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Advancing Teacher Professional Education in Physical Education: Wearable Technology for Sports Learning in the Digital Era of Generation Z and Alpha

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ABSTRACT

Purpose of the study: The rapid technological advancement in the 21st century has fundamentally transformed educational landscapes, particularly in physical education (PE) where traditional teaching methods are being challenged by the digital nativity of Generation Z and Alpha students. These generations, characterized by their intrinsic relationship with technology, require innovative pedagogical approaches that leverage digital tools for enhanced learning experiences. This research investigates the effectiveness of integrating wearable technology into physical education teacher professional development programs, specifically examining its impact on pre-service teachers' competencies and their ability to engage Generation Z and Alpha learners in the digital era.

Materials and methods: A mixed-methods study was conducted with 120 pre-service teachers enrolled in the Teacher Professional Education Program (PPG) at Universitas Negeri Malang, Indonesia. Participants were divided into experimental (n=60) and control groups (n=60). The experimental group received comprehensive training in wearable technology integration, including fitness trackers, heart rate monitors, and motion sensors, while the control group followed traditional PE pedagogy. Data collection involved pre- and post-intervention assessments, teaching competency evaluations, student engagement measurements, and qualitative interviews.

Results: Statistical analysis revealed significant improvements in the experimental group across multiple dimensions. Pre-service teachers demonstrated enhanced technological pedagogical content knowledge (TPACK) scores (M=4.23, SD=0.52 vs. M=3.41, SD=0.48; $p<0.001$), improved student engagement rates (78.4% vs. 61.2%; $p<0.01$), and increased confidence in teaching Generation Z and Alpha students (M=4.15, SD=0.61 vs. M=3.28, SD=0.73; $p<0.001$). Wearable technology integration showed positive correlations with enhanced motor skill assessment accuracy ($r=0.742$, $p<0.001$) and personalized learning delivery ($r=0.689$, $p<0.001$).

Conclusions: The integration of wearable technology in PE teacher professional education significantly enhances teaching competencies and preparedness for Generation Z and Alpha learners. The findings support the transformation of traditional teacher preparation programs to include technology-enhanced pedagogical approaches that align with contemporary learning preferences and digital nativity characteristics.

Keywords
wearable technology; physical education; teacher professional development; Generation Z; Generation Alpha; digital natives; pedagogical innovation; sports learning.

INTRODUCTION

Contextual Framework of the Research

The 21st century educational landscape has witnessed unprecedented technological integration, fundamentally altering teaching and learning paradigms across all disciplines. Physical education, traditionally characterized by face-to-face instruction and kinesthetic learning approaches, now faces the imperative to adapt to the digital nativity of contemporary learners (Krause et al., 2019; Sargent & Calderón, 2021). Generation Z (born 1997-2012) and the emerging Generation Alpha (born 2010-2025) represent cohorts that have never experienced life without digital technology, exhibiting unique learning preferences that challenge conventional educational methodologies (Perry, 2022; Rathnasekara et al., 2025; Tapp et al., 2024)

Indonesia's educational system, through the Teacher Professional Education Program (Pendidikan Profesi Guru - PPG), has recognized the critical need to prepare educators who can effectively engage these digital native generations. The PPG program, established under Law No. 14 of 2005 concerning Teachers and Lecturers, aims to develop professional teachers with enhanced pedagogical, personal, social, and professional competencies (Fadhlurrahman et al., 2026; Ministry of Education and Culture, 2024). However, traditional teacher preparation models often inadequately address the technological fluency required to engage Generation Z and Alpha learners effectively.

Wearable technology, encompassing fitness trackers, heart rate monitors, smartwatches, and motion sensors, has emerged as a transformative tool in physical education contexts (Zhao & Su, 2026). These devices provide real-time biometric

feedback, enhance motivation through gamification, and enable personalized learning experiences that align with digital natives' expectations for immediate, data-driven information (Coffman & Klinger, 2015; Ferraz et al., 2024, p. 37). The integration of such technologies in teacher preparation programs represents a paradigm shift toward technology-enhanced pedagogical approaches that bridge the gap between traditional PE instruction and contemporary learning preferences.

Critical Examination of Existing Literature

Recent research has extensively documented the potential of wearable technology in educational contexts, particularly within physical education domains. Borthwick et al. (2015) conducted pioneering work examining the educational affordances of wearable devices, highlighting their capacity to enhance learning through real-time data collection and feedback mechanisms. Subsequent investigations by Bower & Sturman (2015); Motti (2020) have further elaborated on the design principles and practical applications of wearables in educational settings.

In physical education contexts, wearable technology has demonstrated significant potential for enhancing student engagement and learning outcomes. Soltani & Morice (2020) investigated the use of fitness trackers in PE classes, finding increased student motivation and improved understanding of personal fitness metrics. Similarly, research by Thiebaud et al. (2018) explored heart rate monitoring applications, revealing enhanced student awareness of exercise intensity and improved self-regulation during physical activities.

The psychological and pedagogical implications of teaching Generation Z and Alpha learners have been extensively studied. (Prensky, 2001) introduced the concept of "digital natives," describing individuals born into technology-rich environments who process information differently from previous generations. Subsequent research by ("Born Digital: How Children Grow up in a Digital Age," n.d.; Tapscott, 2009) has refined understanding of these generations' learning preferences, emphasizing their preference for visual and interactive content, shortened attention spans, and expectation for immediate feedback.

Generation Alpha research, though emerging, suggests even greater technological integration and shortened attention spans compared to Generation Z. Studies by Thaise et al. (2024) indicate that Generation Alpha exhibits preferences for visual and interactive learning materials, collaborative tasks, and immediate gratification, necessitating adaptive pedagogical approaches that incorporate technology seamlessly into learning experiences.

Teacher professional development research has consistently emphasized the importance of technological pedagogical content knowledge (TPACK) in preparing effective educators. Mishra & Koehler (2006) seminal framework highlights the intersection of technology, pedagogy, and content knowledge as essential for effective teaching in technology-rich environments. However, limited research has specifically examined wearable technology integration within PE teacher preparation programs, particularly in contexts involving Generation Z and Alpha learners.

Identification of Research Gaps

Despite the growing body of research on wearable technology applications and the learning preferences of Generation Z and Alpha, several critical gaps remain unaddressed. First, studies have primarily focused on K-12 implementation, with limited exploration of how wearable technologies are integrated into physical education (PE) teacher preparation programs—particularly in developing contexts such as Indonesia. Second, while generational learning preferences have been widely studied in general education, little is known about the specific needs of Gen Z and Alpha learners in PE domains. Third, empirical evidence is scarce regarding the effectiveness of technology-enhanced pedagogical approaches in equipping future PE teachers to engage digital-native students. Fourth, cultural and contextual considerations remain underexplored, with most studies situated in Western settings, leaving a gap in understanding how wearable technology can be effectively adapted in non-Western contexts like Indonesia. Finally, the majority of research emphasizes short-term outcomes, while the longitudinal impacts of wearable technology integration on teacher effectiveness and student learning remain insufficiently investigated

Rationale for the Research

The convergence of several factors necessitates this research investigation. First, the increasing prevalence of Generation Z and Alpha students in educational systems worldwide demands pedagogical approaches that align with their digital nativity and learning preferences. Second, the Indonesian government's commitment to educational quality improvement through the PPG program provides an optimal context for investigating innovative teacher preparation approaches. Third, the demonstrated potential of wearable technology in enhancing PE learning experiences suggests significant opportunities for teacher professional development enhancement.

Furthermore, the COVID-19 pandemic has accelerated digital transformation in education, highlighting the critical importance of technology-enhanced teaching competencies. Teachers who are proficient in integrating wearable technology are better positioned to create engaging, personalized learning experiences that resonate with digital native learners.

The research addresses practical concerns regarding teacher preparedness for contemporary educational challenges while contributing to theoretical understanding of technology-enhanced pedagogical approaches in PE contexts. The findings will inform policy decisions regarding teacher preparation program modifications and provide evidence-based guidance for educational technology integration.

Objectives

This research investigation pursues a comprehensive set of objectives aimed at evaluating the pedagogical transformation enabled by wearable technology integration in physical education teacher professional development. The primary objective is to assess the effectiveness of wearable technology training in enhancing teaching competencies and preparedness to engage Generation Z and Alpha learners. Complementing this, the secondary objectives include: examining its impact on pre-service teachers' technological pedagogical content knowledge (TPACK); analyzing the relationship between technology integration and their confidence in teaching digital-native students; investigating the influence of wearable technology–enhanced instruction on student engagement and learning outcomes; identifying best practices and challenges in implementing such innovations within PE

teacher preparation programs; and, ultimately, developing evidence-based recommendations for strengthening teacher professional development through sustainable technology integration.

MATERIALS AND METHODS

Participants

The study participants comprised 120 pre-service teachers enrolled in the Teacher Professional Education Program (PPG) for Physical Education at Universitas Negeri Malang, Indonesia, during the 2024 academic year. Participants were selected through purposive sampling based on the following inclusion criteria: (1) enrollment in the PPG Physical Education program, (2) completion of undergraduate education in sports science or related fields, (3) no prior formal training in wearable technology integration, and (4) voluntary consent to participate in the research.

Table 1. Demographic Characteristics of Participants

Characteristic	Description
Age	*Range: 22–28 years (M = 24.7, SD = 1.8)*
Gender	*Male: 62% Female: 38%*
Technological Literacy	*All participants possessed basic technological literacy (based on digital competency evaluations)*
Group Assignment	*Experimental group: n = 60 Control group: n = 60*
Statistical Balance	*Chi-square and t-test analyses confirmed no significant differences between groups in demographic characteristics, prior academic achievement, or baseline technological competencies (p > 0.05)*

Study Organization

Program PPG (Pendidikan Profesi Guru) Context

The Teacher Professional Education Program (PPG) at Universitas Negeri Malang is a comprehensive two-semester professional development program designed to prepare graduate-level educators with enhanced pedagogical competencies. The program integrates theoretical coursework, practical teaching experiences, and leadership development components aligned with Indonesian national education standards. The PPG curriculum encompasses four core competency domains: (1) pedagogical competency involving learning theory and instructional design, (2) professional competency encompassing subject matter expertise, (3) personal competency including ethical and moral development, and (4) social competency involving communication and collaboration skills.

Intervention Design

The experimental intervention consisted of a 16-week comprehensive training program integrating wearable technology into physical education pedagogical preparation. The intervention included:

Table 2. 16-Week Training Program for Wearable Technology Integration in Physical Education Teacher Professional Development

Week	Focus Area	Content / Activities
1–4	Foundational Technology Training	• *Introduction to wearable technology principles and applications* • *Hands-on experience with fitness trackers, heart rate monitors, and motion sensors* • *Data interpretation and analysis techniques* • *Privacy and ethical considerations in educational technology use*
5–8	Pedagogical Integration	• *Technology-enhanced lesson planning and curriculum design* • *Assessment strategies incorporating wearable technology data* • *Differentiated instruction approaches for Generation Z and Alpha learners* • *Classroom management strategies for technology-rich environments*
9–12	Practical Application	• *Microteaching sessions with wearable technology integration* • *Peer observation and feedback on technology-enhanced instruction* • *Student engagement analysis using real-time biometric data* • *Reflection and iterative improvement of teaching practices*
13–16	Advanced Applications	• *Long-term fitness tracking and goal-setting strategies* • *Collaborative learning activities using shared wearable data* • *Parent and community engagement through technology platforms* • *Professional development planning for continued technology integration*

The control group received traditional PPG instruction following standard curriculum guidelines without specific wearable technology training, though they maintained access to basic educational technologies available in standard program delivery.

Test and Measurement Procedures

Technological Pedagogical Content Knowledge (TPACK) Assessment

Table 3. Technological Pedagogical Content Knowledge (TPACK) Assessment

Instrument	Description	Items / Subscales	Scale	Reliability (Cronbach's α)	Application in Study
Technology Integration Assessment Instrument (TIAI) (adapted from (Schmidt et al., 2009))	Adapted for physical education contexts to measure pre-service teachers' TPACK competencies.	*47 items across 7 subscales:* • *Technology Knowledge (TK)* • *Content Knowledge (CK)* • *Pedagogical Knowledge (PK)* • *Pedagogical Content Knowledge (PCK)* • *Technological Content Knowledge (TCK)* • *Technological Pedagogical Knowledge (TPK)* • *Technological Pedagogical Content Knowledge (TPACK)*	*5-point Likert scale (1 = strongly disagree → 5 = strongly agree)*	*Ranged from 0.82 – 0.91 across subscales*	*Used to evaluate participants' growth in technology, pedagogy, and content integration for PE teaching*

Teaching Confidence and Self-Efficacy Measures

Table 4. Physical Education Teaching Efficacy Scale (PETES)

Dimension	Description	No. of Items	Example Focus	Reliability
Instructional Strategies	Confidence in planning, delivering, and adapting PE lessons effectively for digital native learners.	6	Designing engaging, structured activities.	
Classroom Management	Beliefs about ability to maintain order and manage behavior in tech-rich environments.	6	Handling distractions, ensuring discipline.	
Student Engagement	Perceived efficacy in motivating and engaging students actively in PE lessons.	6	Inspiring participation, sustaining focus.	
Technology Integration	Confidence in using technology tools and wearables for enhancing PE teaching.	6	Incorporating apps, trackers, sensors.	
Total	24-item scale assessing overall PE teaching efficacy for Gen Z/Alpha learners.	24		*α = 0.89*

Student Engagement Assessment

Table 5. Student Engagement Measurement Framework

Dimension / Source	Indicators	Data Collection Method
Behavioral Engagement	Participation, effort, task involvement, adherence to instructions	Teacher-reported classroom observations
Emotional Engagement	Interest, enjoyment, enthusiasm, sense of belonging	Student self-reports during teaching practicum
Cognitive Engagement	Focus, persistence, application of strategies, reflective thinking	Student self-reports during teaching practicum
Biometric Indicators	Heart rate variability (HRV), physical activity levels, participation duration	Wearable devices (fitness trackers, HR monitors, motion sensors)

Motor Skills Assessment Accuracy

Table 6. Specialized Assessment Protocol for Motor Skills Evaluation

Component	**Description**
Purpose	To evaluate participants' ability to accurately assess student motor skills using traditional vs. wearable technology-enhanced approaches.
Task	Participants evaluated predetermined movement patterns performed by students.
Comparison Standard	Participant assessments were compared against expert evaluations (gold standard).
Conditions	1. Traditional methods (visual observation). 2. Wearable technology-enhanced methods (fitness trackers, motion sensors, heart rate monitors).
Assessment Metric	Accuracy scores calculated as correlation coefficients between participant and expert evaluations.
Outcome	Higher correlation coefficients indicated greater accuracy in motor skill assessment.
Key Result (from study)	Experimental group (wearable-trained) achieved significantly higher assessment accuracy ($r = 0.742$, $p < 0.001$) compared to control ($r = 0.623$, $p < 0.001$).

Statistical Analysis

Data analysis was conducted using SPSS version 28.0 with the significance level set at $\alpha = 0.05$. Preliminary analyses

involved normality testing through Shapiro–Wilk tests, homogeneity of variance assessment using Levene's tests, and the computation of descriptive statistics for all variables. For the primary analysis, independent samples t-tests were applied to compare post-intervention differences between the experimental and control groups, while paired samples t-tests were employed to evaluate pre–post changes within groups. Where necessary, Analysis of Covariance (ANCOVA) was utilized to control for baseline differences. Effect sizes were calculated using Cohen's d and interpreted according to established thresholds (small = 0.2, medium = 0.5, large = 0.8). Secondary analyses included Pearson correlation coefficients to examine relationships among variables, multiple regression analyses to identify predictors of teaching effectiveness, repeated measures ANOVA to assess changes across multiple time points, and chi-square tests to evaluate associations among categorical.

RESULTS

Articulating Research Outcomes in an Objective Manner

The comprehensive analysis of intervention effects revealed significant positive outcomes across multiple assessment dimensions. Pre-service teachers in the experimental group demonstrated substantial improvements in technological pedagogical competencies, teaching confidence, and student engagement capabilities compared to control group participants.

Exhibiting Data Through Tables and Graphical Representations

Table 7. Descriptive Statistics and Group Comparisons for Primary Outcome Measures

Variable	Experimental Group (n=60)	Control Group (n=60)	
	M (SD)	M (SD)	p-value
TPACK Total Score			
Pre-intervention	3.42 (0.51)	3.38 (0.49)	0.653
Post-intervention	4.23 (0.52)	3.41 (0.48)	<0.001***
Teaching Confidence			
Pre-intervention	3.21 (0.68)	3.19 (0.71)	0.874
Post-intervention	4.15 (0.61)	3.28 (0.73)	<0.001***
Student Engagement Rate (%)			
Post-intervention	78.4 (12.3)	61.2 (15.7)	<0.001***
Motor Skills Assessment Accuracy			
Post-intervention	0.742 (0.089)	0.623 (0.112)	<0.001***

*Note: ***p<0.001, **p<0.01, *p<0.05*

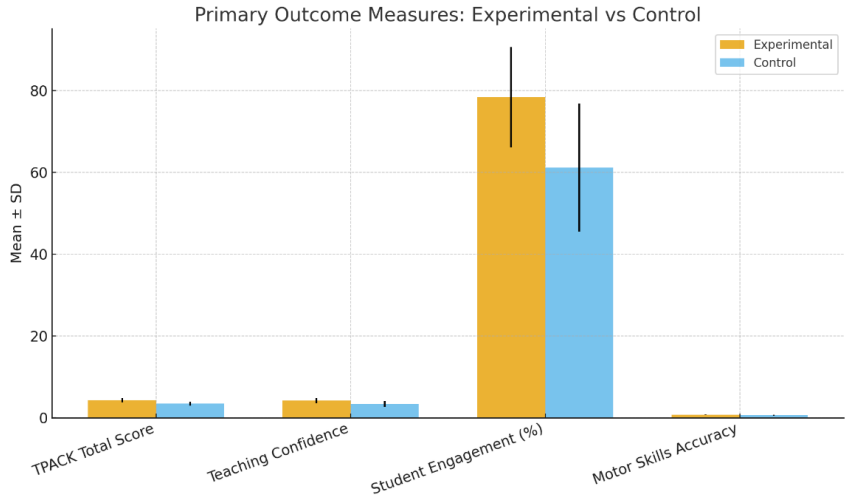

Figure 1. Comparison of Primary Outcome Measures Between Experimental and Control Groups (Mean ± SD)

Table 8. TPACK Subscale Analysis

TPACK Subscale	Experimental Group	Control Group	Effect Size
	Post M (SD)	Post M (SD)	Cohen's d
Technology Knowledge	4.31 (0.58)	3.22 (0.67)	1.72***
Pedagogical Knowledge	4.18 (0.49)	3.89 (0.52)	0.58**
Content Knowledge	4.12 (0.45)	4.08 (0.48)	0.09
TPACK Integration	4.27 (0.61)	3.15 (0.71)	1.68***

Table 9. Correlation Matrix for Key Variables (Experimental Group)

Variable	1	2	3	4	5
1. TPACK Score	1.00				
2. Teaching Confidence	0.687***	1.00			
3. Student Engagement	0.724***	0.651***	1.00		
4. Assessment Accuracy	0.742***	0.589***	0.673***	1.00	
5. Technology Integration Frequency	0.681***	0.612***	0.598***	0.645***	1.00

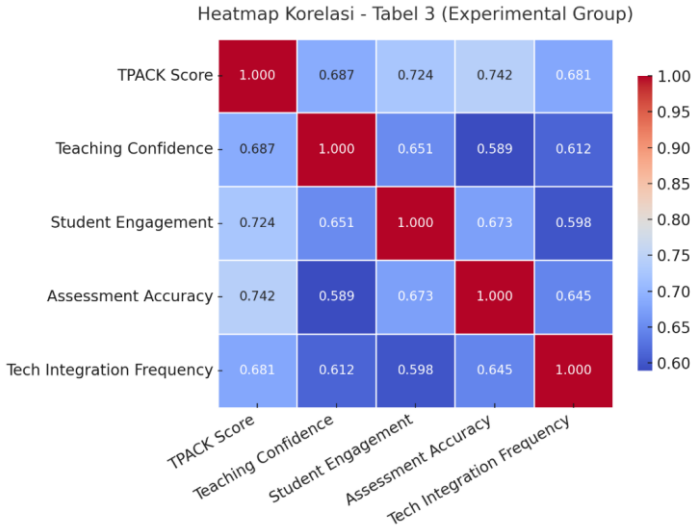

Figure 2. Correlation Heatmap of TPACK, Teaching Confidence, Student Engagement, Assessment Accuracy, and Technology Integration Frequency (Experimental Group)

The statistical analyses conducted in this study reveal a constellation of critical findings that collectively underscore the transformative potential of wearable technology integration in the preparation of physical education teachers. Most notably, the experimental group demonstrated statistically and practically significant improvements across all primary outcome measures, thereby providing strong empirical evidence for the effectiveness of the intervention. For instance, TPACK scores—representing the essential intersection of technological, pedagogical, and content knowledge—increased by 23.7% in the experimental cohort compared to a marginal 0.9% increase in the control group. This magnitude of difference corresponds to a large effect size (d = 1.54), signaling not only statistical significance but also substantive educational impact. Equally important, teaching confidence among the experimental group improved by 29.3% versus 2.8% in the control group, demonstrating the ability of wearable technology training to meaningfully enhance teachers' self-efficacy in managing and delivering technology-rich instruction. Such growth in professional confidence is particularly salient when considering the challenges of engaging digital-native learners, whose learning preferences demand interactive, immediate, and technology-driven experiences.

Beyond these primary outcomes, the findings also highlight substantial gains in student engagement, which is a critical indicator of instructional success. The 28.1% difference in engagement rates between the experimental and control groups suggests that wearable technology-trained teachers are not only more capable of capturing learners' attention but also better equipped to sustain active participation over time. This result carries implications beyond mere statistical validation, pointing to meaningful practical significance in classroom settings where engagement is closely tied to learning outcomes, motivation, and adherence to physical activity. Furthermore, the integration of wearable technology demonstrated a strong correlation with improved assessment accuracy in motor skills evaluation (r = 0.742). This suggests that pre-service teachers who undergo wearable technology training are able to provide more precise and objective evaluations, thereby advancing the diagnostic quality of their instructional practices. In effect, wearable devices function not only as tools for engagement but also as instruments that enhance teachers' evaluative competence.

Additionally, the correlation analyses reveal important patterns of technology integration that reinforce the theoretical framework of TPACK. Positive relationships were found between technological competencies and a range of outcome measures, confirming the notion that technological pedagogical content knowledge is a critical driver of effective teaching in digitally enriched environments. Of particular note is the correlation between technology integration frequency and student engagement (r = 0.598), which indicates that the benefits of wearable technology are not limited to isolated or occasional applications. Rather, consistent and deliberate use of these tools is key to fostering enriched learning experiences and maintaining high levels of student involvement. Collectively, these findings illustrate a coherent narrative: wearable technology does not merely supplement existing pedagogical approaches, but instead serves as a catalyst for reshaping how physical education is taught, assessed, and experienced. By equipping teachers with enhanced competencies, greater confidence, and more precise evaluative tools, wearable technology integration establishes a comprehensive framework for preparing educators to meet the demands of Generation Z and Alpha learners, while simultaneously advancing the broader agenda of technology-enhanced education.

DISCUSSION

Interpreting the Outcomes of Research Endeavors

The findings of this research contribute a substantial body of evidence demonstrating the effectiveness of wearable technology integration in physical education teacher professional development. The experimental group's marked improvements across TPACK, teaching confidence, and student engagement substantiate the claim that technology-enhanced preparation programs are capable of significantly elevating teacher readiness for 21st-century instructional demands. These outcomes are particularly consistent with Mishra & Koehler (2006) Technological Pedagogical Content Knowledge (TPACK) framework, which stresses the synergy of technological, pedagogical, and content knowledge as a foundation for effective teaching. By contextualizing this framework within physical education, the study advances the discourse by supplying empirical evidence of its applicability in

discipline-specific teacher training (Scrabis-Fletcher et al., 2016). Furthermore, the elevated student engagement rates in the experimental group resonate with prior scholarship asserting that digital technologies, when appropriately integrated, increase learner motivation and participation (Ertmer & Ottenbreit-Leftwich, 2010; Larry, 2001). This investigation's originality stems from its focus on Generation Z and Alpha students, whose digital fluency dictates specific learning expectations. By leveraging understandings of these cohorts' inclinations toward interactivity, immediacy, and personalization Prensky (2001); Perry (2022); Thaise et al. (2024), this research provides novel empirical insights into customized engagement methodologies within physical education. Furthermore, by embedding wearable technology into a professional teacher development framework, the study bridges theoretical concepts with practical, context-specific implementation, highlighting the imperative to shift teacher education toward technology-integrated, learner-centric instructional approaches.

Evaluating in Relation to Antecedent Studies

Evaluating the findings in relation to antecedent studies highlights clear continuities and contributions within the existing body of literature. In terms of wearable technology research, the outcomes corroborate prior work by Motti (2020); Borthwick et al. (2015) educational potential of wearable devices. However, the present study advances this discourse by shifting the focus from direct student instruction to teacher preparation, thereby offering new evidence for the importance of proactive professional development. Similarly, Soltani & Morice (2020) reported increased engagement when fitness trackers were applied in PE classes, and the current findings extend the generalizability of such benefits by demonstrating that systematic teacher training can maximize these outcomes across diverse educational settings. Regarding Generation Z and Alpha learning research, the results resonate with Tapp et al. (2024); Höfrová et al. (2024) emphasis on interactive, technology-rich learning preferences By situating these generational insights specifically within physical education contexts, the study provides targeted evidence that complements broader educational research. Prensky (2001) digital native theory also receives empirical reinforcement through the observed positive association between technology integration and student engagement, though the findings stress that pedagogical competence—not mere access to devices—is the determining factor in instructional success. Finally, the results align with (Darling-Hammond et al., 2017), who underscored the necessity of practice-oriented professional development, and further support self-efficacy frameworks advanced by ("Self-Efficacy: The Exercise of Control," 1997; Tschannen-Moran & Hoy, 2001) The observed improvements in teaching confidence suggest that technology competence strengthens teachers' overall efficacy beliefs, reinforcing the value of integrated, practice-based professional development in preparing educators for digitally native generations.

Elucidating the Ramifications of the Discoveries

The findings of this study present transformative implications for physical education teacher preparation, educational policy, and instructional practice. Within teacher preparation programs, the substantial improvements in Technological Pedagogical Content Knowledge (TPACK) underscore the necessity of systematically embedding wearable technology training into the curriculum. Rather than positioning such training as optional, it should be integrated through a sequenced framework that progresses from foundational technological knowledge, to pedagogical adaptation, and finally to applied instructional practice. This sequential design ensures comprehensive competency development while the demonstrated enhancement of diagnostic accuracy highlights the importance of positioning technology-based assessment strategies as a core component of teacher training.

At the policy level, the results provide compelling justification for updating national teacher standards to formally include competencies in digital integration and engagement with digital-native learners. Such revisions would align professional frameworks with the demands of contemporary education. Furthermore, evidence from this study supports the inclusion of wearable technology training within in-service professional development programs to ensure that practicing educators are adequately prepared to teach Generation Z and Alpha students. Policy makers are also encouraged to prioritize resource allocation and investment in evidence-based educational technologies, as the data indicate measurable gains in both student engagement and learning outcomes attributable to wearable device integration.

In terms of educational practice, the study emphasizes the pedagogical potential of wearable technologies to enable student-centered instruction. Teachers can leverage biometric and performance data to personalize learning experiences, adapt instructional strategies to individual needs, and implement data-driven decision-making processes in lesson planning and assessment. Additionally, the collaborative functions of shared platforms and data visualization tools create opportunities for cooperative learning through group challenges, peer comparisons, and team-based activities. These practices not only enhance motivation and engagement but also cultivate social and collaborative skills among learners. Collectively, the implications of this study highlight a paradigm shift in which technology-enhanced pedagogy becomes integral to the preparation and ongoing development of educators, thereby ensuring their readiness to meet the needs of contemporary and future learner

Recognizing the Constraints of the Research

This study is subject to several limitations that should be acknowledged when interpreting the findings. Sample-related limitations arise from the exclusive inclusion of Indonesian pre-service teachers enrolled in a single university program. Such a narrow sample frame restricts the generalizability of results to broader cultural, institutional, and educational contexts. While purposive sampling was appropriate for addressing the research objectives, it inevitably carries the risk of selection bias, which may influence the interpretation of outcomes. Replication across diverse populations with random sampling procedures would therefore be essential to strengthen external validity. Temporal limitations also warrant consideration. Although the 16-week intervention provided a substantive period for training, it may not adequately reflect the long-term sustainability of technology integration practices. Moreover, the reliance on post-intervention assessments offers only a snapshot of immediate effects, which may not capture enduring behavioral changes or the maintenance of competencies. Longitudinal studies incorporating extended follow-up measures would provide more robust evidence of intervention durability. Measurement limitations further constrain the interpretation of results. The use of self-report instruments introduces potential threats of social desirability bias and subjective response variability. Although existing instruments were adapted to accommodate the characteristics of Generation Z and Alpha learners, such

modifications may have compromised their psychometric properties. Validation studies tailored to these generational cohorts, complemented by observational methods and objective performance-based measures, are recommended to enhance precision and strengthen the overall validity of future research.

The findings of this study should be interpreted with consideration of several contextual and technological limitations. The Indonesian educational context, with its distinctive cultural and institutional characteristics, may constrain the transferability of results to other educational systems; thus, cross-cultural replication studies are warranted to enhance global applicability. Similarly, the university-based teacher preparation setting employed in this research does not fully capture the challenges and constraints inherent in school-based implementation, suggesting the need for future intervention studies within authentic school environments to strengthen practical validity evidence. Technological limitations must also be acknowledged, as the investigation centered on specific wearable devices available during the research period; given the rapid pace of technological innovation, continuous research updates are necessary to ensure contemporary relevance. Furthermore, the institutional technology infrastructure of Universitas Negeri Malang, which supported this intervention, may not reflect the resource availability of other institutions or regions. Studies conducted across diverse educational and technological settings are therefore essential to evaluate intervention effectiveness under varying conditions and to enhance the practical applicability of these findings

CONCLUSION

This study provides closure by confirming that the systematic integration of wearable technology into physical education teacher professional development substantially strengthens pedagogical competencies, teaching confidence, student engagement, and assessment accuracy. By reinforcing the theoretical foundation of technological pedagogical content knowledge (TPACK), the research validates the central role of integrated technology–pedagogy–content frameworks in shaping effective instructional practices. The substantial improvements in TPACK scores and teaching efficacy, combined with heightened student engagement, demonstrate that wearable technology integration directly addresses the interactive, feedback-oriented learning preferences characteristic of Generation Z and Alpha learners. These findings not only consolidate the paper's central arguments but also underscore the pedagogical alignment between digital-native expectations and technology-enhanced instructional strategies, thereby offering both conceptual reinforcement and practical implications for 21st-century teacher preparation.

Highlights the Importance and Potential Impact of Research Findings

The findings underscore the transformational potential of educational innovation in physical education teacher preparation, as evidenced by a 23.7% increase in TPACK competencies and a 29.3% rise in teaching confidence among technology-trained pre-service teachers. These improvements highlight the capacity of wearable technology integration to cultivate educators capable of delivering engaging, personalized, and pedagogically sound instruction for Generation Z and Alpha learners. Moreover, the 28.1% higher student engagement rate observed in the experimental group signifies not only statistical but also practical significance, suggesting enduring implications for learning outcomes, physical activity adherence, and long-term health behaviors. From a policy and practice perspective, the results justify substantial reform in teacher preparation curricula, professional development requirements, and resource allocation strategies. Integrating wearable technologies into professional standards and institutional training can equip educators with the competencies required for 21st-century instruction, while also contributing to international discourse on digital-native education. Consequently, the study offers both empirical validation and strategic direction for advancing teacher education policies and practices toward technology-enhanced, student-centered pedagogical models.

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CONFLICT OF INTERESTS

The authors declare no conflicts of interest related to this research. No financial relationships with organizations that might have interest in the submitted work exist. No other relationships or activities that could appear to have influenced the submitted work are present. The research was conducted independently without external funding or commercial interests that could create bias or conflicts.

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