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Enhancing Anatomical Understanding in Medical Education through Integrated 3D Printing Technology Modules

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ABSTRACT

The application of 3D printing in the medical field has grown steadily in recent years, particularly in medical education, simulation, pre-surgical planning, and clinical training. This development is closely linked to the rising demand for high-quality healthcare and the need to better prepare future healthcare professionals. Despite this progress, many medical educators still face practical constraints, especially when access to physical teaching materials and anatomical specimens is limited. Conventional teaching methods, which rely mainly on textbooks, two dimensional images, and lectures, often make it difficult for students to fully understand the spatial relationships of complex anatomical structures. Therefore,, this study investigated the use of 3D printing as a supportive teaching tool. A workflow combining 3D scanning and 3D printing was adopted, allowing real anatomical specimens to be digitised and reproduced as physical models. Plastic organ specimens obtained from a biology laboratory were scanned using a 3D scanner to generate high-resolution digital files. These files were then processed and 3D printed to produce durable and realistic anatomical replicas that could be handled and examined by students. Alongside the development of the physical models, a teaching module known as Real2Replica was designed to integrate the 3D printed organs into structured learning activities. Both the models and the module were implemented in secondary school biology classes. The lessons included game-based activities, such as the Organ Matching Game and the Build a Human Body Puzzle, which encouraged students to actively engage with the material while reinforcing their understanding of human anatomy. Through the combination of hands-on interaction and guided classroom activities, students were able to explore anatomical structures in a more concrete and meaningful way. Overall, the

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integration of 3D-printed models within the Real2Replica module provides a practical, ethical, and cost-effective alternative to conventional teaching aids, while supporting learner-centred and experiential approaches that are central to 21st-century science education.

1. Introduction

The rapid development of Industry 4.0 has led to the integration of advanced digital technologies into many areas of education, including medical training. Among these technologies, three-dimensional (3D) printing and 3D scanning have gained increasing attention for their potential to enhance the teaching and learning of human anatomy [12,14,21,27]. In anatomy education, where a clear understanding of spatial relationships is essential, conventional instructional approaches remain heavily dependent on two-dimensional illustrations, textbooks, and cadaver-based teaching. While these methods have long formed the foundation of anatomical instruction, they do not always provide sufficient support for students to visualise complex three-dimensional structures, nor do they ensure equitable access to learning resources [27]. As a result, there is growing interest in the use of digitally enabled physical models as a means of improving students' conceptual understanding and supporting the development of clinically relevant anatomical knowledge.

Although 3D printing technology has certain limitations, its use has expanded across many medical fields over recent decades. One key advantage of 3D printing is the ability to transform two-dimensional patient images, previously confined to flat screens, into physical, three-dimensional models that can be handled, examined, and customized [1]. This capability is particularly valuable in clinical settings, where understanding complex anatomical relationships and interpreting advanced imaging are essential for diagnosis, treatment planning, and surgery. Consequently, these applications benefit directly from advancements in 3D printing [4,12,24]. However, creating detailed anatomical models using standard 3D software can be challenging, requiring advanced skills and considerable time [27]. In such cases, 3D scanners are highly useful, as they capture intricate anatomical details accurately, enabling the efficient production of precise human anatomy models.

A 3D scanner is a precise instrument that captures the physical shape of anatomical models and converts them into digital 3D representations, enabling accurate replication and interactive examination [10]. These scanners employ technologies such as LiDAR, structured light, or photogrammetry to generate detailed point clouds or meshes, preserving the fine surface features that are essential for educational purposes [7,13,20]. Figure 1 illustrates various 3D scanning methods, including depth sensing, triangulation, laser triangulation, surface reconstruction, and point cloud generation [5,6,9].

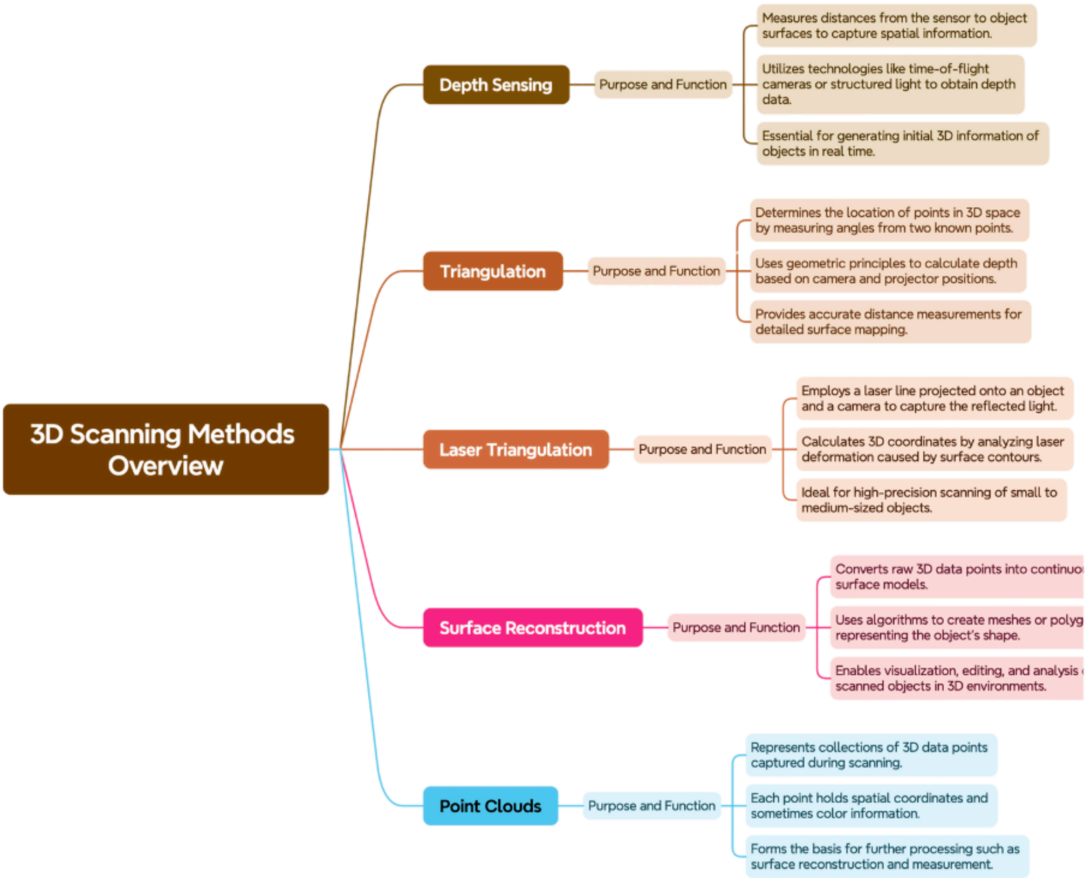


Fig. 1 Types of 3D scanning methods

In anatomy education, 3D-printed models generated from scanned data have been shown to improve learning outcomes and student satisfaction compared with traditional two-dimensional images or plastinated specimens, as reported in randomized controlled trials [2,3]. Workflows based on photogrammetry also enable the creation of realistic, interactive 3D anatomical models that complement physical dissections, which is particularly useful in neuroanatomy where access to cadaver specimens is often limited [16]. These digital models make anatomical content more accessible and engaging, while also allowing students to manipulate, annotate, and share models across devices. By supporting hands-on, interactive learning, they help students develop a clearer understanding of complex anatomical structures [27].

In educational research, the value of tactile and visual anatomical models is often explained through established learning theories. Experiential learning emphasizes the importance of acquiring knowledge through direct experience, where understanding develops through active participation [19]. Kolb's Experiential Learning Theory, in particular, describes learning as a cycle of four interconnected stages: concrete experience, reflective observation, abstract conceptualization, and active experimentation [8,11,19]. According to this framework, knowledge is built through hands-on experience, reflection, and experimentation, illustrating how interacting with physical models can support deeper conceptual understanding [26]. In the context of anatomy education, manipulating three-dimensional structures allows students to actively explore spatial relationships, improving engagement and knowledge retention.

Recent studies indicate a global shift toward the integration of interactive and digital tools in medical courses [7,22]. Previous study has reported that reported that over 70% of medical schools have adopted 3D models and virtual dissection tools as alternatives to cadaveric specimens, primarily to overcome ethical, logistical, and cost-related constraints [23]. These innovations not only enhance visualization but also promote kinaesthetic learning, enabling students to manipulate and examine models in a hands-on manner [25].

Hence, in this study, the Real2Replica kits and module were developed to address the need for accessible, customizable, and cost-effective biology and medical teaching aids. Therefore, 3D scanning, and 3D printing technologies were employed in this study aims to produce high-precision anatomical models that replicate human organs and structures. The study includes the design, development, and implementation of the Real2Replica module for biology and medical education, based on the workflow, learning activities, and potential educational benefits. The conceptual framework in this study was summarize in Figure 2.

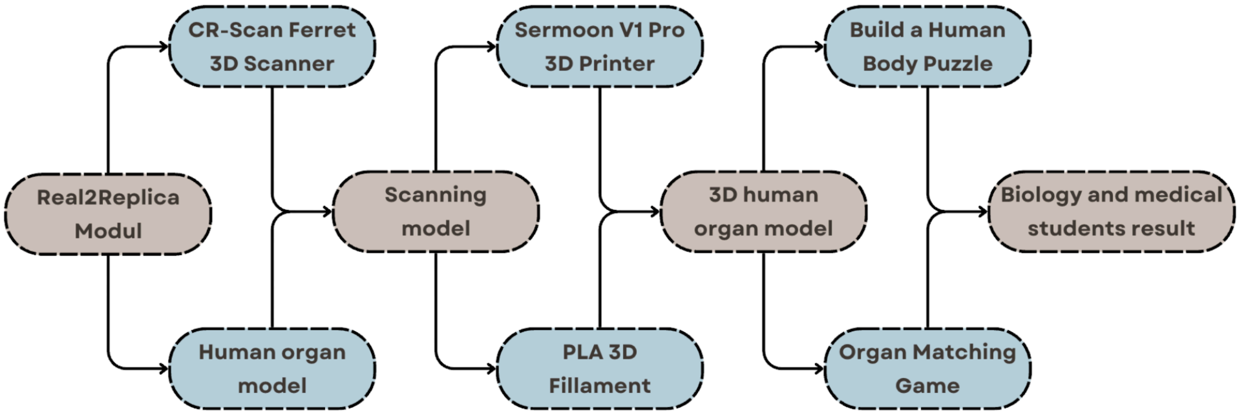


Fig. 2. Conceptual framework of Real2Replica Module

2. Methodology

2.1 Study Design

This study employed a development of scanning process of plastic anatomy model to 3D printed anatomy model and implementation design, focusing on the creation of a practical learning module that integrates 3D scanning technology and 3D printing into biology and medical education specific in anatomy.

2.2 Materials and Equipment

The workflow utilized the CR-Scan Ferret 3D scanner (Creality, China), which operates on light detection and ranging (LiDAR) technology, allowing for accurate capture of complex anatomical geometries. LiDAR emit laser beams and measure the time it takes for the light to return, creating highly accurate 3D maps or point clouds which widely used in topographic mapping and autonomous vehicles [10]. Scanned objects were processed using Creality's slicer software, with subsequent model modification performed in TinkerCAD. The 3D printing stage employed a Creality Sermoon V1 Pro printer, using polylactic acid (PLA) filament due to its affordability, ease of printing, and biodegradability [15]. The materials and equipment used in this study shown in Figure 3.

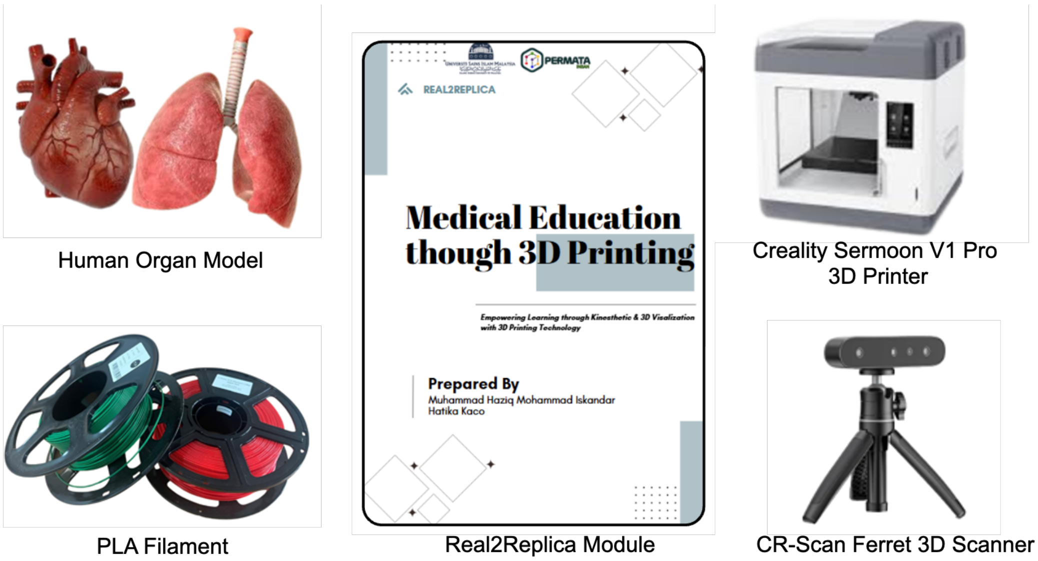
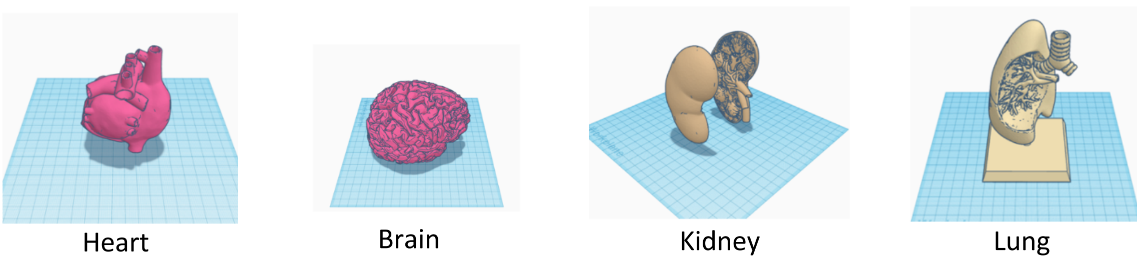


Fig. 3. Materials and equipment in Real2Replica kits module

2.3 Workflow

The development process started with 3D scanning of the selected anatomical models, including the brain, heart, ear, kidney, and lung. These model were scanned and digitilised using a CR-Scan Ferret under controlled lighting conditions to ensure clear and accurate captures, and and the resulting data were saved as mesh (.obj) format [17]. The 3D scanner serves as an imaging tool that captures a detailed view of the model's structure using Light Detection and Ranging (LiDAR) technology. The resulting files were processed in TinkerCAD, where the models were cleaned, repaired, and refined. Their anatomical accuracy was then carefully verified against reference materials to ensure fidelity.The refined models were subsequently prepared for fabrication through slicer (Creality Slicer) which configured with specific print parameters such as layer height, infill density, and print speed, and converted into G-code for production on a 3D printer. 3D printer can only read the G-code file for printing process. The G-code files then used to print the anatomical model using Creality Sermoon Pro 3D printer. The printed anatomical models were applied in educational integration, serving as the basis for interactive learning activities, including an organ matching game and a human body puzzle, both designed to foster spatial reasoning skills and promote collaborative, hands-on learning experiences. Figure 4 shows the workflow of 3D models human anatomy in TinkerCAD for repairing process.



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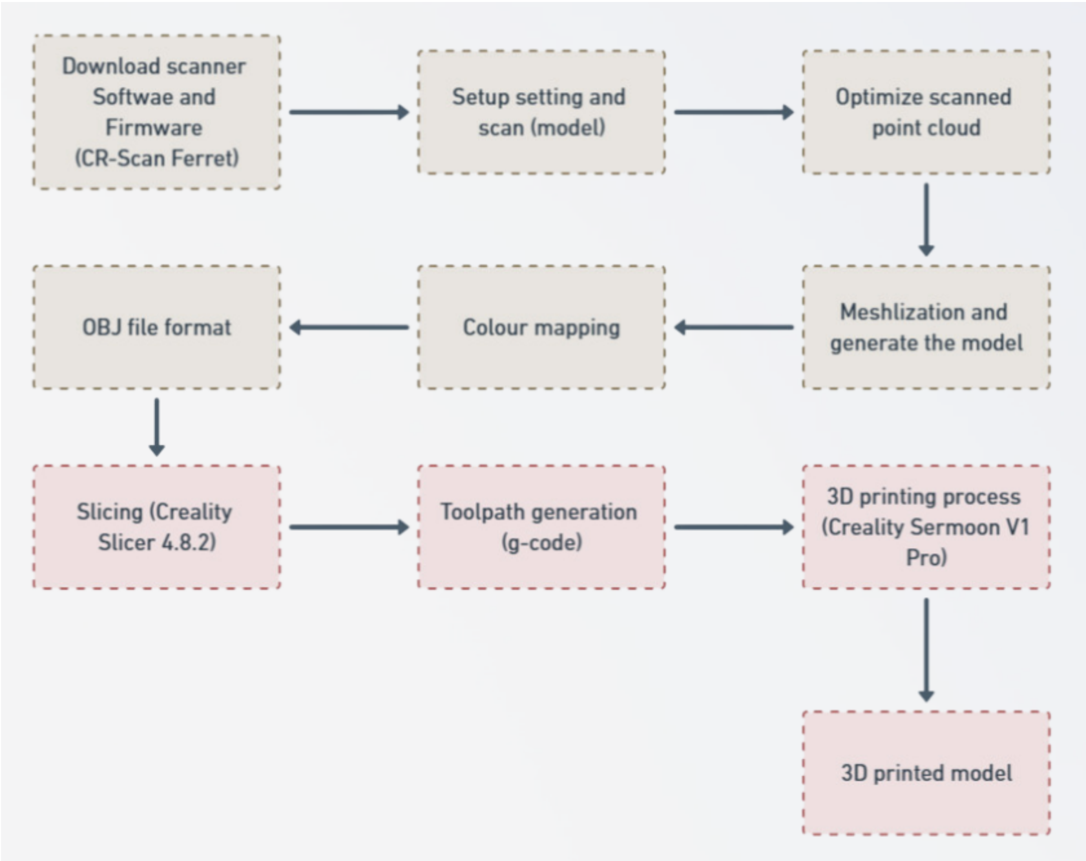


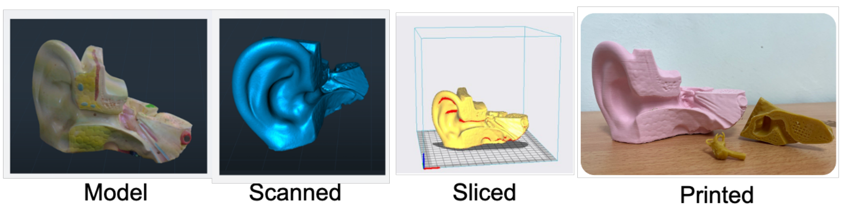
(b)

Fig. 4. (a) 3D models repairing in TinkerCAD and (b) the workflow of development process

3. Results and Discussion

3.1 Development Outcomes

The Real2Replica workflow successfully produced anatomical models including brain, heart, ear, kidney, and lung through a combination of 3D scanning, digital processing, and additive manufacturing. These organs of brain, heart, ear, kidney, and lung were selected in this study due to their fundamental role in human physiology and their frequent inclusion in secondary and early medical anatomy curricula. The scanning accuracy was maintained at a high accuracy, with mesh deviations of less than 0.5 mm compared to original specimens, as verified by overlay analysis in TinkerCAD. Printing time for each model ranged from 3 to 16 hours depending on size, complexity and setting during slicing process, including infill density, infill pattern, speed while material usage per model averaged 50 and 120 grams of PLA filament. Generally, all models were printed using 15% infill density and gyroid as infill pattern. Figure 5 shows the 3D scanned, sliced and printed models of human anatomy (ear, brain and heart).



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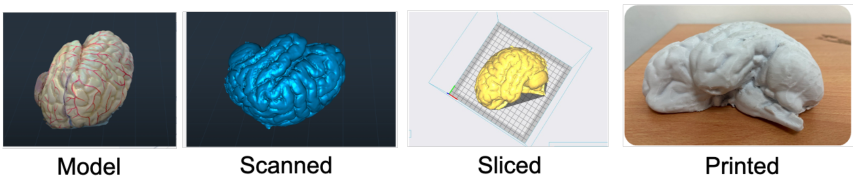

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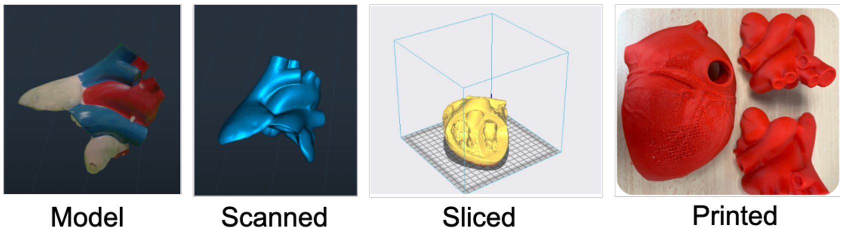


(c)

Fig. 5. 3D scanned, sliced and printed models of (a) ear, (b) brain and (c) heart models

3.2 Developed Module and Game Card

3D printed anatomical organ models were utilized to create a teaching module (Real2Replica: Medical education through 3D Printing) with activities specifically designed to correspond with the organs. These activities aim to enhance students' understanding of human anatomy by offering interactive learning experiences that reinforce knowledge of organ functions, structures, and spatial relationships. The module also seeks to close the gap between theoretical knowledge and practical application through the use of tangible, visual learning tools that support diverse learning styles and increase retention. The illustration of the module presented in Figure 6.

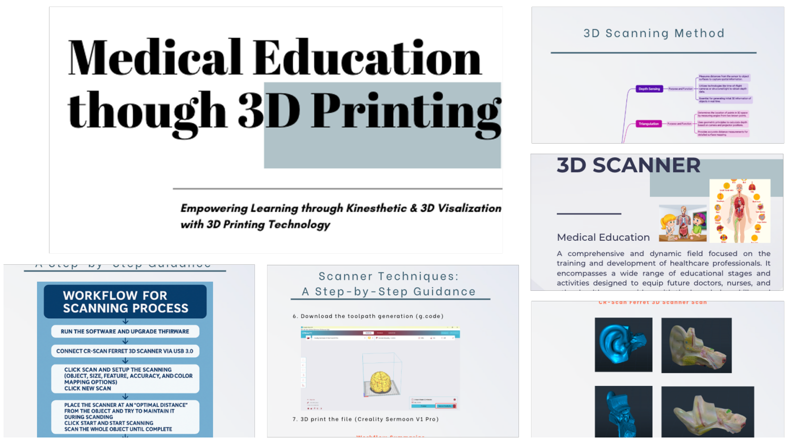


Fig. 6. Illustration of Real2Replica (Medical Education through 3D printing) Module

The printed anatomical models were incorporated into two interactive learning activities aimed at enhancing engagement and comprehension that are Organ Matching Game and Build a Human Body Puzzle. The objective of Organ Matching Game aims for the students to learn organ functions and their role in the human body using 3D-printed organ models, flashcards with organ functions and timer for competitive play. The students were tasked with pairing the printed organ models with corresponding function cards, reinforcing their understanding of organ structure and function through active recall.

Meanwhile, in the human body puzzle activity, the activity aims for the students to learn organ placement in the human body where students assembled the anatomical models into a life-sized body outline, an exercise that promoted spatial understanding and the recognition of anatomical relationships between different organs. These activities were prepared and carried out as a group activity to foster collaboration between the participants. This will develop cooperation whiles develop problem-solving skill. Besides, both activities demonstrate learning style which are kinaesthetic and visual learning which can accommodate more learning skills and enhance understanding in anatomical knowledge. The game instructions and flashcard designs illustrated in Figure 7.

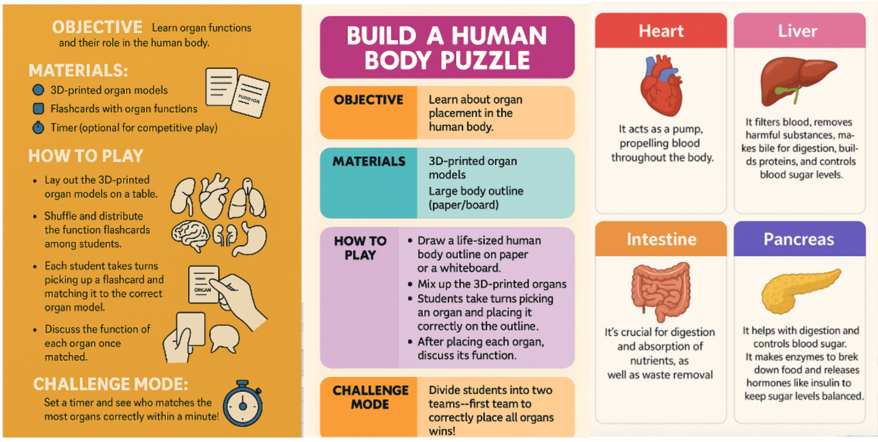


Fig. 7. Illustration of Real2Replica activities of (a) Organ matching game, (b) Build a human body puzzle and (c) flashcard

3.3 Preliminary Implementation

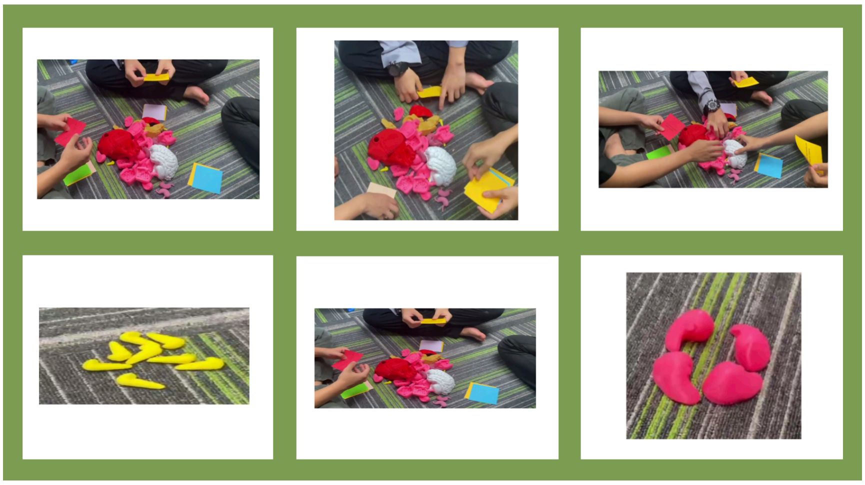
The 3D-printed human anatomy models developed through scanning and additive manufacturing technologies were preliminarily implemented with secondary school students using the developed Real2Replica module. During the preliminarily implementation sessions, the facilitators introduced scientific theories and concepts through hands-on activities with the 3D printed organs. This allows students to explore anatomical structures in an interactive way and this experiential approach was designed to improve both student engagement and understanding. Figure 8 illustrates the preliminary implementation of the Real2Replica module with students during classroom activities. The initial trials indicate that integrating 3D scanning and printing technologies into anatomy education is both practical and educationally valuable. These tools offer a cost-effective alternative to traditional learning resources, supporting hands-on engagement and enhancing students' understanding of anatomical structures.

The workflow produced anatomically accurate models that were incorporated into hands-on activities, allowing students to explore individually and work collaboratively. These preliminary results are consistent with previous studies, which show that 3D-printed anatomical models can improve spatial understanding and help students retain knowledge more effectively [3,28]. In addition, the tactile, hands-on experience provided by the printed organs supports kinaesthetic learners, a group often underserved in anatomy education that primarily relies on static images or digital resources.

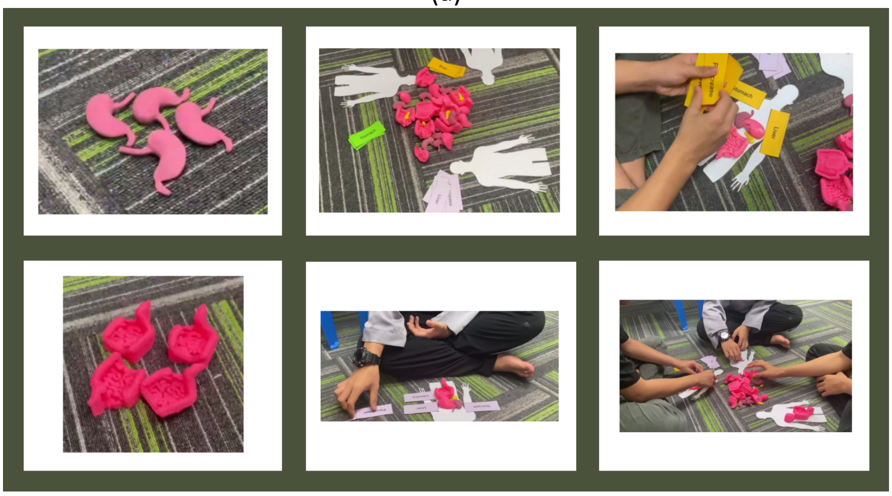
The Real2Replica module included structured activities, such as the Organ Matching Game and the Human Body Puzzle, which actively involved students in learning. These activities are known to improve participation and support long-term knowledge retention in medical education [18].

Importantly, this approach offers a practical alternative to cadaver dissection, addressing both logistical and ethical challenges, and aligns with research highlighting the growing use of 3D-printed and virtual dissection tools in modern curricula [23]. By allowing on-demand, customizable production of anatomical models, the Real2Replica module reduces reliance on costly commercial kits and provides flexible resources that can be tailored to specific learning goals.

Results from this preliminary implementation indicate that the Real2Replica module provides an effective approach for contemporary anatomy education. The 3D printed models engage students in hands-on exploration, promote collaboration and inquiry, and support a student-centered, experiential learning environment by combining digital fabrication with active learning. Linking digital design, physical modeling, and interactive classroom activities helps students better understand spatial relationships, improves knowledge retention, and encourages the development of creativity, problem-solving abilities, and technological skills key competencies for today’s science and medical education.



(a)



(b)

Fig. 8. Preliminary implementation of Real2Replica modules with students during (a) Organ matching game and (b) Build a human body puzzle

4. Conclusion and Recommendations

The Real2Replica models and accompanying with teaching module was successfully established a practical workflow for creating 3D-scanned and 3D-printed anatomical models to support the teaching and learning of human anatomy. This approach implemented and combined the technologies including LiDAR scanning, digital modelling, and 3D printing techniques, to produce anatomy models which were accurate, affordable, and reusable models that support hands-on and kinaesthetic learning skills and strategies. Meanwhile, the integration of the module and models with classroom activities such as the *Organ Matching Game* and the *Build a Human Body* Puzzle highlighted the value of these models in promoting student engagement, strengthening spatial understanding, and supporting long-term knowledge retention. Therefore, as for the future studies, the quantitative assessment of learning outcomes will be conducted and extending the application of this approach to other areas of medical education. In education, 3D scanning and 3D printing technologies offer more than just the production of physical instructional materials. These technologies creating tangible and interactive anatomy models and help students develop a clearer understanding of complex concepts and improve long-term memory retention. As these technologies become more widely adopted, they also contribute to more engaging learning experiences, spark students' curiosity, and encourage educators to adopt creative and flexible teaching practices. Overall, integrating 3D scanning and printing supports a hands-on, multidimensional approach to learning that benefits both students and instructors.

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