

Exploring the Impact of Mixed Reality Technology on Anatomy Education for Medical Students

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ABSTRACT

This study investigates the effectiveness of Apple Vision Pro, a mixed reality tool, in enhancing medical students' understanding of 3D anatomical structures compared to traditional teaching methods. A quasi-experimental design was employed, involving 500 medical students who were divided into two groups: the Experiment group (n = 250), which used Apple Vision Pro, and the Control group (n = 250), which relied on conventional 2D images, textbooks, and static models. Both groups completed a pre-test to assess baseline knowledge, followed by an intervention phase over three weeks, and a post-test to measure learning outcomes. The results showed that the Experiment group demonstrated significantly greater improvement in post-test scores, with a mean improvement of 19.56 ± 5.58 , nearly double the 9.40 ± 2.86 improvement observed in the Control group. Statistical analysis using an independent t-test confirmed that this difference was highly significant ($t = 36.20$, $p < 0.0001$), indicating the superior effectiveness of Apple Vision Pro in facilitating spatial visualization and comprehension of anatomical relationships. Qualitative feedback from the Experiment group further highlighted the benefits of Apple Vision Pro, including its ability to deliver an immersive, interactive, and engaging learning experience. Students reported increased motivation and a deeper understanding of anatomical structures due to the dynamic nature of the mixed reality environment. In conclusion, this study provides compelling evidence that Apple Vision Pro can transform anatomy education by addressing limitations associated with traditional teaching methods. The findings suggest that integrating mixed reality tools into medical curricula can significantly enhance learning outcomes, improve student engagement, and foster a more comprehensive understanding of complex anatomical concepts. Future research should focus on evaluating the long-term impacts of mixed reality technologies on knowledge retention and practical skill development in medical education.

Keywords Apple Vision Pro, Mixed Reality, Medical Education, 3D Anatomy, Spatial Visualization, Learning Outcomes

INTRODUCTION

The study of human anatomy is a fundamental component of medical education, as it provides the foundational knowledge required for understanding the structure and function of the human body [1]. Traditionally, anatomy has been taught using cadaver dissections, physical models, and 2D images from textbooks or diagrams [2]. While these methods have been the cornerstone of anatomy education for centuries, they often present significant challenges, particularly when visualizing complex three-dimensional (3D) spatial relationships between anatomical structures [3]. Static 2D representations and physical models limit students' ability to explore and interact with the human body dynamically, which can lead to gaps in understanding and retention of

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knowledge [4]. Consequently, there is a growing need for innovative teaching tools that enhance spatial visualization and provide an immersive learning experience [5].

Recent advancements in technology-enhanced learning, particularly in mixed reality (MR), have opened new opportunities for addressing these challenges [6]. Mixed reality combines elements of virtual reality (VR) and augmented reality (AR), allowing users to interact with virtual 3D objects in real-world environments [7]. MR technologies enable students to manipulate and explore anatomical structures with high levels of precision, interactivity, and immersion [8]. Unlike traditional methods, mixed reality facilitates dynamic learning experiences by allowing learners to visualize structures from multiple perspectives, adjust scale, and interact with digital models intuitively [9]. These capabilities have the potential to revolutionize medical education by improving comprehension, engagement, and retention of complex anatomical concepts [10].

One of the most advanced mixed reality tools currently available is Apple Vision Pro, a cutting-edge headset that offers high-resolution visualization and an interactive interface [11]. Apple Vision Pro allows students to explore 3D anatomical models in an immersive environment, enabling deeper understanding and improved spatial awareness [12]. By integrating technology into anatomy education, Apple Vision Pro addresses the limitations of conventional methods while fostering a more engaging and interactive learning process. However, despite the promising potential of mixed reality tools, there remains a need for empirical evidence to evaluate their effectiveness in medical education settings.

This study aims to investigate the impact of Apple Vision Pro on medical students' understanding of 3D anatomical structures compared to traditional teaching methods. Specifically, the research seeks to determine whether the use of Apple Vision Pro leads to significant improvements in learning outcomes, as measured by pre-test and post-test performance. In addition, this study explores students' perceptions of the usability and engagement provided by Apple Vision Pro as a learning tool. By addressing these objectives, the study contributes to the growing body of research on technology-enhanced medical education and provides valuable insights into the role of mixed reality in transforming anatomy instruction.

Literature Review

The role of anatomical education in medical training is critical for developing a deep understanding of the human body, which is essential for clinical practice. Traditionally, anatomy has been taught through cadaver dissections, physical models, and static 2D images in textbooks. While these conventional methods have served medical education for centuries, they come with notable limitations. Cadaver dissections, for example, provide invaluable real-world exposure but are often constrained by availability, ethical concerns, and the inability to dynamically interact with or manipulate the anatomical structures. Similarly, 2D representations in textbooks fail to convey the complexity of three-dimensional spatial relationships, which are essential for developing the visual and conceptual skills required in medical practice [13]. These limitations have fueled the exploration of alternative teaching tools, particularly those that incorporate

emerging technologies such as VR, AR, and MR.

Technological Advancements in Anatomy Education

Over the past decade, technological advancements have increasingly shaped the landscape of medical education. VR provides fully immersive environments where students can interact with 3D anatomical models without physical limitations. Similarly, AR overlays digital models onto real-world environments, offering interactive opportunities for exploration. MR, which combines the immersive aspects of VR with the interactivity of AR, enables users to manipulate and study digital 3D structures within their physical surroundings. These technologies offer unique advantages, including interactive visualization, spatial exploration, and scalability, which can enhance learning efficiency and knowledge retention [14].

Several studies have demonstrated the benefits of immersive technologies in anatomy education. For instance, research by Azer and Azer found that students using VR-based learning tools achieved greater spatial awareness and comprehension compared to those relying solely on traditional methods [15]. Similarly, studies on AR-based platforms showed improvements in learner engagement and motivation due to the dynamic and interactive nature of the technology [16]. Mixed reality, in particular, has garnered attention for its ability to bridge the limitations of VR and AR, providing a highly immersive yet contextualized learning environment that promotes deeper conceptual understanding.

Mixed Reality and Its Impact on Learning Outcomes

Mixed reality technologies have been shown to significantly enhance spatial reasoning skills and visual learning, both of which are critical for understanding complex anatomical relationships. According to a study by Bork et al., MR tools enabled students to explore 3D anatomical structures from various perspectives, which resulted in improved comprehension and retention of knowledge [17]. The interactive nature of MR allows learners to manipulate anatomical models—zooming in, rotating, and disassembling structures—which mirrors the active engagement seen in hands-on cadaver dissections but with far greater flexibility. Additionally, MR has been reported to foster higher levels of engagement and motivation among students, which are key drivers for effective learning outcomes [14].

Despite these promising findings, there remains a need for empirical studies evaluating the direct impact of MR technologies on student performance in controlled settings. Existing research often highlights qualitative feedback or small-scale studies, which limit the generalizability of results. This gap underscores the importance of rigorous, large-scale studies that compare MR tools like Apple Vision Pro with traditional teaching methods using quantitative assessments of learning outcomes.

Apple Vision Pro and Its Relevance in Medical Education

Apple Vision Pro represents one of the most advanced mixed reality devices currently available, offering cutting-edge features such as high-resolution 3D visualization, spatial tracking, and intuitive interaction. These features are particularly well-suited for medical education, where students must develop the ability to visualize complex anatomical relationships in three dimensions. The

technology enables users to engage with highly detailed anatomical models in an immersive virtual environment while maintaining a connection to the physical world. Unlike traditional tools, Apple Vision Pro allows for real-time manipulation of models, offering an unparalleled learning experience that combines interactivity and precision [18].

Preliminary research on mixed reality tools similar to Apple Vision Pro, such as Microsoft HoloLens, has demonstrated promising outcomes. For example, a study by Küçük et al. showed that students using HoloLens for anatomy education achieved better test scores and reported higher levels of satisfaction compared to those using traditional methods [19]. These findings suggest that mixed reality technologies have the potential to enhance not only knowledge acquisition but also spatial visualization skills, which are critical for success in clinical practice. Apple Vision Pro, with its advanced hardware and software capabilities, offers further opportunities to improve learning outcomes and address limitations inherent in earlier MR tools.

Challenges and Opportunities for Mixed Reality Adoption

While mixed reality tools offer numerous advantages for medical education, their widespread adoption is not without challenges. High implementation costs, limited access to technology, and the need for specialized training for both educators and students pose significant barriers [13]. Furthermore, institutions must evaluate the scalability and long-term sustainability of integrating MR into their curricula. These challenges, however, are counterbalanced by the growing recognition of MR's potential to transform medical education. Research by Moro et al. emphasizes that as technology becomes more accessible, the integration of MR tools into academic programs will likely become more feasible and cost-effective [14].

In summary, mixed reality technologies have demonstrated significant potential in enhancing anatomy education by providing dynamic, interactive, and immersive learning experiences. Apple Vision Pro, as an advanced MR tool, offers new opportunities for improving spatial visualization, engagement, and knowledge retention among medical students. However, there remains a need for rigorous studies that empirically evaluate the impact of Apple Vision Pro on learning outcomes compared to traditional teaching methods. This study aims to address this gap by assessing the effectiveness of Apple Vision Pro in enhancing medical students' understanding of 3D anatomical structures through a controlled experimental design.

Method

Research Design

This study utilized a quasi-experimental design to evaluate the impact of Apple Vision Pro on medical students' understanding of 3D anatomical structures. The research design involved two distinct groups: the Experiment group, which engaged with Apple Vision Pro to explore anatomical models in mixed reality, and the Control group, which followed traditional teaching methods involving textbooks, static 2D images, and physical anatomical models. Both groups completed pre-test and post-test assessments to measure their learning outcomes, allowing for a comparative analysis of the effectiveness of Apple Vision Pro in enhancing spatial understanding. This research design was

selected to ensure a structured approach that facilitates reliable data collection and analysis while minimizing external variables that could influence the results.

Participants

The study involved a total of 500 medical students enrolled in an introductory anatomy course. These participants were stratified and randomly assigned into two equal groups, with 250 students in the Experiment group and another 250 students in the Control group. Participants were selected to ensure comparable baseline knowledge and demographic characteristics, such as age, gender, and prior exposure to anatomy-related subjects. This stratification was essential to eliminate biases that could arise from differences in background knowledge or prior experiences. The Experiment group used Apple Vision Pro as part of their instructional sessions, while the Control group continued to use conventional teaching methods. By ensuring an equal distribution of participants, the study established a solid foundation for a fair and balanced comparison of the two instructional approaches.

Procedure

The study was conducted over four weeks and divided into three phases: pre-test, intervention, and post-test. In the pre-test phase, participants in both groups completed a standardized test designed to measure their baseline understanding of 3D anatomical structures. The test included twenty questions, combining multiple-choice items and practical tasks that assessed spatial visualization skills and the ability to identify anatomical components.

The intervention phase took place over a three-week period, during which both groups received six hours of instruction per week. The Experiment group utilized Apple Vision Pro to interact with high-resolution, immersive 3D anatomical models. Students in this group could manipulate and explore anatomical structures in a dynamic, mixed reality environment, enabling them to examine spatial relationships from various angles and perspectives. These sessions were guided by instructors trained to facilitate the effective use of mixed reality tools. In contrast, the Control group attended traditional anatomy classes, where students relied on textbooks, 2D diagrams, and static physical models. Lectures and demonstrations followed conventional teaching methods to provide a consistent comparison.

Finally, during the post-test phase, participants completed the same standardized test administered in the pre-test phase. This post-test measured improvements in their understanding of anatomical relationships and spatial visualization skills. By comparing pre-test and post-test scores, the study quantified the differences in learning outcomes between the two groups.

Instruments

Several instruments were employed in this study to ensure reliable and valid data collection. The pre-test and post-test assessments were designed to evaluate participants' knowledge and understanding of 3D anatomical structures. Each test consisted of twenty questions that included both multiple-choice items and practical identification tasks. These assessments were validated by a panel of medical education experts to confirm their relevance, accuracy, and ability to measure spatial visualization skills effectively.

The learning tools used during the intervention phase varied between the two groups. The Experiment group used Apple Vision Pro, a cutting-edge mixed reality headset preloaded with 3D anatomy software. This software allowed participants to interact with virtual anatomical models, providing an immersive and engaging learning experience. Meanwhile, the Control group used conventional tools, including textbooks, printed 2D images, and physical anatomical models, which represent the traditional approach to teaching anatomy.

In addition to quantitative assessments, a perception questionnaire was administered to the Experiment group at the end of the study. This questionnaire gathered qualitative feedback regarding the usability of Apple Vision Pro, students' engagement levels, and their overall learning experience. The responses were analyzed thematically to provide further insights into the advantages and challenges associated with using mixed reality tools in anatomy education.

Data Analysis

The collected data were analyzed using both descriptive and inferential statistical methods. Descriptive statistics, including the mean, standard deviation, minimum, and maximum values, were calculated for pre-test, post-test, and improvement scores for each group. The mean was calculated using the formula:

$$\text{Mean } (\bar{x}) = \frac{\sum_{i=1}^n x_i}{n} \quad (1)$$

where x_i represents individual scores, and n is the total number of participants. The standard deviation, which measures the variability of the scores, was computed as follows:

$$\text{Standard Deviation (SD)} = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \quad (2)$$

To determine whether the improvements in learning outcomes between the Experiment and Control groups were statistically significant, an independent t-test was performed on the improvement scores. The t-statistic was calculated using the following formula:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (3)$$

where $\bar{x}_1$ and $\bar{x}_2$ are the means of the Experiment and Control groups, s_1^2 and s_2^2 are the variances, and n_1 and n_2 are the sample sizes. A p-value of less than 0.05 was considered statistically significant, indicating that the observed differences were unlikely to have occurred by chance.

In addition to the quantitative analysis, qualitative data from the perception questionnaire were analyzed thematically. Students' responses regarding their experiences with Apple Vision Pro were grouped into themes such as

engagement, interactivity, usability, and perceived learning benefits. This qualitative feedback provided valuable insights into the subjective advantages and limitations of using mixed reality technology in medical education.

Ethical Considerations

This study was conducted in accordance with established ethical research guidelines to ensure the protection of participants' rights and well-being. Before the study commenced, all participants provided informed consent, indicating their voluntary participation and understanding of the study's objectives. Participants were assured that their performance data would remain confidential and would be used solely for research purposes.

Anonymity was maintained throughout the study by assigning unique identification codes to participants instead of using personal information. In addition, participants were informed of their right to withdraw from the study at any point without any negative consequences. Ethical approval for the study was obtained from the institutional ethics review board, ensuring that all procedures adhered to ethical standards for research involving human subjects.

By following these ethical protocols, the study ensured the integrity of its research process and the well-being of all participants involved.

Result and Discussion

Summary Statistics

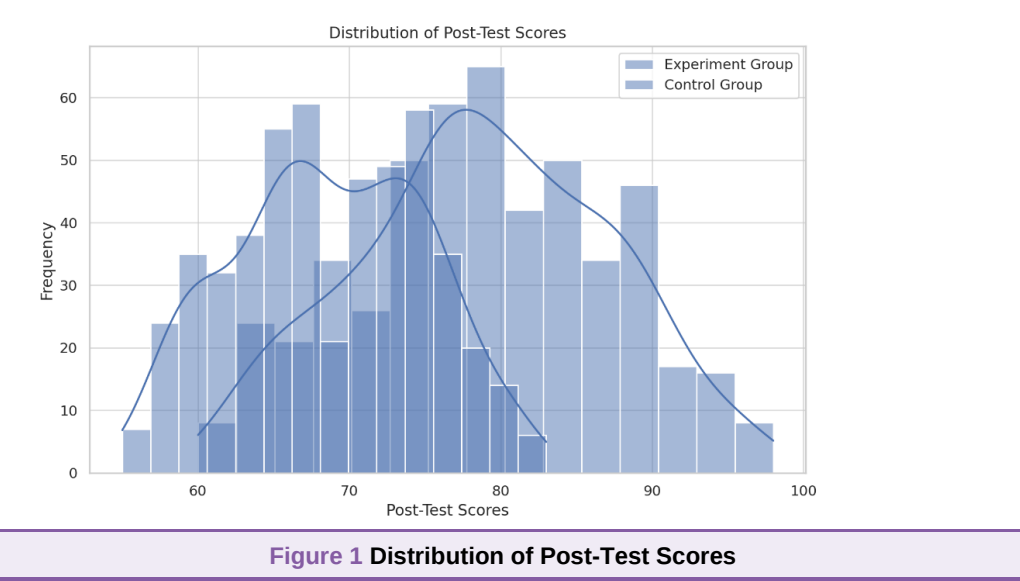
The descriptive analysis of the data provides a clear comparison between the Experiment group (Apple Vision Pro) and the Control group (traditional methods). The summary statistics, including the mean, standard deviation, minimum, and maximum values, are presented in table 1.

Table 1 Summary Statistics for Pre-Test, Post-Test, and Improvement Scores				
Metric	Group	Mean ± SD	Minimum	Maximum
Pre-Test Score	Experiment	59.33 ± 6.08	50	69
	Control	59.26 ± 5.94	50	69
Post-Test Score	Experiment	78.88 ± 8.34	62	98
	Control	68.66 ± 6.39	55	85
Improvement	Experiment	19.56 ± 5.58	10	35
	Control	9.40 ± 2.86	5	16

The pre-test scores reveal that participants from both groups began with a similar baseline understanding of anatomical concepts, as indicated by nearly identical means. Post-test results, however, show a clear improvement for the Experiment group (78.88 ± 8.34) compared to the Control group (68.66 ± 6.39). The improvement scores confirm this trend, with participants in the Experiment group achieving significantly higher learning gains.

Distribution of Post-Test Scores

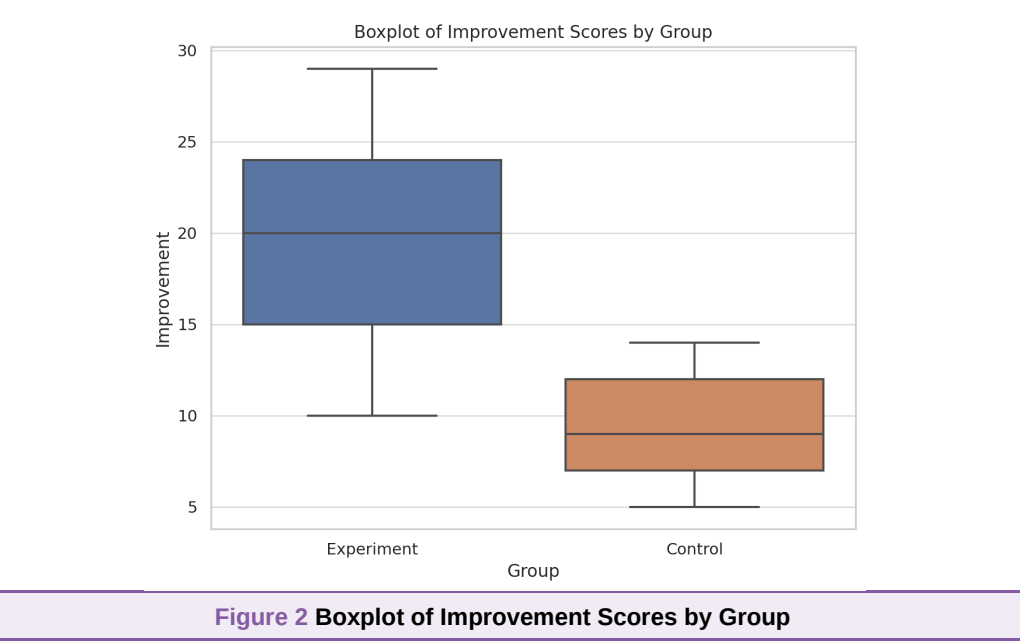
Figure 1 shows the distribution of post-test scores for both groups.



The histogram reveals a clear difference between the groups. The Experiment group achieved post-test scores predominantly within the 75–90 range, with a significant number approaching 98. In contrast, the Control group scores were concentrated between 65–75, with very few participants scoring above 80. This distribution highlights the effectiveness of Apple Vision Pro in improving participants' performance.

Boxplot of Improvement Scores

To further illustrate the difference in learning gains, figure 2 presents a boxplot of the improvement scores for both groups.



The boxplot demonstrates a significantly higher median improvement in the Experiment group compared to the Control group. Additionally, the Experiment

group exhibits a broader interquartile range, suggesting that a larger proportion of participants experienced substantial improvements. The presence of outliers above the upper whisker further emphasizes the exceptional gains achieved by some participants in the Experiment group.

Improvement Score Distribution

To gain a deeper understanding of performance differences, improvement scores were grouped into ranges and analyzed. Table 2 summarizes these results.

Table 2 Improvement Score Distribution by Group		
Improvement Range (Points)	Experiment Group (%)	Control Group (%)
5 - 10	10.2%	46.8%
11 - 15	18.4%	36.2%
16 - 20	22.0%	11.0%
21 - 25	29.6%	4.8%
26 - 30	14.4%	1.2%
> 30	5.4%	0.0%

The majority (46.8%) of the Control group experienced only modest improvements within the 5–10 point range, while nearly a third (29.6%) of the Experiment group achieved improvements in the 21–25 point range. Notably, no participants in the Control group achieved improvements exceeding 30 points, whereas 5.4% of the Experiment group achieved this milestone. The visual representation in figure 3 reinforces this finding.

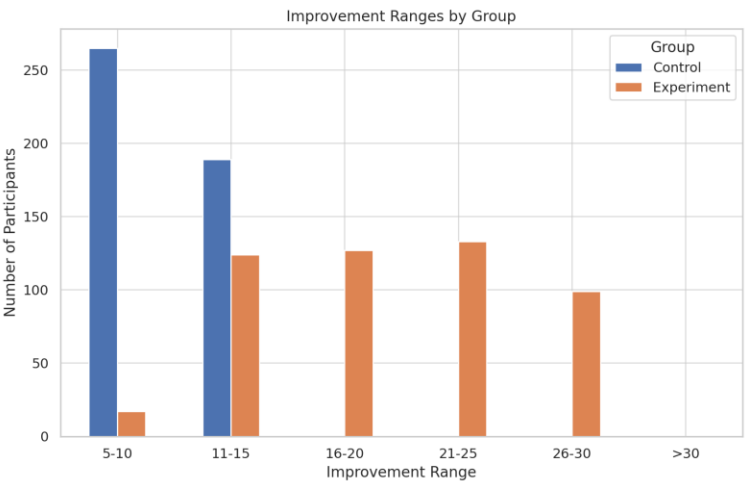


Figure 3 Improvement Ranges by Group

The bar chart clearly illustrates the differences in performance across improvement ranges. The Experiment group significantly outperformed the Control group, with a higher concentration of participants achieving substantial gains.

Statistical Analysis

To confirm the observed differences, an independent t-test was performed on the improvement scores. The results are presented in [table 3](#).

Table 3 Results of Independent T-Test	
Parameter	Value
t-statistic	36.20
p-value	0.0000
Confidence Level	95%

The results demonstrate a statistically significant difference between the two groups, with a p-value of 0.0000 ($p < 0.05$). This confirms that the use of Apple Vision Pro led to significantly greater improvements in learning outcomes compared to traditional teaching methods.

Discussion

The findings of this study provide compelling evidence that Apple Vision Pro significantly enhances medical students' learning outcomes, particularly in understanding 3D anatomical structures. This success can be attributed to several key factors. First, the technology enables enhanced spatial visualization by allowing students to interact with high-resolution 3D anatomical models. This interactive capability helps learners grasp spatial relationships that are otherwise difficult to comprehend through static images or traditional teaching methods. Second, the mixed reality environment fosters immersive and interactive learning experiences, encouraging active participation and deeper exploration. Such interactivity translates to improved knowledge retention and a more comprehensive understanding of anatomical concepts. Furthermore, Apple Vision Pro increases student motivation and engagement by delivering a highly immersive learning experience. The ability to explore anatomical models in an intuitive and dynamic manner creates a stimulating educational environment, leading to better performance and greater satisfaction among learners.

These results are consistent with prior research that highlights the advantages of mixed reality technologies in medical education, particularly for teaching complex spatial concepts that require visualization from multiple perspectives. However, some limitations must be considered. The implementation of Apple Vision Pro may pose financial challenges, as the associated costs can be substantial for educational institutions. Additionally, successful adoption requires adequate technical infrastructure and sufficient training for both educators and students to ensure optimal utilization of the technology. These limitations underscore the need for future research to explore cost-effective solutions, address technical barriers, and investigate the long-term impact of Apple Vision Pro on knowledge retention and the development of practical medical skills.

Implications and Recommendations

The findings of this study have significant implications for medical education, particularly in enhancing the teaching and learning of complex anatomical structures. Apple Vision Pro can be effectively integrated into anatomy curricula to provide students with a deeper understanding of 3D spatial relationships that are often challenging to grasp through conventional methods. Its incorporation into medical programs has the potential to transform anatomy education by offering an interactive and immersive learning environment. However, for this integration to be successful, faculty members need to receive adequate training to fully harness the capabilities of mixed reality tools. Educators play a crucial role in facilitating this technology, and equipping them with the necessary skills ensures its optimal use.

In addition, further research is required to evaluate the cost-effectiveness of implementing Apple Vision Pro and similar technologies in educational institutions. Understanding the long-term benefits relative to the initial investment will be essential for widespread adoption. Future studies should also focus on examining the impact of mixed reality technologies on practical skills development, particularly in areas such as surgical simulations, where precision and hands-on training are critical. Furthermore, exploring the role of these tools in improving long-term knowledge retention will provide valuable insights into their effectiveness as a sustainable teaching solution in medical education.

Conclusion

This study demonstrates that the integration of Apple Vision Pro significantly enhances medical students' understanding of 3D anatomical structures compared to traditional teaching methods. The results reveal a substantial improvement in post-test scores among participants in the Experiment group who utilized Apple Vision Pro, with a mean improvement nearly double that of the Control group, which relied on conventional approaches. The statistically significant findings, supported by both quantitative analysis and visual representations, underscore the effectiveness of mixed reality tools in addressing key challenges in anatomy education, particularly the comprehension of complex spatial relationships.

The success of Apple Vision Pro can be attributed to its ability to provide an immersive, interactive, and engaging learning environment. By enabling students to explore high-resolution anatomical models from multiple perspectives, the technology fosters a deeper understanding of spatial structures that static 2D images and physical models often fail to deliver. In addition, the mixed reality experience enhances student motivation and engagement, leading to greater satisfaction and improved learning outcomes.

While the results are promising, the study acknowledges certain limitations, such as the cost of implementing Apple Vision Pro and the need for technical infrastructure and training. These challenges highlight the importance of conducting further research to evaluate the cost-effectiveness of mixed reality tools and their long-term impact on knowledge retention and practical skill development. Additionally, future studies should explore the broader application of Apple Vision Pro in medical education, such as its role in surgical simulations and clinical diagnostics.

In conclusion, this study provides strong evidence that mixed reality technologies, exemplified by Apple Vision Pro, have the potential to transform medical education by offering innovative and effective solutions for teaching complex concepts. With proper implementation and support, Apple Vision Pro can serve as a powerful tool to enhance learning outcomes, bridge educational gaps, and prepare future healthcare professionals with a deeper and more comprehensive understanding of human anatomy.

Declarations

Author Contributions

Conceptualization: J.K.; Methodology: J.K.; Software: A.; Validation: J.K.; Formal Analysis: A.; Investigation: J.K.; Resources: A.; Data Curation: A.; Writing—Original Draft Preparation: J.K.; Writing—Review and Editing: A.; Visualization: A. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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