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# Cranioplasty Training Innovation Using Design Thinking: Augmented Reality and Interchangeability-Based Mannequin Prototype

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***ABSTRACT***

Cranioplasty, a surgical procedure to reconstruct the anatomical structure of the human skull, is commonly performed in Indonesia due to the malignancy of diseases, traffic accidents, and workplace injuries. If left untreated, this condition can lead to serious complications. Although cranioplasty is generally considered a relatively easy surgery, it has a fairly high postoperative complication rate of around 10.3%. The decreasing availability of cadavers for anatomical studies has significantly limited training opportunities. Therefore, efficient and effective training tools are essential, especially when traditional resources are insufficient to meet educational needs. Additionally, the training capabilities of commercially available mannequins or replicas used in medical institutions remain limited. The main objective of this project was to develop a smart, modular cranioplasty training mannequin designed for repeated use, incorporating Augmented Reality (AR) technology to visualize anatomical structures that cannot be physically replicated. Using a design thinking approach, data was collected through interviews with neurosurgeons, neurosurgery residents, and cranioplasty specialists, as well as through a review of relevant literature. Usability testing of the developed prototype yielded promising results, with high ratings for ease of use (4.8), training effectiveness (4.5), anatomical realism (4.3), and material durability (4.5) on a 5-point Likert scale. These findings demonstrated strong user approval and confirmed the model's potential to support surgical skill development in a practical and reproducible manner. The resulting AR-integrated training mannequin offers an innovative, engaging, and durable solution to address current challenges in neurosurgical education, especially in resource-constrained settings.



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## 1. INTRODUCTION

Dr. Soetomo Hospital in Surabaya collected data on brain injury cases from 2009 to 2013. The average number of brain injuries suffered was 1,178 cases per year, with the death rate ranging from 6.171% to 11.22%. Basic Health Research (Riskesdas) in 2018 collected data on the number of injuries that occurred in Indonesia. Based on the location of the injury, head injuries ranked third, at around 11.9%. Brain tumors, subdural hematomas, brain abscesses, hydrocephalus, work accidents, and traffic accidents were some of the causes of head injuries that led to head defects or cranial bone defects. Meanwhile, the data from 2017–2018 that Undata Hospital summarized showed that most of the cases were trauma cases, accounting for 60.2%, followed by tumors at 15.9% [1, 2]. Although cranioplasty is an essential surgical solution, its implementation carries a significant risk of complications, including infection (10.3%) and mortality (1.5%). Neurosurgery is a medical discipline that requires a high level of skill and precision. Currently, neurosurgery training still relies heavily on conventional methods involving cadavers and hands-on practice on patients [2]. Neurosurgeons require proficient skills when performing cranioplasty surgery to minimize postoperative complications. To support clinical skills, surgeons require a useful learning medium to practice their skills before treating patients. Traditional surgical training may require a longer learning curve and more time to achieve proficiency. This happens because students have to wait for their turn to practice with patients. In addition to the long learning curve, conducting hands-on skill trials with patients allows for the occurrence of the phenomenon of 'surgical errors' and the consequent increase in medical-legal cases [3–5]. Despite improvements in implant materials and cranioplasty procedures, neurosurgical training in Indonesia continues to face several obstacles. Limited availability, high expenses, ethical issues, and legal limitations limit the traditional dependence on cadaver-based instruction. Additionally, diversified, case-based practice is not supported by plastic or mannequin-based models, which frequently lack anatomical reality. Neurosurgery residents would therefore be ill-equipped to perform intricate cranioplasty operations, which raises the possibility of surgical errors and jeopardizes patient safety. A new, reusable, modular, and anatomically realistic training medium that is augmented by immersive technologies, such as Augmented Reality (AR), is urgently needed to facilitate the efficient and thorough skill development of neurosurgery trainees.

Cadavers are used to train knowledge about the anatomy of the human body. However, training neurosurgeons using cadavers is increasingly difficult due to regulatory constraints and declining availability. Licensing in use [5] cadaver as a learning medium is not an easy thing. Clinical autopsies are only performed in rooms in hospitals reserved for that purpose and only in the anatomy wards of a medical school. Alternative simulation methods have emerged. Besides [6], there are alternative learning media that can be used for the learning of a neurosurgery candidate, namely, audio visual media, models and replicas, teleconferences, and patients. A study reports a new training method that utilizes mannequin heads, water balloons, and clay to simulate microsurgery, allowing trainees to practice various hand positions while approaching affected areas located at different depths in the brain from different angles. This provides the potential to incorporate interchangeability systems in neurosurgical training using mannequins. The physical manifestation of mannequins will have many shortcomings compared to the original human physique, so AR features will be incorporated into the training to complement these shortcomings and provide experiences similar to training with real humans. The product development is intended for prospective neurosurgery students who are undergoing the cranioplasty training process. It consists of a mannequin of a human head with a size that adjusts to the case taken, a case component that can be interchanged for more than one case, and packaging that accommodates users to store refills as well as practice. The mannequin will be used to practice before neurosurgery specialist PPDS students conduct training on patients directly at the medical faculty [6, 7]. Another example is a study that employed a cross-sectional approach with pre- and post-intervention evaluations. A simulation model was created using a silicone-latex mannequin and tested for validity before being used in an anal sphincter repair workshop for 22 obstetrics and gynecology residents at Airlangga University, Indonesia. Residents' satisfaction with the simulation model and their level of confidence in the repair procedure were measured through questionnaires before and after the workshop [8–10].

Augmented Reality (AR) is widely used in the field of medical education. AR can improve the way of interacting with digital anatomical representations from all angles, so that it can provide a more immersive experience aimed at improving student understanding [3–5, 11]. Based on the description provided above, there is an opportunity to develop skills training facilities for prospective neurologists in Indonesia, specifically in the form of reusable mannequins. Efforts to enhance medical learning have utilized various technologies, including Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR). Studies have demonstrated the effectiveness of VR-enhanced mannequins (VREM) compared to traditional methods, and the potential of AR/MR as alternatives to cadaver-based learning, particularly in anatomy teaching [12, 13]. Systematic reviews have highlighted the trends and effectiveness of immersive technologies in medical education, including trauma surgery training, radiology education, and anatomical teaching [13–18]. Comparative studies have also shown how AR/MR simulations can replace conventional training methods, improving interactivity and spatial understanding [3, 4, 11]. The physical manifestation of mannequins will have many shortcomings compared to the original human physique, so AR features will be incorporated into the training to complement these shortcomings and provide experiences similar to training with real humans.

Cranioplasty is a medical procedure that can treat cases of head defects. Cranioplasty can be performed either through osteoplastic reconstruction or restoration using alloplastic. Materials commonly used as alloplastic implants are inert metals, polymethylmethacrylate (PMMA), polyethylene (PE), and silicone rubber [19, 20]. Each of the materials and manufacturing methods available for skull/skull reconstruction exhibits specific performance in terms of accuracy, mechanical properties, production time, and cost. The selection of materials and methods for implant manufacture depends on the patient's needs, the shape and location of the bone defect, and the available infrastructure and budget [21]. PMMA is one of the most commonly used alloplastic materials for cranioplasty. PMMA remains a popular choice due to its adaptability and cost-efficiency. The medical use of PMMA has been employed since the 1940s, during the Second World War, and remains in use today as a transparent thermoplastic polymer material. This acrylic resin has the advantage of its use, namely that it can be printed intraoperatively or prefabricated, allowing for adjustment of the defect dimensions [22]. Recent advancements in 3D printing allow precise prefabrication of cranial implants based on MRI or CT scan data. This method can overcome the weakness of the intra-operative method by hand, namely by prefabricating implants. This prefabrication method integrates computer-aided design (CAD) and computer-aided manufacturing (CAM) to create implants with complex structures. Implant dimensions can be accurately created based on defect dimensions, based on the conversion of medical imaging results from magnetic resonance imaging (MRI) and computed tomography (CT) scan instruments into digital modeling [23, 24].

The issue in research is that, despite improvements in cranioplasty methods and materials, neurosurgeons still face significant obstacles in surgical training and skill development. The availability of cadavers, ethical issues, high expenses, and maintenance challenges are all problems with traditional cadaver-based training techniques. Practicing directly on patients during training increases the possibility of surgical blunders and possible legal repercussions. Complex cranioplasty scenarios cannot be effectively simulated by standard plastic models, which lack adequate anatomical realism. The purpose of this study is to develop a cranioplasty surgery training product that can be used repeatedly and durably, with a variety of cases. It has a compact size to facilitate user convenience, including the use of product packaging as a means of work. The primary benefit to be achieved is to enhance the skill training system for prospective neurologists in Indonesia, thereby minimizing failures during the surgical process. These outcomes underscore the necessity for effective training and skill development among neurosurgeons, particularly as limitations in cadaver availability and ethical considerations increasingly constrain traditional learning methods.

## 2. RESEARCH METHOD

This study uses an experimental design approach with the Design Thinking method to develop a cranioplasty training mannequin based on an interchangeable design system and Augmented Reality (AR) [8, 25]. The process consists of five main stages, which are explained below:

a. Empathize (4 weeks): This initial stage involves comprehending user needs in depth through in-depth interviews and firsthand experience with the existing practice of training in cranioplasty. Adopting purposive sampling, the study includes 15–20 participants, with an equal mix of neurosurgeons and neurosurgery PPDS trainees, to achieve diverse viewpoints at various levels of experience. The study employs semi-structured interviews with open-ended questions to systematically explore the pain points of existing training methods in a structured and orderly manner. Observational studies of live training practice in cranioplasty provide contextual details about the tactical challenges. In this manner, the two methods assure that verbalized needs (through interviews) and implicit habits (through observation) are captured, providing a strong foundation for the subsequent stages of design.
b. Define (3 weeks): Formulate problems based on the collected data, following the collection of user demands, the study concentrates on precisely describing the problem statement. The research identifies specific issues related to the shortcomings of existing training systems and establishes goals for creating a new training tool based on data gathered during the empathize stage.
c. Ideate (3 weeks): created new mannequin design ideas. At this stage, several conceptual designs were developed in response to the previously identified challenges and objectives. To explore potential alternatives, brainstorming sessions were conducted. The most efficient and effective approaches toward constructing the cranioplasty training mannequin were defined by developing several sketches and design proposals.
d. Prototype (6 weeks): This phase involves creating operational prototypes of the cranioplasty training system to exclude specific technical details regarding construction materials, hardware components, or software platforms. Prototype construction is centred on three primary elements:
    (a) A system of modular mannequins with changeable elements fashioned to reproduce multiple cranial defect cases and surgical procedures. Functional performance is valued over the specification of materials.
    (b) An integrated augmented reality interface offering surgical guidance, whose evaluation is based on the quality of interaction with the end-user, rather than the technological realization itself.
    (c) Integrated assessment paradigm examining system performance in various training scenarios, operational longevity under repeated usage conditions, and the intuitiveness of user interactions with both physical and digital elements.
    The prototypes are designed specifically for usability testing, with all technical development details intentionally generalized to maintain focus on user experience and training effectiveness. This approach ensures evaluation criteria remain centered on educational outcomes rather than technical specifications.

e. Test (4 weeks): The test phase employs qualitative usability testing among neurosurgery residents and practicing neurosurgeons to evaluate the usability of the prototype training mannequin. Participants conduct mock procedures of cranioplasty using the AR-guided interchangeable mannequin system, while researchers observe and conduct semi-structured interviews. Observed are the following key aspects:
   (a) System Usability – Observing how intuitively users interact with the modular components and AR interface, noting any difficulties in assembly or navigation. The evaluation of anatomical realism, ease of use, training effectiveness, and material durability is conducted.
   (b) Training Effectiveness – Obtaining subjective measures of whether the system enhances knowledge of procedures more than standard procedures of training.
   (c) AR Integration – Assessing the quality and usefulness of the augmented reality overlays in prompting surgical steps.

15 PPDS neurosurgical students conducted the final evaluation during one of the practice lessons led with the mannequin. Each of the students evaluated the mannequin for each criterion on a 5-point Likert scale [26] as in Table 1.

Table 1. Likert Scale

| Score | Description |
|---|---|
| 1 | Very Poor |
| 2 | Poor |
| 3 | Fair |
| 4 | Good |
| 5 | Excellent |

Ratings were collected via a structured evaluation form immediately after the training session. For each parameter, the average rating was calculated using the formula 1.

$$AverageRating = \frac{\sum_{i=1}^{n} xi}{n} \quad (1)$$

Where, $x_i$ is rating given by each participant. $n$ is total number of participants (n=15)

## 3. RESULT AND ANALYSIS

### 3.1. Sketch Ideas and Design Alternatives

The idea exploration process involves sketching various concepts to inspire suitable shapes and functions for product development. At this stage, ideas are categorized into two main groups: mannequin system concepts and shape concepts. A total of 30 sketches were created to determine the most appropriate form and component placement for the product. The ideation process then advances to the selection of design alternatives, where the most promising options are chosen. These selected design alternatives will undergo testing through model studies with potential users to evaluate their practicality and effectiveness. The model study was carried out by creating two alternative models. Alternative models are illustrated in Figures 1 and 2. These two model studies are experimented with users to find out the suitability of the product. The following is a model study that has been carried out.

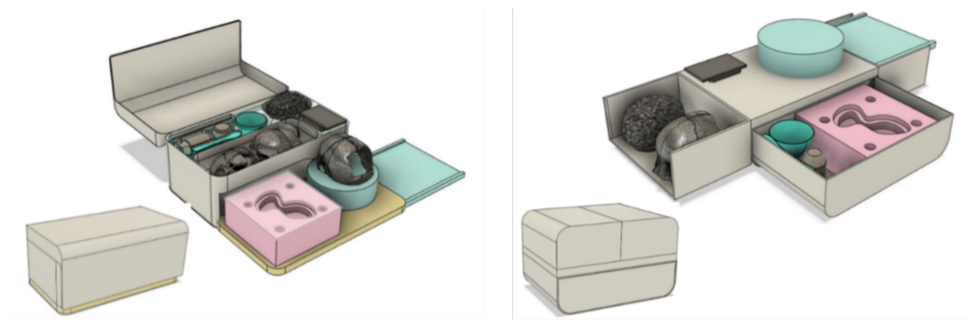

Figure 1. Design Alternatives 1 and 2

After conducting the model study analysis process, the conclusion obtained is that alternative 1 is more feasible than alternative 2, as reviewed from the aspects of ease of user understanding of the product, ease of use of the place, practicality of use, use of area, and size. The results of this analysis will be used to continue a more detailed modeling process, aiming to improve the product.

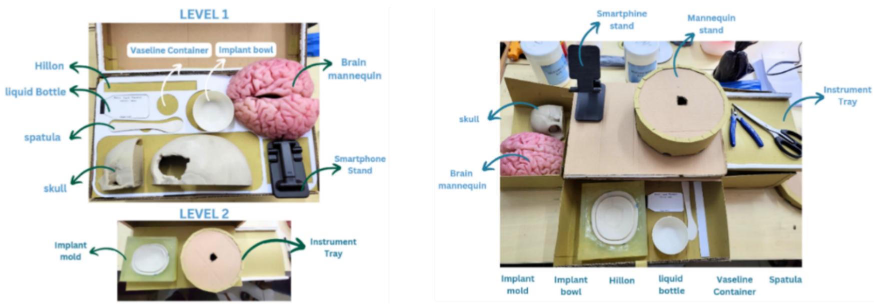


Figure 2. Layout Alternative 1 and Alternative 2

### 3.2. High-Fidelity Prototype

At this stage, the design process reaches its final form, allowing for the creation of a high-fidelity prototype. This prototype is developed to closely resemble the final product, incorporating realistic materials, shapes, textures, and colors (See Figure 3). During this phase, users will undergo another round of testing, and the feedback gathered will be used to refine the design further. Continuous improvements will be made until the product is fully optimized and ready for market release.

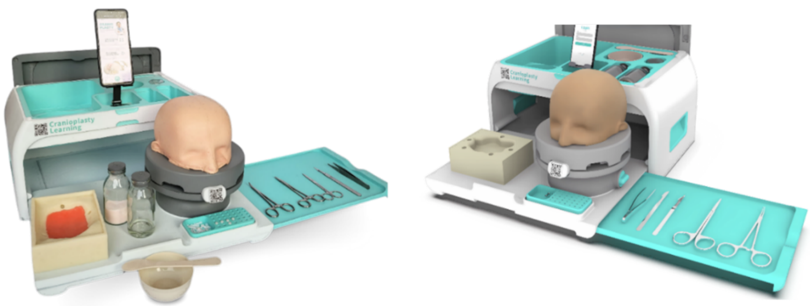

Figure 3. High Fidelity Prototype

### 3.3. Usability Testing

The suitability of the designed cranioplasty mannequin product was assessed through usability testing on neurosurgery students and surgeons. The test findings are summarized as follows:

**Medical Students (Figure 4):**

a. Equipment Preparation: The work area and storage area are appropriately divided, and locks are used to maintain the stability of the skin.
b. Barcode Scanning: Due to its proper location, the product's barcode is easily scanned.
c. Skin Incision Procedure: Since it does not make an incision, there are no noteworthy remarks.
d. Implant Preparation: The implant components are arranged appropriately and are readily accessible for use.
e. Installing the Skull Implant: Users require further details regarding the surgical procedures that can be carried out on the mannequin.
f. Installing the Bolt Plate: Regular iron bolts should be used in place of the nylon ones because they are too short.
g. Re-stitching the Skin: The locks function well, and the skin stays stable during the suturing procedure.

Figure 4. Usability Testing by Medical Student

**Neurosurgeons (Figure 5):**

1. Product Arrangement: The product requires further refinement, but initial impressions are positive.
2. Skin Incision: The skin doesn't tear during the incision and has a genuine texture.
3. Installing an implant is a realistic procedure that involves covering the problem area with skin, much like in an operating room.
4. Screw and Bolt Installation: More precise instructions are required for modifying the mannequin's region.
5. Suturing the Skin: The mannequin's appearance can be enhanced, but its skin thickness is suitable for suturing practice.

Figure 5. Usability Testing by Neurosurgeon

### 3.4. Analysis and Discussion

The interchangeability system-based mannequin outperforms traditional training techniques, according to the test results. The trial's quantitative findings on PPDS neurosurgical students are displayed in Table 2. The four parameters examined in Table 2, Evaluation Parameters and Rating, represent important performance indicators for evaluating the usefulness and quality of a training model. The following is a quick explanation of each parameter. The degree to which the training model closely resembles the genuine human anatomy is known as anatomical realism. A rating of 4.3 indicates that the model's anatomical representation is typically accurate, enabling users to gain a realistic understanding of body structures. For even greater realism, there may be a few small inconsistencies or areas that could be improved. The model's usability during training sessions is reflected in its ease of use. This parameter, with a value of 4.8, indicates that users can easily access and understand the model with minimal guidance or oversight. This simplicity helps lower the learning curve and boost user confidence, particularly for inexperienced learners.

Table 2. Evaluation Parameters and Rating

| Evaluation Parameters | Average Rating (Scale 1-5) |
|---|---|
| Anatomical realism | 4.3 |
| Ease of use | 4.8 |
| Effectiveness in training | 4.5 |
| Material durability | 4.5 |

Training effectiveness assesses how well the model improves users' acquisition of knowledge and skills. With a score of 4.5, it is indicated that the model supports both cognitive comprehension and psychomotor skills, hence making a considerable contribution to training outcomes. For the model to successfully fulfill its educational goal, this parameter is essential. Material durability refers to the model's resilience and lifetime under repeated use. The model is a sustainable and affordable choice for training environments, as indicated by its 4.5 grade, which suggests that it can withstand repeated handling and maintain its structural integrity over time. All factors had scores more than 4, which suggests that people are generally very satisfied. While the efficacy and durability ratings confirm that the model functions effectively as a realistic, long-term teaching tool, the highest ease-of-use score indicates strong usability. The following is a comparative table (research gap) between previous research and currently being conducted, as shown in Table 3.

Table 3. Research Gaps and Contributions of This Research

| No. | Previous Studies | Methods / Technologies Used | Research Focus | Advantages | Research Gap | Research Contribution |
|---|---|---|---|---|---|---|
| 1. | Wickramasinghe et al. [27] | Augmented Reality (AR) in anatomy learning | Evaluation of the effectiveness of AR in understanding anatomical structures | Interactive, enhances spatial understanding | No focus on surgical skills and use of mannequins | Developing AR for cranioplasty surgery training with an interchangeability system |

(continued on next page)

Table 3 (continued)

| No. | Previous Studies | Methods / Technologies Used | Research Focus | Advantages | Research Gap | Research Contribution |
|---|---|---|---|---|---|---|
| 2. | Viglialoro et al. [15] | AR/Mixed Reality (MR) in medical simulation | Use of AR/MR in surgical simulation | Provides a realistic simulation | Not integrating modular systems for different surgical cases | Developing a modular design mannequin for various cranioplasty scenarios |
| 3. | Foronda et al. [13] | Virtual Reality (VR) vs. mannequins in surgical training | Effectiveness of VR compared to mannequins | VR could reduce the need for cadavers | VR does not provide a real physical experience like a mannequin | Bringing together the advantages of physical mannequins with AR technology |
| 4. | Hensenn et al. [28] | AR for clinical anatomy training | An exploratory study of the use of AR in medical education | AR increases student engagement | No focus on the design of specific training devices for cranioplasty surgery | Designing reusable mannequins with AR to enhance learning experiences |
| 5. | Takeuchi et al. [20] | Simple mannequin for microsurgery training | Evaluation of the effectiveness of mannequins in improving surgical skills | Providing hands-on practical experience | Lack of digital elements that increase interactivity | Adding AR features to enhance the mannequin-based learning experience |
| 6. | Syamsuri et al. [24] | Mannequin-based surgical simulation for hysterectomy training | Improving surgical skills using mannequins | Improve skills before practicing on patients | There are no modular features for different operating cases. | It provides an interchangeable design that allows the practice of various cranioplasty surgical cases. |

The findings from Table 1 highlight significant advancements in medical training through the integration of AR and modular mannequin systems, particularly in the field of cranioplasty surgery. While AR has been extensively utilized in medical education, its combination with a modular mannequin specifically designed for cranioplasty remains relatively unexplored. This study addresses that gap by developing a flexible and interactive training platform that allows trainees to engage in realistic surgical simulations. By incorporating interchangeable modular components, this system enhances the adaptability of surgical training, enabling the simulation of diverse procedural scenarios that closely mimic real-life conditions. Unlike previous AR applications in surgical training, which have primarily focused on fields such as spinal surgery and orthopedics, this study specifically targets cranioplasty (a complex procedure requiring precise reconstruction techniques). Given the intricacies of skull reconstruction, conventional training models often fail to provide an accurate representation of the surgical steps involved in this process. The AR-based training device introduced in this study offers a specialized and relevant resource for neurosurgery practitioners, ensuring that medical trainees acquire the necessary skills with greater confidence and precision.

One of the most critical contributions of this study is its emphasis on accessibility and effectiveness in surgical training. Traditional methods heavily rely on cadavers, which are costly, have limited availability, and present ethical concerns. By integrating AR technology with a modular mannequin system, this study offers a hybrid digital-physical training model that enables repeated practice without the constraints of conventional resources. This innovation is particularly valuable for medical institutions that may lack access to cadaveric specimens, allowing trainees to refine their surgical techniques in a cost-effective and controlled learning environment. The interactive capabilities of AR further enhance this approach, providing a comprehensive and immersive training experience that ultimately contributes to improved patient outcomes. Moreover, simulation-based training, including AR-enhanced environments, has been shown to accelerate skill acquisition significantly. Studies indicate that the use of AR and modular systems in training can improve procedural competence up to 30% faster than traditional methods [13]. A key advantage of this technology is its ability to reduce reliance on cadavers while providing high-fidelity simulations that enable repeated practice of cranioplasty techniques. This repetitive training enhances procedural accuracy and fine motor skills (both of which are critical in neurosurgery). By allowing trainees to rehearse complex surgical maneuvers in a customizable and controlled environment, this system helps mitigate the risks associated with operator inexperience, leading to improved surgical safety and better patient outcomes.

To further evaluate the advantages of the AR-based modular mannequin system, a comparative analysis was conducted with conventional training methods. The analysis, presented in Table 4, evaluates key parameters including anatomical realism, interactivity, efficiency, and cost-effectiveness. Conventional mannequins, although beneficial for fundamental skill development, often lack the adaptability required to simulate a wide range of surgical scenarios. In contrast, the AR-based modular system offers a more versatile and cost-efficient alternative by allowing users to manipulate digital overlays and customize training modules to meet specific surgical needs. This comparative assessment underscores the transformative potential of AR technology in medical education, highlighting its ability to enhance surgical precision, expand training accessibility, and optimize resource utilization. As a result, the integration of AR with modular mannequins presents a promising future for neurosurgical training, revolutionizing the way medical professionals acquire and refine their surgical skills.

Table 4. Comparison of Cranioplasty Training Methods

| Aspect | Modular Mannequin with AR | Cadaver | Conventional Plastic Model |
|---|---|---|---|
| Anatomical Realism | High, with AR overlay displaying real-time brain, skull, and blood vessel structures | Very high, as it comes from real human tissue | Low, as it is static and does not represent internal structures |
| Interactivity | Very high, allowing head part interchangeability and practice on various surgical scenarios | Low, only enables practicing certain procedures without condition variations | Low, cannot be modified or adjusted as needed |
| Learning Efficiency | High, as it can be used repeatedly with various surgical scenarios, and AR provides visual guidance | Moderate, dependent on cadaver availability and condition | Low, due to limited anatomical variations |
| Availability | High, can be used anytime without legal or ethical constraints | Low, restricted by regulations and cadaver availability | High, but limited in training variations |
| Safety and Hygiene | Very high, with no risk of infection or exposure to biological materials | Low, with risk of contamination requiring strict safety procedures | High, as it is made from synthetic materials |
| Operational Cost | Relatively low in the long term, as it is reusable and requires minimal maintenance | High, due to preservation, special storage, and medical waste management | Moderate, reusable, but lacks flexibility |
| Surgical Case Variability | Very high, can be swapped for different cranioplasty cases (hematoma, tumor, trauma, etc.) | Low, dependent on the original condition of the cadaver | Low, representing only one fixed anatomy |
| Accessibility for Students | Very high, allowing multiple students to practice simultaneously | Low, available only for limited sessions | High, but does not support complex surgical training |
| Technology Utilization | Advanced, using AR for anatomical visualization and procedural guidance | None, fully reliant on manual observation | None, only a static model without interactive elements |
| Potential for Development | Very high, can be updated with new features, additional anatomical models, and more complex simulations | Cannot be further developed | Low, as it remains fixed and unmodifiable |

The comparison presented in Table 4 highlights the clear advantages of utilizing an AR-based modular mannequin over traditional training methods. This research introduces an innovative contribution to neurosurgical education by integrating interchangeable components with AR technology, effectively addressing the limitations of conventional cadaver-based and plastic model training. By offering enhanced interactivity, cost-effective solutions, and improved learning efficiency, this AR-based approach represents a transformative step toward modernizing neurosurgical training. One of the key limitations of cadaver-based training is its restriction to a single anatomical condition, preventing students from practicing on diverse cases. In contrast, the interchangeability system of the AR-based modular mannequin enables students to simulate various surgical scenarios, such as cranioplasty for different skull defect sizes, hematoma evacuations, or tumor resections. This flexibility allows trainees to gain exposure to a wide range of neurosurgical cases, better preparing them for real-life clinical challenges. Additionally, the integration of AR visualization significantly enhances spatial awareness by overlaying virtual anatomical structures onto the physical model. This feature, absent in traditional plastic models, enables trainees to better understand the relationships between different anatomical components, thereby improving their ability to navigate complex surgical procedures.

Cadaver-based training is associated with high costs, as it requires specialized storage facilities and adherence to ethical and legal regulations. Moreover, the availability of cadavers is often limited, restricting access to hands-on practice for many medical students. The AR-based modular mannequin addresses these challenges by providing a reusable and scalable alternative that reduces the long-term financial burden on medical institutions. Unlike static plastic models, which lack adaptability, the modular design of this mannequin allows students to adjust and replace different parts, closely mimicking real-life surgical procedures. This dynamic training approach enables students to repeatedly practice and refine their techniques without the logistical and financial constraints of traditional methods, thereby making neurosurgical training more accessible across various educational settings. Simulation-based training has been shown to reduce surgical error rates and enhance procedural competence before transitioning to live surgeries. The repeated use of modular mannequins enables students to refine their techniques and develop muscle memory, ultimately minimizing the risks associated with operator inexperience. This is particularly important in neurosurgery, where precision is critical to patient outcomes. Additionally, the integration of AR provides real-time anatomical guidance, enabling trainees to visualize critical structures and enhance their hand-eye coordination. This interactive approach not only enhances procedural accuracy but also instills confidence in trainees, ensuring they are well-prepared for performing surgeries on actual patients.

By combining realistic anatomical structures, interactive learning, and cost efficiency, the AR-based modular mannequin marks a significant advancement in surgical education. It offers a scalable and effective training solution that equips neurosurgery students with comprehensive hands-on experience while overcoming the limitations of traditional cadaveric and plastic model training. This study bridges the gap between conventional surgical education and the future of digital training, paving the way for more immersive, efficient, and accessible neurosurgical learning programs. As medical education continues to evolve, the integration of AR and modular systems will play an increasingly vital role in preparing the next generation of neurosurgeons with the skills necessary for high-precision surgical procedures. The table of interchangeable systems, showing how the head parts can be replaced as needed for cranioplasty mannequin training, is presented in Table 5.

Table 5. Interchangeable System

| No. | Component | Functions in Training | Types of Interchangeability | Applicable Training Scenarios |
|---|---|---|---|---|
| 1 | Scalp | Practice incision and wound closure procedures | Can be replaced with various thicknesses and textures of leather | 1. Standard scalp incision<br>2. Incision with scar tissue condition<br>3. Post-operative suturing technique |
| 2 | Skull | Simulation of drilling and implant placement procedures | Can be replaced with various materials (e.g., PMMA, titanium) and defect sizes. | 1. Standard cranioplasty with PMMA material<br>2. Cranioplasty with titanium mesh<br>3. Small vs. large cranial defects |
| 3 | Brain Model | Visualization of the anatomy of the brain and surrounding structures | Different brain models with different conditions | 1. Normal brain vs. brain edema<br>2. The presence of subdural and epidural hematomas<br>3. Variations in cerebral vascularization |
| 4 | Artificial Dura Mater | Simulation of dural repair and reconstruction | Can be replaced with various thicknesses and elasticities | 1. Normal dura vs. rigid dura due to fibrosis<br>2. Dural closure and repair techniques |
| 5 | Cranioplasty Implants | Training implant placement procedures for cranial reconstruction | Various materials and sizes of implants that can be installed | 1. Preformed implant placement vs. intraoperative molding<br>2. Evaluation of implant fit and stability |
| 6 | Augmented Reality (AR) Overlay | Showing internal anatomical structures in an interactive simulation | Configurable for multiple views | 1. Real-time visualization of brain and skull anatomy<br>2. AR-based operation guide |

The interchangeable system presented in Table 4 highlights the modular components integrated into the AR-based mannequin for neurosurgical training. Each component serves a specific function in simulating various aspects of cranioplasty and brain surgery, providing trainees with a dynamic and adaptable learning experience. By allowing different anatomical structures to be replaced with varying materials, conditions, and textures, this system enhances realism and enables students to practice diverse surgical techniques effectively. One of the fundamental components is the scalp, which is used for practicing incisions and wound closure procedures. The ability to replace the scalp with different thicknesses and textures of leather allows trainees to simulate various skin conditions, including normal and scarred tissue. This interchangeability enables training in post-operative suturing techniques, ensuring that students gain hands-on experience with various skin types and healing conditions. Similarly, the skull component enables the simulation of drilling and implant placement procedures. The ability to replace skull material with PMMA (polymethyl methacrylate) and titanium mesh, and to address different defect sizes, allows trainees to experience real-world challenges such as large cranial defects or small-scale reconstructions.

The brain model plays a crucial role in neurosurgical education by providing a visual representation of internal brain structures. Different brain models can be used to simulate various conditions, including normal brain anatomy, brain edema, subdural and epidural hematomas, and variations in cerebral vascularization. This adaptability ensures that trainees develop a comprehensive understanding of neurological pathologies and their surgical implications. Additionally, the artificial dura mater component facilitates the practice of dural repair and reconstruction. By offering replaceable layers with different thicknesses and elasticities, students can train on normal versus rigid dura, as seen in fibrotic conditions, and practice dural closure techniques used in complex neurosurgical procedures. Another essential component is the cranioplasty implants, which are integral for training in implant placement and cranial reconstruction. The system allows for various implant materials and sizes to be tested, enabling trainees to evaluate fit, stability, and intraoperative modifications. This feature is particularly useful in preparing students for real-world implant placement scenarios, where ensuring proper alignment and integration is critical. Lastly, the augmented reality (AR) overlay enhances the training experience by providing real-time visualization of internal anatomical structures. This feature supports interactive simulations, including AR-based surgical guidance and skull-brain anatomy visualization, helping trainees develop spatial awareness and improve precision in surgical planning, as shown in Figure 6.

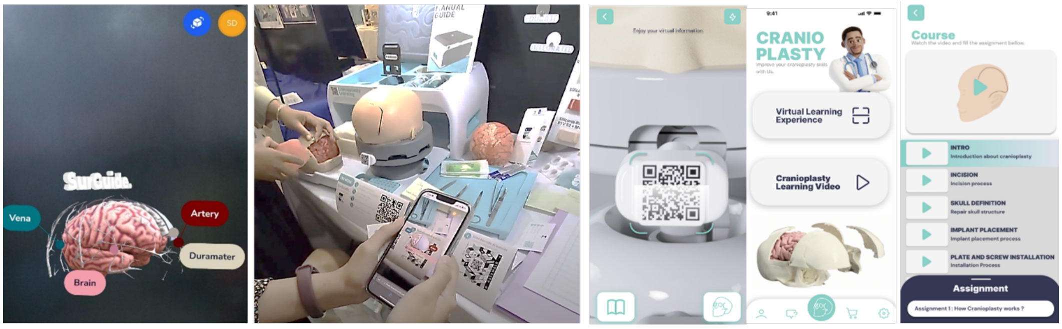


Figure 6. Examples of AR displays and Applications on Smartphones

## 4. CONCLUSION

Medical cranioplasty training using cadavers or direct patient interaction poses significant limitations, particularly in terms of safety, ethical concerns, and continuity of practice. To address these challenges, a specialized mannequin was developed to allow surgical students to practice their skills in a controlled and risk-free environment. This mannequin-based learning system includes a detailed head model with anatomical components readily available in the product. Additionally, Augmented Reality and an integrated application further enhance the training experience, providing interactive guidance and real-time visualization to assist surgical specialist students. The incorporation of an interchangeable design system enables the simulation of various cranioplasty cases, allowing students to train in diverse surgical scenarios. This study demonstrated that the use of mannequins featuring an interchangeable system combined with AR technology significantly enhances the effectiveness of cranioplasty training. Unlike conventional methods such as cadaver-based training or static plastic models, this system offers several advantages. First, it offers broader simulation capabilities, enabling students to practice various surgical scenarios with different anatomical conditions. Second, it offers lower operational costs, as the mannequin can be reused multiple times, reducing the financial burden on medical institutions. Third, it delivers more realistic and interactive anatomical visualization, as AR technology enables enhanced spatial awareness and procedural accuracy. Finally, the system ensures higher safety and hygiene, eliminating concerns associated with cadaver handling while maintaining a sterile and controlled training environment.

High user satisfaction was demonstrated by the usability evaluation, which was based on four important criteria: anatomical realism, convenience of use, training effectiveness, and material durability. With a solid average grade of 4.3 for anatomical realism, the model is useful for immersive learning and closely mimics genuine human anatomy. The model's user-friendly design and accessibility, even for inexperienced users, were reflected in its highest score of 4.8. Training efficacy and material durability both received a rating of 4.5, indicating that the system is robust and reusable over time, and that it significantly improves surgical skill learning. These results support the model's potential as a useful, sustainable, and efficient tool for neurosurgical education.

**The findings** of this study lay the groundwork for further advancements in neurosurgical education in Indonesia, with potential applications in other surgical fields. The integration of AR technology and modular design represents a transformative shift in surgical training, making it more accessible, cost-effective, and interactive. As medical education continues to evolve, the development of innovative training tools, such as this mannequin system, will play a crucial role in equipping future surgeons with the skills and confidence needed to perform complex procedures with precision and efficiency.

Although the results are encouraging, this study has many limitations. Firstly, the current design overlooks alternative neurosurgical operations that could benefit from comparable technological integration, instead focusing solely on cranioplasty training. Broader applicability and increased training efficiency may result from expanding the model to incorporate different kinds of surgical events. Second, augmented reality technology does not provide sufficient haptic input, despite improving visual learning. Haptic feedback devices could be incorporated into the mannequin to simulate bodily sensations and enhance the authenticity of the training experience. Future studies aim to develop a comprehensive training program that provides trainees with feedback and performance evaluation tools to enhance their skills. It would also be advantageous to utilize machine learning algorithms to adjust the training experience according to user performance. Furthermore, to confirm the generalizability and efficacy of the suggested training system, additional validation studies involving a larger range of participants, including seasoned neurosurgeons and medical students from various institutions, will be necessary.

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## 6. DECLARATIONS

AUTHOR CONTIBUTION

**Djoko Kuswanto**: Conceptualization, Methodology, Supervision, Discussion of Results, Approval of The Final Text. **Athirah Hersyadea A.P.**: Writing Original Draft, Discussion of Results, Resources. **Ellya Zulaikha**: Methodology, Supervision. **Tedy Apriawan**: Discussion of Results, Resources, Supervision. **Yuri Pamungkas**: Writing Review and Editing. **Evi Triandini**: Writing Review and Editing, Approval of The Final Text. **Nadya P. Jafari**: Discussion of Results, Resources. **Thassaporn Chusak**: Discussion of Results.

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COMPETING INTEREST

The authors declare that there are no competing interests related to this research, its findings, or its publication.

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