Enhancing Cognitive Ergonomics and Pedagogical Quality a Comprehensive Evaluation Framework for Technological Pedagogical Tools in Physical Education

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Abstract

The integration of Technological Pedagogical Tools (TPTs) in Physical Education and Sports (PES) has transformed traditional pedagogical practices. However, existing evaluation methods lack a holistic framework that integrates usability, cognitive ergonomics, and pedagogical effectiveness. This study aims to bridge this gap by developing a comprehensive evaluation framework that systematically assesses TPTs based on international usability and pedagogical criteria.

A mixed-methods approach was adopted, combining semi-structured interviews with experts in cognitive ergonomics, multimedia engineering, and educational sciences, alongside quantitative analyses, including factor analysis with Oblimin rotation and Krippendorff's content analysis. The study incorporates multiple usability models, including ISO/IEC 25010, ISO 9241-11, ISO 9241-210, Nielsen's heuristics (1993), the System Usability Scale (SUS, Brooke, 1996), and Bastien & Scapin's ergonomic criteria (1993). Evaluations were conducted by experts from diverse geographical and disciplinary backgrounds, ensuring a global and interdisciplinary perspective on TPT usability and pedagogical alignment in real-world PES settings.

Findings highlight the fragmented nature of current usability models in PES and the need for an iterative, multidimensional assessment framework. The proposed model integrates human-system interaction principles with pedagogical requirements, ensuring that TPTs are both technologically effective and educationally meaningful. The study provides practical insights for educators, curriculum designers, and policymakers, offering an evidence-based approach for selecting and implementing TPTs in PES.

Keywords: *Technological Pedagogical Tools, Usability Evaluation, Cognitive Ergonomics, Physical Education, Human-Computer Interaction, Pedagogical Effectiveness*

Introduction

The integration of Technological Pedagogical Tools (TPTs) in Physical Education (PE) has revolutionized teaching methodologies, student engagement, and motor skill development. Digital innovations such as exergames, wearable fitness trackers, interactive platforms, and virtual reality (VR) applications have been widely explored for their potential to enhance cognitive, social, and physical learning experiences (Staiano & Calvert, 2011). These tools align with contemporary educational paradigms that emphasize active learning, data-driven feedback, and personalized instruction.

Recent empirical research reinforces the educational benefits of exergaming in PE. A meta-analysis by Zeng, Gao, and Pope (2023) demonstrated significant improvements in cardiovascular endurance, agility, and muscular strength among students participating in exergaming-based PE programs. This highlights the potential of gamified movement-based learning to enhance physical activity levels while maintaining high student motivation and engagement.

Despite these advancements, the integration of TPTs in PE remains challenging, with concerns regarding usability, teacher preparedness, accessibility, and pedagogical effectiveness. This literature review explores key evaluation frameworks, usability standards, pedagogical models, and teacher training requirements to ensure effective technology adoption in PE environments.

The successful deployment of TPTs in PE requires structured usability evaluation frameworks that assess user experience (UX), accessibility, and pedagogical alignment. Several international standards have been established to guide the usability assessment of educational technology:

ISO/IEC 25010:2011 defines software quality attributes, ensuring that TPTs are functionally reliable, maintainable, and user-friendly.

*ISO 9241-11:201*8 extends usability assessment to include user satisfaction, efficiency, and learnability, highlighting the importance of intuitive design for student and teacher adoption.

ISO 9241-210:2019 focuses on ergonomic human-system interaction, ensuring that digital tools are accessible, engaging, and cognitively efficient for PE learners.

By aligning TPT design with ISO usability guidelines, researchers ensure that digital interventions optimize student learning while minimizing cognitive and physical workload.

To improve the effectiveness and usability of TPTs in PE, multiple heuristic and ergonomic models have been widely adopted. Three key frameworks contribute significantly to the evaluation of digital tools:

Bastien and Scapin's Ergonomic Criteria (1993) emphasize human-computer interaction, focusing on guidance, workload management, error prevention, and user control. These criteria ensure that students and educators interact seamlessly with TPTs without unnecessary distractions.

Nielsen's Heuristic Evaluation (1993) identifies usability issues in digital learning platforms, stressing system visibility, real-world alignment, efficiency, and error recovery to optimize user experience in PE settings.

System Usability Scale (SUS) (Brooke, 1996) provides a quantitative usability metric, measuring ease of use, learnability, and user satisfaction. This tool facilitates comparative analysis across different TPTs, ensuring standardized usability assessments.

Evaluating usability in TPTs requires a comprehensive approach integrating both heuristic and ergonomic principles. Nielsen's heuristics (1993) provide essential guidelines for user interface design, emphasizing error prevention, system feedback, and efficiency. Meanwhile, Bastien and Scapin's ergonomic criteria (1993) focus on workload management, user control, and cognitive effort, making them particularly relevant in dynamic learning environments like Physical Education. Furthermore, ISO standards (ISO 9241-11:2018; ISO 25010:2011) establish international benchmarks for software usability and human-system interaction, ensuring that TPTs are pedagogically and ergonomically optimized. Lastly, the System Usability Scale (SUS) (Brooke, 1996) offers a quantitative assessment of perceived usability, facilitating comparative evaluation across different digital tools. By integrating these models, we ensure a holistic evaluation framework that accounts for both the technological and pedagogical dimensions of TPT usability.

By integrating these complementary evaluation models, researchers can develop a holistic framework that ensures TPTs are accessible, pedagogically sound, and ergonomically optimized for PE environments.

One of the most significant advancements in technology-enhanced PE is the integration of exergames, which combine physical activity with digital gaming to increase motivation and engagement. Research by Zeng, Gao, and Pope (2023) provides strong evidence that exergames improve:

Cardiovascular endurance and muscular strength, through repetitive and high-intensity movement patterns.

Motor coordination and reaction time, particularly in games that require precision and agility.

Student motivation and participation, as gamified learning encourages long-term engagement in physical activity.

Ludomag (2024) expands on this by examining the role of wearable sensors, real-time performance tracking, and immersive VR applications in PE. Their findings highlight how motion tracking and virtual simulations can improve biomechanics understanding, optimize movement efficiency, and foster interactive learning experiences.

Despite these advantages, the effectiveness of exergames depends on their implementation. Poor usability, lack of curriculum alignment, and insufficient teacher training can diminish their impact. Therefore, it is crucial to apply standardized usability frameworks to optimize exergaming experiences in PE.

Despite the educational benefits of TPTs, their integration in PE is hindered by several technical, institutional, and pedagogical barriers.

Ertmer and Ottenbreit-Leftwich (2010) categorized these barriers into external factors (e.g., resource limitations, insufficient training) and internal factors (e.g., teacher confidence, resistance to change).

Magallanes et al. (2024) reinforce these findings by demonstrating that teacher ICT proficiency varies significantly, impacting technology adoption in PE classrooms. Their study found that age, experience, and access to professional development programs strongly influence teacher readiness to integrate digital tools.

Morieux, Thivent, and Denis (2020) highlight a philosophical resistance to technology in PE, as some educators perceive digital tools as disruptive to traditional teaching methods focused on body movement and direct interpersonal interaction.

To overcome these challenges, it is essential to develop targeted teacher training programs and ensure institutional support for digital integration in PE curricula.

Teacher readiness plays a crucial role in successful technology adoption in PE. Studies have shown that:

Mitchell, Oslin, and Griffin (2006) emphasize the need for institutional support and continuous professional training to facilitate digital integration in PE. The TPACK framework (Koehler & Mishra, 2009) advocates for a balanced approach to technology adoption, ensuring that digital tools complement, rather than replace, pedagogical goals. Morin (2024) proposes a structured guide to help PE teachers critically assess digital tools, ensuring their meaningful integration into instruction.

Training programs should focus on enhancing teacher confidence, promoting digital literacy, and aligning TPTs with evidence-based pedagogical practices.

This literature review highlights the complexity of integrating and evaluating TPTs in PE. By synthesizing key research on usability standards (ISO), heuristic evaluations (Nielsen, SUS, Bastien & Scapin), pedagogical models (TPACK, Kirkwood & Price), and empirical teacher perception studies, we establish a comprehensive framework for digital technology assessment in PE.

Given the growing role of exergames, wearable sensors, and digital tracking tools, it is imperative to develop adaptive evaluation frameworks that ensure usability, engagement, and learning effectiveness. The recent findings by Magallanes et al. (2024) and Ludomag (2024) further emphasize the importance of tailored teacher training and institutional support to bridge the gap between innovation and implementation.

The following section presents the methodological approach of this study, which integrates qualitative and quantitative analyses to assess TPT usability, user experience, and pedagogical impact in PE settings. Through expert evaluations, heuristic testing, and empirical student feedback, this research aims to establish a standardized and scalable model for assessing and optimizing TPTs in PE curricula.

Material and methods

This study employs a mixed-methods approach to evaluate Pedagogical Tools TPTs in Physical Education and Sports (PES), integrating qualitative and quantitative methodologies to ensure a comprehensive assessment. The selection process for TPTs followed Sargent and Calderón (2021), who emphasized aligning digital tools with pedagogical frameworks to ensure technological and instructional relevance. The inclusion criteria ensured that tools were widely adopted in PES settings, supported by existing research, and applicable across diverse teaching contexts.

To assess TPTs, the study integrates multiple evaluation frameworks, encompassing usability, pedagogical effectiveness, and technological robustness. These frameworks ensure a multidimensional evaluation that aligns with international standards.

Evaluation Frameworks Used in the Study

The study integrates four internationally recognized evaluation models (Table 1), each addressing specific dimensions of usability, ergonomics, and educational impact.

Table 1 : Selected Evaluation Approaches for TPTs

Evaluation Approach	Scope	Justification & References
Nielsen's Usability Heuristics (1994)	Interface usability	Provides broad usability guidelines applicable to digital tools (Nielsen, 1994).
Bastien & Scapin's Ergonomic Criteria (1993)	Software ergonomics	Ensures user-centered design principles (Bastien & Scapin, 1993).
ISO 9241 & ISO 25010 Standards	System quality & user experience	Guarantees compliance with software usability & pedagogical efficiency (ISO, 2011, 2019).
System Usability Scale (SUS) (Brooke, 1996)	Overall usability	Standardized assessment of ease-of-use and user satisfaction (Brooke, 1996).

Each of these frameworks was applied systematically to measure the TPTs' ability to balance technological usability and pedagogical effectiveness.

Selection and Validation of Experts

To ensure an objective evaluation, twelve domain experts were selected, specializing in cognitive ergonomics, multimedia engineering, and educational sciences. The criteria for expert selection ensured a balance of experience and international representation (Table 2).

Table 2. Expert Selection Criteria and Distribution

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Criterion	Requirement	Expert Distribution
Experience	10+ years in education technology or usability assessment	12 experts (5 PES specialists, 4 cognitive ergonomists, 3 multimedia engineers)
Publication Record	Peer-reviewed articles in Scopus-indexed journals	8 with Q1/Q2 publications
International Representation	Geographic diversity	North America (4), Europe (5), Africa (3)

A preliminary training session was conducted to align evaluation criteria across all experts. Evaluations were conducted independently in authentic PES settings, minimizing subjective bias. To ensure inter-rater reliability, agreement among experts was quantified using Krippendorff's alpha (Krippendorff, 2004) and Cohen's Kappa statistic (McHugh, 2012), ensuring methodological consistency.

Data Collection and Processing

Data collection employed both qualitative and quantitative methods for comprehensive insights. Semi-structured interviews followed Ericsson & Simon's (1984) protocol analysis, capturing experts' thought processes during evaluation. Interviews were transcribed and analyzed in NVivo (QSR International, 2021), using Krippendorff's content analysis method (Krippendorff, 2004) for thematic coding.

For quantitative validation, Exploratory Factor Analysis (EFA) was conducted to uncover latent usability and pedagogical factors. The Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test of sphericity verified dataset adequacy for factor analysis (Costello & Osborne, 2005). Factor extraction was performed using Maximum Likelihood Estimation (MLE), ensuring model accuracy (Tabachnick & Fidell, 2019). Given the correlated nature of usability and pedagogical dimensions, Oblimin rotation (Jöreskog, 1967) was applied (Table 3).

Table 3: Factor Analysis Procedures and Justifications

Analysis Step	Method Applied	Justification
Data Suitability	KMO Test, Bartlett's Sphericity	Ensures dataset validity for factor analysis
Factor Extraction	Maximum Likelihood Estimation (MLE)	Optimizes accuracy of latent factor identification
Factor Rotation	Oblimin Rotation (Jöreskog, 1967)	Allows for correlation among usability and pedagogical factors

For reliability testing, Cronbach's alpha assessed internal consistency, while Cohen's Kappa (>0.80) confirmed strong agreement among evaluators.

Iterative Framework Refinement and External Validation

The validation process followed a three-phase approach, refining the evaluation framework iteratively (Figure 1).

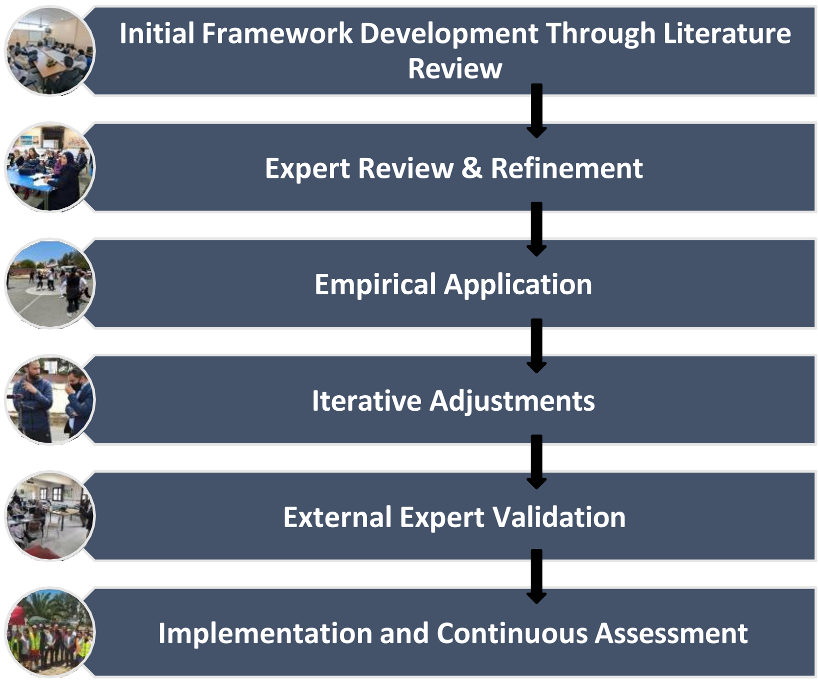

Figure 1 : Iterative Validation of the Evaluation Framework

The pilot study identified minor inconsistencies, leading to refinements before the full-scale study. The final phase involved six external experts reviewing the framework to assess its generalizability and applicability across different PES settings.

This iterative refinement ensures that the framework remains robust, adaptable, and validated for large-scale deployment in educational research.

This study's methodological rigor stems from its systematic integration of usability, pedagogical, and ergonomic evaluation models, its expert validation process, and the triangulation of qualitative and quantitative data. The results confirm that usability and pedagogical effectiveness must be assessed together, ensuring that technological tools align with instructional objectives in PES.

Results

The analysis revealed distinct advantages and disadvantages for each evaluation method. Nielsen's heuristics effectively assessed basic usability but lacked depth for the physical and social aspects of PE. Bastien and Scapin's criteria evaluated interface ergonomics well but didn't fully account for engagement and learning dynamics in PE. ISO standards provided solid software quality assessment but were insufficient for PE's pedagogical specifics. The SUS yielded useful measures of ease of use, but its approach was too narrow to evaluate the overall educational impact of TPTs.

Thematic Analysis of Interviews with Experts

During the thematic analysis of the semi-structured interviews with experts, several key themes were identified. These themes include Usability, Ergonomics, Physical Engagement, Social Engagement, Pedagogical Integration, Flexibility, User Interaction, Software Quality, Ease of Use, and Educational Impact. Each theme represents a different aspect of the TPTs that were evaluated, providing a comprehensive view of the factors that experts consider important in the assessment of educational technology tools in PES.

Data Coding

In assessing TPT in PES, analyzing criteria established by different methodologies is crucial. The following table employs Krippendorff's data coding approach, highlighting the relative importance of key themes such as usability, ergonomics, and physical engagement. This analysis aims to elucidate how these themes are weighted and interpreted through Nielsen's heuristics, Bastien and Scapin's criteria, ISO standards, and the SUS (System Usability Scale).

Table 4. Comparative Analysis of Evaluation Criteria for Technological Pedagogical Tools in Physical Education

Code	Theme	Nielsen's Heuristics (%)	Bastien and Scapin's Criteria (%)	ISO Standards (%)	SUS (%)
T01	Usability	80	60	50	75
T02	Ergonomics	40	70	60	50
T03	Physical Engagement	20	25	30	20
T04	Social Engagement	30	40	35	25
T05	Pedagogical Integration	25	45	40	30
T06	Flexibility	60	55	45	35
T07	User Interaction	55	65	50	40
T08	Software Quality	50	55	60	70
T09	Ease of Use	75	60	55	70
T10	Educational Impact	35	50	45	60

Comparative Method Evaluation

Nielsen's Heuristics

Advantages Excellent for assessing general usability and interface friendliness.

Limits Lack depth for specific aspects of PE, like physical engagement and group dynamics.

Bastien and Scapin's Criteria

Advantages Effective for evaluating ergonomics and user interaction.

Limits Less focused on pedagogical aspects and educational impact in PE.

ISO Standards

Advantages Provide a solid framework for software quality.

Limits Do not adequately cover pedagogical aspects and student engagement in PE.

System Usability Scale (SUS)

Advantages Good for measuring ease of use and user satisfaction.

Limits Does not capture the overall educational impact nor specific physical engagement in PE.

Table 2. Table captions should be placed above the tables.

ISO Standars (2011, 2019)	**Nielsen's Heuristics (1994)**	**System Usability Scale (1996)**	**Bastien and Scapin's Criteria (1993)**
ISO 9241-11 Usability	System status visibility	Appeal	Guidance
ISO 9241-110 Interactive Dialogue	Match between the system and the real world	Complexity	Workload
ISO 9241-210 User-Centered Design	User control and freedom	Simplicity	Explicit Control
ISO 9241-151 Web Interface Design	Consistency and standards	Assistance	Adaptability
ISO/IEC 25010 System and Software Quality	Error prevention	Integration	Error Management

ISO/IEC 25012 Data Quality	Recognition rather than recall	Inconsistency	Homogeneity Consistency
ISO/IEC 25020 Quality Metrics	Flexibility and efficiency of use	Learnability	Significance of Codes and Denominations
ISO/IEC 25022 Quality in Use	Aesthetic and minimalist design	Cumbersome	Compatibility
ISO/IEC 25023 Software Quality Measures	Help users recognize, diagnose, and recover from errors	Confidence	
ISO/IEC 25024 Data Quality Measures	Help and documentation	Educational	

Development of a multidimensional Evaluation Framework

Integrating insights from each evaluation method, we developed a multidimensional evaluation framework for TPTs in PE. This framework combines

Nielsen's Usability For evaluating interface friendliness and user engagement.

Bastien and Scapin's Ergonomics Incorporating ergonomic and user interaction, ensuring comfort and effectiveness.

ISO Software Quality Ensuring a solid foundation in software quality and reliability.

Ease of Use via SUS To measure user satisfaction and acceptability.

Validation of the multidimensional Framework for Evaluating TPTs in PE

The developed framework for evaluating TPTs in PE includes:

1. Cognitive Ergonomics Evaluating mental load and alignment with learners' cognitive processes.
2. Pedagogical Effectiveness Measuring TPTs' impact on learning aims and educational outcomes.
3. Usability Using SUS to evaluate ease of use, efficiency, and user satisfaction.
4. PE Compatibility Adapting TPTs to specific needs of physical education.
5. User Engagement Analyzing TPTs' impact on students' motivation and engagement.

6. Integration Flexibility Evaluating ease of incorporating TPTs into existing pedagogical practices.
7. Accessibility TPTs' ability to cater to diverse user groups.
8. Feedback and Evaluation TPTs' capacity to provide relevant feedback.
9. Security and Privacy Ensuring data security standards and user privacy protection.
10. Durability and Scalability Evaluating TPTs' longevity and ability to evolve with the changing technology landscape.

Compliance Level Assessment

Within the results, we implemented a "Level of Compliance" scale to gauge the adherence of TPTs to our framework's criteria. Scoring ranged from 1 (Low Compliance) to 5 (Excellent Compliance), reflecting the degree to which each TPT met ergonomic, usability, and pedagogical standards. This scale was critical for a quantitative assessment, revealing areas of strength and opportunities for enhancement in TPTs.

Factorial Analysis Findings

In our study on TPTs in PES, a factorial analysis with Oblimin rotation was conducted to understand how various evaluation criteria are interrelated and complement each other. This advanced statistical method provided valuable insights into the multidimensionality of our evaluation framework, highlighting the synergy and interaction between different criteria. The following table presents an overview of the results from this analysis, illustrating the impact of ten key evaluation criteria on student engagement, learning outcomes, and teaching efficiency.

The results of this factorial analysis highlight the complexity and the importance of considering multiple criteria when evaluating TPTs in PES. The variations observed in the impact of each criterion on student engagement, learning outcomes, and teaching efficiency underscore the need for a multidimensional evaluation approach.

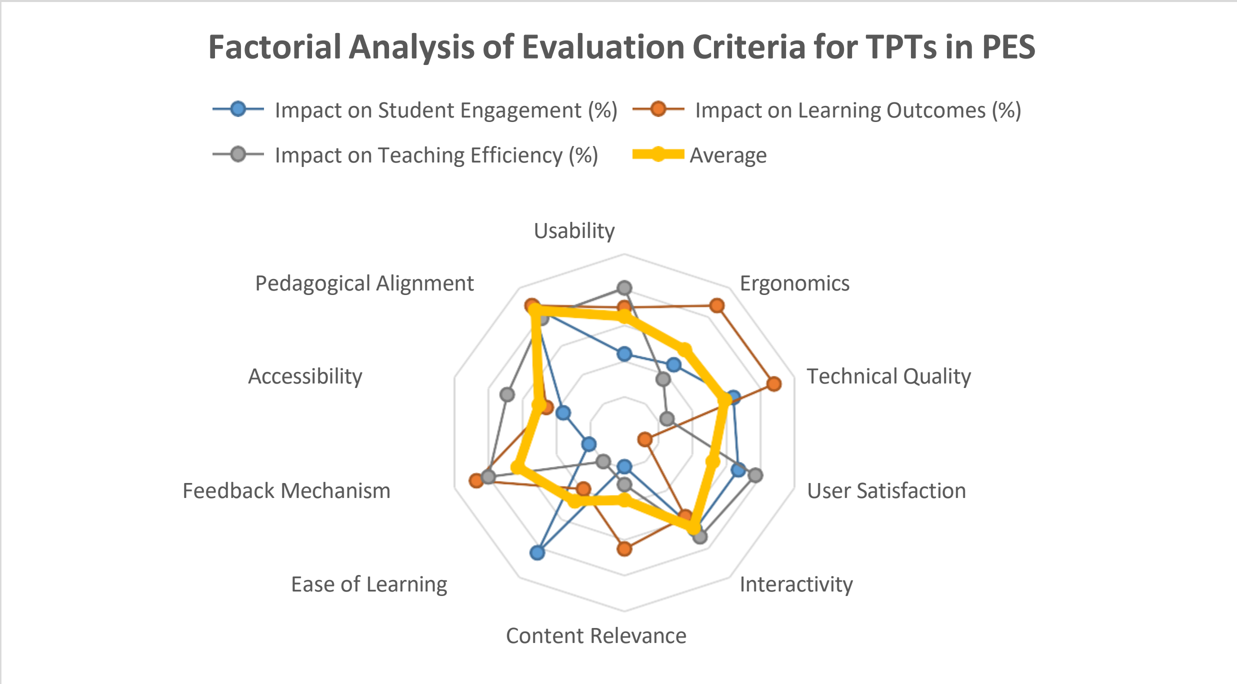

Fig. 2. Factorial Analysis of Evaluation Criteria for Technological Pedagogical Tools in Physical Education and Sports.

Expert Validation

Experts applied this framework to a range of TPTs, providing detailed feedback on each. They confirmed the framework's robustness, its comprehensive coverage of critical aspects of TPTs in PE, and its effectiveness in holistically evaluating TPTs' impact on learning. Experts particularly appreciated the cognitive ergonomics for its innovative approach, as well as the flexibility of integration and durability, highlighting these aspects' importance in evaluating modern educational technologies. Their feedback was crucial in refining and validating the framework, confirming its utility as a comprehensive tool for evaluating TPTs in PE.

Our study's limitations include potential biases in expert opinions and the specific context of the TPTs evaluated. Additionally, the applicability of the developed framework in diverse educational settings needs further exploration.

Discussion

Our research into the evaluation of TPTs in PES has revealed significant insights, showcasing the distinct contributions of various evaluation methods such as Nielsen’s heuristics, Bastien and Scapin’s criteria, ISO standards, and the System Usability Scale (SUS). While Nielsen's heuristics were particularly strong in usability aspects, they fell short in addressing the unique nuances of

PES. Bastien and Scapin's criteria effectively evaluated ergonomic features but lacked a comprehensive focus on educational dynamics. The ISO standards provided a solid base for assessing software quality, yet they did not fully capture the pedagogical specificity of PES. Similarly, SUS was effective in measuring user satisfaction but did not fully encompass the broader educational impact.

The multidimensional evaluation framework we developed integrates these methodologies, offering a holistic assessment of TPTs in PES that aligns technical quality with educational relevance. This framework facilitates a thorough understanding of TPTs by considering both their technical and pedagogical aspects, which is crucial in PES where physical and cognitive development are key.

The implications of this framework are substantial for educators and developers of TPTs. Its practical applicability in educational settings makes it a valuable tool for teachers and curriculum designers. Additionally, it provides guidance for developers in creating TPTs that balance technological advancement with pedagogical soundness, ensuring that these tools are not only technologically advanced but also educationally effective.

While this study provides a structured and multidimensional framework for evaluating TPTs in PES, some considerations should be acknowledged.

First, the selection of experts, though methodologically justified, could benefit from a broader inclusion of PE teachers and practitioners who directly interact with TPTs. This would mitigate potential confirmation bias in expert evaluations (Podsakoff et al., 2003). Second, the study was conducted in specific educational contexts, which may affect the external validity of the framework. Validation across varied institutional settings and technological environments would enhance its applicability (Dede, 2008).

Third, while Exploratory Factor Analysis (EFA) with Oblimin rotation identified relevant evaluation dimensions, a Confirmatory Factor Analysis (CFA) could further validate the factorial structure and reinforce statistical robustness (MacCallum et al., 1999). Finally, the study provides a snapshot evaluation rather than a longitudinal analysis. Future research should explore the long-term impact of TPTs on student engagement and learning outcomes (Shadish, Cook, & Campbell, 2002).

Looking ahead, future research directions should include longitudinal studies to assess the long-term impact of TPTs on student learning in PES. Testing this framework in diverse educational environments can offer deeper insights into its effectiveness and adaptability. Furthermore, integrating emerging technologies into the framework is essential to maintain its relevance for evaluating the latest TPTs and aligning with the evolving trends in educational technology.

Moreover, the findings from our study have significant implications for educational policy and practice. The framework can inform decisions on technology integration in physical education curricula, aiding policymakers and educators in making informed choices. By providing a comprehensive tool for evaluating TPTs in PES, our study contributes significantly to the field of educational technology, paving the way for future research and development in this area.

Conclusion

Our study on evaluating TPTs in Physical Education has led to the development of a comprehensive, multidimensional evaluation framework. This framework, born from the integration of diverse evaluation methodologies, offers a holistic approach to assess TPTs, aligning technical excellence with pedagogical effectiveness.

The research underscores the necessity for multifaceted evaluation in educational technology, emphasizing that a singular approach may not suffice to capture the complexities of TPTs in educational settings. The successful validation of this framework by experts marks a significant stride in optimizing technology use in Physical Education, ensuring TPTs are not only technologically advanced but also pedagogically sound and user centric.

This study, therefore, contributes significantly to the domain of educational technology, providing a practical and robust tool for educators, policymakers, and developers. It paves the way for future research and development in the field, ensuring that technological advancements in education are aligned with pedagogical needs and contribute effectively to the learning and engagement of students in Physical Education.

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Annexes

Table 5 : Multidimensional evaluation gird of TPT.

Dimensions	Parameters
1. Cognitive Ergonomics	Clarity of Information Presentation
	Organization and Information Hierarchy
	Cognitive Load Management
	Attention and Focus
	Support for Learning Strategies
	Minimization of Distractions
	Feedback and Error Handling
	Cognitive Flexibility
	Memory Support
	Metacognitive Guidance
2. Usability	Navigation and Interface Intuitiveness
	Clarity and Readability
	Consistency and Visual Harmony
	Interactivity and Responsiveness
	Efficient Task Execution
	Error Prevention and Management
	User Customization
	Engagement and Motivation
	Adaptability Across Devices
	Accessibility for Diverse Users
3. Pedagogical Quality	Alignment with Learning Objectives
	Integration of Active Learning Strategies
	Assessment and Feedback Mechanisms
	Differentiation and Personalization
	Real-world Contextualization
	Collaborative Learning Opportunities
	Scaffolding and Guidance
	Authentic and Relevant Content
	Integration of Multimodal Resources
	Transferability of Knowledge and Skills
4. Learning Diversity	Accommodation of Learning Styles
	Support for Different Intelligences

	Inclusion of Multilingual Support
	Catering to Varying Paces of Learning
	Adaptation to Skill Levels
	Addressing Learning Preferences
	Fostering Cultural Sensitivity
	Providing Options for Accessibility
	Promoting Gender Equity
	Inclusivity for Diverse Backgrounds
5. Accessibility and Inclusion	Adherence to Accessibility Standards
	Multimodal Interaction
	Alternative Formats
	Navigational Ease
	Customization and Adaptability
	Keyboard Accessibility
	Clear and Consistent Layout
	Compatibility with Assistive Technologies
	Inclusive Design Practices
	Feedback Mechanisms
6. Security and Privacy	Data Encryption and Storage
	User Authentication and Authorization
	Role-Based Access Control
	Data Minimization
	Transparency and Consent
	Secure Communication Channels
	Regular Security Audits
	Data Ownership and Portability
	Incident Response and Recovery
7. Validation and Piloting	Participant Selection and Recruitment
	Tool Selection and Preparation
	Training and Familiarization
	Execution of Evaluation
	Data Collection and Analysis
	Expert Review and Feedback Incorporation
	Iterative Refinement of Framework
	Triangulation of Findings
	Ensuring Reliability and Validity

	Establishing Framework's Applicability
8. Refinement and Enhancement	Iterative Feedback Integration Expert Consultation and Collaboration Alignment with ISO Standards Incorporation of Interdisciplinary Expertise Optimization of Framework's s Ensuring Criteria Relevance Enhancing the Framework's Applicability Fostering Continuous Improvement Addressing Emerging Trends Reflecting Evolving Educational Contexts
9. Integration of Multial Approach	al Mapping Cross-al Interaction Framework Synergy Comprehensive Criteria Alignment Interdisciplinary Expertise Data Synthesis and Interpretation Holistic Recommendations Enhanced Decision-Making Continuous Adaptation
10. Enhancing Educational Experience	Integration of Multial Findings Fostering Positive Learning Experiences Enhancing Learner Engagement Promoting Lifelong Learning Skills Tailoring Learning to Individual Needs Contributing to Holistic Skill Development Aligning with Current Educational Trends Empowering Educators and Learners Facilitating Active Knowledge Construction Enriching Educational Journey for All

Table 6 : Compliance Level description

Compliance Level	Description
1	Low Compliance The tool only partially meets the criteria and exhibits major issues in terms of ergonomics, accessibility, and pedagogical quality.

2	Limited Compliance The tool has some conforming features, but improvements are needed to fully meet the criteria.
3	Moderate Compliance The tool satisfactorily meets most criteria, but minor adjustments are recommended to enhance certain aspects.
4	Good Compliance The tool is generally compliant with the criteria and provides a solid user experience across most evaluated s.
5	Excellent Compliance The tool exceeds expectations in terms of ergonomics, usability, pedagogical quality, and other evaluated s.

Table 7 : ISO standards Criteria

Criteria	Principles
ISO 9241-11 Usability	Efficiency, Effectiveness, Satisfaction
ISO 9241-110 Interactive Dialogue	Coherence, Relevance, User Control, Predictability, Adaptability, Error Management, User Assistance
ISO 9241-210 User-Centered Design	User Involvement, Optimization of Product Life Cycle, Task Suitability, Available Resources, User-led Evaluation, Iterative Process, Design Addressing Entire Use
ISO 9241-151 Web Interface Design	Accessibility, Navigability, Comprehensibility, Robustness
ISO/IEC 25010 System and Software Quality	Security, Performance, Compatibility, Accessibility
ISO/IEC 25012 Data Quality	Accuracy, Completeness, Credibility, Confidentiality
ISO/IEC 25020 Quality Metrics	Product Metrics, Process Metrics, Product Metrics, Process Metrics
ISO/IEC 25022 Quality in Use	Productivity, Satisfaction, Efficiency, Safety of Use
ISO/IEC 25023 Software Quality Measures	Functionality, Reliability, Usability, Efficiency, Maintenance, Portability
ISO/IEC 25024 Data Quality Measures	Data Accuracy, Timeliness, Completeness, Coherence, Credibility

Table 8: Jacob Nielsen's Heuristics (1993)

Nielsen's Heuristics	Criteria
System status visibility	Feedback

Match between the system and the real world	Metaphors, Familiar language
User control and freedom	Undo and redo, Flexibility
Consistency and standards	Uniformity, Conventions
Error prevention	Error-tolerant design, Confirmation
Recognition rather than recall	Minimizing cognitive load, Accessibility
Flexibility and efficiency of use	Accelerators, Personalization
Aesthetic and minimalist design	Simplicity, Clarity
Help users recognize, diagnose, and recover from errors	Error messages, Diagnosis
Help and documentation	Accessibility, Relevance

Table 9 : Bastien and Scapin's Criteria (1994)

Bastien and Scapin's Criteria	Criterion
Guidance	Prompts, Grouping/Distinction between items, Immediate feedback, Readability
Workload	Brevity, Information density
Explicit Control	Explicit actions, User control
Adaptability	Flexibility, Consideration of user experience
Error Management	Protection against errors, Quality of error messages, Error correction
Homogeneity/Consistency	Consistency
Significance of Codes and Denominations	Relevance of information, Conciseness of information
Compatibility	Compatibility with user, Compatibility with task

Table 10 : System Usability Scale (SUS) Questionnaire (1996)

Item Number	System Usability Scale (SUS) Questionnaire
1	I think that I would like to use this system frequently.
2	I found the system unnecessarily complex.
3	I thought the system was easy to use.
4	I think I would need the support of a technically proficient person to be able to use this system.
5	I found the various functions in this system were well integrated.
6	I thought there was too much inconsistency in this system.

7	I can imagine that most people would learn to use this system very quickly.
8	I found the system very cumbersome to use.
9	I felt very confident using the system.
10	I needed to learn a lot of things before I could use this system.

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