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Research Article

Comparative Effectiveness of 2-Dimensional Images, 3-Dimensional Fabricated Models, and Computer-Generated 3-Dimensional Images in Veterinary Anatomy Education

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ABSTRACT

Background: Anatomy education has traditionally relied on Two-Dimensional Images (2DI) and cadaveric dissections. However, newer modalities such as Three-Dimensional Fabricated Models (3DM) and Computer-Generated 3D Images (CG3DI) are increasingly being introduced. Comparative effectiveness evidence remains three dimensional limited. **Objectives:** This pilot study aimed to compare the impact of 2DI, 3DM, and CG3DI on student performance in veterinary anatomy. **Materials and Methods:** Twelve first-year Graduate Entry veterinary students were randomly allocated into three equal groups of four (*n*=4 Graduate Entry per group), each exposed to one of the teaching modalities for a 30-min study period. Pre- and post-intervention assessments, each comprising ten multiple-choice questions, were conducted to evaluate changes in performance. **Results:** Pre-test scores were similar across groups (2DI: mean 5.75/10, SD 0.96; 3DM: mean 5.75/10, SD 1.26; CG3DI: mean 6.00/10, SD 1.15). Post-test scores were: 2DI mean 6.00/10 (SD 2.16; mean change +0.25 questions, Cohen's d=0.15); 3DM mean 5.75/10 (SD 1.50; mean change 0.00, Cohen's d=0.00); CG3DI mean 5.25/10 (SD 1.26; mean change -0.75, Cohen's d=-0.62). No statistically significant within-group or between-group differences were detected (Kruskal-Wallis H=1.63, *p*=0.44), consistent with the very small sample size. **Conclusion:** This pilot study suggests a trend toward score improvement with 2DI, no change with 3DM, and a modest decline with CG3DI over a brief study period. These non-significant findings, limited by the small sample, may inform a fully powered future study of a blended 2D/3D approach in veterinary anatomical education.

Keywords: Active learning, Anatomy Education, Educational Technology, Pedagogy, Simulation-based learning.

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INTRODUCTION

Veterinary anatomical education has traditionally relied on the use of Two-Dimensional Images (2DIs) and systematic cadaveric dissections to teach 3-dimensional structures and their complex relationships. However, in recent years, student access to cadavers has become increasingly limited, resulting in greater dependence on 2DIs.[1-3] This shift presents significant educational challenges, as research has shown that relying predominantly on 2DIs for the study of veterinary anatomy produces inferior learning outcomes compared to the use of cadaveric specimens.[4] The students' resultant inadequate understanding of anatomical relationships may consequently hinder their performance during their clinical years.[5] To address these challenges, educators have been increasingly exploring alternative teaching modalities. Digital tools such as interactive three-dimensional atlases, Virtual Reality (VR), Augmented Reality (AR), and mixed reality platforms allow students to explore anatomy in immersive and interactive ways, while physical resources like plastinated specimens, synthetic cadavers, and Three-Dimensional Fabricated Models (3DMs) provide durable, realistic, and ethical substitutes for traditional dissection. Alternatively, Computer Generated Three-Dimensional Images (CG3DIs) from CT, MRI or ultrasound imaging modalities, help bridge anatomy with clinical practice, and e-learning innovations such as anatomy apps, online modules, and virtual dissection tables (e.g., Anatomage or Sectra) make anatomy accessible beyond the lab.[6] Additionally, sustainable and ethical teaching options such as prosection libraries, photogrammetry, and lifelike surgical simulators are effective in allowing repeated practice without relying solely on animal cadavers.[7] In practice, most veterinary

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programs now adopt a blended approach, integrating cadaveric study with digital platforms, imaging, and synthetic models to balance realism, accessibility, and ethical considerations.

Comparisons between different anatomy teaching modalities remain limited, making it unclear whether these tools offer variable merits in enhancing learning. Several recent studies have compared the use of CG3DIs and 2DIs in veterinary education, with most reporting no significant difference in students' learning outcomes.[8] However, research comparing the use of 3DMs and 2DIs in veterinary anatomical education is limited. This comparison has been more extensively explored in human medical education, where findings suggest that the use of 3DMs produced superior learning outcomes compared to 2DIs.[9] The comparative studies in human medical education may offer valuable insights into the potential usefulness of 3DMs in veterinary medical education. However, their findings are not fully transferable, leaving a significant research gap in veterinary medical education that warrants further investigation. This study aimed to address this gap, by evaluating the most effective teaching modality to enhance veterinary students' understanding of 3-dimensional anatomical structures and their spatial relationships. In this study, we compare students' learning of canine pelvic limb skeletal anatomy using three approaches: 2DIs, a combination of 3DMs and 2DIs, and CG3DIs.

MATERIALS AND METHODS

Study Design and Participants

This pilot randomized controlled study was conducted with first-year Graduate Entry veterinary medicine students at University College Dublin (UCD) who had not yet received formal instruction in canine pelvic limb anatomy. Ethics approval was obtained from the UCD Human Research Ethics Committee (Approval number LS-C-25-003-McCarney). A total of twelve participants were enrolled and randomly allocated into three equal groups of four (n=4 per group) using a random number generator to ensure balanced group sizes and to minimize selection bias.

Intervention Groups

Three educational modalities were compared:

- **2DI Group:** Participants received traditional two-dimensional anatomical images of the canine pelvis and pelvic limb skeleton labeled with the bone names, and a few relevant landmarks. These were selected images from *Guide to Dissection of the Dog* Seventh Edition.[3]
- **3DM Group:** Participants were provided with the same labeled two-dimensional images that were provided to the 2DI group, supplemented with unlabeled three-dimensional cast models of the bones of the canine pelvic limb (two halves of the pelvis, femur, tibia, and fibula).
- **CG3DI:** Participants had access to interactive, labeled three-dimensional computer-generated images of the bones of the canine pelvic limb with rotation and zoom capabilities via VIN (Veterinary Information Network). These participants were not provided with any supplemental images or models.

Study Protocol

Prior to randomization, all participants completed a ten-question multiple-choice pre-test to assess their baseline knowledge of canine pelvic limb skeletal anatomy, including identification of bones, their spatial relationships, and articular surfaces. Each question offered four response options, with one correct answer, for a maximum score of 10. Following randomization, each group received their assigned educational resource for a 30-min self-directed study period. All educational materials depicted equivalent canine pelvic limb skeletal anatomical structures (pelvis, femur, tibia, fibula) to ensure content consistency across modalities. Immediately following the study period, all participants completed a ten-question multiple-choice post-test. The post-test was designed to assess the same anatomical content domains as the pre-test but used distinct questions and images to avoid direct recall effects, while maintaining equivalent difficulty and scope. Both tests were developed by the study team and reviewed for content validity by a veterinary anatomist. Tests were administered in paper format and scored by a single assessor who was blinded to group allocation. The primary outcome was the change in score (number of correct answers) from pre-test to post-test for each participant.

Data Analysis

The primary outcome measure was the change in score (number of correct answers out of 10) from pre-test to post-test within each group. Descriptive statistics (mean, Standard Deviation [SD], median, and range) were calculated for pre-test scores, post-test scores, and score changes for each group. The proportion of participants in each group who improved, showed no change, or declined was also reported. Within-group changes were assessed using the Wilcoxon signed-rank test. Between-group differences in score change were assessed using the Kruskal-Wallis H test, a non-parametric alternative to one-way ANOVA appropriate for small, non-normally distributed samples. Pairwise comparisons were conducted using Fisher's Exact Test on the proportion of students showing improvement versus no improvement. Effect sizes were reported as Cohen's d for within-group changes and as odds ratios for pairwise comparisons. A post-hoc power analysis was performed to estimate the sample size required to detect the observed effect in a fully powered future study (two-tailed α=0.05, power=80%). All analyses were performed using Python (SciPy v1.11). Given the pilot nature of this study and the small sample size (*n*=4 per group), results are reported as preliminary and exploratory; p-values should be interpreted accordingly.

RESULTS

Twelve participants (*n*=4 per group) completed the study. Pre-test scores were comparable across groups (2DI: mean 5.75/10, SD 0.96; 3DM: mean 5.75/10, SD 1.26; CG3DI: mean 6.00/10, SD 1.15), confirming equivalent baseline knowledge prior to the intervention. Individual scores and group-level results are summarized in Table 1. In the 2DI group, 2 of 4 students (50%) demonstrated an improvement in their scores following the intervention (Figure 1). One student (25%) showed no change in performance, while 1 student (25%) experienced a decline. Within the 3DM group, 1 of 4 students (25%) achieved score improvement, 2 students (50%) showed no change, and 1 student (25%) exhibited a decrease in performance. For the CG3DI group, 2 of 4 students (50%) showed no change and 2 students (50%) experienced a decline, with no students showing improvement. Mean score changes were: 2DI +0.25 questions (SD 1.71; mean percentage change +2.5%), 3DM 0.00 questions (SD 0.82; 0%), and CG3DI -0.75 questions (SD 0.96; -7.5%). Effect sizes for within-group change were small for the 2DI group (Cohen's d=0.15) and negligible for the 3DM group (Cohen's d=0.00), but moderate for the CG3DI group in the negative direction (Cohen's d=-0.62). Wilcoxon signed-rank tests revealed no statistically significant within-group pre-to-post change for any group (2DI: W=2.5, *p*=1.00; 3DM: W=1.5, *p*=1.00; CG3DI: W=0.0, *p*=0.50). The Kruskal-Wallis test found no statistically significant difference in score change between groups (H=1.63, d_f=2, *p*=0.44). Pairwise Fisher's Exact Tests on the proportion of students showing improvement versus no improvement likewise yielded non-significant results (2DI vs. 3DM: OR=3.00, *p*=0.50; 2DI vs. CG3DI: OR=undefined, *p*=0.21; 3DM vs. CG3DI: OR=undefined, *p*=0.50). These null results are consistent with the very small sample size. A post-hoc power analysis, based on the observed paired effect size in the 2DI group (Cohen's d=0.15), estimated that approximately 366 participants per group would be required to achieve 80% power at α=0.05 in a future fully powered trial.

DISCUSSION

The present study compared the effectiveness of different teaching modalities i.e., two-dimensional images, three-dimensional models, and computer-generated 3D images in improving student performance in veterinary anatomy. The findings suggest that among the three groups, students utilizing 2D images showed the most consistent improvement, with 50% demonstrating increased scores, whereas the 3DM and CG3DI groups yielded comparatively less favorable outcomes. The superior performance in the 2DI group may reflect students' long-standing familiarity with traditional two-dimensional resources, such as textbooks and atlases, which remain foundational tools in anatomy education.[8] Students may, therefore, have developed stronger skills in interpreting and applying 2D representations, enhancing their performance in assessments based on similar formats. This advantage might also explain why the use of novel resources, such as 3D models, or computer-generated images, did not yield a comparable degree of improvement in test performance within the timeframe of this study.

In the 3DM group, only one-quarter of students improved their scores, while half showed no change, and a further quarter experienced a decline. While 3D models provide tactile engagement and spatial understanding, in this study, these benefits did not translate into a measurable improvement in assessment scores after a short study period, despite also being provided with 2DIs. This could be due to factors such as lack of prior experience using 3D models as a study tool, or the relatively high cognitive load involved in shifting from abstract physical models to test questions presented in a two-dimensional format. Given the short exposure time, these students may also have found the 3DMs distracting, rather than enhancing. Previous studies have shown that hands-on resources can improve long-term retention and comprehension of spatial relationships, but their advantages may not be fully reflected with short exposure times, or in immediate assessment outcomes.[8] Similarly, the CG3DI group showed limited effectiveness, with half of the students experiencing no improvement, or a decline in their scores. Computer-generated 3D images, while visually rich and interactive, may present challenges related to navigation, distracting complexity of material, or over-reliance on visual cues rather than conceptual understanding.[10] Additionally, students who are less accustomed to digital learning platforms may require more time to become proficient in engaging with such tools. The limited exposure, and possible technical barriers, could have diminished the potential benefits of this resource.

In summary, the results from this pilot study indicate that while innovative tools such as 3-dimensional models and computer-generated models hold promise for enhancing spatial understanding, they may not consistently outperform traditional 2D resources in improving student test performance in the short term. It is also important to note that the scope of comparative evidence across modalities remains limited, and different tools may support complementary aspects of learning. For instance, 2D resources may be most effective for foundational knowledge and assessment preparation, while 3D tools may provide deeper insight into complex spatial relationships and foster greater long-term retention. These findings highlight the importance of adopting a blended approach to anatomy education, integrating traditional 2D resources with modern 3D modalities, rather than positioning them as direct replacements. Such integration can cater to diverse learning styles, balance immediate assessment needs with deeper conceptual understanding, and better prepare students for clinical applications. This study has several

Table 1: Individual and group-level pre-test and post-test scores by intervention group.

Subject (ID #)	Group	Pre-test (/10)	Post-test (/10)	Change (Questions)	Change (%)
24	2DI	5	6	+1	+10%
23	2DI	7	7	0	0%
5	2DI	6	8	+2	+20%
16	2DI	5	3	-2	-20%
Group mean	2DI (***n***=4)	5.75 (SD 0.96)	6.00 (SD 2.16)	+0.25 (SD 1.71)	+2.5%
30	3DM	6	7	+1	+10%
7	3DM	4	4	0	0%
2	3DM	6	5	-1	-10%
14	3DM	7	7	0	0%
Group mean	3DM (***n***=4)	5.75 (SD 1.26)	5.75 (SD 1.50)	0.00 (SD 0.82)	0%
17	CG3DI	5	4	-1	-10%
10	CG3DI	7	7	0	0%
29	CG3DI	7	5	-2	-20%
8	CG3DI	5	5	0	0%
Group mean	CG3DI (***n***=4)	6.00 (SD 1.15)	5.25 (SD 1.26)	-0.75 (SD 0.96)	-7.5%

SD=Standard Deviation. 2DI=Two-Dimensional Images; 3DM=Three-Dimensional Fabricated Model; CG3DI=Computer-Generated Three-Dimensional Images. Kruskal-Wallis H=1.63, d_f=2, *p*=0.44 (between-group comparison of score change).

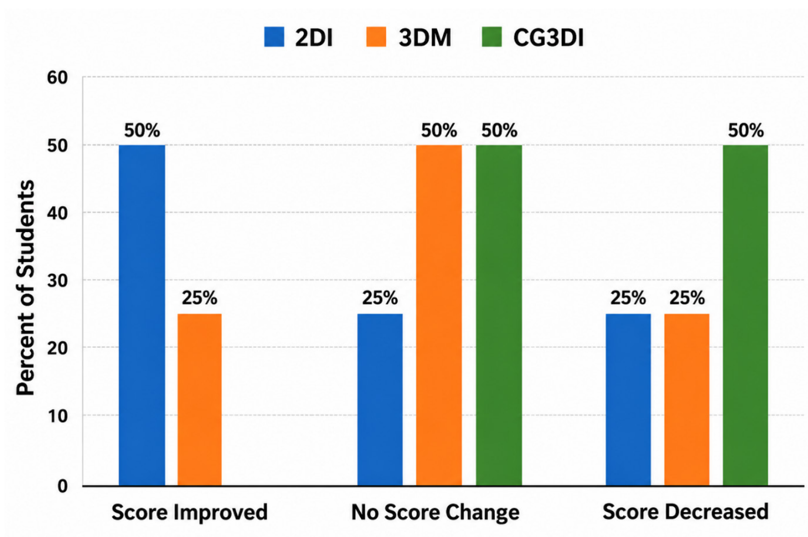

Figure 1: Comparison of student score changes across the three study groups.

important limitations that must be acknowledged. The primary limitation is the very small sample size (*n*=4 per group, *n*=12), which rendered the study underpowered to detect statistically significant differences. A post-hoc power analysis estimated that approximately 366 participants per group would be required to detect an effect of the magnitude observed in the 2DI group with 80% power (α=0.05). As such, the absence of statistically significant findings should not be interpreted as evidence of no effect; rather, the study was insufficiently powered to test this hypothesis. The brief, single 30-min exposure to each modality may also not reflect typical educational use, and the immediate post-test may not capture longer-term retention benefits that 3D tools are hypothesized to provide. Future studies with larger sample sizes and longitudinal follow-up are warranted. It would also be beneficial to explore student experiences with these tools, including ease of use, difficulties encountered, and perceived impact on learning. Further investigations are warranted to clarify the relative merits of different modalities, and to optimize their use in veterinary anatomical education.

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ABBREVIATIONS

2DI: Two-Dimensional Image(s); **3DM:** Three-Dimensional Fabricated Model(s); **CG3DI:** Computer-Generated Three-Dimensional Image(s); **UCD:** University College Dublin; **VIN:** Veterinary Information Network; **CT:** Computed Tomography; **MRI:** Magnetic Resonance Imaging; **VR:** Virtual Reality; **AR:** Augmented Reality; **SD:** Standard Deviation; **ANOVA:** Analysis of Variance; **n:** Number of Participants.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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