P-ISSN: 1412-3746
E-ISSN: 2549-6557

JURNAL KESEHATAN
FAKULTAS KESEHATAN
UNIVERSITAS DIAN NUSWANTORO
Volume 24. No.2, September 2025

AR-MUSCLE: Mobile-Based Augmented Reality Innovation for Interactive Anatomy–Physiology Learning of the Musculoskeletal System in Undergraduate Students

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Article History
Recived : 06-10-2025
Accepted : 09-10-2025
Revision : 13-10-2025

ABSTRACT

The implementation of clinical coding for musculoskeletal disorders requires comprehensive knowledge of human anatomy and physiology. The advancement of Augmented Reality (AR) technology provides an effective approach to addressing students' learning difficulties in health sciences, particularly in understanding the musculoskeletal system. This study aims to develop a mobile-based Augmented Reality application called AR-MUSCLE, designed as an interactive learning medium for health science students. The research background stems from the difficulty students face in mastering complex anatomical and physiological concepts through conventional learning media limited to 2D illustrations and static models. The research employed a Research and Development (R&D) design using the ADDIE model (Analysis, Design, Development, Implementation, Evaluation). The application integrates interactive 3D visualization of the human musculoskeletal system, structured learning modules, and evaluation quizzes. The development process involved needs analysis, system design using the Unified Modeling Language (UML), 3D model creation, AR system integration via Unity Engine, and prototype evaluation. Functional testing (Black Box Testing), usability testing, and user satisfaction assessments were conducted to ensure reliability and effectiveness. The results showed that all application features functioned properly and responsively as designed. The usability testing yielded a very low error rate (<5%), indicating that users could easily navigate and operate the application. The user satisfaction survey demonstrated very high ratings, averaging above 95% across four dimensions: learnability, responsibility, satisfaction, and accuracy. Nevertheless, improvements are required in the system responsibility aspect since the mobile-based application depends heavily on stable internet connectivity and adequate device specifications to support the interactive 3D rendering process. In conclusion, AR-MUSCLE proves to be an effective Augmented Reality-based interactive learning tool that enhances students' conceptual understanding, motivation, and engagement in learning musculoskeletal anatomy and physiology. This research contributes to strengthening digital learning innovation in health education and supports the transformation toward technology-integrated teaching and learning models.

Keywords: Augmented Reality, musculoskeletal system, interactive learning, mobile application, anatomy and physiology, health students

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INTRODUCTION

Anatomy and Physiology constitute foundational subjects in health sciences education, particularly in Health Information Management programs, forming the basis for understanding the structure and function of the human body within the musculoskeletal system and underpinning the establishment of clinical coding. Due to the complexity of the system's architecture and the interrelationships among its components, detailed comprehension and clear visualization are required to enable students to master the material comprehensively.[1] However, many students still struggle to maximally comprehend these concepts using conventional teaching methods, which tend to be passive and limited to two-dimensional media or static models. [2] This underscores the importance of developing more innovative and interactive teaching methods to enhance students' understanding and motivation in learning musculoskeletal anatomy and physiology.[3]

A significant gap still exists between the need for three-dimensional visualization in musculoskeletal anatomy education and the predominantly conventional, less interactive teaching methods currently employed. Recent research data indicate the low effectiveness of traditional learning media in enhancing the understanding of complex concepts among health science students.[4] Meanwhile, the advancement of Augmented Reality (AR) technology offers great potential as an educational medium, enabling interactive visualization and a more organized and immersive learning experience.[5] However, the application of AR in musculoskeletal anatomy education within academic settings remains very limited and underutilized, creating a gap that requires further investigation to develop more effective learning solutions.

Previous studies have demonstrated that Augmented Reality (AR)-based learning media can enhance students' interest and comprehension in anatomy and physiology compared to conventional methods.[6] However, many of these studies remain limited to general AR applications without a specific focus on the musculoskeletal system, which has its own inherent complexities.[7] Furthermore, prior research has often evaluated effectiveness only in the short term and has yet to examine the holistic impact of AR integration within the health sciences higher education curriculum. This highlights the need for further exploration on how AR can be optimized as a musculoskeletal anatomy learning medium that is not only effective but also systematically integrated into the educational process.

This study is crucial to addressing the existing gap by developing and evaluating the effectiveness of Augmented Reality (AR)-based learning media for musculoskeletal anatomy and physiology among health science students. The aim is to create an innovative learning model that enhances conceptual understanding and structural visualization through a more interactive and organized learning experience. The contribution of this research goes beyond providing an empirical foundation for the development of AR technology as a learning medium; it also offers practical implications for curriculum development and teaching methods in higher education health sciences. Therefore, this study is expected to enrich knowledge and significantly improve the quality of musculoskeletal anatomy education.

METHOD

The development of the mobile augmented reality prototype for musculoskeletal anatomy and physiology (AR-Muscle) employed the Research and Development (R&D) method utilizing the ADDIE model (Analysis, Design, Development, Implementation, Evaluation).[8] The initial phase involved a needs analysis, collecting data through literature review and observation. The second phase focused on system design using Unified Modeling Language (UML) to map the application workflow. The third phase comprised the development or implementation of the application using the Unity Engine, which integrates AR technology. The fourth phase involved application testing through feasibility assessments by media experts, content experts, and user respondents. The final phase emphasized evaluation to refine and improve the application to meet expected interactive learning objectives.

The implementing stages of the AR-Muscle prototype through several processes are outlined in the following diagram:

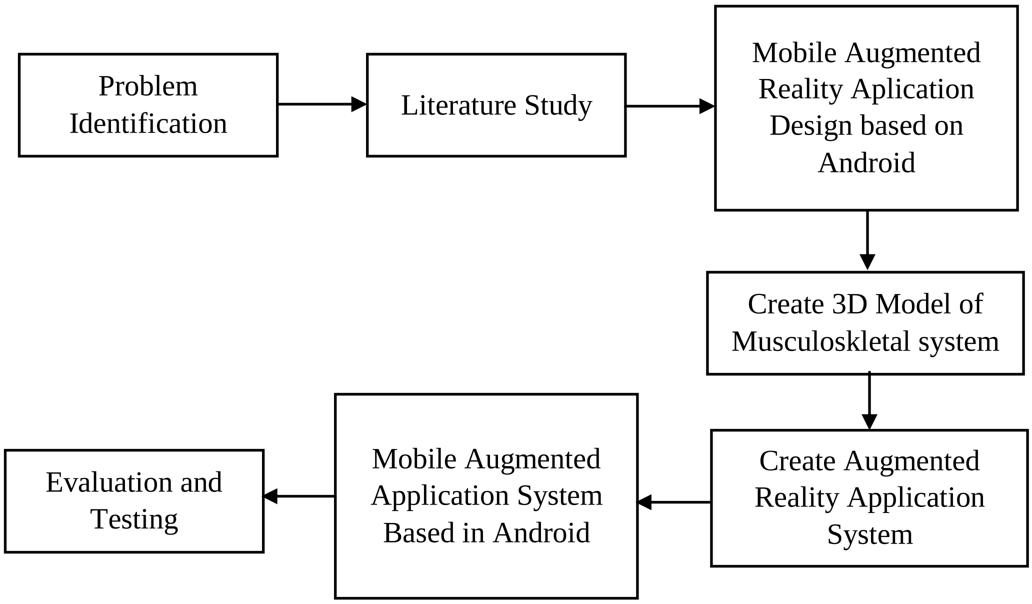


Figure 1. Research Stages

From Figure 1, the research stages in developing the AR-Muscle prototype involve several sequential steps:

Stage 1 is Problem Identification, where students face difficulties comprehending lessons concerning human anatomy. The main obstacle is the limited visualization content in musculoskeletal anatomy and physiology learning media.

Stage 2 a Literature Review is conducted to understand the fundamental concepts of the human musculoskeletal system. This study found that current learning methods predominantly rely on textbooks and 2D illustrations, which are less effective in providing a comprehensive overview of the musculoskeletal system.

Stage 3 involves Designing the Mobile Augmented Reality Application for the Musculoskeletal System on the Android platform. At this stage, the app concept is designed to present medical terminology in a more intuitive and easily understandable format.

Stage 4 is the Creation of the 3D Musculoskeletal System Model, a core element of the application. Upon completion of the 3D model.

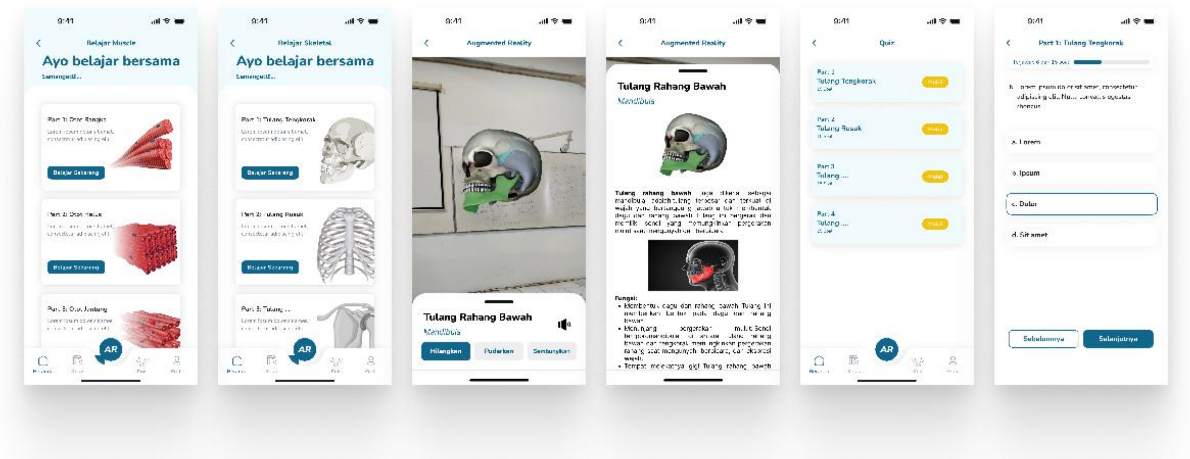
Stage 5 encompasses Developing the Augmented Reality Application System, where the model is integrated into the AR system to be interactively used in the mobile application.

Stage 6 the Mobile Augmented Reality Application for the Musculoskeletal System is developed on the Android platform, combining the 3D model with various other interactive features.

Stage 7 involves Testing and Evaluation to ensure the developed application functions optimally. Evaluation techniques include three testing models: Functional Testing (Black Box Testing), Usability Testing, and User Satisfaction Testing.

RESULTS AND DISCUSSIONS

The initial phase of the research began with problem identification, highlighting the main challenge faced by students in understanding human anatomy, particularly the anatomy and physiology of the musculoskeletal system. The primary obstacle identified was the limited visualization content in conventional learning media, which resulted in students' poor ability to visualize the structural relationships among skeletal components, joints, muscles, and their functional connections. Early observations indicated that two-dimensional representations and textual descriptions alone were insufficient for providing an accurate spatial understanding, making it difficult for students to reconstruct the holistic three-dimensional context of the musculoskeletal system. **Stage 2**, based on the literature review, reveals that current learning paradigms are still dominated by textbooks and 2D illustrations, which often fail to provide a comprehensive understanding of the musculoskeletal system. Key limitations include: (1) the lack of three-dimensional spatial representation necessary for grasping the relationships among bones, joints, muscles, and ligaments; (2) limited functional context linking anatomy with movement mechanics and load dynamics; (3) insufficient opportunities for real interaction with anatomical structures that can enhance conceptual understanding through hands-on exploration; and (4) variability in visualization quality among different reference sources, contributing to inconsistent student perceptions. **Stage 3** design process includes: (1) Interface structure designed for clinical learning contexts, emphasizing simple navigation, interactive labels, and quick access to definitions of medical terminology related to bones, joints, muscles, and ligaments. (2) Key features encompass interactive 3D rendering, contextual AR overlays on real anatomical objects, and step-by-step guided modes for beginners. (3) The pedagogical schema illustrates that placing labels, concise descriptions, and functional relationships between parts enhances conceptual understanding without overwhelming users with excessive information. **Stage 4** involves the creation of the 3D musculoskeletal system model based on collected references using software such as 3DS Max and Autodesk Maya to produce accurate and detailed graphical representations. The process includes geometric modeling, rigging to enable motion animation, as well as texturing and shading to enhance realistic anatomical visualization. Model validation is conducted by comparing with the latest anatomical literature and expert evaluation to ensure structural accuracy, proportions, and functional dynamics. The AR-MUSCLE application is developed following the ADDIE development method, comprising five main stages: Analysis, Design, Development, Implementation, and Evaluation.



Gambar 2. Tampilan Aplikasi AR-MUSCLE

Stage 5 involves integrating the previously created 3D model into the Android-based application using Unity3D to create an interactive Augmented Reality experience. **Stage 6** encompasses the development of the Mobile Augmented Reality Application for the Musculoskeletal System on the Android platform, combining the 3D model while ensuring real-time rendering to maintain consistent visual quality across diverse devices. Interactive features include gestural manipulation of objects (such as translation, scaling, and sectioning of anatomical parts), display of educational labels, and animation of functional movements of muscles and joints. The final phase of development includes validation of interactive functionalities, cross-device compatibility verification for Android devices, and technical documentation covering system architecture and AR workflow.

The human musculoskeletal system studied in this application comprises three main components: bones, muscles, and joints, which work together integratively to enable body movement, provide structural support, and protect internal organs. To facilitate comprehensive understanding, the AR-MUSCLE application offers several thematic learning menus that users can access independently and interactively. The main menus available in the AR-MUSCLE application include:

1. Bone Anatomy – displays 3D models and functional descriptions of various types of human bones.
2. Muscle Structure and Function – presents interactive AR visualizations to study muscle types and contraction mechanisms.
3. Joint System – provides understanding of different joint types and their roles in the movement system.
4. Interactive Quiz – serves as an assessment tool based on AR visual learning.

Stage 7 involved testing the AR-Muscle prototype through multiple methods, including Functional Testing (Black Box Testing), Usability Testing, and User Satisfaction assessment. Functional Testing focused on verifying the application's functionality by testing every button within the AR-MUSCLE app features. This approach is commonly employed in augmented reality applications to ensure all functions operate correctly and align with the intended design.[9] The buttons tested included the app logo button (to access the main page), login button (to enter the app), AR scan button (to display the AR scan page), Skeletal Learning button (for accessing bone learning), Muscle button (for muscle learning), Joint button (for joint learning), clicking bone/muscle/joint images (to display descriptions and 3D objects), quiz button (to access learning evaluations), and logout button (to exit the app). The tests demonstrated that all buttons functioned well and were responsive.

The second phase of testing the AR-MUSCLE prototype involved Usability Testing, which focused on assessing the Error Rate (the frequency of errors and difficulties experienced by users while operating the application) and Task Completion (the percentage of tasks that users could complete without obstacles). The following are the results from the usability testing conducted on the AR-MUSCLE application:

Table 1. Error Rate Using AR-MUSCLE Apps

User Task	Number of Error	Total Attempts	Error Rate (%)
Open the Aplication	2	97	02.06
Menu Navigation	5	97	05.15
Showing Muscles	3	97	03.09
Zooming the AR Object	4	97	04.12
Bones Identifyng	1	97	01.03
Completing Tasks	3	97	03.09

The results of the Error Task calculation for the use of the AR-MUSCLE application indicate that users can understand how to use the application well, although some menu navigation buttons are not yet very familiar to users, necessitating further experience to explore the features and navigation buttons within the application.

The third phase of testing was conducted with a User Satisfaction survey, focusing on user satisfaction when using the AR-MUSCLE application, covering aspects such as Learnability (how easily new users can operate the AR-MUSCLE application), Responsiveness (how quickly the application assists in efficiently completing tasks), Satisfaction (the comfort level and user satisfaction during interaction with the application), and Accuracy (the degree to which the musculoskeletal anatomy objects displayed in AR match user expectations).

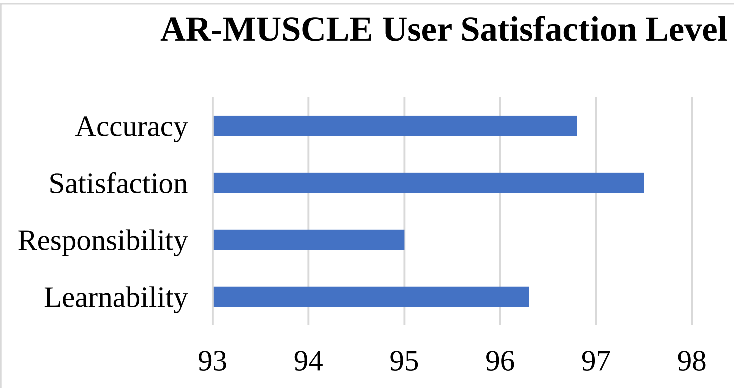


Figure 2. AR-MUSCLE User Satisfaction Level

The results of the Error Task assessment for the AR-MUSCLE application indicate that users generally understand how to use the application effectively; however, some navigation menu buttons are not yet fully familiar to users, necessitating further experience to explore the features and navigation controls. The third phase of testing involved a User Satisfaction survey focusing on user contentment when interacting with the AR-MUSCLE application. This evaluation covered multiple aspects, including Learnability (how easily new users can learn to use the AR-MUSCLE application), Responsiveness (how quickly the application assists users in efficiently completing tasks), Satisfaction (the level of comfort and satisfaction users experience while interacting with the application), and Accuracy (how accurately the musculoskeletal anatomical objects displayed in AR conform to user expectations).[(10)]

The development of the AR-MUSCLE application represents an innovative step in the transformation of learning media for musculoskeletal anatomy and physiology within higher health education. By employing the ADDIE development model, this research successfully produced an interactive Augmented Reality (AR)-based medium that enables students to explore human anatomical structures in three dimensions. The application implementation process demonstrates that AR technology can provide an immersive learning experience that integrates visualization, interactivity, and contextual learning. This finding aligns with research by Chytas et al.[(11)] which asserts that AR-based visual approaches in anatomy enhance students' spatial abilities and conceptual understanding of the complex musculoskeletal system.

The evaluation findings indicate a very high level of user satisfaction with the AR-MUSCLE application, with average scores exceeding 95% across the dimensions of learnability, responsiveness, satisfaction, and accuracy. These results demonstrate that AR-MUSCLE effectively meets the criteria for an effective digital learning medium, both in ease of use and anatomical visualization accuracy. This outcome is consistent with studies by Tene et al. (2024) and Saiydoun et al. (2023), which reported significant improvements in anatomical understanding through AR compared to traditional 2D illustration-based methods.[(12)] Furthermore, the successful implementation of AR-MUSCLE reinforces evidence that integrating interactive visual technology in health science education can enhance cognitive learning outcomes while simultaneously boosting student motivation and engagement.

The evaluation results also identified aspects requiring improvement, particularly in system responsibility. Because this application is mobile-based, its performance and access speed are significantly influenced by internet connection stability and the device's capacity. This issue aligns with research by Corbalán et al.(13) who emphasize that non-functional factors such as system performance, data usage, and hardware specifications are primary determinants of user satisfaction in mobile applications. Therefore, enhancing system efficiency, optimizing file size, and developing an offline-access mode represent critical development directions to ensure AR-MUSCLE can be accessed more broadly and sustainably, especially in academic environments with limited network availability.

This study has several limitations that warrant consideration. First, the evaluation of AR-MUSCLE primarily focused on user satisfaction and visualization accuracy aspects such as learnability, responsibility, satisfaction, and accuracy, without fully exploring long-term cognitive variables like knowledge retention and transfer of learning to clinical contexts. Second, non-functional factors such as internet connection stability, device capacity, and media file size significantly impact application performance, leading to variable satisfaction results across different devices and locations. Third, most participants were drawn from a specific academic environment with uniform network infrastructure and devices, limiting the generalizability of findings to institutions with different characteristics.

Overall, the findings of this research reinforce the position of AR-MUSCLE as an effective and relevant digital learning medium for modern anatomy and physiology education. The application not only addresses the limitations of conventional media but also contributes to the transformation of technology-based pedagogy in healthcare education. The academic implication of this study is the need to integrate AR-based media into higher education curricula to provide students with more interactive and contextual learning experiences. Practically, the development of AR-MUSCLE demonstrates great potential in supporting clinical coding processes and comprehensive understanding of the musculoskeletal system. Thus, this research not only produces educational technology innovation but also opens avenues for further development towards adaptive, user-experience-oriented digital learning systems.

CONCLUSION

Overall, this study contributes significantly to the development of digital technology-based learning media in the health field, particularly by enhancing the effectiveness of musculoskeletal anatomy and physiology education. The AR-MUSCLE application has been demonstrated to improve students' learning experiences through innovative and contextual visualization approaches. Furthermore, this research opens opportunities for further development, including optimizing the system for offline accessibility and integrating it into higher education health curricula as part of the technology-based learning transformation. Consequently, the findings are expected to provide an empirical foundation for future development of AR-based learning media and support the improvement of health education quality that adaptively aligns with digital advancements.

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