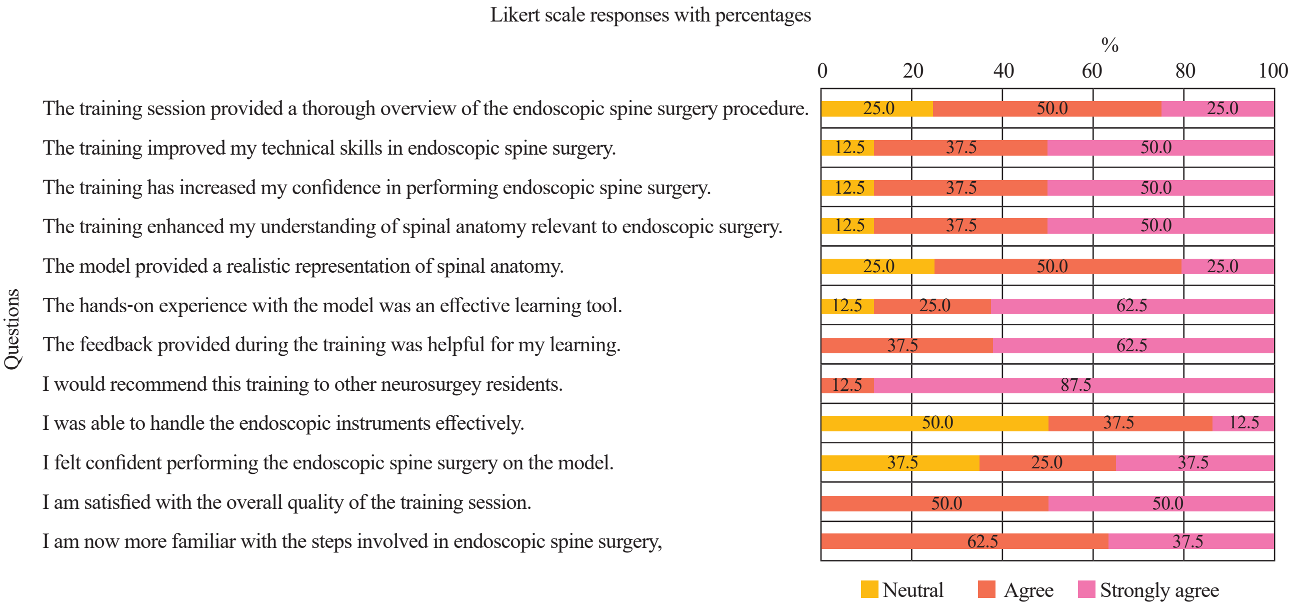

Fig. 4. The Likert scale results have shown that residents were overall satisfied with the training, the details of which can be seen in the Supplement 1.

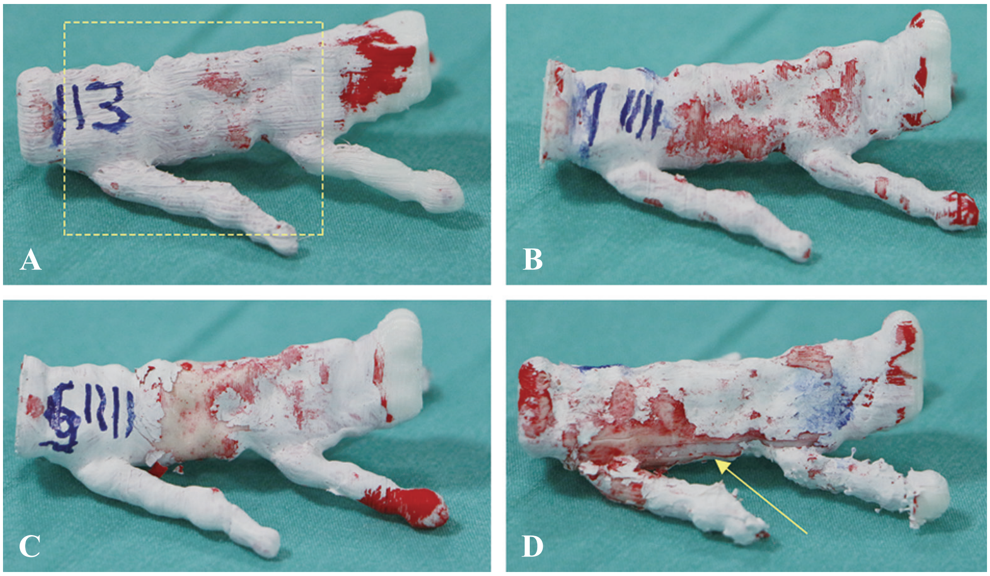

Fig. 5. The amount of peeled paint is used as an indicator of damage to the dura. The area marked with the yellow dashed square is assessed. **(A)** No damage. **(B)** Only white paint peeled. **(C)** Both the white and red paint peeled. **(D)** Direct damage to the thermoplastic polyurethane model. The line where the model was torn is marked with the yellow arrow.

stitutes of Health, Bethesda, MD, USA) again with two blinded raters, and the mean of two values was used [18]. The surgeries where the facet was removed were excluded from the study, as they widened the surgical corridor, reducing the challenge of the procedure.

Statistical analysis

Collected data were analyzed using IBM SPSS ver. 27.0 (IBM Corp., Armonk, NY, USA) and R software ver. 4.0.5 (R Foundation for Statistical Computing, Vienna, Austria). Descriptive statistics were used to summarize the data for numerical variables, including the mean, standard deviation, median, minimum, and maximum values. Interrater reliability of our scale was assessed using Cohen's kappa to determine the agreement level between the two raters evaluating dura mater damage and intraclass correlation (ICC) for the ImageJ-based analysis. A mixed-effects model analysis was conducted to assess the improvement in the surgery time by eight residents over four training sessions. Using an unstructured covariance and restricted maximum likelihood (REML) estimation, the model included a random intercept for each trainee. The fixed effect of time on the surgery time was assessed, and pairwise comparisons among different time points were performed using least square means. The Tukey-Kramer adjustment method was applied to control for type I errors in multiple comparisons. The Brunner-Langer model (F1-LD-F1 design) was used to assess the change in the area with paint removed, providing a nonparametric analysis of the extent of dura mater damage over the training sessions. A *p*-value of <0.05 was considered significant.

Results

A total of 16 training sessions and 32 surgeries were performed; however, in four cases, the facet was removed during surgery, so it was not included, resulting in 28 surgeries. Three facet removals occurred during the first surgery and one during the third surgery. Table 1 presents the descriptive features of the trainees and the surgical results. Individual details of the surgeries are provided as supplementary files (Supplement 1).

Cohen's kappa coefficient was calculated for the agreement between the two raters for the 1–4 scale ($k=0.223$), indicating a fair level of agreement. However, for the ImageJ-based analysis, the ICC was 0.997 (95% confidence interval, 0.993–0.998) with an F test of $F(31, 31)=308.345$ ($p<0.001$), and this method was preferred for its higher reliability.

A mixed-effects model analysis was performed to assess the improvement in the surgery time by eight residents over four training sessions. The model, using unstructured covariance and REML estimation, revealed significant fixed effects for time ($F(3, 17)=19.18$, $p<0.0001$). Least-squares means showed that the surgery times decreased from 21 minutes and 14 seconds in the first session to 7 minutes 46 seconds in the fourth session, and all pairwise comparisons between sessions were significant ($p<0.05$). This indicates a substantial and significant improvement in surgery time across the training sessions (Fig. 6).

Table 1. Descriptive features of trainees and the surgical results (n=28)

Variable	Value
Post-graduate year	2.5 (2–5)
Surgery time overall	0:13:11 (0:05:32, 0:05:29–0:24:15)
Surgery time #1	0:21:18 (0:02:32, 0:18:09–0:24:15)
Surgery time #2	0:13:44 (0:04:38, 0:06:40–0:21:21)
Surgery time #3	0:12:58 (0:02:30, 0:09:13–0:16:47)
Surgery time #4	0:07:45 (0:02:29, 0:05:29–0:13:02)
Overall score	3 (1.5–4)
Score #1	3 (2.5–3)
Score #2	3 (1.5–4)
Score #3	3 (3–3)
Score #4	2.5 (2–3)
Overall damaged area (mm^2)	127.20 (12.62–233.29)
Damaged area #1 (mm^2)	161.80 (85.55–217.83)
Damaged area #2 (mm^2)	158.71 (16.67–233.29)
Damaged area #3 (mm^2)	149.57 (113.59–170.84)
Damaged area #4 (mm^2)	95.13 (12.62–160.54)

Values are presented as median (interquartile range) or mean (standard deviation, range).

The median area with paint removed decreased, i.e., from 161.80 (85.55–217.83) to 95.13 mm^2 (12.62–160.54) (F(2.072, Inf)=2.04, $p=0.128$); however, this was not significant (Fig. 7).

Discussion

In this study, the usefulness of a cost-efficient, easily accessible, and fully 3D-printed model as a training model for endoscopic spine surgery for neurosurgery residents at a beginner level was evaluated. The findings indicate a significant improvement in surgical skills and the residents' confidence levels.

The strongest point of our model is its price. It is suitable for use in any resource setting and costs approximately US$ 1 in material. This is nearly 1/100th the price of commercial spinal training simulator and potentially a fraction of cadaveric training. Although the cost of the 3D printer must be considered, it remains a relatively low, one-time purchase, typically under US$ 200, and should be readily available in most settings. In addition, these hobbyist machines can be operated by nearly anyone, and the model files are readily available. Because the major costs associated with similar projects often stem from design and production efforts, which have already been completed, the final cost of produc-

Fig. 6. The individual time of each surgery over time. Each resident is represented with a separate plot line. Excluded surgeries are marked with asterisks. The mean change in overall surgical time across four surgeries is in black ($p<0.001$).

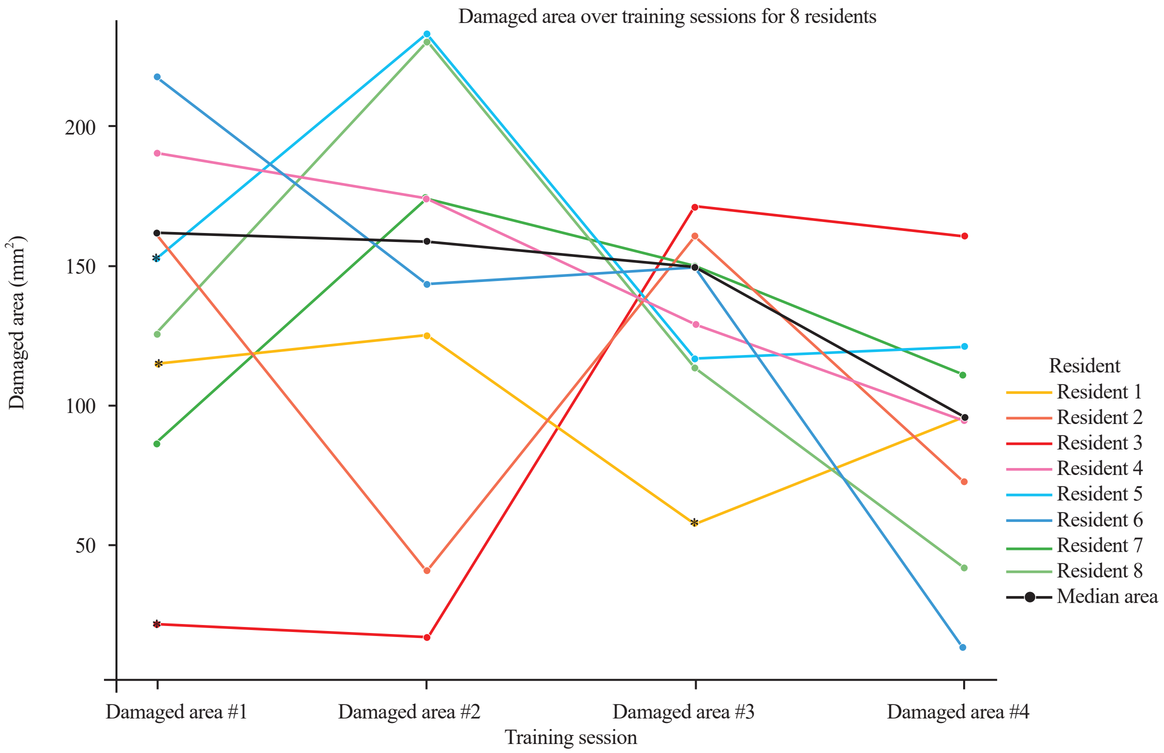

Fig. 7. The individual damaged area of each surgery over time. Each resident is represented with a separate plot line. Excluded surgeries are marked with asterisks. The median amount of damaged area (black line) has shown a trend of decreasing over sessions, yet this was not statistically significant (p=0.128).

ing this model should not significantly exceed the material cost.

In addition to its cost-effectiveness, the developed model also addresses significant ethical concerns associated with traditional training methods. The use of animal models raises ethical issues regarding the welfare and treatment of animals, and cadaver models, although invaluable, involve ethical considerations related to consent, handling, and sourcing of human bodies [19-22].

For model construction, a flexible filament (TPU) was used to mimic the ligamentum flavum, dura mater, nerve roots, and intervertebral disc and thus provide a realistic feel of the surgical procedure. Although these materials are not an exact match for human tissue, they enable the simulation of tissue handling, for example, when removing the ligamentum flavum from the dura mater or palpating the intervertebral disc. Therefore, it allows the residents to perform the technique safely.

Previous studies have used expensive and difficult-to-print materials, such as polypropylene or acrylonitrile butadiene styrene, to simulate the bone, requiring higher-quality FDM printers with specialized printing chambers [12,23]. Conversely, our design can be printed using the most commonly available printers and filaments (PLA and TPU), with increasing availability in all settings.

A valid argument would be against using the Midas Rex drill in training, as these are highly specialized tools that might not be readily available in some settings. However, this training may be conducted using simple engraving tools such as Dremel Stylo+ (Dremel, Racine, WI, USA) [24]. We have also successfully utilized Dremel Fortiflex (Dremel) for this purpose, as it comes with a foot pedal for controlling the drill. However, given its availability, we preferred using Midas Rex to ensure the residents were familiar with the tools provided.

The significant reduction in the mean operation time from 21 minutes 18 seconds to 7 minutes and 45 seconds over four surgeries (p=0.001) and the trend toward reduced trauma, as indicated by the decrease in the area with paint removed from the dura mater, might indicate improved surgical precision and time with repeated practice; however, this was not significant in our analysis (p=0.128). Moreover, this model may not directly apply to real surgery; nevertheless, growing evidence shows that such models are useful in training novice surgeons in endoscopic surgery [25,26]. Thus, our model might be a good stepping stone in this respect.

Feedback from the residents indicated high satisfaction with the model's realism and educational value. The ability to repeatedly practice surgical techniques in a controlled environment allowed residents to gain confidence and improve their skills. This is important in endoscopic spine surgery, which has a steep learning curve. Transitioning from open surgery to endoscopic techniques can be challenging, potentially discouraging some residents from pursuing this specialized skill set.

Despite the promising results, this study has several limitations. First, the small sample size of eight residents may limit the generalizability of the findings. Nevertheless, the power analysis indicated that the observed very large effect size (Cohen's d=4.81) required only three participants to achieve sufficient statistical power (0.80). With eight participants, the study exceeded this requirement, ensuring that the analysis is well-powered statistically. Still, future studies should include a larger cohort to validate these results. Second, while innovative, the assessment of surgical trauma using painted layers on the dura mater may not perfectly replicate the complexities of human tissue, despite our fair interrater reliability score. In addition, the study excluded surgeries where the facet was removed, which could introduce a selection bias; however, the number of remaining surgeries (28 in total) provided enough power for the analysis. Third, our model cannot replicate certain key aspects of a real surgical environment, such as the presence of muscle tissue and management of intraoperative bleeding. In actual endoscopic spine surgery, surgeons must navigate through and detach muscle tissue while controlling bleeding, both of which are critical skills that are not simulated by our model. Fourth, the model does not account for anatomical distortion caused by water inflow, which can increase the risk of dural tears during surgery. However, our model is designed as a beginner's tool aimed at helping residents get familiar with the basic techniques and develop initial confidence in a controlled setting. It serves as an introductory platform for mastering the fundamental steps of endoscopic spine surgery before progressing to more advanced training methods, such as cadaveric models or live surgeries.

Conclusions

This study presents a cost-effective, fully 3D-printed model for effectively teaching endoscopic spine surgery to novice surgeons before progressing to more complex training tools. The training model is easy to reproduce with hobby-grade materials and minimal know-how. This, combined with its very low price, makes it a viable option for training programs worldwide, offering a practical solution to the challenges posed by traditional training methods.

Key Points

- This innovative three-dimensional-printed spine model can be produced at a material cost of only US$ 1 per training session, making it highly affordable.
- When used, the model significantly reduced the surgical time from 21 minutes 18 seconds in the initial session to 6 minutes 45 seconds in the final session.
- The model simulates tissue handling by utilizing thermoplastic polyurethane and polylactic acid materials, providing residents with a beginner-level practical learning experience.
- Residents reported high satisfaction with the educational value of the model.
- This model offers an affordable and accessible alternative to expensive and logistically challenging cadaveric training, making it suitable for various resource settings.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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Formal analysis: BBA, MSB, SO. Validation: HB, TY. Resources: BBA, MSB. Supervision: HB, TY. Project administration: HB, TY. Software: BBA. Visualization: BBA, OSA. Writing–original draft: BBA, MSB. Writing–review and editing: HB, TY. Final approval of the manuscript: all authors.

Supplementary Materials

Supplementary materials can be available from https://doi.org/10.31616/asj.202.0288. Supplement 1. Likert scale questionnaire answers of the residents and their surgery data.

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