DEVELOPMENT OF AN AUGMENTED REALITY WEB APPLICATION FOR TEACHING HUMAN ANATOMY

BY:

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22/10MSS013

DEPARTMENT OF MATHEMATICAL AND COMPUTING SCIENCES,
FACULTY OF COMPUTING AND APPLIED SCIENCES,
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AUGUST, 2025

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THIS REPORT IS SUBMITTED TO THE DEPARTMENT OF MATHEMATICAL AND COMPUTING SCIENCES, FACULTY OF COMPUTING AND APPLIED SCIENCES, THOMAS ADEWUMI UNIVERSITY, OKO, KWARA STATE, NIGERIA.

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE BACHELOR OF SCIENCE (HONOURS) DEGREE IN SOFTWARE ENGINEERING

AUGUST, 2025

CERTIFICATION

This is to certify that I am responsible for the work submitted in this Project, that the original work is mine, except as specified in acknowledgment and references, and that neither the project nor the original work contained therein has been submitted to this University or any other institution for the award of a degree.

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APPROVAL

This project has been approved for the Department of Mathematical and Computing Sciences, Faculty of Computing and Applied Sciences, Thomas Adewumi University, Oko, Kwara State, Nigeria

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Signature and Date : ....

DEDICATIONS

This project is dedicated to the Lord Jesus, who sustains me, to my amazing family, who support me, and to the next generation, who look up to me. The greatness you witness is barely a glimpse of what is to come.

ACKNOWLEDGEMENTS

I would first like to acknowledge my supervisors, Professor Abejide Ade-Ibijola and Professor Francisca Oladipo, for their unwavering support, for giving me a ladder to climb, and for constantly showing me all that is possible to achieve.

I would also like to acknowledge the Department of Mathematical and Computing Sciences for giving me a conducive environment to grow and realize my full potential. I thank Thomas Adewumi University at large for being an avenue through which I could achieve great things.

I especially acknowledge my colleagues and friends, both home and away, who have been present when I was in doubt, when my ability was insufficient, or when I simply needed a friend. Your company is greatly appreciated. To Ushewa, to Gumpo, to Albert, to Bimbo, to Afolayan, to Alyasau, and my brothers: the software boys of 2025, thank you.

ABSTRACT

The progress report issued by the United Nations for 2025 regarding the fourth Sustainable Development Goal highlights the importance of integrating technology into education to ensure that young people and future generations have access to relevant, high-quality content that prepares them for a rapidly evolving labour market. However, in universities across Nigeria, the integration of digital technology into education is still not encouraged enough to facilitate widespread adoption. This mainly affects fields where genuine knowledge is primarily achieved through practical experiences, e.g, Anatomy. Earlier research has revealed that anatomy education in Nigeria faces major challenges with traditional methods of teaching, such as scarcity of cadavers and inadequate teaching facilities. Many studies across borders have proposed the integration of Augmented Reality (AR) into anatomy education, and although successes in improving academic results and student participation have been recorded, limitations still exist in terms of accessibility, usability, and pedagogical significance. This study proposes an innovative approach that is not limited by the challenges faced by conventional teaching methods in Nigeria, while addressing the gaps in the area of research globally. This study focused on creating an AR web application called AR-NATOMY that allowed learners to study and interact spatially with anatomical parts superimposed onto natural surroundings. The application was developed following the agile development methodology, and was thereafter evaluated based on learner retention, engagement, and enthusiasm towards learning. The evaluation was carried out using feedback submissions via AR-NATOMY and an administered survey. Results showed that it was easy for learners to register and make use of AR-NATOMY; AR-NATOMY captured the attention of its learners and stimulated their interest in learning anatomy; and learners would prefer to use an application like AR-NATOMY to study anatomy in the future. AR-NATOMY contributes to knowledge by promoting the development of more innovative technologies for education in Nigeria, offering benefits to society by increasing opportunities for tech developers. By minimizing the need for plastic learning apparatus and cadavers, the environmental detriment associated with their preparation and disposal is reduced.

Keywords: Augmented Reality (AR), Human Anatomy, Educational Technology.

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LIST OF ABBREVIATIONS

3D - Three-Dimensional
3NF - Third Normal Form
ADDIE - Analysis, Design, Development, Implementation, Evaluation
API - Application Programming Interface
AR - Augmented Reality
ARM - Advanced RISC Machine (processor architecture)
AI - Artificial Intelligence
CDN - Content Delivery Network
CI - Confidence Interval
CI/CD - Continuous Integration and Continuous Delivery
CPU - Central Processing Unit
CSS - Cascading Style Sheets
DFD - Data Flow Diagram
ERD - Entity Relationship Diagram
HTML5 - HyperText Markup Language version 5
HTTPS - HyperText Transfer Protocol Secure
IDE - Integrated Development Environment
IoT - Internet of Things
iOS - iPhone Operating System
PC - Personal Computer
PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QR-Code - Quick Response Code
RAM - Random Access Memory
RBAC - Role-Based Access Control
R&D - Research and Development
RCTs - Randomized Controlled Trials
RGB-D - Red, Green, Blue, Depth
SDG4 - Sustainable Development Goal 4
SMD - Standardized Mean Difference
SMTP - Simple Mail Transfer Protocol
SOI - Selecting, Organizing, Integrating
SQL - Structured Query Language
SSL/TLS - Secure Sockets Layer/Transport Layer Security
STEM - Science, Technology, Engineering, and Mathematics

UAT - User Acceptance Testing
UC3M - Universidad Carlos III de Madrid
UI - User Interface
UN - United Nations
URL - Uniform Resource Locator
VR - Virtual Reality
WebXR - Web Extended Reality
XSS - Cross-Site Scripting

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The fourth sustainable development goal of the United Nations seeks to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all (United Nations, 2025). However, despite the implementation of artificial intelligence (AI) and innovative tools in education, the progress towards achieving SDG4 is slowing, with the UN estimating that 300 million students will lack basic numeracy and literacy skills needed to improve their quality of life (Ade-Ibijola, Sukhari, & Oyelere, 2025). Technologies arising in the Fourth Industrial Revolution have disrupted how academic content is presented and assimilated, providing avenues for access to education to all students, irrespective of physical location (Oke & Fernandes, 2020). In Nigeria, a major factor that drove the adoption of educational technology was COVID-19, forcing virtually all educational institutions to employ online teaching and virtual classrooms; however, for this to be sustainable, the Nigerian education system must show a pragmatic attitude towards the adoption of such innovation rather than a conservative attitude (Ogwu, Emelogu, Azor, et al., 2023). Anatomy education in Nigeria already faced critical challenges with conventional teaching methods even before COVID-19 (Chia & Oyeniran, 2019), and although diverse technological solutions to these problems already exist around the world, there is a very wide gap in innovative technology for anatomy education with a Nigerian origin and specifically tailored to the Nigerian education system. This study aims to change the narrative by introducing a web-based AR application to allow students, instructors, and any other individual with a desire for knowledge to study and interact with human anatomical models via mobile devices. AR is defined as a tool that superimposes virtual objects onto physical objects in real space and allows individuals to interact with both simultaneously (Bölek, De Jong, & Henssen, 2021). AR stands at the forefront of technological innovation, offering a way to revolutionize the landscape of education by overlaying digital content onto the physical world (Bhargav Palada, 2024). This capability gives the use of AR in education, particularly in anatomy education, an advantage over traditional methods such as cadaver dissections and 2D images, allowing users to virtually assemble and disassemble anatomical parts irrespective of their location or expertise (Bölek et al., 2021).

1.2 Statement of the Problem

Human body dissection can and should not be entirely replaced by technology because it permits a direct approach to the human body, as well as allowing medical students to experience their very first patient-physician relationship. However, problems arise with this method of teaching anatomy in terms of the scarcity of bodies received through body donation programs, the difficulty of accessing a clear enough view of anatomical structures, and also, the problems that can derive from an eventual emotional involvement (Neri et al., 2024). Based on a study performed on 130 medical students from the University of Bologna (Neri et al., 2024), it was shown that the implementation of AR in human anatomy teaching can be a helpful strategy to overcome some of these difficulties. Although AR presents an equitable, cost-effective solution that reduces crowding in the confined spaces of the dissection labs, the benefits of AR-supported undergraduate medical education have been poorly investigated (Zammit, Calleja-Agius, & Azzopardi, 2022). Anatomy, as a vital subject for healthcare professionals, is widely practiced in Nigeria across different levels of education. However, the teaching and learning of Anatomy in Nigeria and most sub-Saharan countries (with a possible exception of South Africa) is plagued with a series of challenges, such as inadequate teaching facilities, scarcity of cadavers, and shortage of anatomy teachers (Chia & Oyeniran, 2019). Fortunately, these pedagogical challenges are problems that can be managed with the ubiquitous incorporation of AR into anatomy education. By allowing students/learners to view and study anatomical parts in self-paced and immersive experiences, the effect of these issues on the spatial knowledge, retention, and academic performance can be significantly minimized in Nigeria (Neri et al., 2024).

1.3 Aim and Objectives of the Study

The primary aim of this study is to explore the effectiveness of AR in enhancing the teaching and learning of human organ systems in anatomy education. To achieve this, this study focused on achieving the following objectives:

i. To design and develop a web-based augmented reality application for teaching human anatomy via its organ systems.

ii. To evaluate the impact of AR on students' comprehension and retention of anatomical parts using recorded feedback and quantitative analysis.

iii. To measure the level of student engagement during AR-based anatomy instruction, as well as their resulting attitude towards learning after academic AR experiences.

1.4 Significance of the Study

Incorporating AR into the Nigerian education system offers many benefits outside its effect on academic results. The adoption of this innovative teaching technology will potentially lead to the development of more interactive, scalable, and cost-effective educational platforms for universities in Nigeria, furthering innovation and contributing to knowledge. Aside from its contribution to knowledge, as technology is encouraged in the Nigerian education system, the demand for innovative educational tools also increases, creating opportunities for tech developers. Also, by encouraging the use of digital tools, traditional cadaver-based dissections and the use of plastic anatomical models are reduced, minimizing the environmental detriment associated with their preparation and disposal. This study not only proves its significance in the area it is directly concerned with, but also does so in terms of innovative, societal, and environmental criteria.

1.5 Scope of the Study

This study focuses on providing all human organ systems in AR, along with educational content on mobile devices, only allowing learners to view, study, and interact with them spatially in their natural environments. This includes embiggening, shrinking, rotating, and moving the models around within their immediate environment. It currently does not include virtual dissections, AR quizzes/assessments, and cross-sectional manipulation of the models, but all these are considered for future improvement.

1.6 Limitations of the Study

i. Hardware capabilities of common mobile devices are not optimized for quality AR experiences, putting a strain on the device's processing power and reducing the impact of the AR experience. Although still relatively cost-effective compared to cadaver procurement, effective study and interaction with the AR objects in this study will require the use of high-end mobile devices.

ii. This method of anatomy education increases the learning curve for learners and instructors who are unfamiliar with AR technologies or lack the technical expertise to operate such systems. Although the proposed system seeks to be as simple to operate as possible, this barrier still remains across diverse institutions in Nigeria.

iii. For an AR system primarily meant for mobile devices, complex functionalities such as gesture-based virtual dissections are very difficult to implement. The software for such does not singularly exist yet; however, such functionalities can be achieved by combining multiple tools, which requires a large workforce and an abundant supply of resources.

1.7 Definition of Terms

i. **Anatomy:** the study of the structure of living organisms, including their form, shape, and organization.

ii. **Augmented Reality:** a technology that enhances the real world by overlaying computer-generated images, sounds, or other information onto it.

iii. **Virtual Reality:** a technology that simulates a computer-generated environment, allowing users to interact with a realistic, three-dimensional world as if they were actually there.

iv. **Artificial Intelligence:** the ability of computer systems to perform tasks that typically require human intelligence, such as learning, problem-solving, and decision-making.

v. **Fourth Industrial Revolution:** also known as Industry 4.0, is a period of rapid technological advancement characterized by the fusion of technologies like artificial intelligence.

vi. **Virtual Classrooms:** an online learning environment that allows students and teachers to interact in real-time, similar to a traditional classroom, but without the physical presence of everyone in the same location.

vii. **Web-based Application:** software accessed through a web browser that doesn't require installation on your specific device.

viii. **Gesture-based Interaction:** a method of interacting with technology using physical movements, like hand gestures, rather than traditional input methods like keyboards or mice.

ix. **Cadaver:** a dead human body or the physical remains of a dead human body.

x. **Spatial Knowledge:** the understanding of locations, distances, and relationships between objects in space.

CHAPTER TWO

LITERATURE REVIEW

2.1 Historical Perspectives of AR in Anatomy Education

The concept of AR dates back to the 1960s, with Ivan Sutherland's pioneering work on the "Sword of Damocles" with his students at the University of Utah (Sutherland, 1968). This is widely considered the first functional AR system because it allowed the user to still see their natural environment via a head-mounted display with three-dimensional tracking capabilities, as shown in Figure 1 (Van Krevelen, 2007).

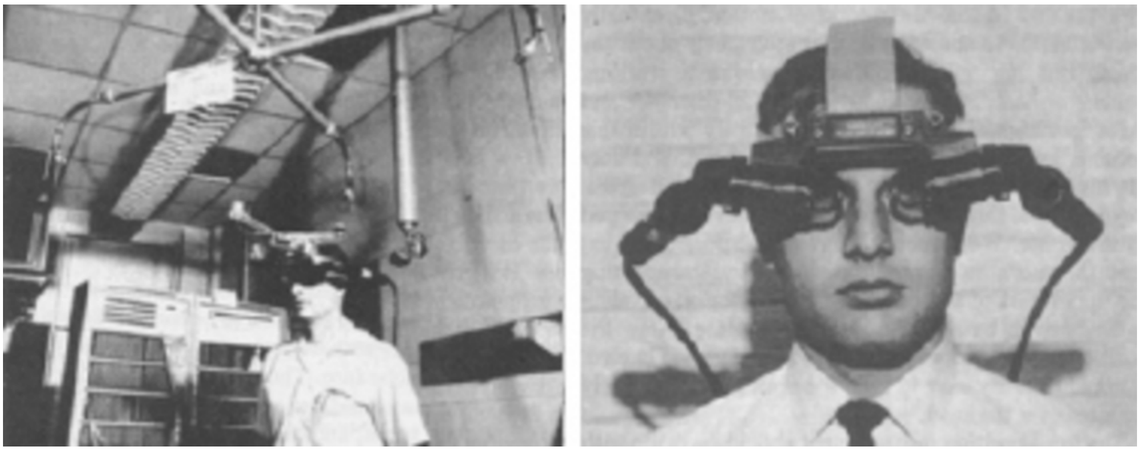

Figure 1: Ivan Sutherland's Head Mounted Display

As time passed, further developments were made in mobile and wearable computing, eventually leading to the term "Augmented Reality" being coined by Thomas Caudell in 1992, during the development of the Boeing 747 (Caudell & Mizell, 1992). Caudell, in this case, referred to the use of digital overlays to assist aircraft assembly. As AR became a research field on its own, many other innovative tools were developed in the 1990s. Louis Rosenberg developed the first commercial AR system, known as "Virtual Fixtures", which provided mixed reality overlays (e.g., a ruler guiding a pencil) to enhance human performance in real-world tasks (Rosenberg, 1992).

In the early 2000s, AR technology began to become more popular in various industries, including entertainment, gaming, and military training (Bhargav Palada, 2024). A notable AR system that was a product of this decade is "ARQuake", an outdoor AR gaming system developed by Wayne Piekarski that allowed gamers to walk around and receive augmented graphics based on their physical location using a gyroscope, instead of using a joystick (Piekarski & Thomas, 2002).

In the 2010s, the launch of smartphones equipped with cameras, sensors, and powerful processors paved the way for the widespread adoption of mobile AR applications (Bhargav Palada, 2024). In 2013, Google introduced Project Tango, a platform for mobile devices that enabled advanced AR experiences using depth-sensing cameras (Bhargav Palada, 2024). The release of ARKit by Apple in 2017 and ARCore by Google in 2018 democratized AR development, allowing developers to create modern AR applications for iOS and Android devices (Bhargav Palada, 2024).

In the context of anatomy and medicine, two categories of AR programs have successfully been implemented in this field: treatment programs, involving systems that help patients and/or practitioners within a clinical setting, and training programs, designed to aid teaching and learning within an educational setting (Dhar, Rocks, Samarasinghe, Stephenson, & Smith, 2021). In 2022, while undergoing a study to develop an innovative AR tool for anatmoy education, Cerecenelli *et al.* (Cercenelli et al., 2022), highlighted that in recent years AR has been proposed and applied as an aiding tool in many healthcare sectors, including neurosurgery (Chidambaram et al., 2021), urology (Reis et al., 2021), orthopedics (Verhey, Verhey, & Hartigan, 2019), and craniomaxillofacial surgery (Battaglia et al., 2020).

AR is rapidly growing with many new potential applications also in the medical education field (Tang, Cheng, Mi, & Greenberg, 2020). To date, AR applications have been adapted to every stage of medical training as anatomical teaching tools (Jain, Youngblood, Hasel, & Srivastava, 2017), classroom study aids (Wang, Wu, Bilici, & Tenney-Soeiro, 2016), image training simulators (Kamphuis, Barsom, Schijven, & Christoph, 2014), and clinical skills interaction simulators (Chaballout, Molloy, Vaughn, Brisson III, & Shaw, 2016).

2.2 Theoretical Framework

The integration of Augmented Reality (AR) in education is supported by several foundational learning theories that emphasize active engagement, experience-based learning, and cognitive efficiency. Understanding these theories is crucial for learners, instructors, academics, and researchers as they explore how AR can enhance learning outcomes in anatomy education.

2.2.1 Constructivist Learning Theory

In 1936, Jean Piaget proposed a theory of cognitive development that served as a basis for the establishment of this learning theory (Pakpahan & Saragih, 2022). The constructivist learning theory is one with the premise that individuals construct new knowledge based on prior knowledge and experiences (Tsulaia, 2023). Cognitive constructivism refers to learning as an active process of building knowledge carried out by learners, such that they actively construct their own understanding and knowledge through interaction with their environment, emphasizing hands-on, experiential learning, and encouraging students to explore and discover concepts independently (Bhargav Palada, 2024; Tsulaia, 2023).

The proposed system leverages the concept of this learning theory by making the AR experiences self-paced and exploratory, such that learners can manipulate anatomical parts spatially within their immediate environment. By this, learners can build spatial knowledge of anatomical parts independently without the need of a supervisor, without restrictions of location (i.e, being in an anatomy laboratory), at any time they wish, and as many times as they require, giving learners full control over their learning experiences and complete freedom with the anatomical models.

2.2.2 Cognitive Load Theory

John Sweller introduced the cognitive load theory in the 1980s as an instructional design theory, suggesting that learners can only process a limited amount of information at a time (Kairu, 2021; Sweller, van Merriënboer, & Paas, 2019). This theory is grounded on our knowledge of human cognition and uses evolutionary psychology to assume that knowledge should be divided into biologically primary information that we have specifically evolved to acquire and biologically secondary information that we have not specifically evolved to acquire (Sweller, 2020). Essentially, this theory suggests that complex information should be split into smaller parts that are easier to comprehend in order to grasp that piece of information effectively. By doing this, the cognitive load that would potentially be inflicted when trying to understand a complex system as a whole is reduced.

The proposed system conforms to the principles set forth by this theory by allowing users to view organ systems in segments rather than just as a whole. Users can view the organs in a specific region of the human body, allowing them to fully understand the components that make up an organ system consecutively before trying to understand the entire system, reducing the cognitive load of taking it all in at once.

2.2.3 Cognitive Theory of Multimedia Learning

Developed by John Mayer in 1997, the cognitive theory of multimedia learning is an evidence-based theory for managing cognitive load in learning by delivering information via multimedia forms (R. Mayer & Moreno, 2005). This theory draws from Paivio's dual coding theory (Clark & Paivio, 1991), Baddeley's model of working memory (Baddeley, 1992), Wittrock's generative theory (Tobias, 2010), and Mayer's SOI model of meaningful learning (R. E. Mayer, 1996). According to this theory, learners possess a visual information processing system and a verbal information processing system, such that auditory information goes into the verbal system, whereas visual information goes into the visual system (R. Mayer & Moreno, 2005). It essentially suggests that it is more effective for learners when information is presented in both these forms of media, rather than just one of them.

The general concept of AR is supported by this theory, not to mention its application in anatomy education. The proposed system provides written educational content for learners to read and siphon knowledge from, in addition to the visual AR experiences that are available. Although the system does not present any information via audio narrations, this theory lays the foundation for a potential improvement in future works.

2.3 Review of Related Work

The previous sections have provided a broad overview of research that has taken place on the application of AR in anatomy and general education. Below is a review of existing relevant literature and works specifically on the subject matter, as carried out and narrated by various researchers

(Iparraguirre-Villanueva, Andia-Alcarraz, Saba-Estela, & Epifanía-Huerta, 2024) carried out research on 60 primary school students to assess the effectiveness of a mobile AR application on the learning of human skeletal anatomy . This study employed a quantitative, pre-experimental design, using pre- and post-tests to evaluate three key indicators: perceived learning time, average grades, and student interest.

Based on the results of these tests, Iparraguirre-Villanueva and his team discovered that students' perceptions of learning time remained unchanged; however, there were significant improvements in both academic performance (a 3.7-point increase on a 20-point scale) and attitude towards learning, with 65% of students expressing enthusiasm in using AR technology to learn anatomy.

Similarly, (Cercenelli et al., 2022) conducted a study aimed at developing and testing AEducaAR, an innovative tool for medical education in human anatomy that combines AR technology and a tangible 3D printed model that could be explored and manipulated by trainees, favoring a three-dimensional and topographical learning approach, as shown in Figure 2. The study involved 62 second-year degree medical students at the University of Bologna, comparing their understanding of human anatomy using AEducaAR with their understanding using traditional anatomy atlases.

The results of this study did not indicate any significant difference in the theoretical knowledge acquired through both methods; however, students who used AEducaAR showed slightly better results in many practical tasks, such as identifying the posterior edge of the eyeball and lacrimal gland on a 3D printed skull model.

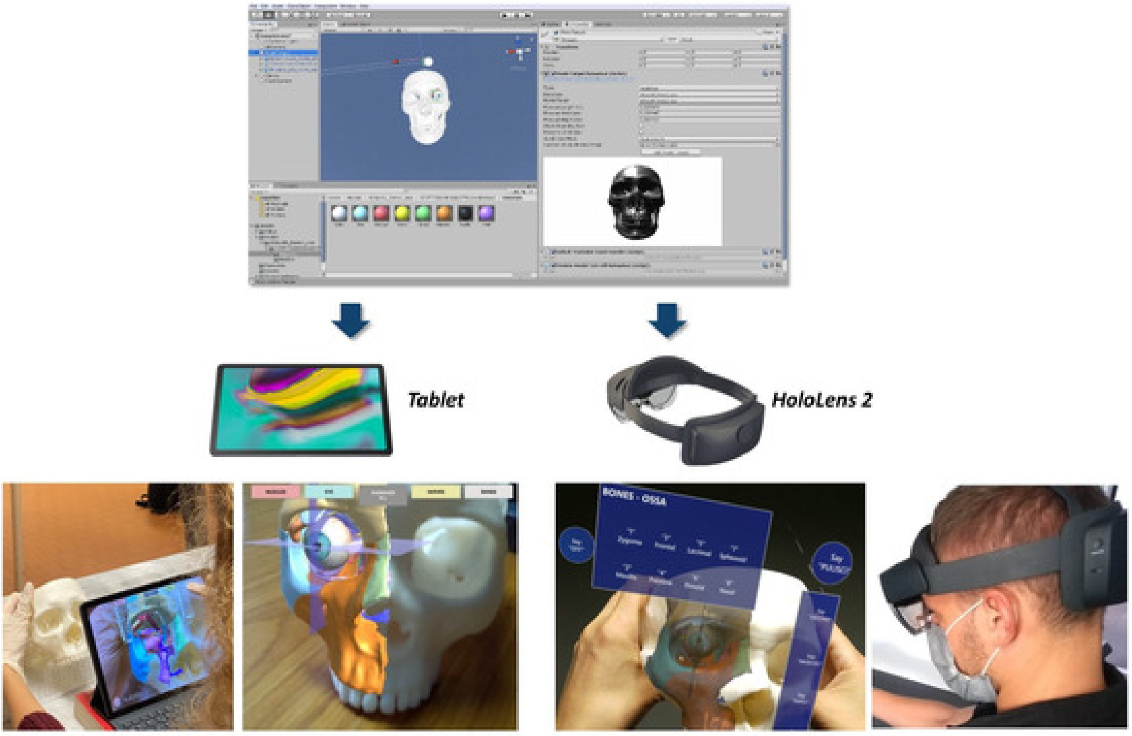

Figure 2: AEducaAR application implemented for use on tablet or HoloLens 2 smart glasses

Ma et al. (2015) on ‘Personalized augmented reality for anatomy education’ discussed how anatomy education is a challenging but vital element in training future medical professionals. The researchers created a personalized and interactive augmented reality system that helps in facilitating learning. This system behaves as a “magic mirror”, which allows users to see the anatomy visualizations on their own bodies. This gives the impression that users can actually look inside themselves through the application of real-time visualization. Also, the system comprises an RGB-D sensor as a real-time tracking device to detect the user moving in front of a display. In addition, the magic mirror system shows text information, medical images, and 3D models of organs that the user can interact with.

Through the participation of 7 clinicians and 72 students, two user studies were designed to assess the precision and acceptability of the magic mirror system for education. The results of the first study demonstrated that the average precision of the augmented reality overlay on the user's body was 0.96 cm, while the results of the second study indicate 86.1% approval for the educational value of the magic mirror, and 91.7% approval for the augmented reality capability of displaying organs in three dimensions. The usefulness of this unique type of personalized augmented reality technology has been demonstrated in this paper.

Rodríguez Pardo, Hernandez, Patricio, Berlanga, and Molina (2015) on "An Augmented Reality Application for Learning Anatomy" relied on the project of the Applied Artificial Intelligence Group at UC3M, called "Augmented Science", in order to disseminate and support education in science through Augmented Reality (AR) tools. The project is part of new developments provided with AR systems on mobile devices and their application in promoting STEM teaching. The study explores the suitability of the use of Artificial Intelligence techniques for the development of AR applications. As a use case, the development of an application for Android devices, which, through techniques of AR overlays, describes a bony hand model. Also, the application allows user interaction in order to discover the names of the bones of the hand. The article conducts an assessment of the application to analyze its educational impact.

Kiourexidou et al. (2015) describe the development of a web application, which enhances users' medical knowledge concerning the anatomy of the human heart through augmented reality. Evaluation is conducted in two different facets. In the first one, the study evaluates the feasibility of a three-dimensional human heart module using one investigator under the supervision of an expert. In the second, the evaluation aims at identifying usability issues by means of the cognitive walkthrough method. Three medical students are called upon to perform three target tasks in the web application. Task completion is appreciated in light of the standard set of cognitive walkthrough questions. Augmented reality content misses are revealed by means of the first evaluation in an effort to enhance the educational utility of the three-dimensional human heart. Cognitive walkthrough provides further improvement points, which may further enhance usability in the next software release. This study constitutes the pre-pilot evaluation. Standardized methodologies are utilized in an effort to improve the application before its wider piloting to proper student populations. These evaluations are considered important in experiential learning methods, aiding online education of anatomy courses.

Layona, Yulianto, and Tunardi (2018) conducted a study titled "Web based Augmented Reality for Human Body Anatomy Learning". The study focused on the development of an AR application that makes learning about human body anatomy more interesting and easier for students to understand. This application allows students to learn human body anatomy through 3D object interactions, thereby moving away from traditional textbooks and plastic models.

The study adopts the quantitative research method, which involves the collection of data and developing a prototype to prove its effectiveness. The application development method is done through the waterfall method, which consists of requirement gathering and analysis (planning), user interface and system design, implementation, and testing. The results of the research, which is the AR application for human body anatomy learning that features 3D objects, explanation of organs, and their positions, are available online.

Kurniawan, Suharjito, Diana, and Witjaksono (2018) carried out research known as 'Human Anatomy Learning Systems Using Augmented Reality on Mobile Application', aimed at developing a human anatomy learning system through augmented reality technology. Through this system, students are expected to understand the human body anatomy more easily through 3D image visualisations, where users capture a picture of the marker, broken into segments, and the pattern is compared with images stored in the database. The Floating Euphoria Framework, in combination with the SQLite database, is used. The augmented reality anatomy system offers features that allow for interactive displays of the entire body or specific human organs. To evaluate the efficiency of the app, the augmented reality anatomy system was used with both high school and medical students to facilitate their learning of human anatomy. The findings indicate that the interactive augmented reality visualization significantly aids students in understanding human anatomy more effectively.

Barmaki et al. (2019) conducted a study titled "Enhancement of Anatomical Education Using Augmented Reality: An Empirical Study of Body Painting" that presented a creative, hands-on approach to teaching the human musculoskeletal system. The goal was to boost students' engagement and retention of knowledge. This research introduced a collaborative learning method utilizing the REFLECT system, which stands for augmented reality for learning clinical anatomy. This system employs an augmented reality magic mirror technique to overlay anatomical images onto the user's body on a large screen, making it seem like they can see the relevant anatomical diagrams within their own body.

The effectiveness of this innovative system was assessed through a large-scale controlled study involving a team-based muscle painting activity with undergraduate premedical students ($n = 288$) at Johns Hopkins University. The students' baseline knowledge and their knowledge after the intervention were evaluated before and after the painting activity, based on their assigned groups in the study. The findings from knowledge assessments and other collected data indicate that this interactive system significantly improved learning about the musculoskeletal system, leading to better knowledge retention ($F(10,133) = 3.14$, $P < 0.001$), more time spent on tasks ($F(1,275) = 5.70$, $P < 0.01$), and a high level of engagement ($F(9,273) = 8.28$, $P < 0.0001$). The REFLECT system is expected to serve as a valuable supplementary tool for anatomy education for students.

Chytas et al. (2020) study on “The role of augmented reality in Anatomical education: An overview” notes that the impact of augmented reality (AR) in teaching anatomy has not been reviewed so far. Therefore, the study focuses on a narrative review of the literature concerning this topic. To carry out their research, several academic papers were consulted from research databases, including PubMed, Scopus, Cochrane, ERIC, CINAHL Plus, and Web of Science, for research with the purpose of examining the outcomes of the implementation of AR in anatomical education. Out of the papers consulted, seven research papers are used for analysis, consisting of five comparative and two non-comparative studies. Three out of the seven papers evaluate students’ perceptions about AR, and the remaining four papers examine students’ examination performance after using AR. Totally, the research submits that AR is efficient in helping students understand the three-dimensional organization of structures and achieve good examination results. However, there still exists minimal research on anatomical education, but the findings of this research show a green light regarding its teaching potential. Through this finding, anatomy educators are encouraged to adopt the tool in their teaching methodology.

Also providing a review of literature regarding augmented reality application in anatomy, a study by Uruthiralingam and Rea (2020) titled “Augmented and Virtual Reality in Anatomical Education: A Systematic Review” examines in greater detail the literature specifically to see what the best practice in this field could be. Conducting a systematic review using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, this study searched for articles in both Web of Science and PubMed. Using the terms “augmented reality" and "teaching anatomy”, the results yielded 88 articles. While “virtual reality" and "teaching anatomy” resulted in 200 articles. This study explores these articles, including those on augmented reality and virtual reality used to teach anatomy to undergraduate and postgraduate students, residents, dentists, nursing, and veterinary students. Articles that were excluded are those of systematic reviews, literature reviews, review articles, news articles, articles not written in English, and any literature that presented how a virtual model was created without the evidence of students testing it. The inclusion and exclusion criteria for virtual reality are the same as augmented reality. In addition, the study examines the articles to identify if they contain data that is quantitative, qualitative, or both.

The articles were further separated into those that were pro, neutral, or against the use of these digital technologies. Of the 288 articles, duplicate articles totaling 67 were removed, and 134 articles were excluded according to the exclusion criteria. Of the 31 articles related to augmented reality, 30 were pro, one neutral, and no articles were against the use of this technology. Fifty-six articles related to virtual reality were categorized, resulting in 45 pro, eight neutral, and three against the use of this technology. All in all, the results indicated that most articles identified related to both virtual and augmented reality were for the use of those technologies, rather than neutral or against. This systematic review highlights the recent advances of both augmented reality and virtual reality in implementing the technology into the anatomy course.

“The effectiveness of the use of augmented reality in anatomy education: a systematic review and meta-analysis” was a study conducted by Bölek et al. (2021). This study highlighted the role of Augmented Reality (AR) in anatomical education. Apart from its ethical and financial benefits, AR has been described to reduce cognitive load while increasing the motivation and engagement of the students. Although, the effects of AR on learning outcomes differ in different studies, and there is a research gap in the overview of AR and its effect on learning anatomy. Therefore, a meta-analysis on the effect of AR vs. traditional anatomical teaching methods on learning outcomes was performed.

Systematic database searches were examined using two independent investigators who applied predefined inclusion and exclusion criteria. This yielded five papers for meta-analysis, totaling 508 participants; 240 participants in the AR-groups and 268 participants in the control groups (306 females/202 males). Meta-analysis showed no significant difference in anatomy test scores between the AR group and the control group (-0.765 percentage-points (%-points); P = 0.732). Sub analysis on the use of AR vs. the use of traditional 2D teaching methods showed a significant disadvantage when using AR (-5.685%-points; P = 0.024). Meta-regression analysis showed no significant correlation between the mean difference in test results and spatial abilities (as assessed by the mental rotations test scores). Student motivation and/or engagement could not be included since studies used different assessment tools. This meta-analysis showed that insufficient evidence is present to conclude that AR significantly impacts learning outcomes and that outcomes are significantly impacted by students’ spatial abilities. However, only a few papers were suitable for meta-analysis, indicating that there is a need for more well-designed, randomized controlled trials on AR in anatomy education research.

Crew, Hasibuan, Azmin, Nasution, and Chairad (2022) describe the development design of a web-based AR assessment tool for anatomy, focusing on the implementation of the system and teachers’ response to the use of the system. The research is conducted at the State University of Medan. The web-based assessment development design is based on the Borg & Gall research and development (R&D) stage pattern as adopted by Sugiyono. As for the product design model, the web-based assessment follows the ASSURE model. The results of this study indicate that the product developed, namely web-based assessment, has gone through design and testing, and revision, so the product is declared suitable for use. Students also gave a good response, namely 92%, for the use of the web as an assessment tool equipped with Augmented Reality (AR)-based animations.

Putra, Dawa, Burgos, and Maulana (2023) conducted a study titled “Implementation of Augmented Reality in Study for Human Anatomy”, which aimed to create and assess an Augmented

Reality tool focused on human anatomy, including the human body, muscles, skeleton, lungs, eyes, ears, and digestive system. This AR technology is suggested for educational purposes because it has great potential to enhance understanding of various concepts. Thus, their research intended to develop and evaluate how augmented reality can be used in biology classes to teach human anatomy. The study follows the ADDIE model, which includes analysis, design, development, implementation, and evaluation stages.

The findings indicate that the AR application created can assist students in grasping human anatomy and learning its details. Feedback from students collected through questionnaires showed that they had a positive view of the application, particularly regarding its user-friendliness, the clarity of information provided, and its effectiveness in aiding the learning process. The AR application developed in this research was shown to enhance the quality and effectiveness of biology education through innovative and interactive technology.

Salimi, Asgari, Mohammadnejad, Teimazi, and Bakhtiari (2024) made use of meta-analysis to evaluate the effectiveness of VR and AR in anatomical education. The protocol was registered in Prospero. Scopus, PubMed, Web of Science, and Cochrane Library databases were searched. From the 4487 articles gathered, 24 randomized controlled trials were finally selected according to the inclusion criteria. According to the results of the meta-analysis, VR had a moderate and significant effect on the improvement of knowledge scores in comparison with other methods (standardized mean difference = 0.58; 95% CI = 0.22, 0.95; $p < 0.01$). Due to the high degree of heterogeneity (I 2 = 87.44%), subgroup analyses and meta-regression were performed on eight variables. In enhancing the “attitude,” VR was found to be more “useful” than other methods ($p = 0.01$); however, no significant difference was found for “enjoyable” and “easy to use” statements. Compared with other methods, the effect of AR on knowledge scores was non-significant (SMD = -0.02; 95% CI = -0.39, 0.34; $p = 0.90$); also, in subgroup analyses and meta-regression, the results were non-significant. The results indicate that, unlike AR, VR could be used as an effective tool for teaching anatomy in medical education. Given the observed heterogeneity across the included studies, further research is warranted to identify those variables that may impact the efficacy of VR and AR in anatomy education.

Neri et al. (2024) conducted a study titled: “Dissecting human anatomy learning process through anatomical education with augmented reality: AEducAR 2.0, an updated interdisciplinary study”. The goal was to improve the interactive features of the AEducAR prototype, an AR tool created by the University of Bologna (Cercenelli et al., 2022), and to investigate its effects on the learning process of human anatomy among 130 second-year medical students at the International School of Medicine and Surgery of the University of Bologna. A diverse team consisting of anatomists, maxillofacial surgeons, biomedical engineers, and educational scientists worked together to ensure a thorough understanding of the study’s goals. The students utilized the updated AEducAR version, called AEducAR 2.0, to learn about three anatomical subjects: the orbit zone, facial bones, and mimic muscles.

AEducAR 2.0 provided two types of learning activities: one that was explorative and another that was interactive. After each activity, students took a test to evaluate their learning outcomes. They also filled out an anonymous questionnaire to share background information and their thoughts on the activity. Additionally, 10 students were interviewed for more detailed insights. The findings showed that AEducAR 2.0 significantly enhanced learning and student engagement. The students achieved high scores on both quizzes and expressed enjoyment of the interactive features that were added. Furthermore, the interviews highlighted the intriguing concept of blended learning. Specifically, this study indicates that integrating AR into medical education, along with traditional teaching methods, could be beneficial for students' academic success and future careers. Thus, this research adds to the increasing body of work that highlights the potential impact of AR on the future of medical education.

2.4 Gaps in Existing Research

We have reviewed several studies that have examined the use of Augmented Reality (AR) in anatomy education. While these studies are important, there exist several unaddressed research gaps, especially in the context of web-based applications.

Firstly, there are limited web-based implementations of AR in anatomy education. A series of AR tools have been used for anatomy learning, most of which are standalone mobile applications, as this is evidenced in the studies of (Kurniawan et al., 2018; Ma et al., 2015) or hardware-dependent systems like the "magic-mirror" interfaces as used by (Barmaki et al., 2019). Although studies like (Kiourexidou et al., 2015) and (Layona et al., 2018) have examined web-based AR solutions, these studies lack scalable integration. The proposed study seeks to address this gap by offering a web application, freely available on all internet-enabled devices.

Moreover, empirical evidence about the effectiveness of AR in improving academic performance is mixed, while AR applications consistently receive positive feedback on engagement usability, this results in insufficient evaluation of the learning outcome. For example, Bölek et al. (2021) and Salimi et al. (2024) show that AR does not significantly perform stronger than traditional methods in knowledge scores, and meta-regression shows inconsistent results. Therefore, these findings underscore the need for more depth and comparative studies to examine the educational value of AR in web-based settings.

Most existing AR platforms also focus only on single anatomical systems such as the hand bones or heart modules, as exemplified by (Rodríguez Pardo et al., 2015) and (Kiourexidou et al., 2015), with a smaller scope for interactive exploration. There exists a gap in creating a modular, multi-system AR environment that gives room for diverse anatomy topics to be examined interactively through web browsers (Neri et al., 2024; Putra et al., 2023). In an effort to overcome this gap in existing solutions, the proposed study offers all human organ systems, as wholes or segments, for study in AR experiences.

Lastly, few studies have incorporated widespread demographic testing that cut across various educational levels, such as secondary schools vs medical students, or examined the long-term retention and transfer of knowledge using web-based AR. There is a gap for more inclusive and longitudinal research to validate the quality of generalization and equity of web-based AR.

2.5 Summary of the Literature Review

The various literature and research work that have been reviewed in this section have explored different innovative solutions that applied AR and related concepts to anatomy education. Consequently, insights from these works will go on to influence the overall development of the proposed solution. Table 1 provides a concise summary of the reviewed literature.

Table 1: Summary of findings

Study	**Data**	**Settings/Method**	**Key Findings**
Ma et al. (2015)	7 Clinicians, 72 students	Magic mirror AR system with RGB-D sensor; evaluated for precision and acceptability	Illustrated a high precision of 0.96cm in anatomical overlay; 86.1% of users found it beneficial for education and 91.7% appreciated its ability to visualize organs in 3D, thereby promoting personalized learning.
Rodríguez Pardo et al. (2015)	—	Android-based AR app showing hand bones; user interaction to identify bones	Demonstrated that integrating AI and AR promotes active user engagement in learning anatomy and can support science education beyond traditional techniques.

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Study	**Data**	**Settings/Method**	**Key Findings**
Kiourexidou et al. (2015)	3 medical students	Web-based 3D heart model evaluated using expert observation and cognitive walkthrough	Revealed AR content mismatches and usability issues; feedback informed future software revisions and guided future improvements.
Layona et al. (2018)	—	Web-based 3D AR with Waterfall model development	Enhanced anatomy comprehension and engagement, and enabled more engaging learning via interactive 3D anatomy content.
Kurniawan et al. (2018)	High School and Medical Students	Mobile AR using the Floating Euphoria Framework and SQLite; marker-based segmentation	Revealed a significant improvement in the understanding and retention of human anatomy using marker-based 3D visualization.
Barmaki et al. (2019)	288 pre-med students	AR-enhanced REFLECT system; body painting activity with magic mirror AR	Enhanced statistically significant improvements in retention and knowledge (significant learning improvement) and also validated AR for collaborative and experiential anatomy education.
Chytas et al. (2020)	7 studies reviewed	Narrative literature review of comparative and non-comparative studies on AR in anatomy education	Found the effectiveness of AR in teaching 3D structure comprehension and emphasized the need for more systematic research.
Uruthiralingam and Rea (2020)	288 articles (31 AR)	PRISMA-based systematic review; categorized articles as pro, neutral or against AR	Out of the 31 AR studies, 30 showed positive impact and support broader AR adoption.

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Study	Data	Settings/Method	Key Findings
Bölek et al. (2021)	5 RCTs, 508 participants	Meta-analysis comparing AR vs traditional methods	No significant test score difference and calls for more robust trials.
Crew et al. (2022)	—	Web-based AR assessment using ASSURE and Borg-Gall models	Resulted in 92% high acceptance from both students and educators; illustrated that AR can be integrated into web-based testing.
Cercenelli et al. (2022)	62 second-year medical students	Compared their understanding of human anatomy using AEducaAR with their understanding using traditional atlases	No significant difference in the theoretical knowledge acquired through both methods; however, use of AEducaAR slightly improved students' results in many practical tasks.
Putra et al. (2023)	—	AR tool developed through ADDIE model covering multiple anatomical systems	Resulted in students demonstrating the tool positively for ease of use, content clarity and improved learning. Also, outlined the AR app's potential for broad classroom adoption.
Salimi et al. (2024)	24 RCTs	Systematic review and meta-analysis on AR and VR	VR showed moderate knowledge gain while AR showed no significant effect.
Neri et al. (2024)	130 medical students	AEduCAR 2.0 evaluated through the use of quizzes, questionnaires and interviews	Highlighted improved learning and strong student engagement and supported blended learning through the combination of AR and traditional teaching.

Continued on next page

Study	**Data**	**Settings/Method**	**Key Findings**
Iparraguirre-Villanueva et al. (2024)	60 primary school students	Assessing the effectiveness of a mobile AR application on the learning of human skeletal anatomy	Students' perceptions of learning time remained unchanged; however, significant improvements were observed in both academic performance (a 3.7-point increase on a 20-point scale) and attitude towards learning, with 65% of students expressing enthusiasm in using AR technology to learn anatomy.

CHAPTER THREE

SYSTEM DESIGN AND METHODOLOGY

3.1 Review of the Proposed System

The proposed system, titled AR-NATOMY, is a web-based augmented reality (AR) application built specifically to facilitate the teaching and learning of human organ systems. It addresses the limitations of traditional methods such as cadaver dissection, flat diagrams, and textbook visuals, which often fail to provide the spatial interactivity and immersion learners require for effective comprehension of anatomy. AR-NATOMY utilizes WebXR technologies to enable students and educators to explore interactive 3D anatomical models directly in their real-world environment using internet-enabled and camera-enabled mobile devices.

Through the platform, users can interact with anatomical systems by rotating, zooming, and studying organs in a contextual and spatially accurate AR setting. The application provides descriptive text and labels for each model to aid understanding. Theoretical educational content is presented in a clear and non-interactive manner, accompanying each available organ system.

AR-NATOMY was developed using the ASP.NET Core framework for the backend, with C# as the primary programming language. The frontend was designed using HTML5, CSS, and JavaScript to handle the logic and leverage ARCore, Google's platform for building and enhancing AR experiences on Android devices, and ARKit, Apple's framework that enables building of AR experiences on iOS devices. Microsoft SQL Server manages the database, which stores user profiles, anatomical model metadata, and feedback. The system emphasizes modularity and scalability, allowing for future improvements, including the potential incorporation of IoT tracking or integration with AR headsets. The system is accessible via any modern web browser on mobile devices with internet access and a functional camera.

3.2 System Requirements

3.2.1 Functional Requirements

These specifications provide exact details on what AR-NATOMY should do in order to meet the needs of the users, outlining its expected features and functionalities. The system shall: (i) allow users to register and log in via a web interface; (ii) display a list of human organ systems and corresponding parts; (iii) enable users to select, load, and view 3D anatomical models in AR; (iv) provide interactive functionalities such as rotate, zoom, and move models; (v) display descriptive educational content for each organ system and 2D labeled illustrations for each model; (vi) Allow users to submit feedback on their experience using the application. (vii) Ensure real-time communication between the client interface and server-side APIs.

3.2.2 Non-Functional Requirements

These requirements describe how AR-NATOMY should perform the functions highlighted above, specifying its quality attributes and how well it meets user needs.

In terms of performance, the system must load AR scenes within 10–15 seconds, depending on internet speed and device capability. The system must also display model portability, being accessible from any internet-enabled mobile device with a functional camera.

As the system facilitates user interactions, all user communication must be encrypted using HTTPS, and sensitive data must be stored securely, ensuring optimum security. The system architecture must also support future expansion, such as collaborative learning or instructor dashboards.

The system must be developed to facilitate maintainability. Backend and frontend codebases must follow clean architecture principles for easy maintenance and updates. Additionally, since this is a web application, continuous internet access is required for use, minimizing compatibility issues; however, the application must work on both Android and iOS devices and must be compatible with all modern browsers that support WebXR (e.g., Chrome, Safari).

3.3 Development Methodology

The development of AR-NATOMY followed the Agile software development methodology, allowing flexibility and iterative development. The agile methodology supported adaptive planning, rapid delivery, and easier fixes, which were essential in the development of AR-NATOMY due to its complexity and need for interactive features. This methodology was also the best to follow to achieve optimum results within a relatively short amount of time.

Development was structured around two-week sprints. Each sprint was focused on delivering a functional increment of the product and included phases for design, implementation, testing, and review. Each of these phases was integral in building the full stack of the application, including all aspects revolving around delivering a working product, from the user interface design, database integration, backend development, and AR rendering. Feedback from expert reviewers, anatomy lecturers, and trial users informed design decisions and refinements.

GitHub was an important tool in the development, enabling version control and potential open source collaborations, while deployment pipelines are managed through Azure. This continuous integration and delivery (CI/CD) practice ensures that each build is tested and deployed efficiently without disrupting the overall development workflow. The application is continuously improved based on usage and feedback accumulated over time.

3.4 System Architecture

AR-NATOMY operates on a three-tier client-server architecture comprising:
Client Tier: Developed with HTML, CSS, and JavaScript. Responsible for rendering the user interface and initiating AR scenes.
Application Tier: Built using ASP.NET Core with C#, it processes requests, handles business logic, and manages communication with the database.
Database Tier: Uses Microsoft SQL Server to store user data, anatomical model metadata, and user-submitted feedback.

All components communicate over secure method calls within the application, while 3D models are stored on a cloud content delivery network (CDN) for faster access.

3.4.1 Use Cases

The use cases highlighted below describe how users would interact with the system to achieve specific goals, subject to the functionalities the system delivers. Figure 3 visually illustrates the use cases in AR-NATOMY, giving a clear picture of the possible user interactions. These use cases include user registration and login, viewing anatomical systems, interacting with AR models, reading descriptive educational content, submitting feedback, and the release of updates exclusively by the developer/admin.

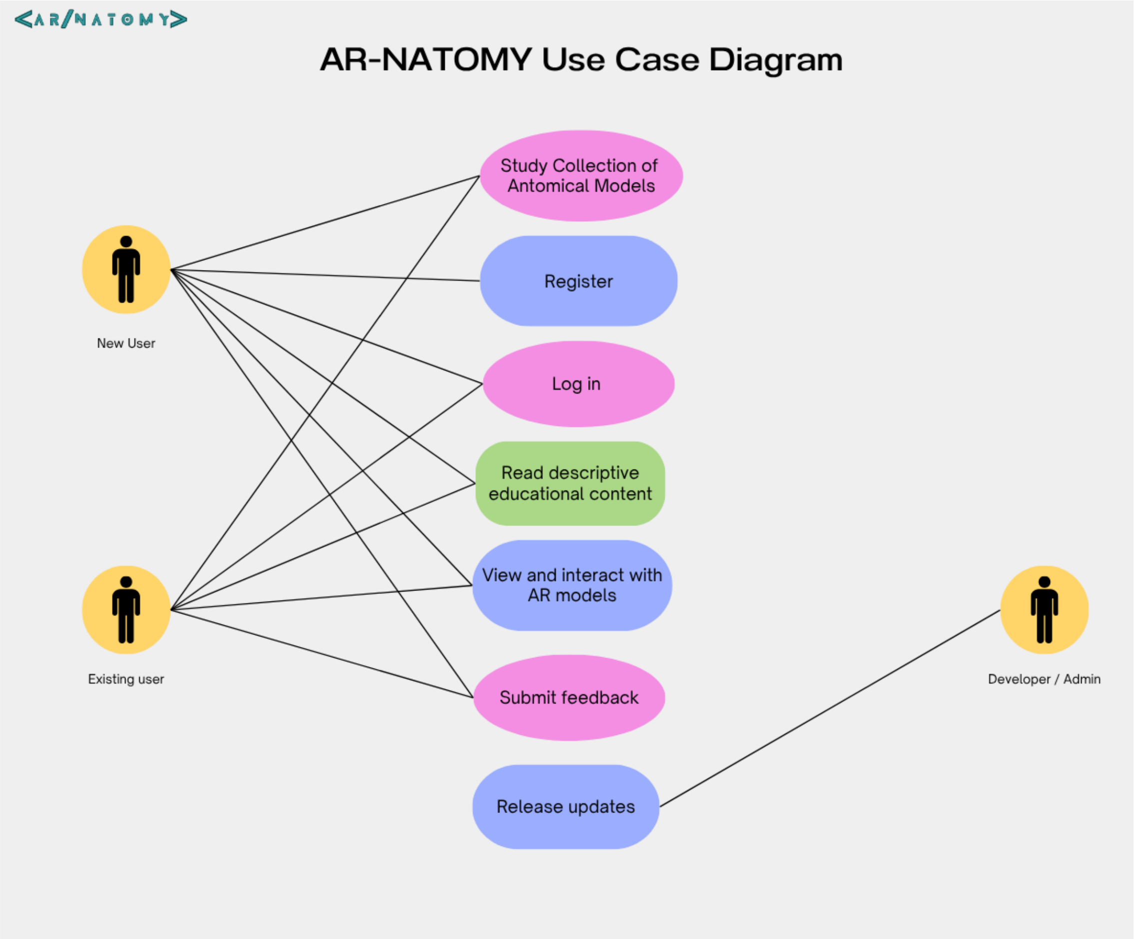


Figure 3: AR-NATOMY Use-Case Diagram

3.4.2 Data Flow Diagram

Figure 4 is a data flow diagram that provides a visual representation of the flow of data through the system. The diagram, being level 0, illustrates how user requests flow through the entire system, and provides a high-level overview of the system, representing it as a single process. In the illustration below, a new user registers, and a request is sent to the server to store the data in the database. Thereafter, to log in, a user goes through authentication, sending a request to the server, and fetching data from the database to confirm the validity of the entered login details.

After authentication, a user can now choose to view available content or submit feedback on any of the AR experiences, which sends a request to the server to store data in the database.

The major functionality involves a user viewing the anatomical models and educational content. At this stage, a user can now proceed to load an AR scene, which sends a request to the server and fetches the stored 3D model, displaying it in the AR scene.

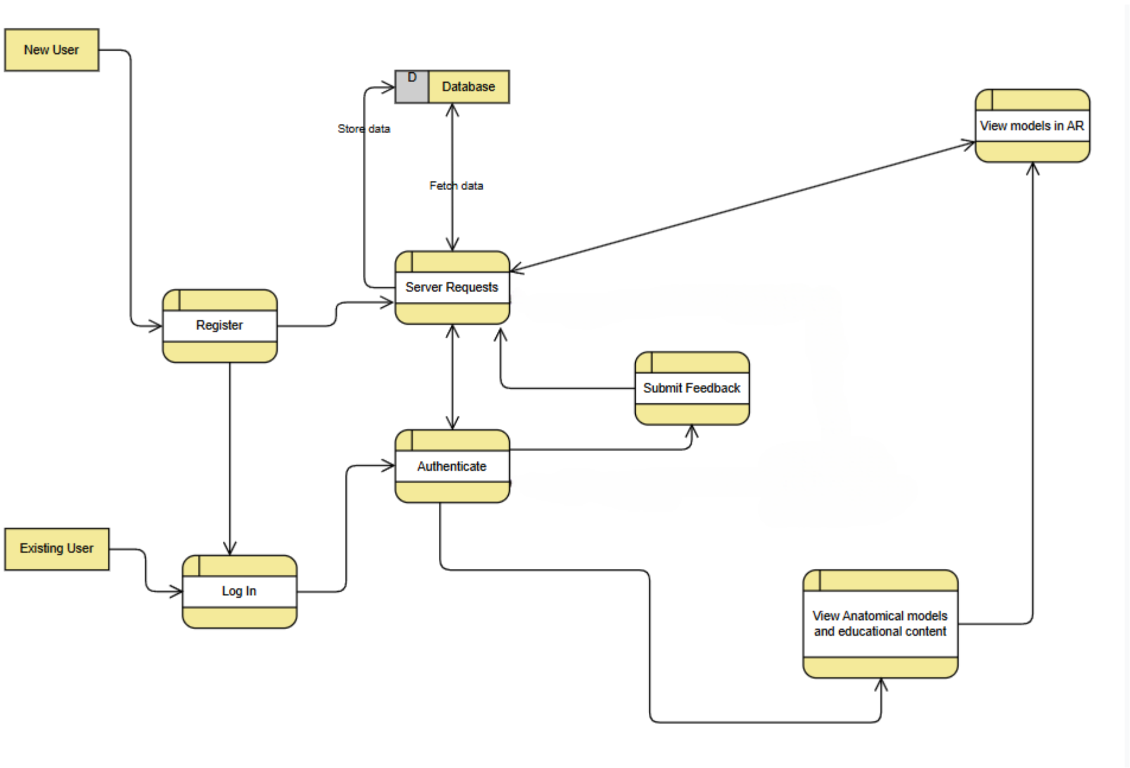


Figure 4: AR-NATOMY Data Flow Diagram (Level 0)

3.4.3 Flowchart of System Operation

Figure 5 shows the flow of operations within AR-NATOMY, from opening the website on a mobile device to viewing an AR scene. The key steps include: (i)user registration/login; (ii) homepage with model list; (iii) selecting an organ system and reading content; (iv) viewing AR scene; (v) submitting feedback on available models

3.4.4 Entity Relationship Diagram

The proposed system was developed using the Entity Framework, which allowed the database data to be treated as objects (entities) within the codebase. Figure 6 provides a visual representation of how these entities (users, feedback, organ models) relate to each other within the system.
The primary entities and their attributes include:

i. User (UserID, FirstName, LastName, CourseOfStudy, School, Email, Role, Password)

ii. Models (ModelID, OrganName, Description, FilePath)

iii. Feedback (FeedbackID, UserID, ModelID, Comment, Rating)

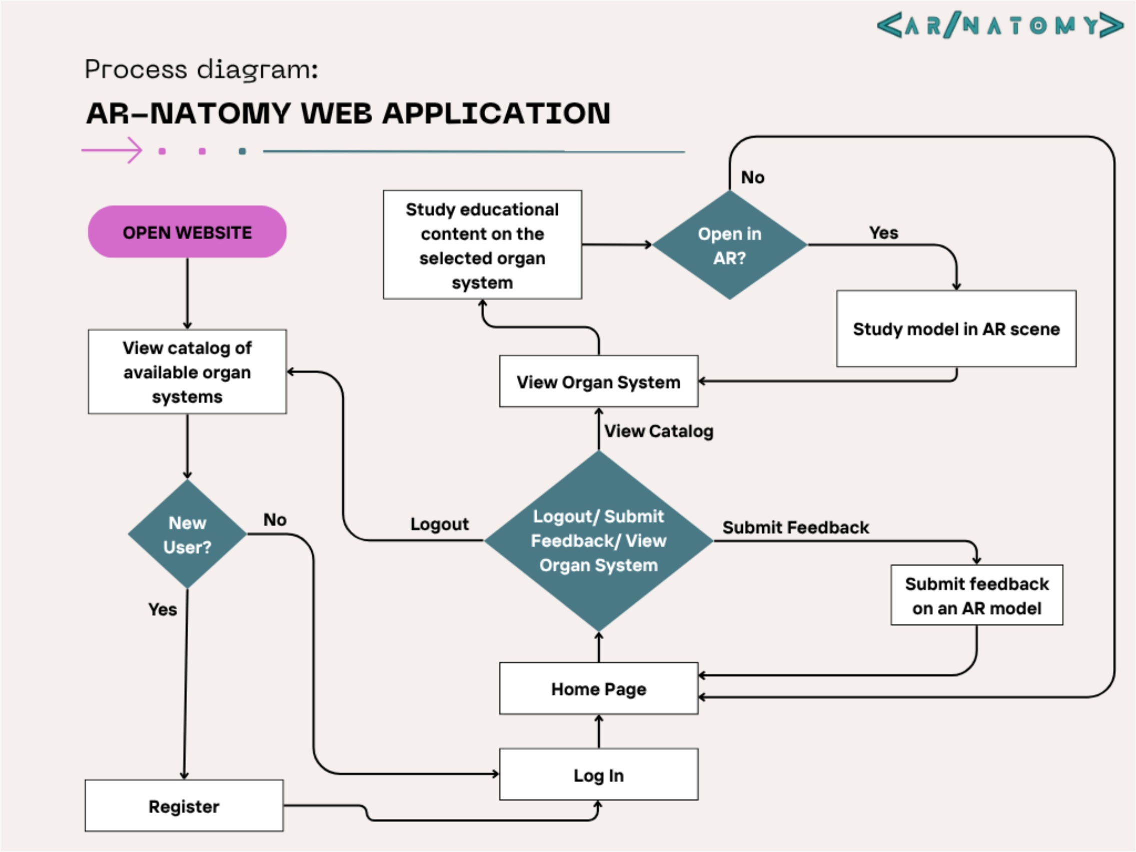


Figure 5: AR-NATOMY Process Flowchart

Entities sometimes have relationships that define how they store data with respect to one another. For AR-NATOMY, only two relationships exist between entities:

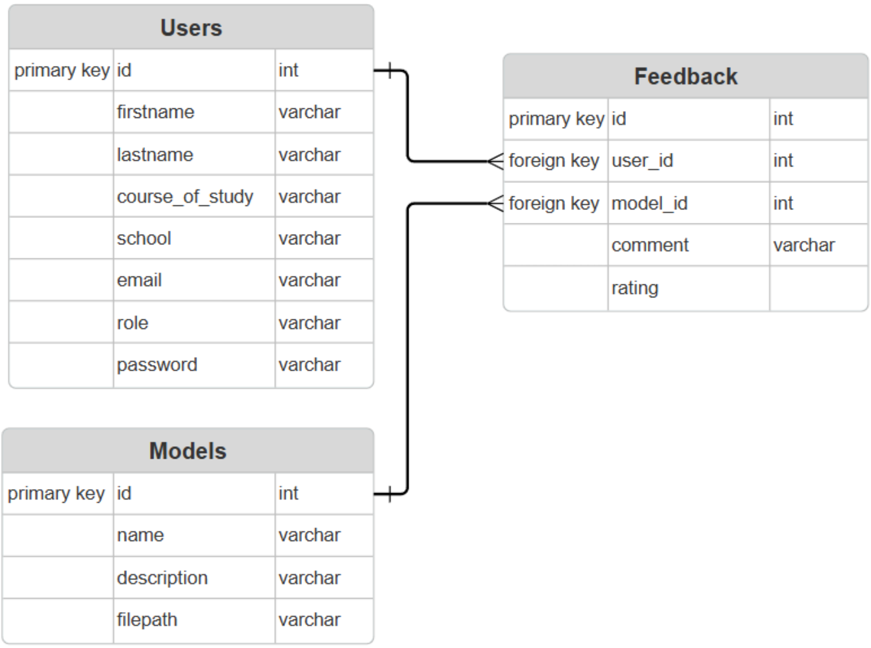
i. **One-to-Many:** One User can submit many Feedback entries.

ii. **One-to-Many:** One Organ Model can have multiple feedback entries associated with it.

3.5 Technologies Used

3.5.1 Frontend Technologies

The frontend of the web application was built with the basic tools (HTML5, CSS, JavaScript), leveraging third-party libraries like Bootstrap, SweetAlert, and Toastify for easier development and to facilitate a responsive and visually appealing UI.



Users

primary key	id	int
	firstname	varchar
	lastname	varchar
	course_of_study	varchar
	school	varchar
	email	varchar
	role	varchar
	password	varchar

Feedback

primary key	id	int
foreign key	user_id	int
foreign key	model_id	int
	comment	varchar
	rating	

Models

primary key	id	int
	name	varchar
	description	varchar
	filepath	varchar

Figure 6: AR-NATOMY Entity Relationship Diagram

3.5.2 Backend Technologies

The backend of AR-NATOMY was written entirely in the C# programming language and built on ASP.NET Core, a server-side web framework that integrates seamlessly with the Microsoft ecosystem, allowing easy use of other vital tools for development such as the Integrated Development Environment (Visual Studio 2022), the database management system for the relational database (Microsoft SQL Server Management Studio) and the platform for hosting & deployment (Microsoft Azure).

3.5.3 3D Modeling Technologies

Each of the 3D anatomical models was designed and modeled with Blender, a powerful 3D modeling environment, leveraging Z-Anatomy, an open-source 3D atlas of the human body.

3.5.4 Cloud Services

In order to improve scalability and speed, AR-NATOMY was built to leverage various cloud services for the storage of its 3D models and the deployment of the web application. As earlier mentioned in Section 3.5.2, Microsoft Azure is the cloud service platform handling the hosting of both the web application and the SQL database, as well as managing deployment pipelines to ensure easy and fast updates of the application. Storage of the 3D models, on the other hand, is handled via a secure CDN (Content Delivery Network) delivered by Bunny.net, a global edge platform used to provide secure CDNs, characterized by its speed, security, and reliability.

3.6 Database Design

The system's database is structured to ensure data consistency, scalability, and security, following a relational model and normalized to third normal form (3NF). The database design involves three major tables handling both user data and organ model metadata.

The ***Users*** table stores first name, last name, course of study (if applicable), school/university (if applicable), email, role, and hashed password. The ***OrganModels*** table contains model name, description, and a link to the 3D model file. The ***Feedback*** table stores ratings and user comments on anatomical models.

No quiz, progress, or assessment data is collected or stored in this version of AR-NATOMY. All content is static and descriptive. Only user-submitted feedback is stored to enable iterative improvements.

3.7 System Security

While the current version does not include multi-factor authentication or role-based access control (RBAC), the following security measures are implemented:

An **authentication** mechanism is put in place to ensure that users register with an email and password, among others. Only authenticated users can access the system's functionalities. The current version of the system gives all users the same level of access. Thus, only the developer can modify content or the database.

The system also ensures that all personal information is stored in **encrypted form**, and sensitive operations like email sending are protected via SSL/TLS. Before these sensitive operations can be triggered, **input validation** is enforced to prevent SQL injection and cross-site scripting (XSS).

CHAPTER FOUR

IMPLEMENTATION AND TESTING

4.1 System Development

A web-based AR experience named AR-NATOMY was created to aid the teaching and learning of human anatomy among learners and instructors. The development process of AR-NATOMY consisted of different stages involved in transforming the conceptual design into a working educational platform. Guided by the Agile methodology, iterative sprints were used to implement functional modules of the application, test their performance, and also refine the system based on feedback received from trial users and expert reviewers.

The system was built using a modular and scalable architecture that would support its core functionalities such as user registration, AR interaction, and feedback submission. The frontend, which facilitates user interaction, was developed with HTML5, CSS3, which were responsible for the UI, and JavaScript, which was responsible for handling the logic of the application's frontend, leveraging the specific device tools/platforms that support AR functionalities (Apple's ARKit and Google's ARCore) to power the rendering and visualization of the 3D anatomical models in AR. On the backend, the ASP.NET web framework was employed to manage server-side logic, handle authentication, and serve data to the frontend via secure method calls, all written in the C# programming language. Microsoft SQL Server was used to store and manage structured data, necessary for the usage of the application, including user data, anatomical model metadata, and feedback submissions. The 3D models themselves were designed in Blender and stored on the cloud via secure CDNs, provided by Bunny.net, which also enabled hosting and serving of the files. To ensure security and data integrity, AR-NATOMY was developed to use HTTPS communication, encrypted user data storage, and server-side input validation mechanisms.

4.2 System Implementation

The system was implemented following a modular structure, such that the core functionalities were organized into interdependent classes, such as Login, Register, ResetPassword, and so on. The entirety of the code was written in Visual Studio 2022, an integrated development environment that makes it easier to build ASP.NET Core web applications and seamlessly integrates with other Microsoft tools.

i. **User Registration:** Users can access AR-NATOMY via the link embedded in the QR-Code in Figure 7. For new users visiting the website, they are required to register via the interface shown in Figure 8 before they can be granted access to use the application's features. The logic behind the register functionality is handled within the 'Register.cshtml.cs' file, which receives data from the frontend (Register.cshtml) and communicates with the database to create a new user and store the entered user data if it passes validation checks, e.g a user's first name and last name are required, password must be of a certain length and must contain certain characters, etc. After all validation checks are satisfied and the user passes registration, an email similar to the one in Figure 10 is sent to the entered email address containing a link to confirm the user. Once this link is clicked, the user is confirmed and can now log in to access the platform. Figure 9 shows a code snippet of the Register.cshtml.cs file that handles the logic described above. In this snippet, the system tries to create a new user with the entered data and stores the result of the trial in a variable (a mutable data container). If this result succeeds, it then attempts to send the confirmation email.

ii. **User Log in & Authentication:** After a user is registered and confirmed, they can now access the system via the link gotten by scanning Figure 7. The logic of this functionality is handled in the Login.cshtml.cs file. To be authenticated and gain access to the system, the email and password used upon registration are required to be entered via the interface shown in Figure 11. Once the user's credentials are entered, the system checks their validity and grants access, if successful, to the home page shown in Figure 13. This mechanism is shown in the code snippet in Figure 12

iii. **Reset Password:** To enhance the user friendliness of the system, AR-NATOMY implements a password reset functionality for the possibility of a user forgetting their password. Upon accessing the 'Forgot Password?' page shown in Figure 14, a user is simply prompted to enter the email associated with their account, and a password reset email will be sent, supposing the email is valid, with a link allowing the user to reset their password. The email shown in Figure 15 redirects the user to the password reset page shown in Figure 16, where they can now enter and confirm their new password.

iv. **AR Scene Rendering:** Once a user is logged in, they can now access the core functionalities of the system, such as opening anatomical models in AR. As shown in Figure 17, the user simply taps on the 'View in AR' button and is then directed to their device's AR support platform and is prompted to follow the next set of instructions to view the

Figure 7: AR-NATOMY QR-Code

model. For ease of use and faster opening of models, users are advised to access the models in well-lit environments. Once a user opens the web page of any organ system, the system detects the operating system of the user's device based on the browser being used to access the system. This functionality is enabled via JavaScript in a script file linked to the organ system's web page's frontend file. A snippet of this script is shown in Figure 18. Figure 19 shows the instruction process on iOS devices, and Figure **??** shows the instruction process on Android devices. After this stage is passed, the model is then available to interact with as shown in Figure 21.

v. **Non-Mobile Detection:** To ensure an optimal experience, AR-NATOMY only allows AR experiences on mobile devices. Thus, as shown in Figure 22, if the website is opened on a non-mobile device, such as a PC (Personal Computer), the system alerts the user and informs them that to view models in AR, the system must be opened on a mobile device.

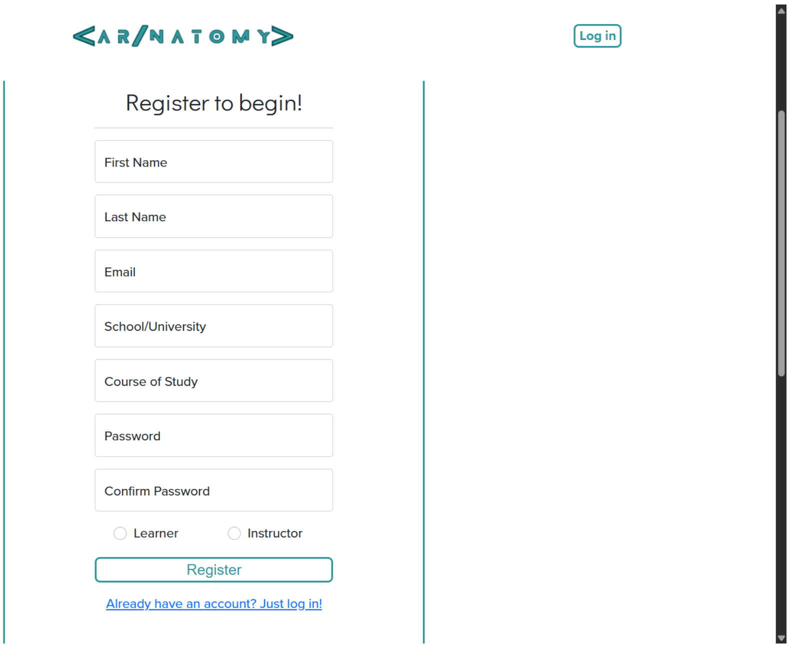


Figure 8: Register Interface

This functionality is handled in JavaScript as shown in Figure 23.

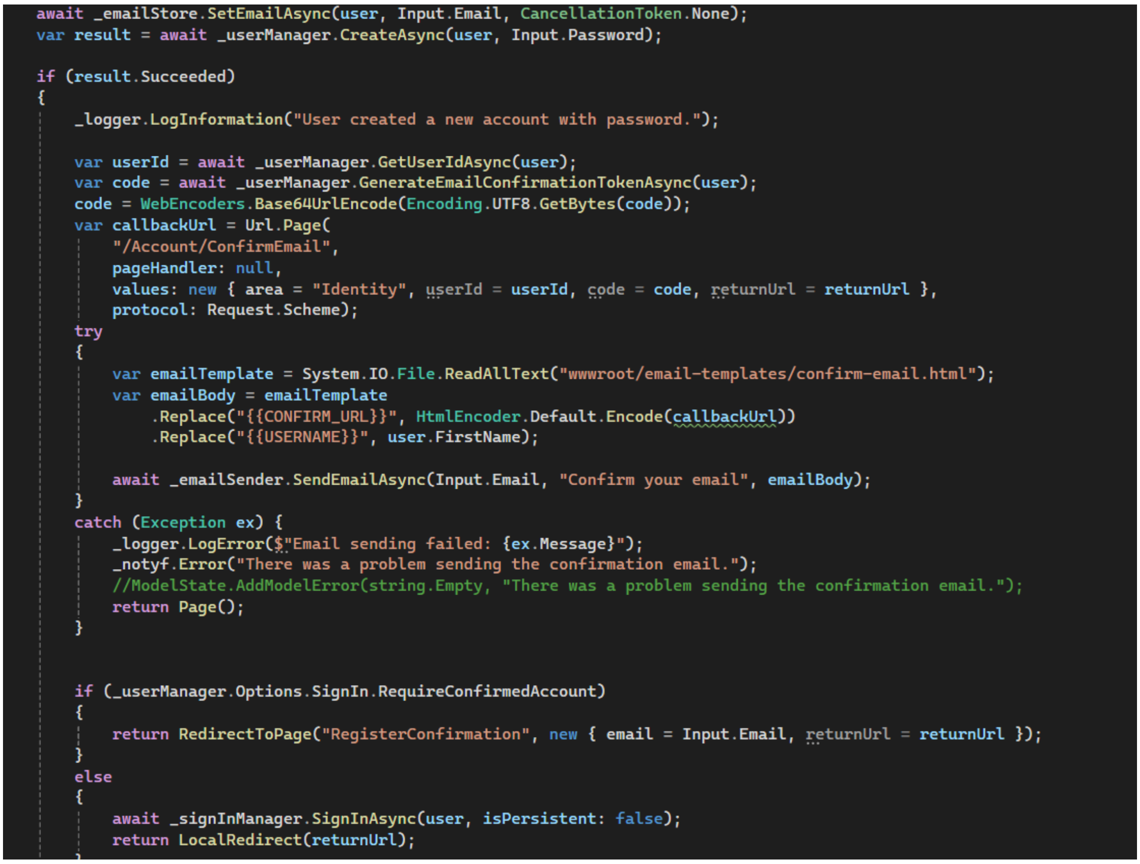
vi. **Feedback Submission:** The feedback functionality allows users to rate their experience with particular models used on AR-NATOMY as shown in Figure 24. The user is to select an available model and provide feedback on it by giving a rating on a scale of 0-5 and leaving an optional comment. This interface was achieved mainly in the frontend, such that accurate data is sent to the backend, which communicates with the database.

4.3 Testing Strategies

To ensure AR-NATOMY functioned reliably and met user expectations, there were several layers of testing that took place throughout development. The testing phase followed a structured approach involving Unit Testing, Integration Testing, and User Acceptance Testing (UAT). Each strategy was aimed at validating different components and functionalities of the system.

4.3.1 Unit Testing

The objective of unit testing was to verify that individual modules and functions operate correctly in isolation, before integrating them into the system to work interdependently. To achieve this, each functionality in the backend (e.g., user registration, authentication, AR scene rendering, password reset, etc) was tested using dummy data inputs to ensure correct responses. User login and registration functions were validated using correct and incorrect credentials for each field. The SMTP (Simple Mail Transfer Protocol) server, responsible for sending out emails,



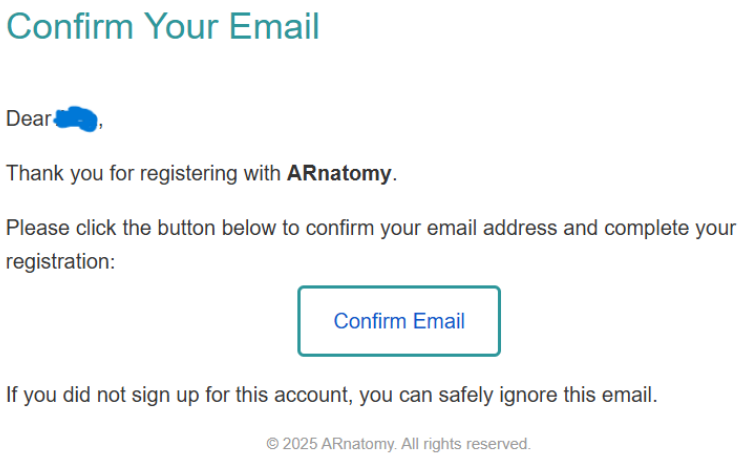
```
await _emailStore.SetEmailAsync(user, Input.Email, CancellationToken.None);
var result = await _userManager.CreateAsync(user, Input.Password);

if (result.Succeeded)
{
    _logger.LogInformation("User created a new account with password.");

    var userId = await _userManager.GetUserIdAsync(user);
    var code = await _userManager.GenerateEmailConfirmationTokenAsync(user);
    code = WebEncoders.Base64UrlEncode(Encoding.UTF8.GetBytes(code));
    var callbackUrl = Url.Page(
        "/Account/ConfirmEmail",
        pageHandler: null,
        values: new { area = "Identity", userId = userId, code = code, returnUrl = returnUrl },
        protocol: Request.Scheme);
    try
    {
        var emailTemplate = System.IO.File.ReadAllText("wwwroot/email-templates/confirm-email.html");
        var emailBody = emailTemplate
            .Replace("{{CONFIRM_URL}}", HtmlEncoder.Default.Encode(callbackUrl))
            .Replace("{{USERNAME}}", user.FirstName);

        await _emailSender.SendEmailAsync(Input.Email, "Confirm your email", emailBody);
    }
    catch (Exception ex) {
        _logger.LogError($"Email sending failed: {ex.Message}");
        _notyf.Error("There was a problem sending the confirmation email.");
        //ModelState.AddModelError(string.Empty, "There was a problem sending the confirmation email.");
        return Page();
    }


    if (_userManager.Options.SignIn.RequireConfirmedAccount)
    {
        return RedirectToPage("RegisterConfirmation", new { email = Input.Email, returnUrl = returnUrl });
    }
    else
    {
        await _signInManager.SignInAsync(user, isPersistent: false);
        return LocalRedirect(returnUrl);
```

Figure 9: Register.cshtml.cs Code Snippet

was tested with Gmass, an SMTP test tool, to verify that the server was functional and would deliver results before being used. Dummy emails were also sent when the functionality itself was built. AR scene rendering was tested by opening the files locally on mobile devices to ensure functional and visual accuracy. As each core backend function passed unit testing with expected outputs under normal and edge-case conditions, it could safely be integrated into the whole system as an interdependent component.

4.3.2 Integration Testing

Integration testing was carried out to assess how well the system modules will interact with each other to deliver their functionalities collectively. This was performed by simulating the use cases of the system in real flows — such as logging in, selecting a model, viewing in AR, and submitting feedback. To ensure that the UI was responsive, frontend interactions were also tested in the browser using different resolutions and optimized for use on mobile devices. Data flow from Microsoft SQL Server to the frontend through the backend was tested and verified before confirming its viability. 3D models were also loaded dynamically from the dashboard to ensure they integrated well with the web interface. User feedback, specifically the ratings, also had to be confirmed to reflect the intended values in the database so the frontend could be adjusted


Confirm Your Email

Dear [redacted],

Thank you for registering with **ARnatomy**.

Please click the button below to confirm your email address and complete your registration:

If you did not sign up for this account, you can safely ignore this email.

© 2025 ARnatomy. All rights reserved.

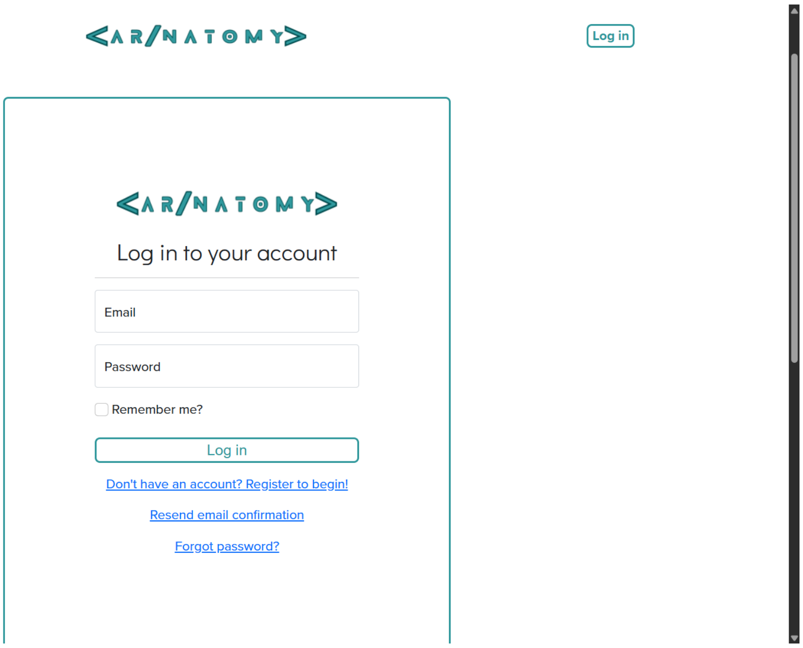
Figure 10: Account Confirmation Email

accordingly. Although minor latency in the loading of the 3D models was observed in older devices, the overall outcome of this was that the system components integrated successfully, and a need to optimize asset sizes was recorded.

4.3.3 User Acceptance Testing (UAT)

To evaluate the system's usability, functionality, and satisfaction level of users, a small group of test users, including anatomy students and academics, was asked to use the application, test all its functionalities, and provide feedback via the feedback mechanism on the system. The test users were informed to be as extensive as possible with their tests, but to ensure that navigation and interaction, accuracy and clarity of AR-rendered 3D models, responsiveness of UI, and educational usefulness of content were all verified. The outcome of the UAT showed successful functional performance, as well as satisfactory usability, with minor comments to improve the system. As recorded from the Feedback table, some of these comments are as follows:

- "My experience was very smooth, the learning process about the skull exterior was very impactful. Great app!" - 5 star rating.
- "It is really fascinating and full of information. I love how the images are in 3D. But I really wish the diagrams have colors so that it will make it easier to differentiate the parts and see the labeling." - 5 star rating. (This suggestion has been implemented and resulted in an improvement in usability)
- "The user interface was very easy to interact with." - 5 star rating.
- "Great experience, labels could be clearer" - 5 star rating. (Work is in progress to



Log in to your account

Don't have an account? Register to begin!

Resend email confirmation

Forgot password?

Figure 11: Log-in Interface

implement this)

4.4 Test Cases and Results

Table 2 provides a summary of the test cases that were performed as well as their respective outcomes. Although the majority of the test cases passed, a significant disadvantage was observed on low-end mobile devices that would affect the experience with the system.

Table 2: Test Cases and Results

Test Case ID	Test Scenario	Expected Result	Actual Result	Status
TC001	User Registration with valid input	Account successfully created and user is redirected for email confirmation	Account created, redirect successful	Pass
TC002	User Registration with invalid input	Error message indicating invalid input is displayed	Descriptive error message is displayed	Pass
TC003	Sending of account confirmation email	Email received with correct confirmation link	Email received by user and account was successfully confirmed	Pass

Continued on next page

Test Case ID	Test Scenario	Expected Result	Actual Result	Status
TC004	User Login with unconfirmed user credentials	Error message: "Invalid login attempt" is displayed	Error message displayed	Pass
TC005	User Login with invalid credentials	Error message: "Invalid login attempt" is displayed	Error message displayed	Pass
TC006	User Login with valid credentials	User is redirected to home page successfully with full access	User logged in successfully	Pass
TC007	Reset password	User receives reset link via email and can reset password and login with new password successfully	Email received, password reset, and user logged in successfully	Pass
TC008	Resend email confirmation	User receives confirmation email again	Email received, link to confirm works	Pass
TC009	Selecting a model for AR view	3D model of organ loads in AR scene	Model rendered successfully in AR	Pass
TC010	AR interaction – rotate model	Model rotates in real-time with touch gestures	Rotation smooth and functional	Pass
TC011	AR interaction – zoom and pan	Model zooms and moves within user environment as expected	Zoom and pan responded correctly	Pass
TC012	Feedback submission with comment and rating	Feedback submitted and success message displayed	Feedback stored in database and confirmation notification shown	Pass
TC013	Accessing the app on a non-mobile device	Alert describing incompatibility, prompting user to switch to a mobile device to display	Compatibility alert displayed correctly	Pass

Continued on next page

Test Case ID	Test Scenario	Expected Result	Actual Result	Status
TC014	Loading 3D model on low-end mobile device	Model loads within 20-30 seconds	Model loaded slowly but within acceptable time	Pass (with delay)

4.5 Performance Evaluation

In order to assess the efficiency, scalability, and responsiveness of AR-NATOMY, it was necessary to evaluate its performance under various conditions. This involved putting the system in the context of various real-world scenarios to determine how well it would perform, especially in terms of model loading times, application responsiveness, and efficiency across different mobile devices and browsers.

Table 3 provides a summary of the evaluation results obtained from using AR-NATOMY on different devices. The evaluation results reiterated the high possibility of suboptimal AR experiences on low-end devices characterized by the longer time taken to load 3D models and the smoothness of the AR rendering.

Table 3: Loading times on different devices

Device Type	Connection Speed	Average Model Load Time (seconds)	Remarks
High-end Android phone	5G / Wi-Fi	4 – 10 seconds	Fast and responsive with smooth AR interactions
High-end iPhone	5G / Wi-Fi	6 – 10 seconds	Very responsive; smooth AR interactions
Mid-range iPhone	4G	8 – 15 seconds	Good, fast performance; phone begins overheating after 10-15 minutes, dropping the performance, however, AR interactions before this are smooth, without any faults.

Continued on next page

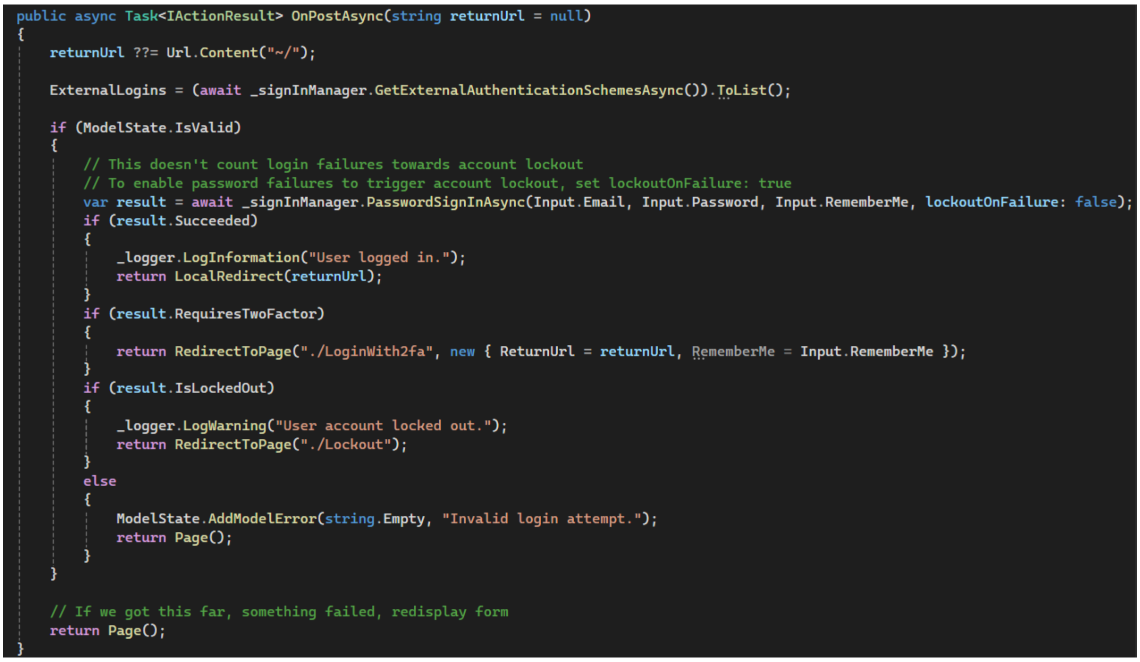
Device Type	**Connection Speed**	**Average Model Load Time (seconds)**	**Remarks**
Mid-range Android phone	4G	10 – 15 seconds	Average performance; AR interactions are less smooth and experience occasional lag, but still somewhat acceptable
Low-end iPhone	3G	15 – 20 seconds	Less than ideal performance with noticeable delay; phone overheats after ±2 minutes and drops performance even further.
Low-end Android phone	3G	20 – 30 seconds	Very prominent delay and lag; requires asset optimization

Another vital aspect of the performance evaluation involved using the Azure portal and browser dev tools to evaluate CPU, RAM, and bandwidth usage during AR sessions. Table 4 shows the results observed, indicating that the application is resource efficient with optimized assets that minimize the load on client devices and the server.

Table 4: Resource utilization results

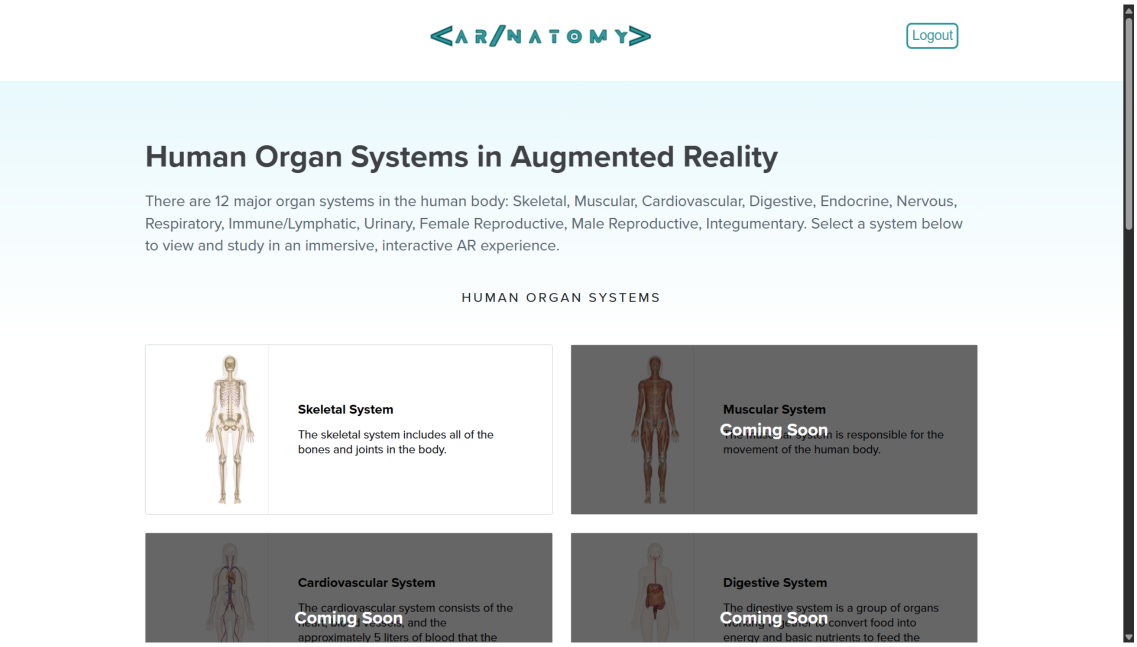
Metric	**Observed Value (Avg.)**	**Threshold**	**Performance**
CPU Usage	10–50% (during AR session)	<70%	Efficient
Memory Usage	50-100MB (while rendering)	<800MB	Efficient
Bandwidth Usage	~4–8MB per 3D model load	<10MB	Optimized

AR-NATOMY was used on different browsers across various devices to evaluate its cross-platform compatibility. Table 5 shows the different devices and browsers that were tested and confirmed to support AR-NATOMY's AR functionalities. AR-NATOMY was developed to support AR features for mobile devices only, and based on the evaluation results, the major browsers used on both types of mobile devices (Android or iOS) are all compatible with the AR features.



```
public async Task<IActionResult> OnPostAsync(string returnUrl = null)
{
    returnUrl ??= Url.Content("~/");

    ExternalLogins = (await _signInManager.GetExternalAuthenticationSchemesAsync()).ToList();

    if (ModelState.IsValid)
    {
        // This doesn't count login failures towards account lockout
        // To enable password failures to trigger account lockout, set lockoutOnFailure: true
        var result = await _signInManager.PasswordSignInAsync(Input.Email, Input.Password, Input.RememberMe, lockoutOnFailure: false);
        if (result.Succeeded)
        {
            _logger.LogInformation("User logged in.");
            return LocalRedirect(returnUrl);
        }
        if (result.RequiresTwoFactor)
        {
            return RedirectToPage("./LoginWith2fa", new { ReturnUrl = returnUrl, RememberMe = Input.RememberMe });
        }
        if (result.IsLockedOut)
        {
            _logger.LogWarning("User account locked out.");
            return RedirectToPage("./Lockout");
        }
        else
        {
            ModelState.AddModelError(string.Empty, "Invalid login attempt.");
            return Page();
        }
    }

    // If we got this far, something failed, redisplay form
    return Page();
}
```

Figure 12: Login.cshtml.cs Code Snippet



Human Organ Systems in Augmented Reality

There are 12 major organ systems in the human body: Skeletal, Muscular, Cardiovascular, Digestive, Endocrine, Nervous, Respiratory, Immune/Lymphatic, Urinary, Female Reproductive, Male Reproductive, Integumentary. Select a system below to view and study in an immersive, interactive AR experience.

HUMAN ORGAN SYSTEMS

Skeletal System

The skeletal system includes all of the bones and joints in the body.

Muscular System

Coming Soon

The muscular system is responsible for the movement of the human body.

Cardiovascular System

The cardiovascular system consists of the heart, blood vessels, and the approximately 5 liters of blood that the

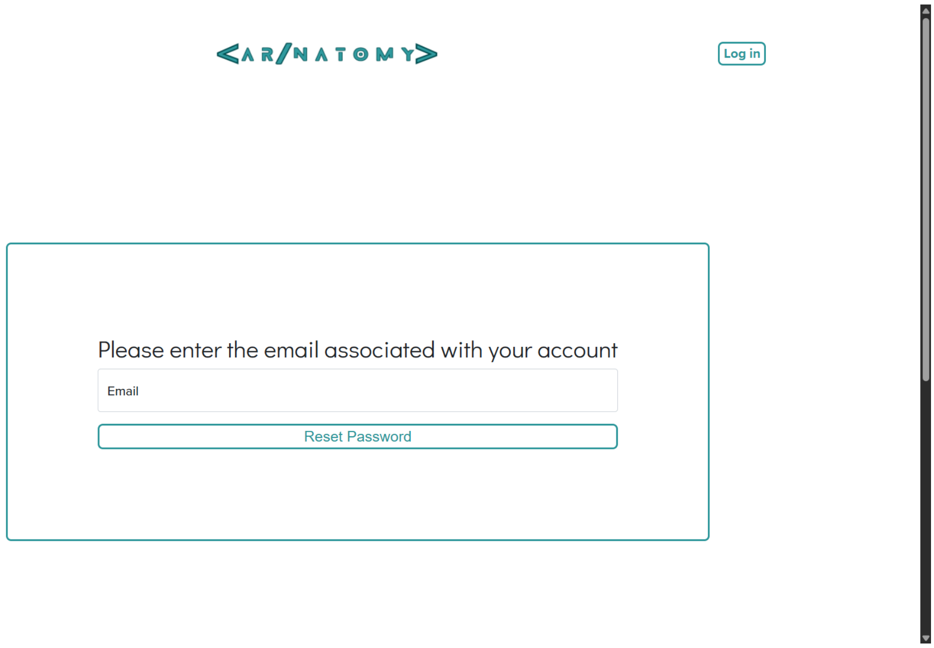
Coming Soon

Digestive System

The digestive system is a group of organs working together to convert food into energy and basic nutrients to feed the

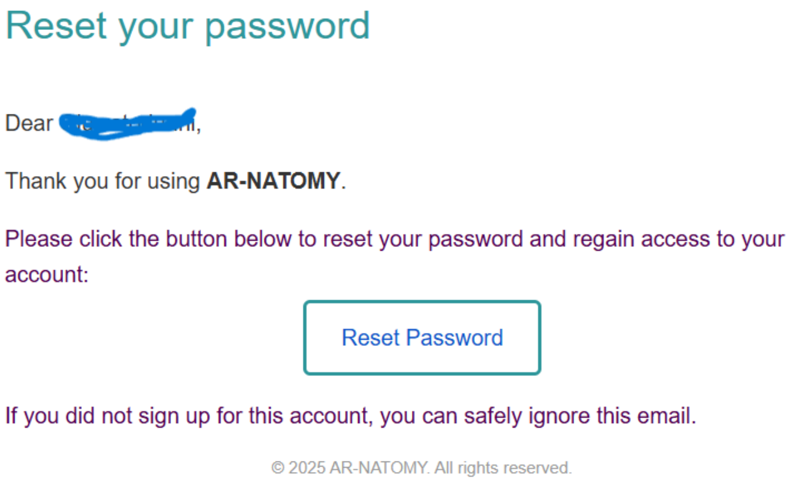
Coming Soon

Figure 13: AR-NATOMY Home Page



Please enter the email associated with your account

Figure 14: Forgot Password Interface



Reset your password

Dear [redacted],

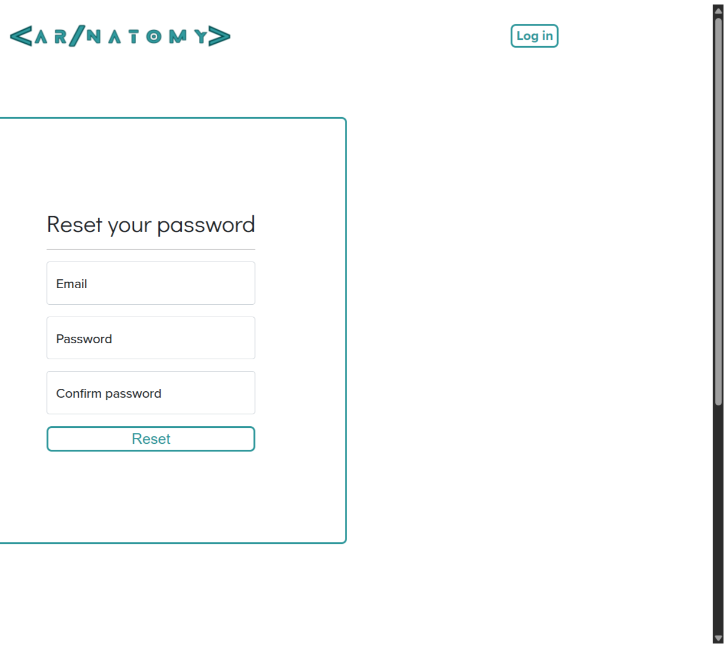
Thank you for using **AR-NATOMY**.

Please click the button below to reset your password and regain access to your account:

If you did not sign up for this account, you can safely ignore this email.

© 2025 AR-NATOMY. All rights reserved.

Figure 15: Reset Password Email



Reset your password

Email

Password

Confirm password

Figure 16: Reset Password Interface

Table 5: Platform and Browser Compatibility

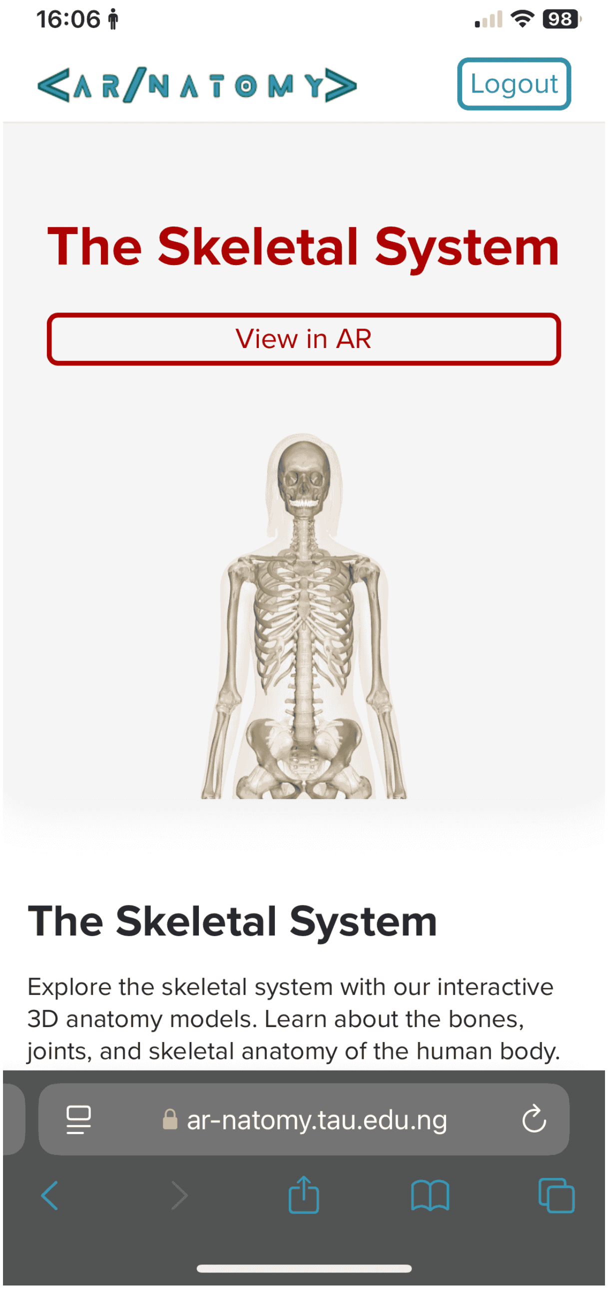
Platform	Browser	AR Support	Result
Android	Chrome, Firefox, Opera (Android 7.0 Nougat+)	Yes	Fully functional
iOS	Safari, Chrome (iOS 11+)	Yes	Fully functional
Windows	Chrome, Edge, Firefox	No	AR features not supported
macOS	Safari, Chrome	No	AR features not supported

Based on the performance evaluation results gathered from real-world usage of AR-NATOMY, the minimum and recommended device requirements are summarized below:

Minimum System Requirements:

i. **Operating System:**
  - Android: Android 7 Nougat or later
  - iOS: iOS 11 or later

ii. **Processor: Quad-core ARM processor**
  - Android: Snapdragon 625 or later
  - iOS: A9 processor or later



The Skeletal System

The Skeletal System

Explore the skeletal system with our interactive 3D anatomy models. Learn about the bones, joints, and skeletal anatomy of the human body.

Figure 17: Skeletal System Page

```
function isIos() {
    const ua = window.navigator.userAgent;
    const iOS = /iPad|iPhone|iPod/.test(ua);
    const iPadOS = navigator.platform === 'MacIntel' && navigator.maxTouchPoints > 1;
    return iOS || iPadOS;
}

document.addEventListener("DOMContentLoaded", function () {
    const ios = isIos();
    const mobile = isMobile();
    if (mobile) {
        Object.entries(models).forEach(([id, filename]) => {
            const el = document.getElementById(id);
            if (!el) return;

            if (ios)... else {
                el.href = ...;
            }
        });
```

Figure 18: Operating System Detection Script

iii. **Storage:**

  - RAM: 2GB or higher
  - Internal Storage: 100MB or larger

iv. **Display: 1280×720 or higher**

v. **Browser: Any supported web browser**

vi. **Connectivity: Stable 3G/4G mobile data or Wi-Fi connection**

vii. **Battery: 30% charge**

Recommended System Requirements:

i. **Operating System:**

  - Android: Android 10 or later
  - iOS: iOS 14 or later

ii. **Processor: Octa-core ARM processor**

  - Android: Snapdragon 845 or later
  - iOS: A12 Bionic or later

iii. **Storage:**

  - RAM: 4GB or higher
  - Internal Storage: 200MB or larger

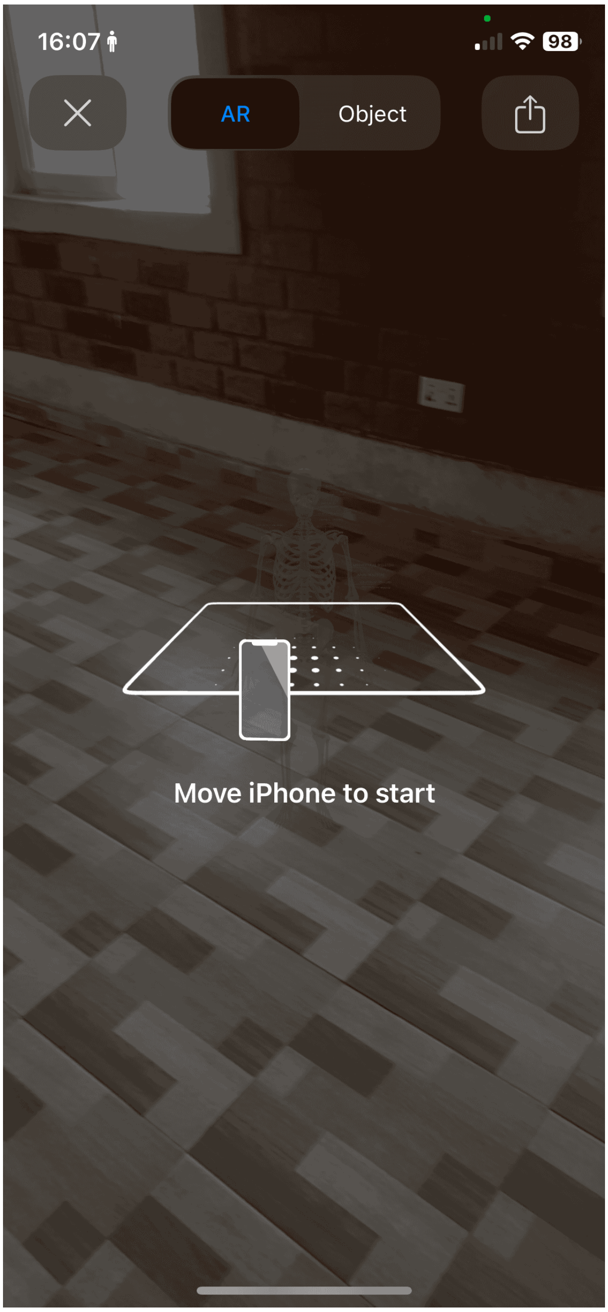
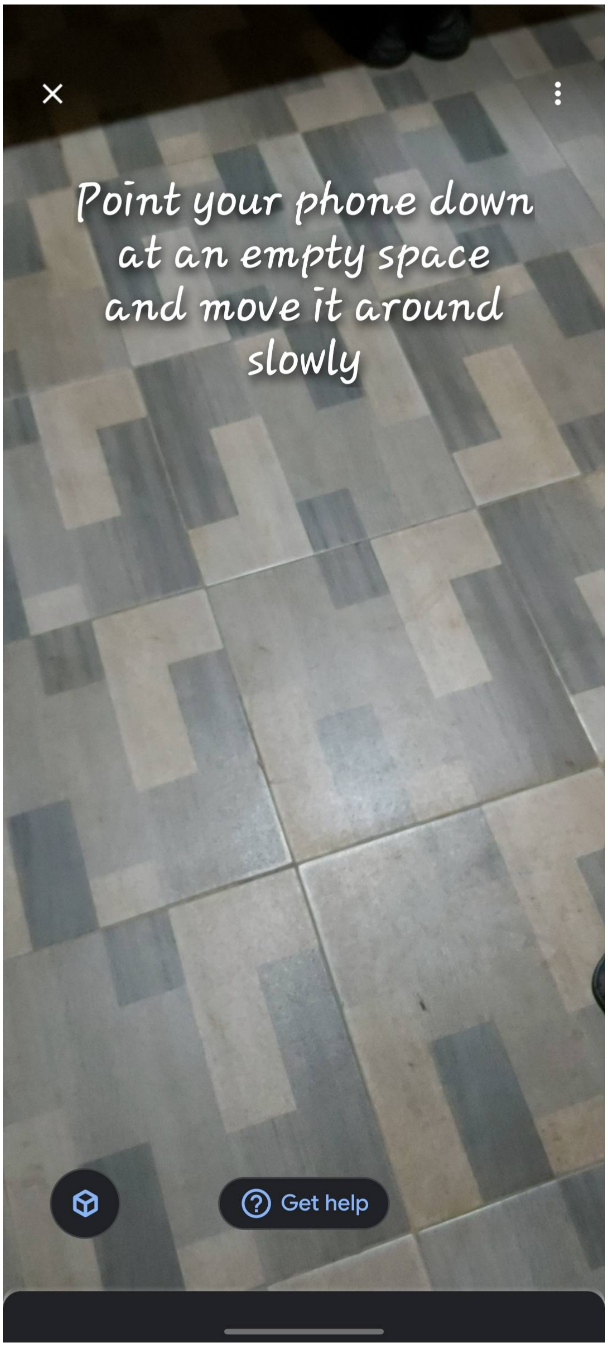


Figure 19: iOS Instruction Process



Point your phone down at an empty space and move it around slowly

Figure 20: Android Instruction Process

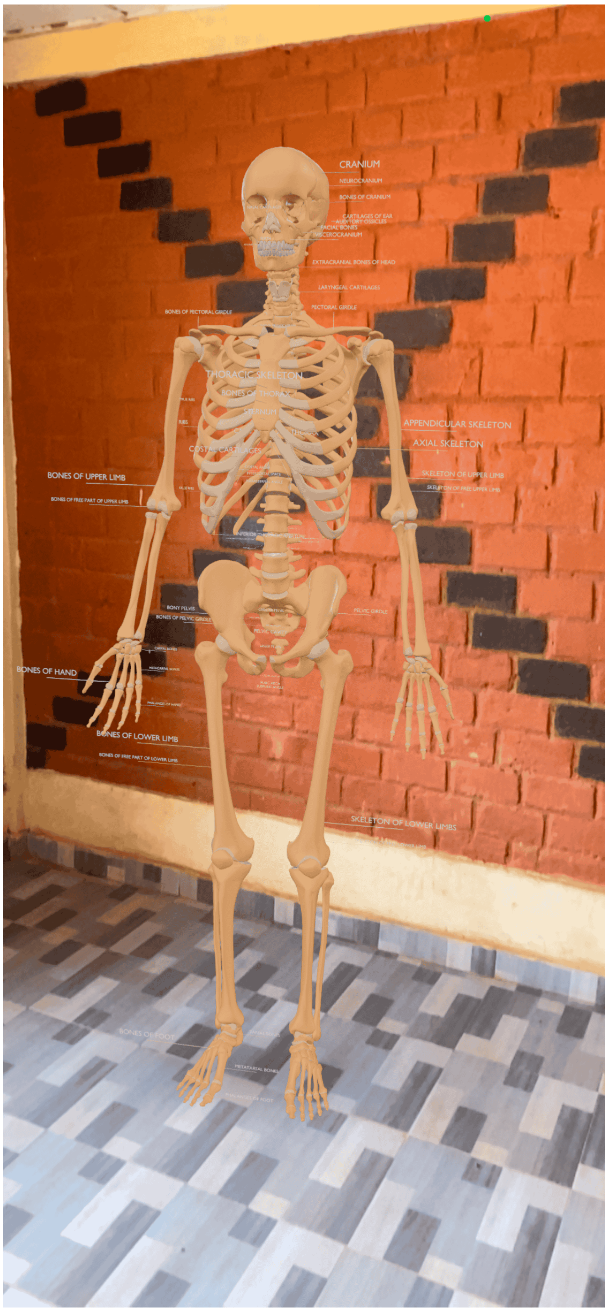
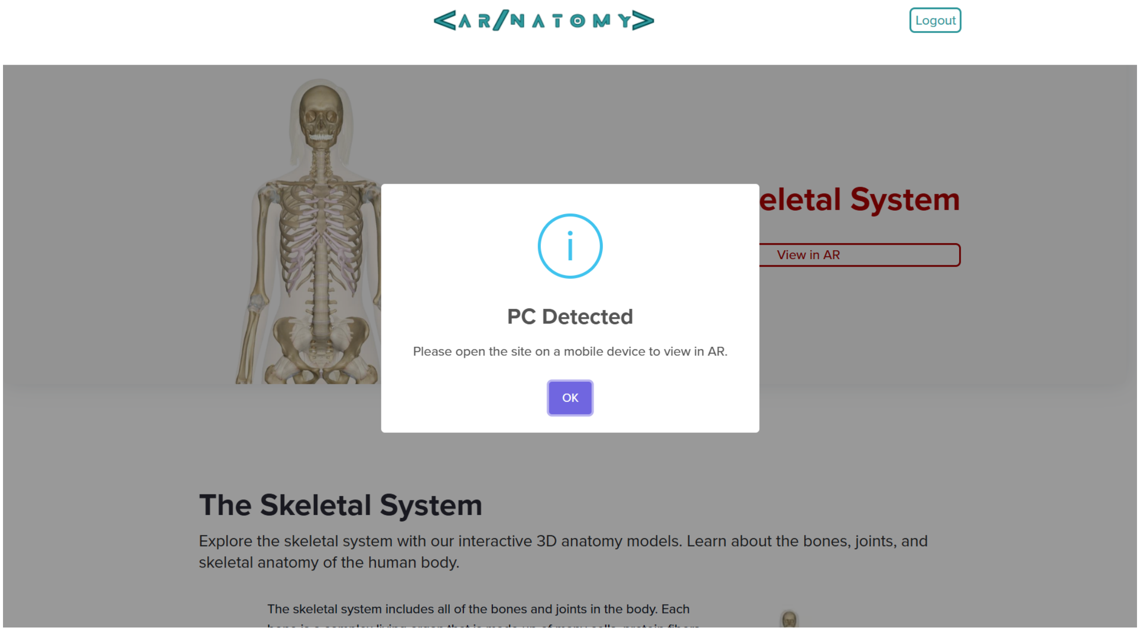


Figure 21: Full Skeletal System Model



PC Detected

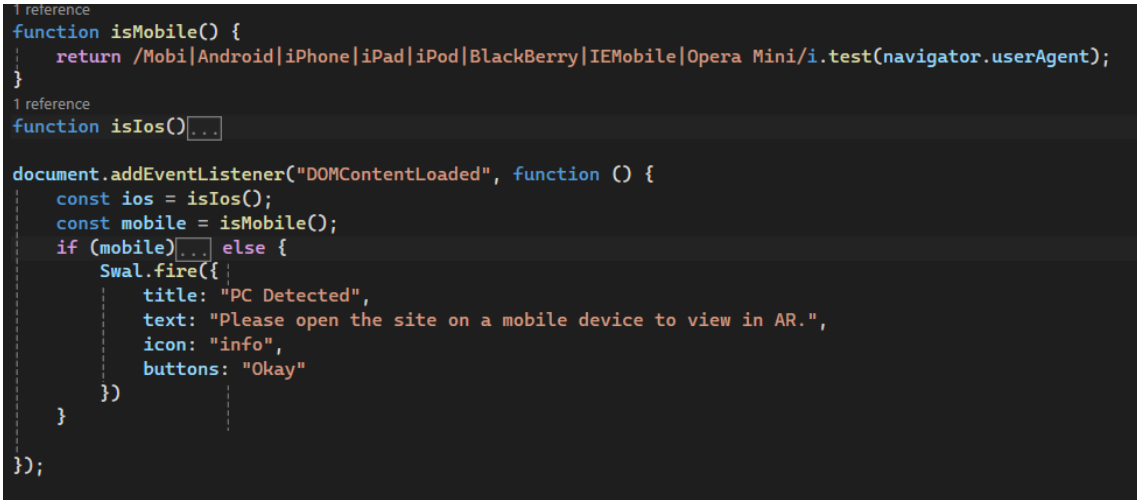
Please open the site on a mobile device to view in AR.

The Skeletal System

Explore the skeletal system with our interactive 3D anatomy models. Learn about the bones, joints, and skeletal anatomy of the human body.

The skeletal system includes all of the bones and joints in the body. Each

Figure 22: Non-Mobile Detection Alert



```
1 reference
function isMobile() {
    return /Mobi|Android|iPhone|iPad|iPod|BlackBerry|IEMobile|Opera Mini/i.test(navigator.userAgent);
}
1 reference
function isIos()...

document.addEventListener("DOMContentLoaded", function () {
    const ios = isIos();
    const mobile = isMobile();
    if (mobile)... else {
        Swal.fire({
            title: "PC Detected",
            text: "Please open the site on a mobile device to view in AR.",
            icon: "info",
            buttons: "Okay"
        })
    }

});
```

Figure 23: Non-Mobile Detection Script

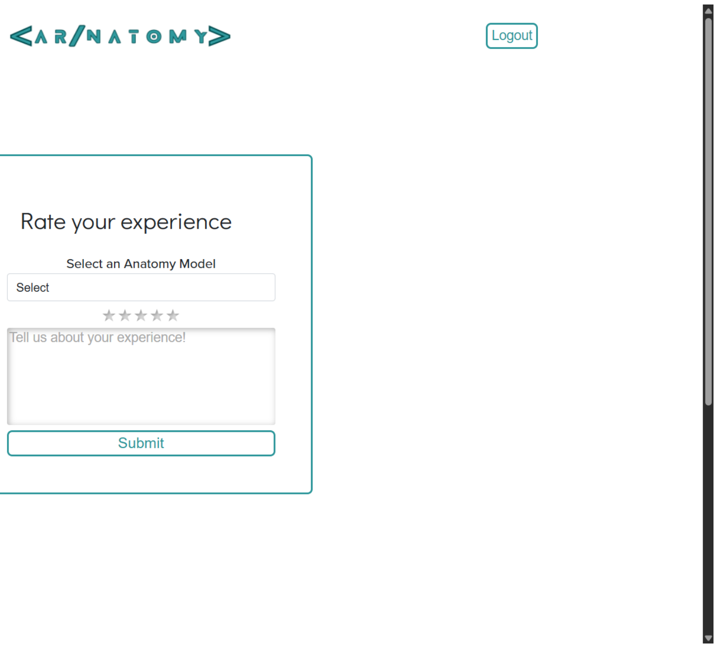


Figure 24: Feedback Interface

iv. **Display: 1920×1080 or higher**

v. **Browser: Any supported web browser**

vi. **Connectivity: Fast 4G/5G mobile data or Wi-Fi connection**

vii. **Battery: Fully charged or connected to power**

4.6 Application Manual

To aid the usability of AR-NATOMY, especially for users unfamiliar with the use of AR technologies, a user guide for the application is summarized below:

i. **Step 1: Access the website**
Open a WebXR-supported browser on an Android or iOS device (e.g., Chrome, Safari) and visit the application's web URL `https://ar-natomy.tau.edu.ng`. Ensure that the device has a stable internet connection and a functional camera.

ii. **Step 2: Register or Log In**
Tap on the button that says "Log in" in the top-right corner. For a new user, tap on the link to register below the login form, follow the instructions to sign up, and log in when your account is created and confirmed. For a previous user, provide your email and password to gain access to the system.

iii. **Step 3: Browse Organ Systems**
After logging in, users are directed to the home page where organ systems are displayed

as clickable cards (e.g., Skeletal System, Nervous System). Browse through the catalog of available organ systems and select one you’d prefer to study.

iv. **Step 4: Select an Organ**
Users can study the content within each available organ system to view its details and activate an AR experience by selecting a model within the organ system. This could either be the full system or segments of it.

v. **Step 5: Launch AR Model**
Upon selection, a 3D anatomical model loads in augmented reality. In a well-lit environment, and depending on your device platform (Android or iOS), follow the instructions displayed on the screen to render the model in AR. The model then appears in the real-world environment through the device screen.

vi. **Step 6: Interact with the Model**
Users can rotate, zoom, or reposition the model using touch gestures for better clarity or ease of use. Adjacent to the model, 2D labeled illustrations are shown.

vii. **Step 7: Submit Feedback (Optional)**
After exploring the model, users can return to the web page by tapping on the return button and rate the experience via the feedback button in the footer.

viii. **Step 8: Log Out**
Users can safely exit the session by tapping on the "Log Out" button in the top-right corner.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary of Findings

The evolution of teaching and learning methods is something that can hardly go unnoticed, especially with the advancements in technology increasingly coming to light. In this age of artificial intelligence and ubiquitous computing, it is essential to ensure that every new innovation makes a meaningful contribution to knowledge, society, and the environment.

Knowledge is the foundation on which any innovative solution is conceived, and the most effective way of impacting knowledge is through education. As the world grows, conventional methods of education become increasingly inefficient, emphasizing the necessity for technological and innovative integrations.

Augmented Reality (AR) has proved to be a powerful tool, capable of revolutionizing the way knowledge is propagated and solving many challenges that are faced with conventional methods. Human anatomy is a vital field of education because it is necessary for understanding the composition of the human body, making it a key factor for ensuring the well-being of every human.

This study has shown the potential of AR for improving the education of human anatomy. The system developed, "AR-NATOMY", demonstrated its viability for delivering the required purposes and will continue to prove its relevance in human anatomy education. Its evaluation was carried out on 18 undergraduate students, and was guided by the research questions highlighted in Table 6, providing data that showed promising results. The evaluation comprised different sections made up of questions structured to gauge the usability of AR-NATOMY, learners' attitudes and perceptions during and after usage, and their pedagogical experiences (Ade-Ibijola et al., 2025).

Table 6: AR-NATOMY evaluation questions

	Questions	Reference
Q1	I consent to participating in the evaluation of AR-NATOMY	Authors
Q2	I have used the AR-NATOMY web application on my mobile device and interacted with its augmented reality experiences	Authors
Q3	It was easy to sign up on AR-NATOMY	(Martins, Kirner, & Kirner, 2015)
Q4	It was easy for me to use AR-NATOMY	(Georgiou & Kyza, 2017)
Q5	I found the use of colour and design layout of the augmented reality animation on AR-NATOMY pleasant.	(Ibrahim, 2011)
Q6	AR-NATOMY captured my attention	(Georgiou & Kyza, 2017)
Q7	I found AR-NATOMY appealing, engaging and highly motivating to use	(Georgiou & Kyza, 2017)
Q8	I liked AR-NATOMY because the use of augmented reality in learning anatomy was novel.	(Georgiou & Kyza, 2017)
Q9	I found an improvement in my understanding of human organ systems in anatomy after interacting with the models in AR-NATOMY.	(Grivokostopoulou, Paraskevas, Perikos, Nikolic, & Kovas, 2018)
Q10	After using AR-NATOMY, the augmented reality functionality stimulated my interest in learning anatomy	(Georgiou & Kyza, 2017)
Q11	After using AR-NATOMY, I am more confident about my knowledge of human organ systems in anatomy	(Grivokostopoulou et al., 2018)
Q12	I would prefer to use an application that has augmented reality functionality, like AR-NATOMY, to study anatomy in the future.	(Ade-Ibijola et al., 2025)
Q13	AR-NATOMY's 3D models helped me to understand the spatial properties of human anatomical parts	Authors

Continued on next page

	Questions	Reference
Q14	AR-NATOMY's AR experiences reduced the effort I expended on studying anatomy	(Ade-Ibijola et al., 2025)
Q15	I found the written educational content in AR-NATOMY helpful to my learning process	Authors
Q16	I found the visual animation on AR-NATOMY useful to my learning process.	(Ade-Ibijola et al., 2025)
Q17	Overall, I am satisfied with AR-NATOMY	(Lewis, 1995)
Q18	I would recommend AR-NATOMY to my peers. If not, please provide reasons.	(Lund, 2001)
Q20	What do you like the most about AR-NATOMY? (Open-ended)	(Schaeffer, 2014)
Q21	What do you dislike the most about AR-NATOMY? (Open-ended)	(Schaeffer, 2014)
Q22	Do you have any comments to help improve AR-NATOMY? (Open-ended)	(Schaeffer, 2014)

As shown in Table 7, AR-NATOMY was easy to use. Although the results show a slight variation in Q3, the majority proved that the mechanisms set in place for registration and login were easy to navigate, and the AR experiences were easy to set up. To further reduce variation in future instances, improvements will be made on the user interface to increase user friendliness, making it easier for learners to navigate the system to meet their needs.

Table 7: Usability evaluation results

	Q3	Q4	Q5
1: strongly disagree	0	0	0
2: disagree	0	0	0
3: somewhat disagree	1	0	0
4: somewhat agree	0	1	0
5: agree	6	11	12
6: strongly agree	11	6	6

Table 8 shows the results of the attitude and perception evaluation. These metrics show that AR-NATOMY positively influenced the interests of the students towards learning anatomy, and they enjoyed the learning experience with AR models. The results prove that the students got a

’confidence boost’ after using AR-NATOMY, such that the experiences polished their previous theoretical knowledge and gave them a spatial understanding of anatomical parts to a level where they became assertive of their skills.

Table 8: Attitude and perception evaluation results

	Q6	**Q7**	**Q8**	**Q9**	**Q10**	**Q11**
1: strongly disagree	0	0	0	0	0	0
2: disagree	0	0	0	0	0	0
3: somewhat disagree	0	0	0	0	0	0
4: somewhat agree	0	0	1	1	2	2
5: agree	8	9	7	11	7	10
6: strongly agree	10	9	10	6	9	6

The last section of the evaluation survey was to assess the pedagogical experiences of the students after using AR-NATOMY. As shown in Table 9, the results showed a slight variation in Q14, which was to measure the efficiency of studying anatomy with AR-NATOMY as opposed to conventional methods. Although this value represents a need for improvement, the majority showed positive results, with respondents indicating that AR-NATOMY was beneficial in their learning of anatomy, and they would prefer AR-NATOMY as a pedagogical method rather than other avenues.

Table 9: Pedagogical experience evaluation results

	Q12	**Q13**	**Q14**	**Q15**	**Q16**	**Q17**
1: strongly disagree	0	0	0	0	0	0
2: disagree	0	0	1	0	0	0
3: somewhat disagree	0	0	0	0	0	0
4: somewhat agree	2	2	2	1	0	1
5: agree	7	8	12	11	9	7
6: strongly agree	9	8	3	6	9	10

5.2 Conclusion

To conclude, this study has successfully met all the previously outlined objectives: delivering a functional web-based AR application, evaluating its impact on student retention and comprehension, and gauging student engagement and attitude while using the developed system. The outcome of this study has shown positive results, setting the stage for further improvements to increase the developed system's effectiveness and efficiency, both functionally and in terms of usability.

5.3 Contributions to Knowledge

This study has addressed majority of the gaps identified in Section 2.4, providing insights on the outcomes of delivering a web-based solution that offers all human organ systems in augmented reality, and providing further knowledge on the impact of AR on student participation and academic performance, both generally and in the context of anatomy-related coursework.

5.4 Recommendations

Based on the feedback acquired both through AR-NATOMY's feedback mechanism and the administered survey, significant areas for improvement on the system were noted, focusing on its overall ability to provide meaningful educational value.

A user submitted a comment to an open-ended question, advising that a medical practitioner/expert be kept in the loop to ensure accuracy as the system gets updated over time. The comment in question, *"Make sure to take along a medical practitioner, especially an anatomist, and be sure to be updated too. Keep it up"*, emphasized the importance of an expert's touch, indicating a vital area for future improvements.

Another response to a question in Table 6 expressed the need for audio narrations during the AR experiences. Following the Cognitive Theory of Multimedia Learning highlighted in Section 2.2.3, the importance of propagating information in an audio-visual manner was emphasized, indicating an area for future improvement on the system. The comment, *"A voice over during the AR experience"*, showed that although the AR models were beneficial, the effectiveness of their impact could be significantly increased with the addition of an audio voiceover, explaining the anatomical part being rendered.

5.5 Future Work

Future work in this field would involve timely updates and additions to the catalog of available organ systems. A user's response to Q21 in Table 6 was *"Nothing yet, but I want to see all anatomical structures that aren't finished with yet"*, indicating that, having used the system, users are pleased with the learning opportunities it provides, and they are enthusiastic about the future of anatomy education with AR, as they look forward to how more anatomical parts would be visualized in an AR scene.

Additionally, the system is currently made to provide AR experiences only on mobile devices. Future work would involve upgrading the technical capabilities of the system, allowing it to be used across all internet-enabled devices, such as VR headsets and personal computers, providing smooth AR experiences irrespective of device platform.

As technology continues to advance, new functionalities will potentially be able to be integrated, such as virtual dissections. This would allow users to do more than just study AR models spatially, but also obtain practical knowledge in a cross-sectional context, allowing them to see how these different organs are layered on top of each other and how they relate interdependently.

Another functionality that would benefit from advancements in technology would be remote collaborative study among learners. As time passes, the system would potentially evolve into allowing users who are not in the same geographic space to have joint study sessions, where they can collectively interact with anatomical parts in AR.

Lastly, to ensure real-time measurement of the pedagogical impact of the AR experiences, virtual assessments and quizzes will potentially be implemented. This would allow users to test their knowledge of anatomical parts spatially and receive feedback about their performance in real-time.

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APPENDICES

APPENDIX A1

Code for Database Tables

```csharp
using Microsoft.AspNetCore.Identity;

namespace ARnatomy.Models
{
    // users
    public class ApplicationUser : IdentityUser
    {
        public ICollection<Feedback> Feedback { get; set; } = new List<Feedback>();
        public string FirstName { get; set; }
        public string LastName { get; set; }
        public string? School { get; set; }
        public string? CourseOfStudy { get; set; }

        public string Role { get; set; }
    }

    // 3d models table
    public class OrganModel
    {
        public ICollection<Feedback> Feedback { get; set; } = new List<Feedback>();
        public int Id { get; set; }
        public string Name { get; set; }
        public string Description { get; set; }
        public string FilePath { get; set; }
    }

    // feedback table
    public class Feedback
    {
        public int Id { get; set; }
        public string UserId { get; set; }
        public ApplicationUser User { get; set; }
        public int OrganModelId { get; set; }
        public OrganModel OrganModel { get; set; }
        public string? Comment { get; set; }
        public int Rating { get; set; }
    }
```

```
}
```

Listing 1: C# code for Data Models in AR-NATOMY

APPENDIX A2

Code for Home Controller

```
using System.Diagnostics;
using System.Net.NetworkInformation;
using ARnatomy.Models;
using Microsoft.AspNetCore.Mvc;
using Microsoft.AspNetCore.Identity;
using ARnatomy.Data;
using AspNetCoreHero.ToastNotification.Abstractions;

namespace ARnatomy.Controllers
{
    public class HomeController : Controller
    {
        private readonly ILogger<HomeController> _logger;
        private readonly SignInManager<ApplicationUser> _signInManager;
        private readonly ApplicationDbContext _context;
        private readonly UserManager<ApplicationUser> _userManager;
        private readonly INotyfService _notyf;

        public HomeController(
            ILogger<HomeController> logger,
            SignInManager<ApplicationUser> signInManager,
            ApplicationDbContext context,
            UserManager<ApplicationUser> userManager,
            INotyfService notyf)
        {
            _logger = logger;
            _signInManager = signInManager;
            _context = context;
            _userManager = userManager;
            _notyf = notyf;
        }

        public IActionResult Index()
        {
            return View();
        }

        public IActionResult Privacy()
        {
```

```
        return View();
    }

    public IActionResult SkeletalSystem()
    {
        if (_signInManager.IsSignedIn(User)){
            return View();
        }
        else {
            return RedirectToPage("/Account/Login", new { area = "Identity" });
        }
    }

    public IActionResult MuscularSystem()
    {
        if (_signInManager.IsSignedIn(User)){
            return View();
        }
        else {
            return RedirectToPage("/Account/Login", new { area = "Identity" });
        }
    }

    public IActionResult DigestiveSystem()
    {
        if (_signInManager.IsSignedIn(User)){
            return View();
        }
        else {
            return RedirectToPage("/Account/Login", new { area = "Identity" });
        }
    }

    public IActionResult EndocrineSystem()
    {
        if (_signInManager.IsSignedIn(User)){
            return View();
        }
        else {
            return RedirectToPage("/Account/Login", new { area = "Identity" });
        }
    }
```

```

    public IActionResult NervousSystem()
    {
        if (_signInManager.IsSignedIn(User)){
            return View();
        }
        else {
            return RedirectToPage("/Account/Login", new { area = "Identity" });
        }
    }

    public IActionResult Feedback()
    {
        if (_signInManager.IsSignedIn(User)){
            var organModels = _context.OrganModels.ToList();
            return View(organModels);
        }
        else {
            return RedirectToPage("/Account/Login", new { area = "Identity" });
        }
    }

    [HttpPost]
    public async Task<IActionResult> CreateFeedback(FeedbackDto feedbackDto)
    {
        var user = await _userManager.GetUserAsync(User);
        var userId = user?.Id;
        if (userId == null){
            _notyf.Error("You're not logged in.");
            return RedirectToPage("/Account/Login", new { area = "Identity" });
        }

        if (!ModelState.IsValid){
            _notyf.Error("Please select a model.");
            return RedirectToAction("Feedback", "Home");
        }

        Feedback feedback = new Feedback()
        {
            UserId = userId,
            OrganModelId = feedbackDto.OrganModelId,
            Comment = feedbackDto.Comment,
```

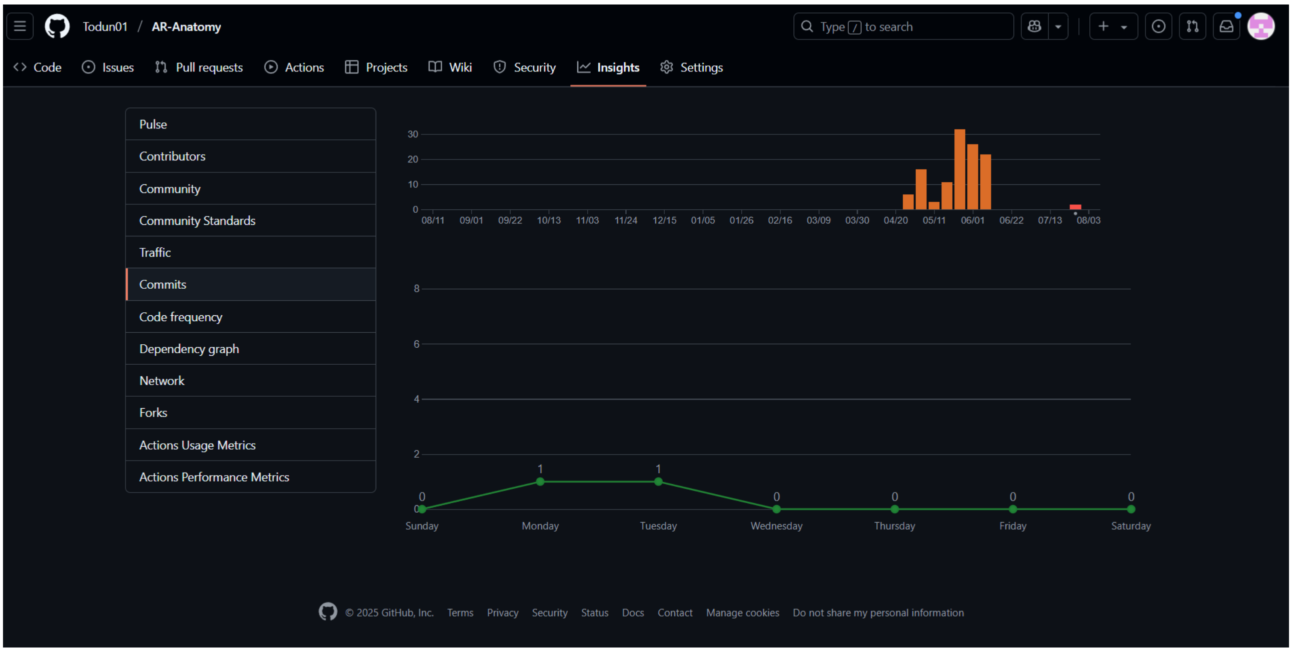
```
                Rating = feedbackDto.Rating,
            };

            _context.Feedback.Add(feedback);
            _context.SaveChanges();
            _notyf.Success("Feedback submitted successfully!");
            return RedirectToAction("Feedback", "Home");
        }

        [ResponseCache(Duration = 0, Location = ResponseCacheLocation.None,
    NoStore = true)]
        public IActionResult Error()
        {
            return View(new ErrorViewModel { RequestId = Activity.Current?.
   Id ?? HttpContext.TraceIdentifier });
        }
    }
}
```

Listing 2: Main Controller for AR-NATOMY: HomeController.cs

APPENDIX A3



GitHub Commit History for AR-NATOMY