



Integrating augmented reality into engineering education: Development and evaluation of tensile testing learning media

Uum Sumirat^{1*}, Juliana¹, Lazuardi Imani Hakam¹, Usep Suhud²,
Inomjom Qudratov³

¹Universitas Pendidikan Indonesia, Indonesia

²Universitas Negeri Jakarta, Indonesia

³Tashkent State University of Economics, Uzbekistan

*Corresponding Author: sumiratuum@upi.edu

ABSTRACT

The integration of Augmented Reality (AR) into technical and vocational education has gained considerable attention as a means of bridging the gap between abstract theoretical content and applied industrial competencies. However, empirical evidence regarding its effectiveness in mechanics of materials instruction, particularly within the context of manufacturing engineering training, remains limited. This study aimed to design, develop, and evaluate an AR-based instructional medium for tensile testing procedures, targeting competency development among engineering students. The development process followed the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) instructional design model, incorporating competency-based and mastery learning frameworks. A pre-experimental one-group pretest-posttest design was employed with 36 engineering students drawn from three higher education institutions in Indonesia. Media feasibility was assessed through expert validation, yielding scores of 79% for media quality and 91% for content accuracy, both indicating suitability for instructional use. Learning outcomes were measured using normalized gain (N-Gain) analysis, with results indicating a mean N-Gain score of 0.47, classified as moderate improvement according to Hake's (1998) criteria. These findings suggest that AR-based instructional media may serve as an effective tool for supporting technical training in mechanics of materials, particularly for facilitating three-dimensional visualization of complex physical phenomena such as tensile deformation and stress-strain behavior. Nevertheless, the moderate gain score indicates that further development, notably the incorporation of audio elements and higher-order synthesis tasks, may be required to fully support advanced competency levels. The study contributes empirical evidence to the growing body of literature on immersive technology integration in engineering education within Industry 4.0 contexts.

Keywords: augmented reality, engineering education, mechanics of materials, ADDIE model, competency-based training

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INTRODUCTION

The fourth industrial revolution, widely referred to as Industry 4.0, has fundamentally reshaped the competency landscape of manufacturing engineering, demanding that technical graduates possess not only domain-specific knowledge but also the capacity to operate within increasingly digitised and automated production environments (Hernandez-de-Menendez et al., 2020; Kodrat, 2021; Damayanti et al., 2026). Central to this transformation is the imperative for educational institutions and industrial training providers to redesign their instructional approaches in ways that align with the technological demands of modern manufacturing (Ahmad et al., 2024;

Menne et al., 2024; Iskandar et al., 2026; Ruyadi et al., 2026). Conventional training methods, which often rely on physical equipment and static instructional materials, are increasingly regarded as insufficient for developing the complex, multi-dimensional competencies required in Industry 4.0 settings (Gualtieri et al., 2024).

Among the emerging digital technologies proposed as solutions to this pedagogical challenge, Augmented Reality (AR) has attracted growing scholarly and practitioner interest. AR enables the superimposition of three-dimensional virtual content onto real-world environments in real time, thereby allowing learners to interact with otherwise invisible or inaccessible physical phenomena (Hincapie et al., 2021). In engineering education specifically, AR has been applied across a range of technical subjects, from linear control systems (Kaur et al., 2021) and structural mechanics (Hu et al., 2021) to engineering drawing (Awuor et al., 2024) and CNC machining instruction (Prasetya et al., 2026), with evidence consistently indicating its potential to enhance spatial understanding and learning outcomes. In the Indonesian educational context, AR-based mobile multimedia has also been shown to support learning by presenting three-dimensional objects that can be viewed from different positions, thereby helping learners understand movement-based or spatially complex material (Muktiani et al., 2022). A meta-analysis by Lin and Yu (2023) further corroborates this trajectory, reporting significant positive effects of AR on learning performance across STEM disciplines when deployed within interactive instructional environments.

Despite this broader evidence base, the application of AR to mechanics of materials instruction, and to tensile testing in particular, remains underexplored. Tensile testing is a foundational competency in manufacturing engineering, requiring learners to understand abstract stress-strain relationships, material deformation behaviour, and failure mechanisms that are inherently difficult to visualise through conventional two-dimensional media (Bernardini et al., 2026). Existing studies have largely focused on AR for geometry, chemistry, or general physics, with comparatively little attention directed toward materials science and mechanical property testing (Hedenqvist et al., 2023; Mojidra et al., 2025). This constitutes a meaningful research gap, particularly given the high cost and logistical complexity of conducting physical tensile testing in industrial training contexts, a challenge documented in the Indonesian manufacturing sector where per-session equipment operating costs may render large-scale practical training financially prohibitive. Similar challenges have been documented in civil engineering education, where immersive virtual reality has been used to address limited access to construction sites, safety concerns, logistical constraints, and the gap between theoretical instruction and practical experience (Kuncoro et al., 2025).

A further gap concerns the methodological integration of AR development with established instructional design frameworks in vocational and engineering contexts. While the ADDIE model is widely recognised as a systematic approach to competency-based instructional media development (Johan et al., 2026; Lah et al., 2024), its application to AR-based media specifically targeting mechanics of materials in industrial training settings has not been thoroughly documented. This study addresses both gaps by reporting the design, development, and evaluation of an AR-based instructional medium for tensile testing, developed within a competency-based and mastery learning framework using the ADDIE model.

The study was conducted with 36 engineering students across three Indonesian higher education institutions and assessed media feasibility through expert validation and learning effectiveness through N-Gain analysis. The primary contributions are threefold: (1) empirical evidence of AR effectiveness for mechanics of materials instruction in a manufacturing engineering training context; (2) a replicable ADDIE-based development process for AR instructional media targeting industrial competencies; and (3) identification of specific instructional design limitations, notably constraints of AR media in supporting higher-order synthesis tasks, that warrant attention in future development efforts.

The application of AR in engineering education has expanded considerably over the past decade, driven by technology's capacity to render abstract technical concepts perceptible through interactive three-dimensional visualisation (Suhail et al., 2024). Foundational work by Faridi et al. (2021) demonstrated that an AR-based learning environment significantly improved both

critical thinking ability and learning gain among engineering students exposed to abstract physics concepts, compared to a conventional teaching group of equivalent size. Similarly, Kaur et al. (2021) developed a framework for AR-enhanced instruction in linear control systems, reporting improved concept comprehension and spatial visualisation. More recently, Giancaspro et al. (2024) employed AR with guided inquiry for distributed forces instruction, finding that active AR-mediated engagement supported deeper mechanical reasoning than lecture-based alternatives.

Reviews and meta-analyses of this literature confirm the consistency of these positive effects. Lin and Yu (2023) conducted a meta-analysis across 84 AR studies in interactive STEM learning environments, reporting a statistically significant overall effect on learning performance, with particularly strong effects observed in engineering and physics contexts. Yuan et al. (2025) further identified AR as the most frequently adopted immersive technology in higher engineering education, noting that its effectiveness is moderated by instructional design quality, subject-matter complexity, and the extent to which the AR experience supports active knowledge construction. Taken together, these findings suggest that AR is not inherently effective but rather conditionally effective, contingent on how well its affordances are aligned with the learning tasks it is designed to support (Shrestha et al., 2025).

Of particular relevance to the present study is the application of AR to the visualisation of physical and mechanical phenomena. Hedenqvist et al. (2023) demonstrated that AR improved students' learning of engineering mechanics, specifically torque and rotational concepts, by enabling real-time visualisation of force vectors that are otherwise invisible. Hu et al. (2021) reported comparable results in structural engineering, where AR allowed non-engineering students to visualise load-bearing systems with a level of spatial clarity not achievable through static diagrams. Bernardini et al. (2026) addressed visualisation challenges in materials science education, finding that a low-cost mobile AR application significantly mitigated spatial reasoning difficulties associated with crystallographic and microstructural concepts. Mojidra et al. (2025) further reported that mobile AR facilitated immersive learning of structural analysis, improving both conceptual understanding and practical problem-solving among engineering undergraduates.

Beyond higher education, AR has been increasingly positioned as a strategic tool for bridging the competency gap in vocational and industrial training contexts, particularly as Industry 4.0 demands workforce capabilities that traditional training infrastructures are ill-equipped to develop (Hernandez-de-Menendez et al., 2020; Ahmad et al., 2024). Liu et al. (2024) conducted a systematic review of AR and VR applications in vocational education, identifying three primary models of deployment, namely simulation-based, guidance-based, and assessment-integrated, and reporting consistent positive effects on skill acquisition and motivation across vocational domains. Efendi et al. (2025) specifically addressed the industry 4.0 skills gap in an Indonesian vocational context, finding that mobile AR significantly enhanced technical competency outcomes among students who engaged with immersive AR-based instructional content compared to those receiving conventional instruction.

In industrial training settings, Gualtieri et al. (2024) provided particularly compelling evidence through their study of a visual management and AR-based training module for complex machinery setup, demonstrating superior short- and long-term procedural knowledge retention among operators compared to traditional working procedures. Hernandez-Rodriguez and Guillen-Yparrea (2023) similarly reported that AR-supported competency development in a manufacturing engineering programme enhanced self-directed learning and reduced dependence on instructor-led demonstrations. Vavenkov (2022) extended this argument to heavy industry, demonstrating that AR and VR technologies enabled effective process safety and operational training for engineers in contexts where live equipment training was logistically or economically impractical.

The ADDIE model, comprising the phases of Analysis, Design, Development, Implementation, and Evaluation, provides a systematic and iterative framework for instructional media development that is well suited to the complexity of AR application design (Johan et al., 2026). Lah et al. (2024) employed ADDIE to develop and validate a mobile AR application for chemistry instruction, reporting high expert validity scores and significant pre-post improvement

in student performance. Papakostas et al. (2023) grounded their AR spatial ability training application in a theoretically informed design process, demonstrating that structured instructional design substantially moderated user acceptance and learning outcomes. These studies suggest that the quality of ADDIE-aligned design processes, including competency mapping, iterative prototyping, and systematic expert validation, plays a critical role in determining the instructional effectiveness of the resulting AR media. In the Indonesian educational context specifically, ADDIE has been applied to AR media development across disciplines, with Qumillaila et al. (2017) reporting that an Android-based AR medium for human excretory system learning achieved consistently high expert validation and field trial scores, demonstrating the model's reliability as a development framework for AR instructional media.

The present study is theoretically grounded in two complementary frameworks. First, cognitive load theory (Sweller, 1988) posits that instructional effectiveness depends on the management of working memory resources, distinguishing among intrinsic load (inherent to the subject matter), extraneous load (arising from poor instructional design), and germane load (associated with schema formation). AR-based instruction is expected to reduce extraneous cognitive load by replacing complex two-dimensional diagrams with interactive three-dimensional simulations, thereby freeing working memory resources for deeper conceptual processing. Second, the cognitive theory of multimedia learning (Mayer, 2009) predicts that well-designed AR media, which integrates visual simulation with textual annotation in a spatially contiguous manner, should enhance knowledge encoding and retention relative to text-only or static image-based instruction.

METHOD

This study employed a research and development (R&D) approach, specifically utilising the ADDIE instructional design model to systematically develop and evaluate an AR-based instructional medium for tensile testing in mechanics of materials. To assess instructional effectiveness, a pre-experimental one-group pretest-posttest design was adopted. While this design does not incorporate a control group, a limitation acknowledged in the Conclusion section, it was considered appropriate for the exploratory, development-oriented nature of this study, consistent with analogous AR media development research employing similar pre-experimental frameworks (Lah et al., 2024; Hidayat et al., 2025).

Participants comprised 36 final-year engineering students drawn from three Indonesian higher education institutions: Institut Teknologi Nasional (Department of Mechanical Engineering), Universitas Pendidikan Indonesia (Department of Mechanical Engineering Education), and Universitas Gadjah Mada (Department of Mechanical Engineering). Final-year students were pursued pursuing the grounds that they had completed the prerequisite academic requirements in engineering design and manufacturing fundamentals, ensuring a sufficient prior knowledge baseline for engagement with tensile testing content.

The AR instructional medium was developed using Unity 3D and Vuforia, incorporating three-dimensional simulations of the tensile testing procedure, including loading initiation, necking behaviour, and fracture. The development process followed five ADDIE phases. Analysis involved identification of competency gaps through preliminary observation at PT Semen Indonesia Group, where physical training on ball mill operation was found to impose substantial operational costs estimated at IDR 15 million per hour. Design entailed the formulation of competency-based learning objectives aligned with industrial standards, structured around mastery learning principles. Development involved the production of 3D models simulating tensile deformation behaviour, assembled within a marker-based AR environment using Vuforia's image-tracking engine within the Unity 3D platform. Implementation consisted of deploying the AR medium with 36 participants, preceded by a pretest assessing baseline comprehension of mechanics of materials concepts. Evaluation encompassed expert validation of media feasibility prior to deployment and pre-post assessment of learning outcomes following implementation.

Media feasibility was assessed by two independent validators: a media expert from Universitas Pendidikan Indonesia and a content expert from Universitas Gadjah Mada, each

assessing the medium against structured rating instruments covering technical media quality and content accuracy respectively. A 19-item essay-based achievement test was administered as both pretest and posttest, distributed across four assessment aspects targeting comprehension and application of tensile testing concepts, including graphical interpretation, numerical calculation, and conceptual description. The instrument underwent content validity, construct validity, and face validity assessment by subject matter experts prior to use. Reliability was established using Cronbach's alpha formula for polytomously scored items (Arikunto, 2011).

Learning outcome improvement was quantified using the normalised gain (N-Gain) index as formulated by Hake (1998), calculated as $g = (S_{post} - S_{pre}) / (100 - S_{pre})$. N-Gain scores were interpreted according to established criteria: $g > 0.7 =$ high; $0.3 \leq g \leq 0.7 =$ moderate; $g < 0.3 =$ low. Prior to interpretation, the normality of pretest and posttest score distributions was examined using the Shapiro-Wilk test, given the sample size of fewer than 50 observations.

FINDINGS AND DISCUSSION

Findings

Expert validation of media feasibility

Prior to implementation, the developed AR medium was subjected to expert validation by two independent validators. The media expert yielded a mean validation score of 79%, falling within the feasible category. The content expert yielded a validation score of 91%, classified as highly feasible. These results indicate that the developed AR medium was considered suitable for instructional deployment. Table 1 presents a summary of expert validation scores.

Table 1. Summary of expert validation scores

Validator	Domain	Score	Category
Media Expert (UPI)	Technical media quality	79%	Feasible
Content Expert (UGM)	Content accuracy and alignment	91%	Highly Feasible

Normality of score distributions

Prior to N-Gain analysis, the normality of pretest and posttest score distributions were examined using the Shapiro-Wilk test. Results indicated that posttest scores approximated a normal distribution ($W = 0.924$, $df = 21$, $p = .103$), whereas pretest scores showed a significant departure from normality ($W = 0.838$, $df = 21$, $p = .003$). Given this asymmetry, N-Gain analysis was retained as the primary outcome measure, as it operates on individual gain ratios rather than distributional assumptions.

Learning outcome improvement: N-gain analysis

Table 2 presents summary statistics of pretest, posttest, and N-Gain scores for the 36 participants.

Table 2. Summary of pretest, posttest, and n-gain scores (N = 36)

	Pretest	Posttest	N-Gain	Category
Highest	90	100	1.00	High
Lowest	0	37	-0.58	Low
Mean	54.44	77.97	0.47	Moderate

The mean N-Gain score of 0.47 falls within the moderate improvement category ($0.3 \leq g \leq 0.7$) according to Hake's (1998) criteria, indicating a statistically meaningful improvement in learning outcomes following AR-based instruction. Analysis of individual N-Gain scores revealed that 12 participants (33.3%) achieved high gain, 22 participants (61.1%) moderate gain, and 2 participants (5.6%) low gain.

Performance across assessment indicators

Item-level analysis indicated that initial performance was highest on assessment indicator 1, targeting comprehension-level understanding of tensile testing principles, with a mean pretest

score of 73%. By contrast, assessment indicator 2, targeting higher-order synthesis and application tasks, showed comparatively lower initial performance. Following AR-based instruction, posttest scores improved across all indicators with a mean improvement of approximately 5 percentage points per indicator. The relatively modest gain on synthesis-level items suggests that the AR medium was effective in supporting foundational comprehension but may not have fully scaffolded the cognitive demands associated with higher-order task performance.

Discussion

The expert validation scores obtained in this study, 79% for media quality and 91% for content accuracy, are consistent with feasibility thresholds reported in comparable AR media development studies employing ADDIE-based design processes. Lah et al. (2024) reported similarly high content validity scores, attributing the outcome to the systematic alignment of content with curriculum standards during the design phase. Johan et al. (2026) likewise obtained strong expert validation in their ADDIE-based AR application, noting that iterative formative evaluation substantially reduced content-related validation concerns. The comparatively lower media validation score (79%) suggests that technical dimensions of the AR application, including user interface design, interaction quality, and audio integration, represent areas for improvement in subsequent development iterations.

The mean N-Gain score of 0.47, classified as moderate improvement, indicates that the AR-based instructional medium produced meaningful learning gains relative to participants' baseline knowledge of tensile testing. This finding is broadly consistent with the existing literature on AR effectiveness in engineering and technical education. This moderate gain is comparable to findings in physics learning, where interactive multimedia-based problem solving produced an average N-Gain of 0.50, also indicating moderate improvement in students' thinking ability (Manurung & Panggabean, 2020). Faridi et al. (2021) reported moderate to high learning gains in an AR-based engineering physics intervention, noting that gain magnitude was positively associated with the extent to which the AR experience enabled interaction with abstract spatial phenomena. Lee and Hsu (2021) similarly reported moderate gains in an AR-based vocational certification course, attributing the outcome to the medium's capacity to reduce cognitive load associated with abstract technical content.

The moderate rather than high N-Gain score warrants careful interpretation. Item-level analysis revealed that gains were stronger on comprehension-level tasks than on synthesis-level tasks requiring design reasoning. This limitation suggests that AR visualization should be complemented with explicit design-based or project-oriented tasks. In STEM education, creative thinking and innovation are strengthened when learners are guided to design prototypes, apply scientific principles, and engage in problem-solving and teamwork (Sutaphan & Yuenyong, 2023). This pattern suggests that the AR medium was more effective in supporting conceptual understanding than in facilitating the integration and application of knowledge at Bloom's synthesis level. This finding is consistent with Hernandez-Rodriguez and Guillen-Yparrea's (2023) observation that AR-mediated learning in manufacturing engineering contexts tends to produce robust gains in procedural knowledge and conceptual comprehension while offering comparatively less scaffolding for design-level synthesis tasks. Awuor et al. (2024) made a similar observation in their study of 3D AR for engineering drawing, noting that spatial visualisation gains did not automatically transfer to higher-order design competencies without additional instructional support.

These interpretations collectively suggest that the moderate effectiveness observed in this study should not be attributed to limitations of AR technology per se, but rather to specific instructional design decisions, particularly the absence of audio narration, the limited provision of synthesis-level task scaffolding, and the lack of interactive problem-solving elements within the current version of the medium. Rahmawati et al. (2026) argue that 3D AR applications in engineering education achieve higher learning gains when combined with collaborative and guided inquiry elements that explicitly prompt higher-order reasoning.

Within the theoretical frameworks adopted in this study, the findings are interpretable as follows. The AR medium's capacity to present complex mechanical phenomena through dynamic three-dimensional simulation may have reduced extraneous cognitive load associated with interpreting static two-dimensional diagrams (Sweller, 1988), consistent with the spatial contiguity principle of multimedia learning (Mayer, 2009). However, germane cognitive load, the load associated with schema formation at higher cognitive levels, was not fully activated by the current instructional design, pointing to the need for more explicit metacognitive prompts and problem-solving scaffolds in future iterations.

From a practical standpoint, the present study contributes to a growing body of evidence that AR-based instructional media can serve as a cost-effective complement to physical equipment-based training in manufacturing engineering contexts. Gualtieri et al. (2024) demonstrated that AR-based training for complex machinery setup produced superior knowledge retention compared to traditional working procedures. The present study extends this evidence to the specific domain of mechanics of materials instruction, where the cost and logistical complexity of physical tensile testing equipment represents a documented barrier to competency development in the Indonesian industrial training context. This position is further supported by Kuncoro et al. (2025), who demonstrated that VR-based immersive learning in civil engineering education can effectively replicate field-based practical experiences at significantly lower operational cost, a finding that aligns with the cost-reduction rationale motivating the present study's AR-based approach to tensile testing instruction.

CONCLUSION

This study aimed to design, develop, and evaluate an AR-based instructional medium for tensile testing in mechanics of materials using the ADDIE model within a competency-based and mastery learning framework. Three conclusions are drawn. First, the AR medium was found to be feasible for instructional use, as evidenced by expert validation scores of 79% for media quality and 91% for content accuracy, indicating that the medium meets the threshold for deployment in engineering education and industrial training contexts. Second, the ADDIE-based development process provides a replicable methodological template for AR instructional media development targeting industrial training in manufacturing engineering. Third, the AR medium demonstrated moderate effectiveness in improving participants' learning outcomes, as indicated by a mean N-Gain score of 0.47, suggesting that AR-based instruction can produce meaningful competency gains at the comprehension and application levels while revealing limitations at the synthesis level that warrant targeted design improvement.

Several limitations of this study warrant acknowledgement. The absence of a control group limits causal attribution of observed gains to the AR medium. The sample of 36 students drawn from three institutions limits generalisability to broader engineering student populations. The current AR medium lacks audio narration and explicit synthesis-level task scaffolding, which may have constrained learning gains at higher cognitive levels. Future studies should adopt a quasi-experimental design incorporating a control group, redesign the AR medium to incorporate audio narration and interactive problem-solving modules targeting higher cognitive levels, investigate the medium's effectiveness across extended instructional periods with larger samples, and explore the cost-effectiveness of AR-based training as a complement to physical equipment-based instruction using economic evaluation methodologies.

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