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Enhancing Veterinary Anatomy Education Outcomes through a Multimodal, Student-Centered Approach

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Abstract: Veterinary anatomy education has traditionally relied on in-class lectures and cadaveric dissection labs. However, this approach is limited in accessibility and visualization of complex structures, raising ethical concerns regarding animal use and welfare. To address these challenges, we implemented a unique multimodal, student-centered teaching approach in two veterinary anatomy courses and explored its feasibility and impact. This approach integrated various digital resources (virtual flashcards, 3D anatomical models, educational websites, video demonstrations) and active learning strategies (peer instruction, collaborative learning, project-based learning, and guided pre-lab video preparation). The study involved 60 second-year veterinary students and employed a mixed-methods evaluation, combining student surveys and comparisons of exam performance with a previous cohort as a control. The results revealed overwhelmingly positive student feedback, with learners reporting enhanced understanding of anatomical concepts, increased engagement and motivation, and improved collaboration and communication skills. The multimodal group outperformed the traditional group with average exam scores increasing by 5–7 percentage points ($p < 0.001$). Survey results showed strong student approval, with 85–90% agreeing that interactive tools enhanced their learning. Implementing digital resources also allowed a ~20% reduction in the number of cadavers used, contributing to improved alignment with animal welfare principles. These findings underscore the effectiveness of a multimodal, student-centered approach in veterinary anatomy education, providing a more accessible, engaging, and effective learning experience while adhering to the 3Rs principles of animal welfare. This comprehensive approach reinforces content mastery and fosters critical thinking, problem-solving, and better prepares students for the dynamic landscape of veterinary medicine.

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1. Introduction

Veterinary anatomy is a fundamental component of veterinary medical education, traditionally taught through didactic lectures and hands-on cadaveric dissections (McLachlan et al., 2004; Menon et al., 2021). While this conventional approach provides essential physical experience, it is constrained by limited access to specimens, ethical concerns regarding animal use, and the difficulty of visualizing complex three-dimensional (3D) anatomical relationships (Wainman et al., 2021). These longstanding challenges have catalyzed interest in alternative teaching tools and methods that can replace certain aspects of traditional anatomy instruction (Barmaki et al., 2023).

In recent years, the push for innovation in anatomy education has accelerated, particularly after the COVID-19 pandemic, which forced a rapid transition to remote and hybrid learning formats (Sadeghinezhad et al., 2023). The pandemic highlighted the need for flexible, strong teaching strategies that ensure continuity of high-quality anatomy education despite disruptions (Iwanaga et al., 2021; Kapoor & Singh, 2022). Beyond emergency remote teaching, veterinary educators recognize the opportunity to integrate technology-driven resources into standard curricula to enhance learning outcomes (Bevis et al., 2023).

Advances such as 3D digital models, virtual reality (VR) simulations, and interactive online platforms offer new ways to engage students and improve their spatial understanding of anatomy (Azer & Azer, 2016; Hackmann et al., 2019; Strzałka et al., 2023). Likewise, pedagogical techniques like peer instruction and collaborative learning have successfully promoted active engagement and better understanding in science education (Freeman et al., 2014; Prince, 2004).

There is growing evidence that specific multimodal tools can benefit anatomy learning. For instance, virtual dissection software and web-based 3D visualizations have improved students' grasp of anatomical structures and relationships (Wainman et al., 2021; Petersson et al., 2009). Flashcards can enhance remembering specialized terminology (Kornell, 2009; Schmidmaier et al., 2011). However, much of the existing literature examines these resources in isolation. Less is known about the combined effect of incorporating multiple digital resources alongside active, student-centered learning approaches in a well-organized curriculum. It remains to be explored how a general multimodal strategy might influence student engagement, performance, and overall learning experience in veterinary anatomy.

This study presents an exploratory field report on implementing a multimodal, student-centered anatomy teaching approach and evaluates its feasibility and outcomes in a second-year veterinary anatomy curriculum. Our approach integrated digital learning materials (including interactive 3D models, online videos, virtual flashcards, and dedicated course websites) with active learning strategies (peer instruction sessions, collaborative group work in labs, and project-based learning assignments). We observed one cohort of veterinary students exposed to this enriched curriculum and compared their learning outcomes to those of a prior cohort taught via traditional methods. We also collected detailed student feedback through surveys to test their engagement, perceptions, and satisfaction with the new learning methods.

Therefore, this study aimed to investigate the implementation and impact of a multimodal, student-centered teaching approach in veterinary anatomy. Specifically, we aimed to: (1) assess the feasibility of integrating diverse digital and active learning resources into an existing anatomy course; (2) evaluate the effect of this approach on student performance and student learning outcomes; and (3) examine students' perceptions of the usefulness and effectiveness of the multimodal learning tools. By sharing these findings, we provide preliminary evidence and practical insights for veterinary anatomy educators considering similar innovations. Ultimately, this work contributes to the growing movement toward more accessible, engaging, and ethically responsible anatomy education models that leverage technology and active learning to complement and enhance traditional teaching.

2. Materials and methods

2.1 Courses and study design

This study took place in two core second-year veterinary anatomy courses: Animal Anatomy I (VMED100) and Animal Anatomy II (VMED150). These sequential courses cover domestic animals' fundamental structural and comparative anatomy, with VMED100 focusing on the musculoskeletal system (bones, joints, muscles) and VMED150 on internal organ systems (visceral anatomy, including vascular and nervous supply). Ethical approval for this educational study was waived, as the research involved anonymized student performance data and voluntary, anonymous course feedback. No personal or sensitive information was collected.

60 veterinary students participated in the new multimodal curriculum during one academic year. The same instructor team taught both courses using the integrated approach described below. To compare learning outcomes, we identified a control group from the previous academic year's offering of these courses. The control cohort (n ≈ 60 students) was taught by the same instructors and covered the same content and assessments using traditional teaching methods only.

In the traditional approach, students received classroom lectures (with slide presentations) and performed cadaveric dissections in lab sessions, without the enhanced digital resources or structured active learning interventions. The exams and grading standards were equivalent between the two years to enable a fair comparison. While the study did not utilize a randomized controlled trial design, it employed a quasi-experimental framework that facilitated a comparative analysis between a cohort exposed to a multimodal, student-centered intervention and a prior cohort serving as the baseline. We ensured the curriculum topics, instructional hours, and exam formats were aligned between the two cohorts for maximal comparability.

2.2 Digital learning resources

To address the limitations of traditional methods, we developed and created a variety of digital learning materials for use throughout the courses:

Vocabulary flashcards (Quizlet & Memrise): To help students master complex anatomical terminology, we created comprehensive digital flashcard sets using the Quizlet and Memrise platforms. Two interactive flashcard courses (one per anatomy course) were developed, encompassing hundreds of key terms and definitions across all significant topics. These flashcards employed spaced repetition and active recall techniques to reinforce memory. Students had on-demand access to the flashcard decks and were encouraged to practice regularly at their own pace, with the apps' built-in progress tracking to monitor their learning.

3D Virtual anatomical models: We integrated online 3D anatomical model resources to improve visualization of structures in three dimensions. For each significant anatomical region or system covered in the curriculum, students were provided with links to interactive 3D models. These models could be rotated, zoomed, and virtually "dissected" via a web interface, allowing students to explore anatomical spatial relationships that are difficult to gather from static textbooks. The 3D models served as a safe, accessible supplement to cadaver dissection, enabling repeated practice without the constraints of physical lab availability.

Color-labeled anatomical photographs: To aid in identifying structures in real specimens, we developed a series of high-resolution anatomical photographs with color highlighting. Dozens of images of dissected animal specimens were prepared in the lab, in which different anatomical structures were colored or outlined in distinct colors. For example, we produced a color-cast image of the arterial system in a camel brain (arteries filled with dyed resin to highlight the cerebrovascular anatomy) (Al Aiyan et al., 2023, 2024) and a color-labeled multi-view photograph of an equine humerus (with muscle attachment sites shaded). These visual aids were uploaded to the course website for students to study, helping them delineate boundaries between structures and recognize anatomical details during dissections.

Professional anatomy video demonstrations: We created a dedicated YouTube channel, "Veterinary Anatomy", hosting an extensive collection of anatomy demonstration videos. Over 100 live-recorded dissection demonstrations (15–35 minutes each) were produced, covering all major course topics and dissection procedures. Students were assigned to watch specific videos as pre-lab preparation before certain dissection sessions. By previewing the procedures and anatomical structures on video, students could enter the lab with better context and spend lab time more efficiently. The videos were also available for review after class, allowing students to revisit complex concepts at their own pace.

Course websites and learning platform: A centralized course website was developed as a hub to organize all learning materials and activities. The main site provided an overview and links to sub-pages for each unit or anatomical chapter (e.g. Thoracic Limb Musculoskeletal Anatomy, Cardiovascular System, etc.). About 15 topic-specific web pages for each course were created, aligning with the lecture/dissection schedule across both courses. Each page assembled all relevant resources for that topic in one place including downloadable lecture slides, supplemental reading, links to the flashcard sets, embedded 3D model viewers, pertinent videos from the YouTube channel, self-assessment quizzes, and discussion forums. This structured online platform ensured that students could easily access and navigate multimodal resources by topic, and it encouraged them to engage with the materials outside of class hours.

Online anatomical forums: We provided an online discussion forum (via the course website's forum tool) to facilitate peer-to-peer and student-instructor interaction for each anatomical topic. Students could post questions about lecture content, dissection findings, or any difficulties studying a particular structure. Instructors and teaching assistants monitored the forums and responded with explanations or guidance.

Students were also encouraged to answer each other's questions and share study tips. These forums essentially created a virtual extension of classroom discussion, available 24/7, and helped build a learning community where uncertainties could be addressed promptly. Many students who hesitated to speak up in class found the forums a comfortable place to seek clarification, thus increasing overall engagement.

2.3 Active learning strategies

In addition to digital content, we implemented several active and student-centered learning techniques to increase involvement and deepen understanding: Peer instruction sessions: We incorporated structured peer-teaching opportunities into the lecture schedule. The class was divided into small teams of ±5 students, and each team was assigned a specific sub-topic or case study during the course. Under guidance from the instructor, each team researched their topic and prepared a short teaching presentation (~10–15 minutes) with visuals or demonstrations. On designated days (typically one session per week), one student team would deliver their presentation to the rest of the class.

They actively engaged their peers by explaining concepts, posing questions, and leading brief discussions or quiz questions during the session. After each student-led lesson, the instructor facilitated a Q&A and provided feedback or clarification as needed. These peer instruction sessions required students to teach and learn from each other, reinforcing their grasp of the material through explaining it (Crouch & Mazur, 2001). This approach also kept students attentive and involved, as they knew their classmates would contribute to the lectures in an interactive format.

Collaborative dissection labs: In the anatomy laboratory sessions, we emphasized cooperative learning by assigning students to work in consistent small groups (typically 4–5 students per cadaver) for each dissection. Each group had to coordinate tasks (e.g. one student carefully dissects a region while others read instructions or identify structures) and collectively problem-solve if they had trouble locating or distinguishing an anatomical part. Instructors circulated among groups to coach and ask questions, but students were encouraged to discuss their findings with other teams. This team-based approach in the lab mirrored real clinical teamwork and helped students learn from other team observations. The collaborative lab work complemented the peer instruction in lectures, creating a consistently interactive learning environment (Laal & Ghodsi, 2012; Gokhale, 1995).

Project-based learning (PBL): To facilitate interdisciplinary knowledge integration and foster advanced cognitive skills, we implemented a semester-long project-based learning (PBL) assignment. This approach encourages students to engage critically in diverse topics and apply their learning in practical contexts. Students formed project teams of 3–4 members (separate from the peer-instruction teams) and each team worked on an in-depth anatomical project throughout the course.

Projects were designed to address open-ended questions or real-world challenges in veterinary anatomy. For example, one project had students compare the anatomical adaptations of the forelimb in a horse and a cow and create a poster illustrating how form relates to function for different locomotion needs. Another project involved designing a 3D-printed model of a canine heart with movable parts to demonstrate blood flow, aimed at creating a teaching aid for future classes.

However, another project had a clinical twist: students were asked to develop a case study of a standard veterinary surgical procedure (such as repairing a canine cranial cruciate ligament) and highlight the key anatomical structures that must be understood to perform it successfully. Throughout the semester, teams researched their project topic, continually consulted instructors for guidance, and applied concepts learned in class to their project's context.

In the final week, each team produced a presentation and/or physical model and presented their findings and creations to the class and faculty. These projects required students to apply anatomical knowledge creatively and practically, reinforcing their learning through problem-solving and collaboration. PBL also cultivated skills in research, communication, and critical thinking (Prince, 2004; Freeman et al., 2014).

2.4 Student feedback survey

To assess student engagement and perceptions of the new teaching methods, we developed a comprehensive end-of-course survey. The survey instrument was developed by the course instructor. To establish content validity, the survey was reviewed by two independent experts in veterinary anatomy education who assessed the relevance, clarity, and alignment of the items with course objectives.

In addition, the survey was pilot tested with a small group of five volunteer students (not enrolled in the course), and minor revisions were made based on their feedback to improve clarity and comprehension.

The survey was anonymous and asked students to evaluate various aspects of the learning experience. It included both Likert-scale questions and open-ended prompts:

Likert-scale items: Students were presented with a series of statements regarding the effectiveness and usefulness of each learning tool or activity and their overall satisfaction and engagement. They rated each statement on a 5-point scale (1 = Strongly Disagree, 5 = Strongly Agree). Example statements included:

> *The 3D virtual models helped me understand the spatial relationships of anatomical structures,* and *Peer instruction sessions made the class more engaging than traditional lectures.*

Additional statements evaluated overall course satisfaction

> (*I found this multimodal anatomy course more effective for learning than courses taught with traditional methods*) and (*My understanding of anatomy improved significantly due to the resources and activities in this course*).

Open-ended questions: The survey provided several free response questions to capture qualitative feedback. Students were asked to describe which course components they found most beneficial and why, any challenges or drawbacks they experienced, and suggestions for improvement in future course iterations. These prompts allowed students to elaborate in their own words on their learning experience.

The survey was distributed online to all 60 students in the multimodal cohort after each semester. We achieved a 100% response rate, as participation in the feedback process was encouraged, though voluntary and not graded. For analysis purposes, we combined the feedback from both courses since the questions were similar; students typically responded based on their cumulative experience across the year.

3. Data collection and analysis

For this study, we collected two main types of data: student performance data (exam scores) and survey data (quantitative ratings and qualitative comments).

Academic performance measures: To evaluate learning outcomes, we compared the exam results of the multimodal cohort to those of the control cohort (previous year). In each course (VMED100 and VMED150), students completed a similar set of assessments, including written theory exams (covering identification and functional questions on anatomy) and practical lab exams (identifying structures on specimens).

We computed their overall course score as a percentage for each student, giving equal weight to theoretical and practical components, mirroring the grading scheme used in both years. We then aggregated these scores by cohort and course. The primary comparison was between the mean exam scores of the two cohorts for each course. We also examined performance on specific components, including the practical exam alone, to see if improvements were consistent across different assessment types.

Statistical analysis: We used descriptive statistics (mean ± standard deviation) to summarize exam scores and Likert-scale survey responses. To test for significance in performance differences, independent-samples *t*-tests were applied, comparing the multimodal and control cohorts' mean scores for VMED100 and VMED150. In addition, we performed a two-way analysis of variance (ANOVA) with factors Teaching Method (Traditional vs. Multimodal) and Course (VMED100 vs. VMED150) to determine if there was a significant overall effect of the new teaching approach on scores and whether that effect was similar in both courses. Before conducting t-tests and ANOVA, we assessed normality and confirmed homogeneity of variances. The assumptions for parametric testing were met. Statistical significance was set at $p < 0.05$. All quantitative analyses were conducted using SPSS (v27) software.

Likert-scale survey results were analyzed by calculating the percentage of students who agreed or strongly agreed with each statement and the mean rating for each item. These results were tabulated to identify which tools or activities students found most effective. The small sample (n=60) and ordinal nature of Likert data meant we focused on descriptive insights rather than advanced statistical tests for survey items.

Qualitative Analysis: The open-ended survey responses were analyzed using thematic analysis. Two researchers independently read all the students' comments and performed open coding to label key ideas or sentiments (e.g., increased motivation, technical issues with videos, appreciation of flexibility). The researchers then met to discuss and reconcile the codes, grouping similar codes into broader themes. We identified a set of recurring themes that captured the principles of students' qualitative feedback. Representative quotes were extracted anonymously to exemplify each theme. This qualitative analysis provided context and depth to the numerical survey results, highlighting what aspects of the multimodal approach were most valued by students and what challenges they faced.

4. Results

4.1 Student engagement and perceptions

Quantitative Survey Findings: Overall, student reception of the multimodal, student-centered approach was positive. Table 1 presents a summary of the survey evaluations for different educational tools and activities.

Table 1. Student Survey Ratings of multimodal teaching methods (n = 60).

Learning Tool / Method	Mean Rating (± SD)	Agree (%) †
Vocabulary flashcards (Quizlet/Memrise)	4.0 ± 0.7	75%
3D digital anatomical models	4.2 ± 0.6	82%
Colored anatomical photographs	3.8 ± 0.8	70%
Anatomy instructional videos	4.4 ± 0.5	90%
Course website and online resources hub	4.3 ± 0.6	85%
Online anatomical forums	4.0 ± 0.7	78%
Active learning	4.3 ± 0.6	88%

Note: Likert-scale results are shown for key course components, with higher mean values indicating more positive perceptions. "Agree (%)" represents the percentage of students who responded "Agree" or "Strongly Agree" to the effectiveness of each component.

All the introduced resources were rated favorably (average ratings around 4 out of 5 or higher), indicating that students found each component helpful for their learning. Remarkably, specific tools were exceptionally effective from the students' perspective. The anatomy instructional videos received the highest score: 90% of students agreed that the videos were informative and valuable supplements to lab sessions, giving this resource an average rating of 4.4 out of 5.

The suite of active learning strategies (peer instruction, group work, and projects) was also highly regarded (88% agreement, mean rating 4.3), with many students noting that these activities made the course more engaging and improved their understanding of complex concepts. Interactive 3D models were another highlight (82% agreement, mean ~4.2), as they helped students visualize anatomical structures in ways that are not possible with textbooks alone.

75% of students reported that the vocabulary flashcard apps significantly aided their memorization of terms (mean rating ~4.0), and 70% said that the color-labeled photographs improved their ability to identify anatomical structures in real specimens (mean ~3.8). While slightly lower than other tools, this still indicates a positive effect. 85% of students appreciated a centralized course website, with an average rating of around 4.3. Students agreed that having all course materials organized online and accessible from the first day of the semester made it easier to learn and review content. Additionally, the online discussion forums were valued: 78% of respondents agreed that the forums were a useful platform for clarifying doubts and learning from peers. However, a few students noted that not everyone actively participated in the forums, and some preferred just to read the answers.

Overall, every modality in the multimodal course received more than two-thirds positive agreement, demonstrating broad student support for the diverse learning methods. When asked to compare this with traditional anatomy classes, a substantial majority of students (over 90%) either agreed or strongly agreed that the multimodal, student-driven format provided a superior learning experience in terms of engagement and accessibility.

From these results, the anatomical video and active learning emerged as the most universally praised elements, closely followed by the comprehensive course website and 3D models. Even the lower rated items (e.g., colored photos) were still considered helpful by most students. This suggests that combining multiple modalities allowed each student to find resources that suited their learning style, while the interactive sessions kept nearly everyone engaged in class.

Qualitative Feedback (Thematic Analysis): The open-ended survey responses provided deeper insight into why students felt the way they did about the course. Several clear themes emerged from the comments:
Enhanced engagement and motivation: Many students remarked that the various activities made the class more interesting and kept them actively involved. They enjoyed listening to lectures and being more involved, whether quizzing themselves with flashcards, manipulating a 3D model, or participating in a peer presentation.

Many said this made them excited to attend class. An example written by a student was *"It was the first time I actually looked forward to anatomy lab"*, crediting the interactive nature of the course for boosting their motivation. Peer instruction was often mentioned as a standout feature, with students explaining that teaching each other was fun and breaking up traditional lectures' monotony.

Better understanding through multiple modes: Students overwhelmingly felt that having multiple representations of anatomical information improved their comprehension. They cited examples such as being able to watch a dissection video before doing it themselves, which helped them know what they to expect in the lab, and then later using the 3D anatomical models at home to rotate the organ and reinforce what they saw in the lab. This combination of visual, auditory, and hands-on learning was praised.

One student said,

> *"The 3D models allowed me to see structures from all angles; it really clicked for me after struggling to imagine things in 2D."*

Others noted that the flashcards and online quizzes helped them reinforce terminology, making it easier to follow the lab instructions and discussions. The concepts of visualization and reinforcement frequently appeared, as students believed the tools worked together to strengthen their understanding.

Flexibility and accessibility: Students liked being able to access materials anytime and anywhere, especially the recorded videos and the course website. Several comments mentioned that if something was unclear in class, they could later revisit the online resources to study at their own pace. The ability to pause and replay video demonstrations or spend extra time on a 3D model was a significant advantage for different learning speeds. *"Having everything online meant I could study whenever I had time and repeat the difficult topics as much as I needed."* This flexibility was beneficial for students who might need more review or those who wanted to get ahead, since both were accommodated.

Collaboration and communication skills: Students noted that the active learning components also improved their skills. Working in lab groups and on projects taught them how to communicate effectively with classmates. A few students admitted they were initially nervous about presenting to the class but finally found it rewarding and confidence-building. They also felt a sense of community forming in the class: *"We were all helping each other to learn."* This supportive, interactive atmosphere contrasted with more individual and passive experiences typical of a traditional classroom setting. We believe that these collaborative experiences were engaging and good practice for students' future teamwork in clinical settings.

Challenges and Suggestions: While feedback was largely positive, students did provide some constructive criticism. The most common challenge was technical difficulties loading the 3D models on their home computers. Another suggestion was to integrate the anatomical forums into the class by allocating a small participation grade to encourage more questions online, as some felt only a portion of the class actively posted. These comments point to areas for minor improvement, such as providing clearer guidance on how to navigate the resources and ensuring technical support for the digital platforms.

Overall, the student feedback indicates that the multimodal approach succeeded in creating an engaging and flexible learning environment. Both the quantitative and qualitative data suggest high student satisfaction and pedagogical benefit from this student-centered, resource-rich approach.

4.2 Learning outcomes and academic performance

The multimodal approach yielded measurable improvements in student learning outcomes. Exam performance in both anatomy courses was higher for the cohort that experienced the new teaching methods compared to the previous year's cohort taught with traditional methods. Table 2 presents the average course scores for each group, alongside statistical test results.

Table 2. Comparison of exam scores between traditional and multimodal teaching cohorts

Course	Traditional Teaching (Mean ± SD)	Multimodal Teaching (Mean ± SD)	% Improvement	*p*-value (t-test)
VMED100 (Anatomy I)	78.4% ± 5.3%	85.9% ± 5.1%	+7.5%	$p < 0.001$
VMED150 (Anatomy II)	80.1% ± 5.5%	85.5% ± 5.7%	+5.4%	$p < 0.001$

Values mean overall course scores (percentage ± SD) for each group (n ≈ 60 per cohort). P-values are from independent t-tests between cohorts for each course.

Students in the multimodal cohort scored significantly higher on average than the traditional cohort in Animal Anatomy I (VMED100). The mean overall score for VMED100 in the control group was 78.4% (SD 5.3), whereas the multimodal group's mean was 85.9% (SD 5.1), corresponding to an improvement of approximately 7.5 percentage points. This difference is visually presented in Figure 1, which illustrates the average exam scores between the two cohorts.

In Animal Anatomy II (VMED150), a similar trend was observed: the traditional cohort's mean score was 80.1% (SD 5.5) versus 85.5% (SD 5.7) in the multimodal cohort, an increase of about 5.4 points. Figure 2 presents this comparison clearly, highlighting the consistent performance advantage under the multimodal approach. The effect size of the improvement was moderately too large for VMED100 and moderate for VMED150, indicating a meaningful performance improvement.

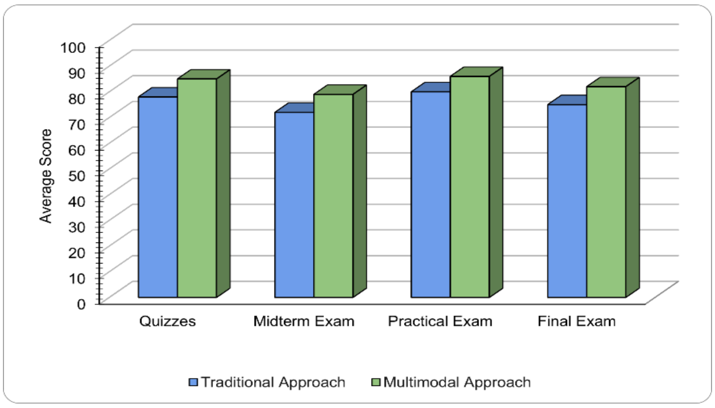

Figure 1: Comparison of VMED100 Exam Scores: Traditional vs. Multimodal Approach.

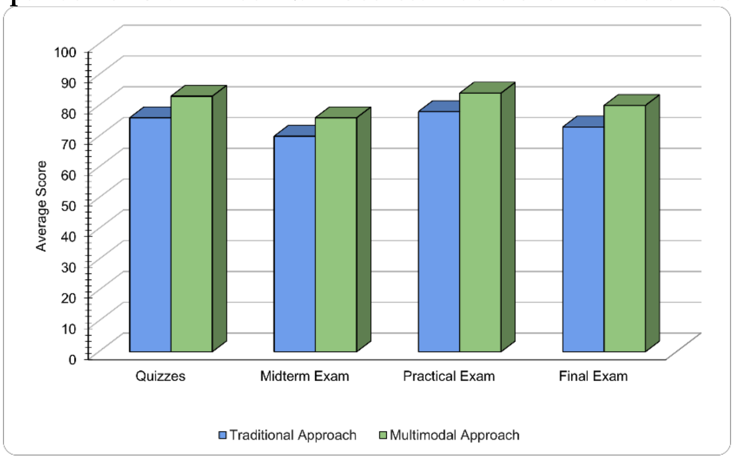

Figure 2: Comparison of VMED150 Exam Scores: Traditional vs. Multimodal Approach.

Notably, the performance benefits of the multimodal approach were seen across all types of assessments within the courses. In VMED100, for example, students taught with the new methods outperformed the previous cohort in the written midterm, the lab practical exam, and the final theory exam, suggesting a broad-based improvement in understanding and holding of anatomical knowledge. A similar pattern was held for VMED150. The increases were not confined to a particular type of exam question; instead, students showed improvement in remembering and applying their knowledge in practical situations. No exam scores in the multimodal group were lower than the prior year's averages for any assessment category.

To further analyze the data, we conducted a two-way ANOVA on student scores with teaching method (Traditional vs. Multimodal) and course (VMED100 vs. VMED150) as factors. The ANOVA results showed a significant main effect of teaching method on exam scores ($F(1, 116) \approx 45.2$, $p < 0.001$), confirming that overall, the multimodal teaching was associated with higher performance.

The effect of course was not significant ($p > 0.3$), and there was no significant interaction between method and course ($p > 0.5$). This indicates that the improvement provided by the multimodal approach was consistent in both courses. In other words, the teaching method benefited student performance in Anatomy II just as much as in Anatomy I, with no evidence that one course gained more than the other.

From an educational perspective, an average improvement on the order of 5–7 percentage points are significant, especially considering that both cohorts were similar in academic caliber and the exams were of comparable difficulty. This finding provides realistic support that the combination of digital resources and active learning strategies can translate into better mastery of course content.

In addition to exam scores, we observed additional benefits of the new approach during the course implementation. Remarkably, because students had access to high-quality digital resources, the number of actual animal cadaver specimens required for labs was reduced. Instructors reported using approximately 20% fewer animal cadavers than in previous years for the same courses. This reduction did not negatively impact student learning as evidenced by improved performance. This outcome has positive implications for ethical considerations and resource use, aligning with the principles of Replacement and Reduction in animal use for education.

5. Discussion

This exploratory implementation suggests that a multimodal, student-centered approach significantly enhances veterinary anatomy education. By integrating various digital tools with active learning, students displayed greater engagement, satisfaction, and higher academic performance compared to traditional lectures. This combination of positive experiences and outcomes indicates that these innovations effectively improved students' understanding of anatomy.

The feedback from students regarding the various components of the multimodal curriculum was positive. The high utilization and appreciation of digital resources underscores the importance of accommodating various learning styles and needs in modern teaching (Kornell, 2009; Muca et al., 2023; Schmidmaier et al., 2011). Different students tended to prefer different tools. Some benefited greatly from the 3D interactive models to visualize three-dimensional relationships, while others relied on flashcards and quizzes for memorization, and others found the videos to be their favored revision method.

The presence of multiple modalities allowed each student to adapt their study approach, which likely contributed to the overall improvement in understanding. Providing multiple ways to access information helps reinforce learning for everyone, including those who learn best visually, audibly, or through hands-on activities. (Azer & Azer, 2016). It also aligns with findings in human anatomy education, where mixed-media approaches have improved comprehension and retention of complex material (Petersson et al., 2009).

Among the tools, the professional anatomy video demonstrations were particularly impactful. Students' qualitative comments revealed that the videos helped bridge the gap between theory and practice by watching a professional dissection or explanation, they came to the lab better prepared and more confident. This flipped classroom approach allowed for more efficient use of lab time for hands-on learning as supported by recent studies (Kapoor & Singh, 2022). The consistent popularity of the videos aligns with the findings of Attardi et al. (2018), who stated that high-quality online anatomy videos can significantly improve student engagement and act as valuable alternatives or additions when access to physical labs is restricted. Our study suggests that videos do not replace the value of dissection but strengthen it by giving students a preview and review tool.

The strong positive response to active learning strategies in our study reinforces a large body of educational literature emphasizing the benefits of student-centered learning. By explaining concepts to peers, students often explained their understanding, reflecting the adage, to teach is to learn twice.' The effectiveness of peer instruction we observed is verified in other disciplines (Crouch & Mazur, 2001; Vickrey et al., 2015).

Similarly, the use of collaborative group work in labs and projects contributed to a more interactive and supportive classroom culture. Prior research has shown that collaborative learning can improve critical thinking and problem-solving (Gokhale, 1995) and increase students' sense of community (Laal & Ghodsi, 2012; Rauch et al., 2023). Students reported that collaborating on dissections and projects improved their communication and critical thinking about anatomy. These soft skills are beneficial since veterinary medicine is inherently collaborative, making teamwork and communication training crucial during pre-clinical education.

Students indicated that interactive elements like videos, peer teaching, and 3D models were more effective than traditional study aids, highlighting the importance of active engagement in learning. This aligns with educational theory, which suggests that dynamic and social aspects promote deeper understanding compared to passive observation (Prince, 2004; Freeman et al., 2014). Our results suggest transitioning from a lecture-centric model to one where the instructor acts as a facilitator of diverse learning experiences.

This does not mean traditional lectures have no value; in fact, our approach still included brief lectures and direct instruction, but these were combined with other methods to reinforce and immediately apply knowledge. Our study found that the quantitative improvement in exam scores provides strong evidence that this approach did not just make students feel like they learned more, but they demonstrated higher achievement.

The ~6% average increase we observed in final grades is comparable to the improvements reported by Freeman et al. (2014) in a meta-analysis of active learning, where performance in active classrooms was typically better than in traditional ones. Improvements in both anatomy courses suggest a general benefit from the approach, as students showed better anatomical identification and reasoning. The multimodal course likely facilitated more varied practice, leading to enhanced scores. Importantly, these gains were observed in a whole classroom setting, highlighting the potential for scaling up such interventions.

The multimodal approach contributed to ethical and logistical improvements. By incorporating digital dissection alternatives, we were able to reduce the reliance on actual animal cadavers in our teaching by an estimated 20%. This is a significant step toward the principles of the 3Rs (Replacement, Reduction, Refinement) in animal use (Prescott et al., 2017). While cadaveric dissection remains an important part of anatomy education by providing hands-on experience, our study indicates that certain learning objectives can also be achieved through virtual methods without compromising educational outcomes.

In some cases, the virtual models offered perspectives that cadavers could not provide, such as the ability to view an organ from multiple angles or examine it in a healthy state, which is often not possible with preserved specimens of variable quality. Therefore, a blended approach can enhance learning while reducing the use of animals, addressing the ethical considerations in modern veterinary training (McLachlan et al., 2004).

The positive outcomes from this study suggest that veterinary anatomy and potentially other preclinical subjects can significantly benefit from blending traditional and innovative teaching methods. We believe that educators should consider progressively incorporating digital models, interactive media, and peer-based activities to augment dissection and lectures. Even if not all tools are used, adding just a few tools like a 3D atlas and some group case discussions could enhance student engagement. Faculty development and support are crucial.

Instructors may need training to facilitate active learning effectively. Our implementation experience can guide others in sequencing activities. A clear structure, like a centralized website, helps prevent students from feeling exhausted. Clearly defining the purpose and timing of each tool enhances the consistency of the multimodal approach rather than treating them as add-ons.

While our findings reported improved outcomes under the multimodal approach, we acknowledge that students in the intervention group may have spent more time engaging with course materials compared to the traditional cohort. Future studies should aim to monitor and equalize student time investment between groups to more precisely isolate the effects of instructional methods. While student feedback suggests that instructional videos, 3D models, and peer instruction were particularly valued, future research should investigate the individual and combined effects of each element.

Isolating these impacts through controlled comparisons would help educators identify the most effective components, especially when time or resources prevent full implementation of a multimodal approach. Exploring new technologies like virtual and augmented reality and AI-assisted veterinary anatomy education could enhance anatomy learning. We believe that follow-up studies are needed to assess whether the benefits of multimodal learning persist in later improved clinical skills. Expanding collaboration through inter-institutional studies can help apply and assess the multimodal approach in diverse veterinary programs, leading to larger samples and stronger evidence of its effectiveness.

6. Conclusion

In conclusion, this study shows that a multimodal, student-centered approach to veterinary anatomy education is both achievable and highly beneficial. By utilizing advanced teaching methods and a variety of digital tools, we created a more engaging, effective, and accessible learning environment compared to traditional models. The implementation of interactive 3D models, online videos, virtual flashcards, and collaborative projects not only enhanced students' understanding of anatomical concepts but also fostered essential skills such as critical thinking, communication, and teamwork. Students responded enthusiastically to these new methods, demonstrating increased motivation and confidence in their anatomy studies. Importantly, this approach aligns with ethical best practices by reducing reliance on cadaveric materials, thereby adhering to animal welfare principles while improving education.

Our study highlights the benefits of modernizing anatomy curricula in veterinary education. Integrating multimodal resources and active learning strategies improves student perceptions and learning outcomes. As veterinary programs adapt to contemporary learners, technology-enhanced, student-centered learning will be essential. Continued innovation in veterinary anatomy education can enhance efficiency and enjoyment, ultimately producing graduates better equipped for clinical practice and lifelong learning. Future studies should use controlled experimental designs or longitudinal follow-up to confirm these findings and explore their long-term impact on clinical performance and professional competency.

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The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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The author declares that there are no competing interests.

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