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ORIGINAL RESEARCH

Teaching Pterygopalatine Fossa Anatomy Using 3D Images and Physical Model: A Novel Teaching Strategy

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Abstract

Medical students often struggle to appreciate the anatomy of the pterygopalatine fossa. This is due to the difficulty in understanding the spatial orientation through textbook diagrams, as well as its deeper location and smaller size in cadaveric specimens. Research has proven that three-dimensional visualization enhances the spatial understanding of anatomy. However, studies have not compared the effectiveness of two different instructional designs that cater to 3D visualization. We conducted a mixed methodology (quasi-experimental pre-test/post-test control design with additional qualitative components) study to compare the effectiveness of a physical model and a 3D image in small-group teaching. The students were divided into control and intervention groups based on their roll numbers. The control group utilized a series of 3D images delivered through Microsoft PowerPoint software on computers. The students in the intervention group used a physical model made of cardboard, with colored wires representing the neurovascular structures. We used 20 spatial anatomy-based multiple-choice questions (MCQs) to assess knowledge acquisition before and after the small group discussion. Additionally, we utilized a validated 10-item feedback questionnaire to evaluate participants' perception of the teaching sessions. There was no significant difference in the knowledge gain and perception scores between the control and intervention groups. These findings suggest that a well-designed 3D image can provide an equivalent learning outcome and level of satisfaction compared to a physical model.

Keywords Pterygopalatine fossa · 3D images · Physical model · Anatomy education

Introduction

The pterygopalatine fossa (PPF) is an "inverted pyramid"-shaped space located in the skull base, immediately posterior to the orbit. It is a significant neurovascular junction that connects the cranial cavity, orbit, nasal cavity, and oral cavity [1]. A thorough knowledge of the spatial anatomy of the PPF is essential for administering a sphenopalatine block, diagnosing neoplastic conditions, and understanding the perineural spread of tumors from adjacent structures [1]. A recent review has reported that many undergraduate students and junior doctors do not feel confident in assessing and managing patients with ear, nose, and throat disorders [2]. This difficulty in managing ENT conditions could be attributed to a lack of sufficient time dedicated to teaching ENT topics or the utilization of ineffective teaching methodologies by educators [2, 3]. For instance, medical students often struggle to appreciate PPF anatomy, owing to the difficulty in understanding the spatial orientation through textbook diagrams or the deeper location, smaller size of the space in cadaveric specimens, and lack of interest [1]. However, studies have documented that the use of three-dimensional visualization techniques to deliver complex spatial anatomy results in enhanced learning [4].

To provide a three-dimensional representation, studies have utilized 3D images, virtual models, and physical models [4]. Designing 3D images from CT/MRI images necessitates infrastructural support and proficiency in software usage. To address these concerns, physical models have traditionally been used in anatomical teaching to provide spatial orientation of anatomical structures. Hands-on

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learning with physical models is an effective strategy, as color coding and tactile stimulation promote the learner's interest and active participation [5–7]. In contrast to high-fidelity models, low-fidelity models do not depict intricate anatomical details. Instead, they serve as a tool to understand the relationships between anatomical structures. Since these models depict minimal detail, they also reduce cognitive load, enabling better understanding [8].

Studies have compared the effectiveness of static images, physical models, and virtual models and found that the group using the physical model outperformed the groups using images and virtual models [5, 6]. The investigators reported that the simplicity of depicting anatomical structures, the ability to perceive depth, and the ease of handling physical models contributed to a higher level of learning [5, 6]. The aforementioned studies were conducted with smaller sample sizes and variable study durations among the groups. These studies primarily focused on larger anatomical areas, such as the foot and pelvis. These anatomical regions have minimal overlap of structures, which requires the learner to have minimal spatial ability in order to orient themselves to the anatomical structures. A key element that the aforementioned studies failed to consider is the similarity between the models being investigated. We want to emphasize that both models should have a similar structure and color coding in order to demonstrate that the outcome is truly a result of tactile manipulation. To achieve design similarity, we have developed an innovative design technique known as schematic modeling. This technique involves constructing anatomical images or physical models using 2D shapes, which are then layered to create 3D representations. To date, no study has compared the learning outcomes between a similarly designed schematic 3D image and a physical model.

Previous studies on PPF teaching have focused on the development of virtual models, 3D printed models, and web-based models [9, 10]. We differ from previous studies by creating a schematic PPF teaching resource in both image and physical formats, using easily accessible materials. This study aims to compare the learning outcomes and perception levels among students exposed to 3D images and physical models of PPF. Investigating the effectiveness of static image format and physical models in depicting schematic 3D anatomy is of particular interest to anatomy educators. This is due to ethical concerns surrounding the handling of cadaveric materials and the increasing use of student-centered teaching strategies [11]. The outcome of this study could be beneficial for educators in understanding the reasons behind the acquisition of spatial knowledge using anatomical models. The hypothesis of the study is, "In small group discussion, physical model teaching improves the knowledge retention as compared to virtual model." The objectives of the study are as follows: (1) compare the test scores of the student cohort taught using 3D images and the physical PPF model; (2) compare the perception scores of the student cohort taught using 3D images and the physical PPF model.

Materials and Methods

The present study was conducted following mixed methodology (quasi-experimental pre-test/post-test control design with additional qualitative components) over a 6-week period from March to April 2022. Institutional research and ethical committee approval (EC/05/2022) was obtained before starting the study. The primary and secondary investigators explained the protocol of the study to the first-year medical students and obtained their written informed consent. The students were instructed that they have to attend the small group teaching sessions, but their participation in the MCQ assessment and feedback questionnaire is voluntary. The authors could not find a similar study with two groups comparing the 3D images with a physical model. So, the mean and standard deviation were derived from the pilot study, which included 30 senior batch students resulting in a sample size of 64 per group. The sample size was calculated using the formula, $\text{n} = [(\text{Z}1 - \alpha/2 + \text{Z}1 - \beta)^2 \times (\text{SD}1^2 + \text{SD}2^2)/(\text{mean}1 - \text{mean}2)^2]$. The study participants included 150 first-year MBBS students from a private medical college in Puducherry, India. The first-year medical students who expressed willingness to participate in the assessment and feedback sessions were included in the study. The study participants who did not complete the pre-test or post-test were excluded from the study. The confidentiality of the participants data and their anonymity was maintained throughout the study. The study participants had no prior exposure to the PPF anatomy.

The authors reviewed anatomical books and research articles to standardize the PPF model and constructed the image using Microsoft PowerPoint (PPT) software. We designed the 3D image from a lateral perspective to accurately represent the natural opening of the pterygomaxillary fissure (Fig. 1). This approach allows for better depth perception and clear visualization of the course of the neurovascular structures along the various walls of the PPF. To create the PPF template, we connected three triangular shapes in the inferior aspect to represent the anterior, medial, and posterior boundaries of the PPF. Then, we used a quadrangular shape to connect the triangular shapes at the top, forming the roof of the fossa. We added color coding with 50% transparency to the shapes in order to distinguish the individual boundaries and enhance depth perception. Lastly, we embedded oval shapes filled with white colors within the triangular shapes to represent the sphenopalatine foramen (medial wall), foramen rotundum, the pterygoid canal (posterior wall), and the inferior orbital foramen (anterior wall).

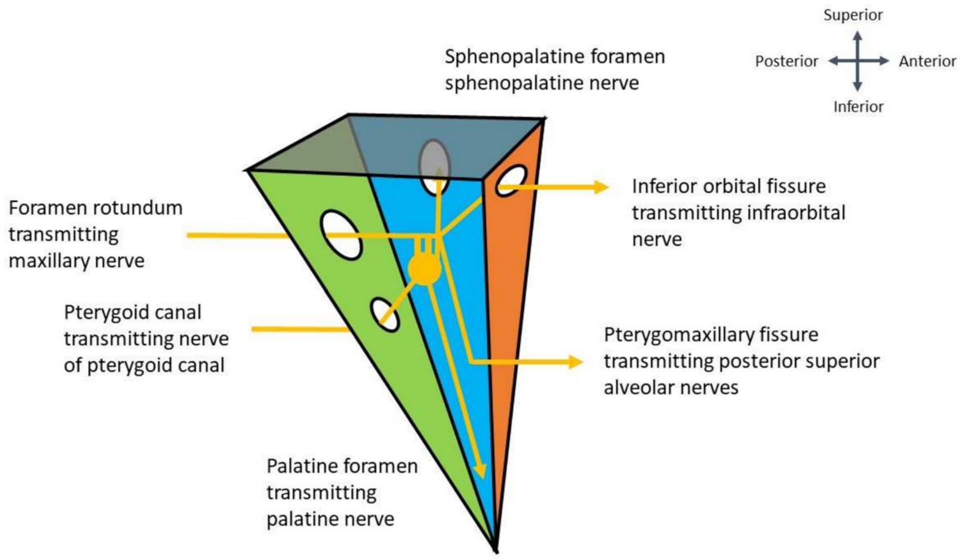

Fig. 1 3D image of pterygopalatine fossa depicting the course of nerves, designed using Microsoft PPT software

Later, we added a circular shape to represent the ganglion and we connected colored lines (yellow for nerves and red for arteries) to represent the continuity of the neurovascular structures. These lines were either moved closer to or further away from the white oval shape to create the illusion of the neurovascular structures passing through the foramina. We excluded the palatovaginal and palatine canals because their inclusion resulted in overcrowding of the neurovascular structures, which could impede the comprehension of the spatial anatomy. To simplify the model, the greater and lesser palatine nerves/vessels were represented as a single structure. Two senior anatomists validated the model for anatomical accuracy, which included the shape, spatial orientation, the position of the foramina, and the course of the neurovascular structures. We constructed physical models using cardboard sheets and electrical wires based on the 3D image model. The yellow cables were passed through their respective foramina and connected to a plastic sphere symbolizing the pterygopalatine ganglion. Similarly, we used cellophane tape to join the red wires, illustrating the branching pattern of the maxillary artery (Fig. 2). The authors ensured that the physical model included all the 3D image elements.

The investigators framed a total of 20 visuospatial anatomy-based multiple-choice questions (MCQs) with five options each to minimize student guessing [12]. The MCQs

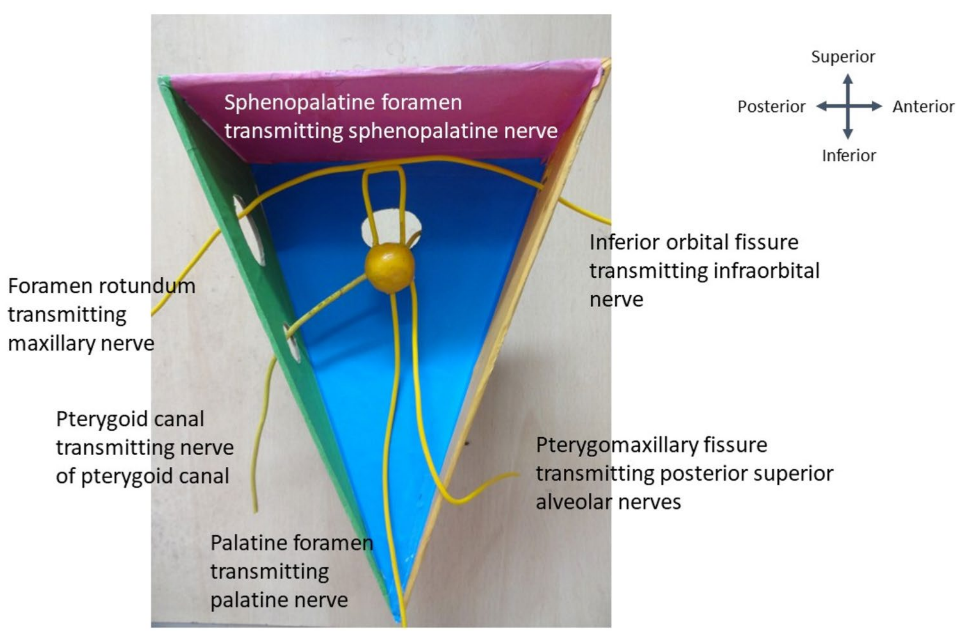

Fig. 2 Physical model of pterygopalatine fossa depicting the course of nerves, designed using cardboards

assessed knowledge of the boundaries of the fossa, the location of the foramina, and the neurovascular structures that pass through the foramina. Three anatomy faculty members evaluated the MCQs for face and content validity. We choose MCQs as the mode of assessment because of their feasibility and objectivity in evaluating a large number of students simultaneously. Similarly, the items for the perception questionnaire were developed based on literature review and focus group discussions. We tested the internal consistency of the feedback questionnaire among 15 students using Cronbach's alpha ($\alpha = 0.880$). The questionnaire utilized a 5-point Likert scale (5 being the highest score) to assess perceptions regarding the following aspects of teaching: (1) interest, (2) knowledge acquisition, and (3) satisfaction. The questionnaire also included two open-ended questions regarding the strengths and suggestions for the teaching session. The questions were, (1) What specifically did you like about the teaching session? Please explain why, and (2) How the teaching session can be improved?.

The students' baseline knowledge was tested using a pre-test questionnaire (paper-based) 1 week prior to the small group sessions. Then, we divided the students into four groups based on their roll numbers (roll numbers 1 to 37 was batch A, 38 to 75 was batch B, 76 to 113 was batch C, and 114 to 150 was batch D). Due to time constraints and varying class schedules across departments, we were unable to randomize the students. To avoid investigator bias, the first author facilitated the 3D image group (batch B) on day 1 and the physical model group (batch D) on day 2 of the teaching session. The second author facilitated the physical model (batch A) on day 1 and the 3D image group (batch C) during day 2 of the teaching session. For the 3D image group, we divided the participants into groups of six to seven members and allocated them with computers equipped with a Microsoft PowerPoint (PPT) presentation that included a sequence of four 3D images. The inherent nature of the activity allowed the learners to move to the next or previous image but prevented the students from using zoom and rotate functions on the images. The physical model group was divided into groups of six to seven members and assigned to the cardboard model with wires representing the neurovascular structures. The students held the physical model (along with the wires) in hand and manipulated its view according to their needs. The instructor provided handouts and a skull to both groups in order to help them become familiar with anatomical terms and understand the communication of PPF with other spaces. The students utilized the resources and studied the visuospatial anatomy of the depicted region followed by the facilitator addressing their queries. We ensured that the subject content and the duration of delivery were consistent for both groups. The students were given the same test questions and feedback questionnaire (paper-based) 4 weeks after the teaching session to assess their level of knowledge retention. This timeframe was chosen based on the Ebbinghaus curve, which suggests that only 21% of knowledge is retained after 3 weeks of learning [13]. An external faculty member, who was blinded to the study's objectives, conducted the data collection.

We calculated the score improvement for an individual student using the formula: post-test score minus pre-test score. The mean and standard deviations for the score improvement and perception scores were calculated. The difference in knowledge retention and perception scores between the control and intervention groups were estimated using the Mann-Whitney test. We used SPSS version 23 (IBM Corporation, Armonk, NY, USA) for conducting statistical analysis. A P value of less than 0.05 was deemed to be statistically significant.

Results

The age range of the study participants was 17 to 20 years. We analyzed the scores of 144 students (71 students in the 3D image group and 73 students in the physical model group) who attended pre-test and post-test sessions for statistical analysis. Among them, 57 (39.6%) were male, and 87 (60.4%) were female. The Shapiro-Wilk test indicated that the data was non-normally distributed. The mean score improvement for the 3D image and physical model groups is presented in Table 1. We found no significant difference in the score improvement between the group that used 3D images and the group that used physical models ($P = 0.36$) (Table 1). The teaching perception scores of 141 students who have completed the feedback questionnaire was analyzed (70 students in the 3D image group and 71 students in the physical model group). The mean perception score was higher than 4 in both groups. However, we found no significant difference in the perception score between the two groups (Table 2). Thematic analysis of the open-ended question yielded the following themes in the 3D image group: (1) images were helpful in understanding spatial

Table 1 Comparison of score improvement between 3D image and physical model groups

Student groups	Score improvement	Statistics Mann-Whitney *U* test
3D image group ($n = 71$) (mean ± SD)	5.53 ± 3.50	0.366
Physical model group ($n = 73$) (mean ± SD)	5.55 ± 2.36	

SD standard deviation

P value < 0.05 indicates a significant difference

Table 2 Comparison of perception scores between 3D image and physical model groups

Statement	3D image group (n = 70) Mean ± SD Median (interquartile range)	Physical model group (n = 71) Mean ± SD Median (interquartile range)	P value (Mann- Whitney U test)
Model was easy to understand	4.14 ± 0.8 4 (1)	4.25 ± 0.8 4 (1)	$P = 0.30$
Learning with the model was enjoyable	4.17 ± 0.8 4 (1)	4.11 ± 0.9 4 (1)	$P = 0.78$
Model stimulated my interest in the class content	4.2 ± 0.9 4 (1)	4.03 ± 0.9 4 (1)	$P = 0.17$
Model motivated me to take part in class discussion	4.04 ± 0.9 4 (2)	4.01 ± 0.8 4 (1)	$P = 0.83$
Model improved my spatial understanding on PPF anatomy	4.13 ± 0.9 4 (1)	4.06 ± 0.9 4 (1)	$P = 0.69$
At the end of the sessions, I could enumerate the boundaries and contents of PPF	4.26 ± 0.7 4 (1)	4.01 ± 0.9 4 (2)	$P = 0.14$
My knowledge attainment is better with the model as compared to 2D textbook drawings	4.23 ± 0.8 4 (1)	4.27 ± 1 5 (1)	$P = 0.50$
Model had a positive impact on my learning experience	4.13 ± 0.9 4 (1)	4.18 ± 0.8 4 (1)	$P = 0.82$
I am satisfied with this approach of learning	4.17 ± 0.8 4 (1)	4.18 ± 0.9 4 (1)	$P = 0.75$
I would like to have similar method of teaching in other disciplines	4.36 ± 0.8 5 (1)	4.22 ± 1 5 (1)	$P = 0.70$

SD standard deviation

P value < 0.05 indicates a significant difference

anatomy (14 responses), and (2) videos or animations could be added (10 responses). The themes among the physical model group were (1) the model and wires helped in understanding the course of the neurovascular structures (21 responses), and (2) demonstrating the neurovascular structures in prosected specimens can aid better understanding (5 responses). Other responses were nonspecific in nature only mentioning about how engaging and enjoyable they found the session.

Discussion

This study compared the learning outcomes between the group exposed to 3D images and the group using physical PPF models during a 2-h small group teaching session. We used a non-randomized pre-test/post-test control design to compare the knowledge gained between the 3D images and the physical model group. The investigators utilized 20 visuospatial multiple-choice questions and a 10-item validated perception questionnaire to assess the learning outcomes and students' perception of the model-based teaching. Our results have demonstrated that there was no significant difference in long-term learning outcomes or students' perception of the learning taught by 3D images and physical models.

Khot et al. utilized a randomized control design to compare the learning outcomes between three groups: one using a 3D computer-based model, another using a plastic model, and a third using two-dimensional photographs of the plastic model (pelvic model). They reported a significantly higher score in the plastic model group than in the virtual reality/image group [5]. Similarly, Preece et al. conducted a study among third-year veterinary students to compare the learning outcomes between the physical, 3D computer model, and textbook groups (equine foot model). They reported a significantly higher assessment score in the physical model group compared to the textbook and 3D computer model groups [6]. The superiority of the physical model was attributed to its ability to provide a stereoscopic sense of vision and the ability to manipulate [5, 6]. The present study is similar to the aforementioned studies in comparing the learning outcomes between tactile and non-tactile teaching materials. The differences include the complexity of the anatomical region, the use of a series of static 3D images designed to replicate the physical model, and the methodology, which involves small group sessions with equal time allocated for both groups of students.

The lack of significant knowledge gain between the groups using 3D images and physical models could be attributed to the below discussed three factors: (1) The ability of the 3D image to accurately depict the spatial anatomy of the PPF. Keedy et al. compared the flash-based interactive 3D module with static images obtained from the 3D module and found no significant difference in hepatobiliary knowledge acquisition [14]. Similarly, Hariri et al. compared the virtual reality surgical simulator with textbook images and found no significant difference in the student's ability to identify anatomical structures as they appeared in a recorded video of shoulder arthroscopic procedure [15]. Stereoscopic vision describes the brain's ability to perceive three-dimensional shape and form from visual inputs [16]. A physical model provides stereoscopic vision, while a 3D image creates an illusion of depth perception. The authors ensured that the static pictures accurately represented the physical model in terms of shape, color coding, location of foramina/neurovascular structures, and depth perception. Most likely, the 3D images offered a similar visuospatial orientation to comprehend the PPF anatomy, and the learners were able to perform at the same level as the physical model group. (2) The design of the model ensures that there is no need for any physical manipulation in order to comprehend the anatomy. Wu et al. reported a significantly higher score in the 3D printed model group compared to the traditional radiographic image group in the pelvis/spine module, but not in the upper and lower limb modules. The authors suggested that understanding the spatial anatomy of limbs is easier without the need for 3D printed models to teach spatial orientation [17]. Abid et al. taught peritoneal embryogenesis through 3D visualization and traditional chalk technique and evaluated their performance at the end of the course. He reported that there was no significant difference between 3D and traditional groups on questions which focused on static phenomena, but the rate of correct answers was higher in the 3D group which focused on dynamic phenomena [18]. The inherent static nature of the anatomical region being investigated or the lack of necessity to manipulate the 3D images for visuospatial orientation could be reasons for the inability to establish the superiority of the physical model. (3) The mode of assessment — previous studies have used cadaveric specimens and cross-sectional CT/MRI scans to evaluate the learning outcomes of their research [5, 6, 19]. Preece et al. justified the use of MRI images as an assessment modality, as it helps prepare veterinary students to diagnose foot pathology [6]. Estevez et al. stated that physical modeling activities, when compared to traditional teaching methods, resulted in a significant improvement only in the 3D image-based score. However, no significant improvement was observed in the scores for the 2D text-based and overall practical examinations [19]. The current study differs from the abovementioned studies by using multiple-choice questions (MCQs) as the assessment method. This choice was made because MCQ-based tests are objective, practical, familiar to first-year medical students, and suitable for evaluating the session objectives. The authors assumed that the deeper location and smaller size of the space in the cadaveric specimens could hinder the spotter-based assessment. Furthermore, measuring spatial relations based on CT/MRI images was inappropriate for first-year medical students due to the inherent difficulties in interpreting the cross-sectional images.

In the present study, we measured the students' perceived interest, satisfaction, and knowledge acquisition to assess their level of engagement. An average perception score of more than 4 for both the 3D image and physical models indicates that both teaching resources effectively enhanced student engagement. The higher rating for both 3D images and physical models could be due to the non-traditional teaching approach, the simplification of anatomical relationships, and the learners' perception of them as valuable educational resources. These findings are similar to other studies that have reported positive student perceptions about using 3D visualization and the beneficial role it plays in promoting spatial anatomy learning [4, 20]. Previous studies have reported that tactile manipulation of physical models provides higher satisfaction compared to traditional 2D images [4, 20]. The lack of significant differences in interest, knowledge attainment, and satisfaction between the groups may be due to the similarity in design of the model or in the nature of knowledge acquisition. Hence, we assert that non-traditional ways of teaching spatial anatomy promote a positive perception of the teaching methods, regardless of the instructional medium.

In our study, we measured visuospatial understanding after 4 weeks. This timeframe was chosen based on the Ebbinghaus curve, which suggests that only 21% of knowledge is retained after 3 weeks of learning [13]. The study's strengths include a large sample size, equal time allocation for the groups, and the comparison of learning outcomes between two identical models that differed in their tactile perception. The score improvement utilized in the study is a more reliable indicator for assessing the knowledge gained than the post-test scores, which may not accurately reflect the actual level of knowledge acquired. The limitations of the study include the use of a representational version of PPF, which lacked realism. Additionally, the study used a physical skull for both groups, restricted the participants to students from a single institution, and did not account for potential interference from factors outside the study design. The study has not addressed whether the learning in the 3D image group is exclusively due to the use of the images or the adjunct use of computers. Due to feasibility issues, we were unable to randomize the study participants or identify the learners based on their spatial abilities. Educators should consider these factors before generalizing the findings for a broader interpretation.

The current study has detailed the methodology for developing schematic 3D images and physical models using readily available resources. A well-designed 3D image can provide an equivalent learning outcome and student engagement as compared to physical models. Designing and implementing schematic 3D images is an easy, feasible, and cost-effective approach to imparting spatial anatomy. This format presents a task that is less cognitively demanding because the user does not have to mentally rotate the object. Added advantages of schematic 3D images are that they can cater to a large group of students and could help avoid the drawbacks of physical models, such as cost, storage requirements, and potential physical damage [21]. Educators in low resource settings can utilize easily available materials like cardboard and electrical wires to design cost-effective anatomical models. The authors recommend training educators in the development of schematic and representational images/models that can be used in various anatomical disciplines to impart better spatial orientation to undergraduate students. Future research can focus on creating similar models in other disciplines of anatomy and analyzing the effectiveness of model-making compared to using pre-designed models.

Conclusion

To conclude, with respect to pterygopalatine fossa anatomy, a well-designed 3D image can provide an equivalent learning outcome and perception score compared to schematic physical models.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40670-024-02063-3.

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Declarations

Conflict of Interest The authors declare no competing interests.

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