BRIDGING THE GAP BETWEEN THEORETICAL KNOWLEDGE AND PRACTICAL SKILLS: AN AR-BASED INSPECTION SYSTEM TO ADDRESS LEARNING DEFICITS IN CLINICAL ENGINEERING EDUCATION

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Abstract:

This research addresses a critical gap in clinical engineering education: the disconnection between theoretical knowledge and hands-on expertise. We first analyzed reports from 63 freshmen using KH Coder to visualize their internal knowledge structures. Surprisingly, the data showed that while students understood basic physics, they lacked a concrete grasp of internal hardware like capacitors. To solve this, we developed a dedicated AR-based inspection support system. Testing with 10 senior students revealed that hands-free AR guidance significantly cuts inspection time. By switching to a wireless controller, the SUS usability score jumped from 51.25 to 63.8. Our findings suggest that AR acts as a vital "cognitive scaffold," turning fragmented theory into reliable clinical skills.

Keywords:

Clinical Engineering; Augmented Reality; Text Mining; Medical Device Safety; Education DX

1. Introduction

As medical devices become more sophisticated, the importance of knowledge regarding their principles, operation methods, and proper maintenance has increased significantly. In Japan, there is a shortage of clinical engineers, who play a central role in the safety management of medical devices, in many medical institutions. Therefore, the standardization of examination methods and the development of systems that can be used by a wide range of healthcare professionals are urgent issues.

Traditional educational approaches have struggled to bridge the gap between theoretical understanding and practical application [1], [2]. In lectures, students appear to have a solid understanding of the principles and uses of defibrillators. However, even with comprehensive manuals and prior paper-based explanations, students frequently hesitate or completely freeze during actual examination procedures. This suggests that traditional educational methods fail to connect abstract data with the spatial and tactile intuition required in clinical settings. Furthermore, the effectiveness of immersive technologies, such as augmented reality (AR) and virtual reality, in enhancing health science students' spatial understanding, complex conceptual learning, and learning outcomes has been increasingly documented [3], [4]. This study first identifies structural gaps in students' knowledge using text mining, and then evaluates an AR-based system designed to address these gaps. By integrating data-driven educational insights with wearable technology, the aim is to establish a more effective training model for future clinical engineers.

2. Methods

This study was conducted in two phases: a baseline assessment of student knowledge through text mining and the subsequent evaluation of an AR-based support system designed to address the identified pedagogical gaps. The framework consists of two stages: (1) baseline knowledge deficit identification using KH Coder, and (2) AR-based inspection support evaluation.

Consistency of Student Cohorts: The text analysis was conducted on first-year students immediately after they completed foundational physics and medical equipment courses, which establishes a precise baseline of the initial structural knowledge gap before clinical exposure. The AR-based evaluation was subsequently conducted on third-year students. This selection is based on the curriculum structure where third-year students possess the advanced clinical and technical expertise required to perform real-world device inspections, thereby representing the appropriate target cohort for hands-on application.

2.1. Phase 1: Assessment of Knowledge Structure

To clarify the baseline understanding of clinical engineering students, we analyzed reports from 63 first-year students enrolled in 2023 regarding the principles and operation of defibrillators. The analytical process was implemented as follows:

- ✓ *Data Collection*: Descriptive texts were obtained from students following a specialized lecture on medical engineering.
- ✓ *Coding and Categorization*: The collected texts were coded based on key terms from previous national examinations. These were categorized into four specific domains: (1) Operating Procedures, (2) Principles of Defibrillation, (3) Waveform Types, and (4) Components.
- ✓ *Statistical Analysis*: Word frequency analysis and co-occurrence network analysis were performed using KH Coder [5]. A Minimum Spanning Tree (MST) was constructed to visualize the structural relationships between the terms utilized by the students.

2.2. Phase 2: Implementation and Evaluation of the AR System

Based on the identification of specific knowledge deficits regarding hardware components and procedures, an AR-based inspection support system was developed and evaluated. The experimental procedures were organized as follows:

- ✓ *Development of Training Materials:* Instruction videos for the periodic inspection of electrosurgical units (14 minutes) and defibrillators (10 minutes) were produced to provide standardized guidance.
- ✓ *Experimental Setup:* The evaluation was conducted with ten third-year students (four males and six females). Participants performed inspections using three different modalities: a conventional smartphone and two types of spectacle-type wearable AR devices. The wearable systems included a wired configuration and a wireless configuration integrated with a single-board computer (Raspberry Pi).
- ✓ *Evaluation Metrics*: Two primary metrics were utilized for the assessment:

  1. *Efficiency:* Inspection times were recorded and compared across the different devices to measure operational speed.
  2. *Usability*: The System Usability Scale (SUS) was administered to quantitatively evaluate the user interface and overall experience [6], [7].

- ✓ *Statistical Analysis*: To ensure scientific rigor, a Wilcoxon rank sum test was employed to compare the usability between smartphones and wired smart glasses. Additionally, a Welch's t-test was conducted to analyze the performance differences between the wired and wireless wearable systems.

3. Results

3.1. Quantitative Text Analysis of Knowledge Structure

To identify the baseline knowledge of clinical engineering students, we analyzed reports from 63 first-year students regarding defibrillators using KH Coder. The following key findings were obtained:

- ✓ *Conceptual Dominance*: High-frequency terms such as "defibrillation" and "energization" showed strong co-occurrence. This indicates that the students possessed a deep understanding of the core physical principles and primary functions required by the national examination.
- ✓ *Structural Gaps*: In contrast, terms related to specific "components" and "detailed operations" appeared significantly less frequently. These terms were located at the periphery of the co-occurrence network, suggesting a lack of integration into the students' primary knowledge structure.
- ✓ *Educational Deficit*: These findings suggest that while students possess abstract conceptual knowledge, a deficit exists regarding the concrete understanding of hardware and specific inspection procedures necessary for practical safety management.
- ✓ *Knowledge Network Topology:* As illustrated in Figure 1, the minimum spanning tree (MST) was constructed to visualize the conceptual connections in the students' reports. A highly connected "backbone" was observed, consisting of core terms such as defibrillation and energization linked to operational procedures. However, several technical terms related to "components" (e.g., battery, capacitor) were identified as isolated nodes or peripheral subgraphs (Subgraphs 08–14). This topology

indicates that while the students understand the functional flow, their knowledge of the internal hardware remains fragmented and not yet integrated into a holistic mental model.

- ✓ *Correlation with National Standards:* As illustrated in Figure 2, a correspondence analysis was performed to visualize the relationship between the terminology utilized by students and the keywords from national examination options. The network reveals a central cluster where student-derived terms overlap significantly with exam-required knowledge, particularly in core principles. However, the scattered nature of certain nodes indicates that technical terms related to specific device components are less integrated into the students' conceptual framework.

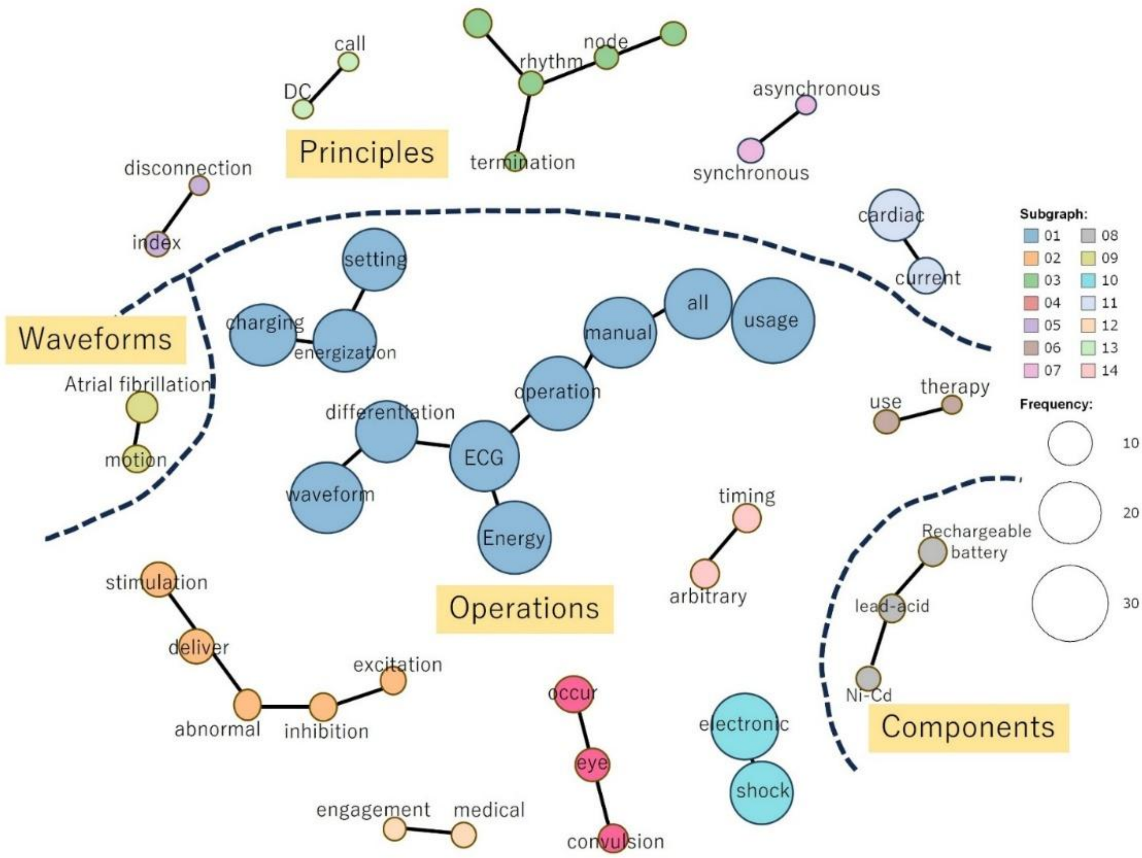

FIGURE 1. Minimum Spanning Tree (MST) of student reports.
The network visualizes the structural relationships between the terms used by students.

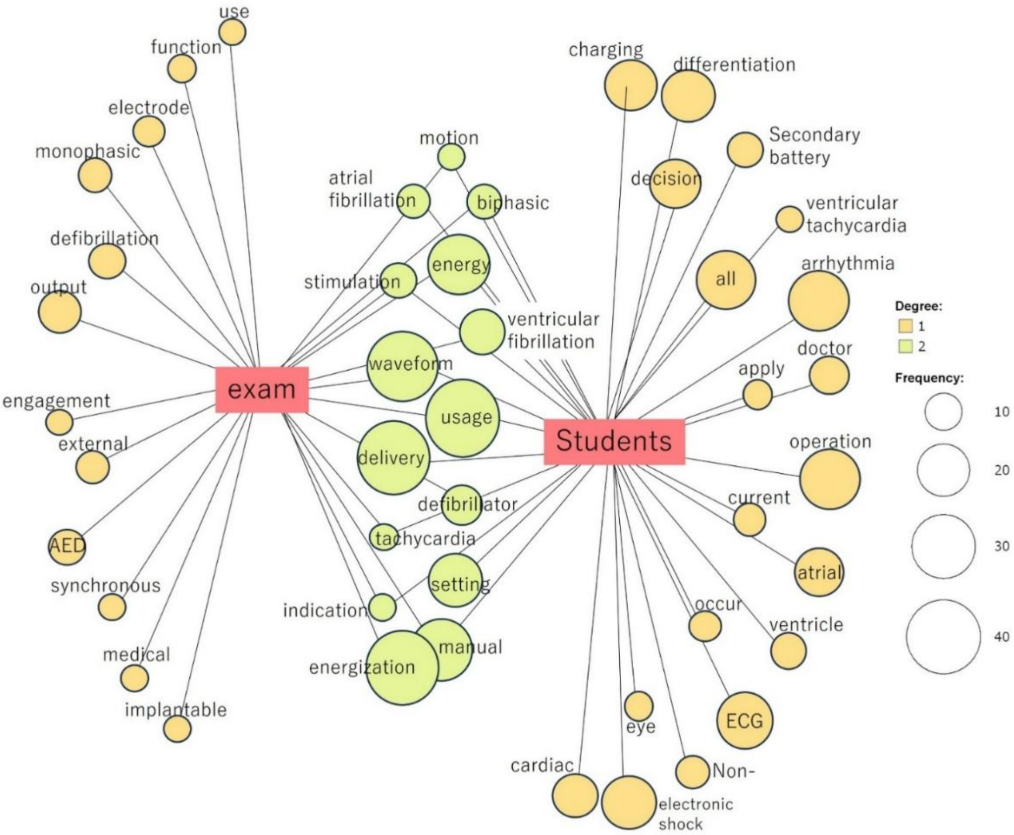

FIGURE 2. Correspondence analysis between student vocabulary and national examination keywords. The proximity of nodes represents the strength of the association between terms found in student reports and exam requirements.

3.2. Performance and Usability of the AR-Based System

Following the identification of these gaps, an AR-based inspection support system was evaluated with 10 third-year students to bridge the gap between abstract knowledge and practical skills.

- ✓ Operational Efficiency: The inspection time for medical devices, specifically electrosurgical units and defibrillators, was significantly reduced when using spectacle-type wearable devices compared to smartphones. This improvement is attributed to the minimization of eye movement and the hands-free nature of the AR interface.

- ✓ Comparative Usability of Devices:

1. *Smartphone vs. Wired Smart Glasses:* As illustrated in Figure 3, a Wilcoxon rank sum test ($p < 0.01$) revealed that the experience of using wired smart glasses was significantly preferred over smartphones.

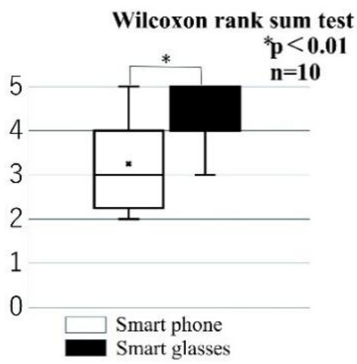

FIGURE 3. Comparison of devices usability

2. *Wired vs. Wireless Systems:* Figure 4 shows the experimental setup with wearable devices attached. As illustrated in Figure 5, a Welch's t-test ($p < 0.05$) demonstrated a significant preference for the wireless system integrated with a single-board computer. The average SUS score improved from 51.25 for the wired configuration to 63.8 for the wireless configuration, with a maximum score of 82.5 recorded for the latter (Table 1).

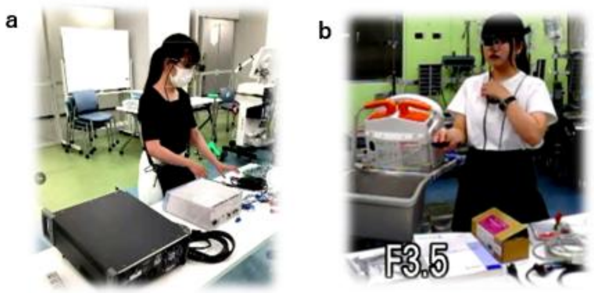

FIGURE 4. Experimental situation with the device attached. A. Before improvements to spectacle wearable devices. B. After improvements to spectacle wearable devices. (Note: The label "F3.5" in the image indicates the frame capture point from the original training video used in the experiment.)

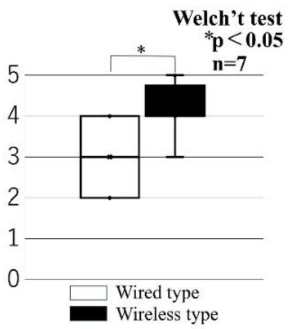

FIGURE 5. Comparison of the usability of two types of smart glasses

TABLE 1. SUS score

SUS score	Pre	Post
Highest score	70	82.5
Lowest score	42.5	52.5
Average score	51.25	63.8

SUS scores showed the wearable device before and after the improvements.

4. DISCUSSION

4.1. Performance and Usability of the AR-Based System

The quantitative text analysis in Phase 1 revealed a significant structural gap in student knowledge. As shown in the co-occurrence network (Figure 1), while students successfully integrated core principles such as "defibrillation" and "energization," technical terms related to "components" (e.g., capacitors, batteries) and "detailed operations" remained at the periphery of their mental models. This fragmented knowledge structure suggests that traditional lecture-based education effectively conveys abstract concepts but fails to foster a concrete understanding of the physical apparatus. In clinical engineering, such gaps pose a critical risk, as the inability to relate a device's internal state to its external operation can lead to errors during emergency troubleshooting.

4.2. Role of AR in Bridging Knowledge Gaps

The implementation of the AR-based system in Phase 2 demonstrated a clear improvement in inspection efficiency. By providing a "hands-free" visual overlay, the system allows students to map their theoretical knowledge directly onto the physical components of the device in real-time [1], [2]. This spatial anchoring of information acted as a cognitive scaffold, transforming what was previously "peripheral" knowledge into an integrated part of the core operational workflow. The reduction in inspection time confirms that AR technology can effectively bridge the gap between abstract understanding and practical application, aligning with recent findings that immersive AR applications improve healthcare students' spatial learning and practical skills [3], [4].

4.3. Usability and Human Factors in Clinical DX

The transition to a wireless AR system resulted in a notable increase in SUS scores, from 51.25 to 63.8. This improvement underscores the importance of ergonomics and mobility in clinical engineering tasks. While the scores reflect an improved level of usability, they still fall within the "marginal" range according to the Bangor scale [8]. This indicates that hardware constraints, such as field-of-view (FoV) and device weight, remain hurdles for the full-scale adoption of AR in medical education. However, the introduction of intuitive controllers significantly enhances student confidence and operational speed.

4.4. Implications for Standardized Education

The integrated framework proposed in this study—

identifying gaps via text mining and addressing them via AR—offers a data-driven pathway for standardizing medical device training. As Japan faces ongoing labor shortages in clinical engineering, such systems ensure that even less experienced personnel can perform high-stakes inspections with a standardized level of accuracy and safety. Furthermore, objective evaluation of knowledge structures allows instructors to identify specific "weak points" and tailor AR content to reinforce those areas, moving toward a more personalized and effective educational model.

4.5. Generalizability of the Framework

While this evaluation focuses on defibrillators as a representative case study, the proposed framework is not a standalone solution limited to a single device. Integrating quantitative text mining with AR-based spatial scaffolding to identify structural knowledge gaps, this approach is highly scalable. This approach is inherently applicable to other complex medical devices, such as electrosurgical devices, which are currently under further investigation. By systematically visualizing cognitive deficits and developing device-agnostic AR examination overlays, this data-driven educational model establishes a universal standard for clinical engineering education and medical device safety management.

5. CONCLUSION

This study established a data-driven educational framework by integrating quantitative text mining with AR-based task support. Text analysis using KH Coder proved to be an effective tool for objectively identifying specific weaknesses in students' knowledge structures. By utilizing these insights to design an AR-based intervention, it was demonstrated a successful method for bridging the gap between theoretical knowledge and clinical competency.

The results indicate that AR technology serves as a vital bridge to practical application, significantly improving efficiency. Future work will focus on scaling this system to other complex life-support devices, such as ventilators and hemodialysis machines, and investigating the long-term retention of skills acquired through AR-supported training. This integrated approach offers a promising pathway for the digital transformation (DX) of medical device safety management education

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