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DIGITAL TECHNOLOGIES FOR EMERGENCY RESPONSE IN OUTDOOR AND MOUNTAIN SETTINGS: A SYSTEMATIC REVIEW USING SWIM

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ABSTRACT

Chronic Digital technologies such as wearable devices, unmanned aerial vehicles (UAVs), and e-learning platforms are increasingly applied to enhance safety and emergency response in outdoor and mountain environments. However, evidence regarding their effectiveness, feasibility, and implementation remains limited and scattered across disciplines. This systematic review aimed to synthesize current findings on digital technologies supporting emergency preparedness and response in outdoor activities. Following the PRISMA 2020 guidelines, a comprehensive search was conducted across PubMed/MEDLINE, Scopus dan sciencedirect, including grey literature, for studies published up to October 30, 2025. Eligible studies examined (a) wearable or mobile-based fall detection systems, (b) UAV-based search-and-rescue (SAR) applications, or (c) e-learning interventions for rescue personnel. Two reviewers independently performed study selection and data extraction. Risk of bias was appraised using appropriate tools according to study design (QUADAS-2, JBI, and MMAT). Due to heterogeneity and the small number of studies, a narrative synthesis approach following the SWiM framework was applied. Out of 161 records identified, three studies met the inclusion criteria. One simulation-based study on wearable fall detection reported 97.9% sensitivity and 99.9% specificity in recognizing fall events with real-time location tracking. A feasibility study demonstrated the operational potential of UAVs in avalanche search-and-rescue scenarios but lacked standardized performance indicators. An e-learning intervention among rescuers showed significant improvement in knowledge retention, especially among professionals compared to volunteers after 12 months. Overall, the methodological quality of included studies was moderate to low. Digital technologies show promising potential to improve emergency preparedness and response in outdoor and mountain settings. Nonetheless, the evidence remains preliminary due to limited sample sizes, heterogeneous designs, and simulation-based validation.

Keywords: E-learning; emergency preparedness; search and rescue; unmanned aerial vehicles; wearable electronic devices

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INTRODUCTION

Outdoor recreational activities, including mountain climbing and hiking, are increasingly popular as forms of leisure and physical exercise worldwide. However, mountain environments present unique challenges characterized by extreme temperatures, geographic isolation, dynamic terrains, and limited communication infrastructure. These conditions significantly elevate the risk of medical emergencies, ranging from hypothermia and traumatic injuries to respiratory complications and (Oshiro & Murakami, 2022). The remote nature of mountain settings demands rapid responses and well-coordinated emergency interventions to prevent serious complications and ensure patient . In this complex context, advances in digital technology offer promising opportunities to enhance emergency detection, monitoring, and response mechanisms, enabling more precise and timely interventions than traditional approaches.

Recent technological innovations have transformed mountain emergency care capabilities. Wearable sensor devices—including inertial measurement units (IMUs) and in-ear monitors—enable continuous physiological monitoring and automated event detection (such as fall identification), which can trigger real-time notifications and location tracking for rescue teams (Bagalà et al., 2012; Wu et al., 2015). Unmanned aerial vehicles (UAVs/drones) have expanded search and rescue (SAR) capabilities in challenging terrains, including snowy and remote areas where conventional access is difficult or impossible (Guzzi et al., 2024; Messmer et al., 2024). Furthermore, digital learning interventions and e-learning platforms target the enhancement of knowledge and preparedness among rescue personnel for critical scenarios in the field (Karnjuš et al., 2023). Complementing these advances, low-power communication technologies and wide area networks (LPWAN) enable the transmission of essential data even in regions with limited infrastructure (Garg et al., 2021; Lodewyk et al., 2025).

Despite ongoing advancements, scientific evidence evaluating the performance, implementation readiness, and practical challenges of these technologies in mountain emergency settings remains scattered and heterogeneous. Previous reviews have predominantly focused on isolated technology domains (e.g., wearable devices alone or exclusively rescue personnel training), leaving gaps in the understanding of the cross-platform effectiveness of these integrated systems. Current literature lacks a comprehensive synthesis of detection accuracy, operational SAR performance metrics, knowledge retention among rescue personnel, and evidence-based implementation barriers across technology clusters. There is a critical need for a systematic mapping of evidence integrating findings among these three technology clusters. The primary focus is on the practical implications for nurses and emergency medical personnel in field triage and sensor-based decision-making.

This review aims to (i) identify and evaluate evidence regarding the utilization of wearable devices, UAV platforms for SAR, and e-learning in supporting safety and emergency response in outdoor/mountain activities; (ii) synthesize findings related to key performance outcomes (e.g., fall detection accuracy, UAV operational metrics, and changes and retention of rescuer knowledge); and (iii) elaborate on opportunities and implementation challenges relevant to emergency nursing practice in the field. This review emphasizes practical consequences for nurses including device interoperability requirements, reliability in extreme conditions, and digital competency standards as the foundation for future research recommendations and service adoption.

METHOD

Reportingframework.

This review follows the 2020 PRISMA guidelines (Page et al., 2021), with search strategy reporting adhering to PRISMA-S; no protocol registration was performed.

Eligibility criteria (PICOS)

The PICOS framework (Population, Intervention, Comparator, Outcome, Study Design) was used to specify eligibility criteria (Higgins & Thomas J, 2024). The targeted population included individuals involved in outdoor/mountain activities—such as hikers and mountaineers—as well as rescue personnel operating in these contexts. The evaluated interventions or technologies comprised three clusters: first, wearable devices for fall event detection/monitoring; second, unmanned aerial vehicles (UAVs) for search-and-rescue (SAR) operations; and third, digital learning (e-learning) interventions for rescuers. Comparators could be routine practice or no comparator, given the anticipated study design variability.

Primary outcomes were pre-specified for each cluster: for wearables, these included sensitivity, specificity, false alarm rate, and notification latency; for UAVs, operational feasibility and standardized performance indicators where available—such as time-to-locate and search coverage; for e-learning, changes in pre–post knowledge scores and follow-up retention. Eligible study designs consisted of empirical primary studies, including diagnostic/engineering accuracy (wearables), feasibility/prototype studies (UAVs), and non-randomized pre–post intervention studies (e-learning). Publication range was restricted to 2015–30 October 2025, with no language limitations as long as translation was feasible. Research settings were required to be relevant to safety and emergency response in outdoor/mountain/remote environments. Included publications were peer-reviewed journal articles or peer-reviewed proceedings/Procedia presenting adequate methodological details.

Information sources
Electronic searches were conducted in PubMed/MEDLINE, Scopus, and ScienceDirect, as well as backward–forward citation tracking of included studies. The last search was performed on 30 October 2025.

Search strategy
The search strategy combined controlled vocabulary and free-text terms, reviewed by a librarian. An example PubMed query is provided; the full search strategy (with field tags, limits, and line numbering) is available in Supplement 1 (PRISMA-S). (("wearable devices"[MeSH] OR wearable* OR "fall detection" OR IMU OR "in-ear sensor" OR "mobile application*" OR app OR "unmanned aerial vehicle*" OR UAV OR drone* OR "e-learning" OR "online training") AND (mountain* OR outdoor* OR hiking OR mountaineer* OR alpine OR avalanche) AND (emergency OR "search and rescue" OR SAR OR safety OR "first aid")) Duplicates were removed using [Mendeley] with the Bramer de-duplication approach, followed by manual verification.

Selection process
Two reviewers independently screened titles/abstracts and full texts against eligibility criteria. Discrepancies were resolved by discussion or third-reviewer adjudication when necessary. The PRISMA diagram summarizes identification, screening, eligibility, and inclusion stages (records identified: 161; studies included: 3). Cohen's kappa was calculated on a random subset to assess reviewer agreement at the title/abstract screening stage (Cohen, 1960)

Data collection process
A standardized extraction form was piloted prior to implementation in accordance with mandatory Cochrane requirements (Higgins & Thomas J, 2024). Two reviewers independently extracted data using a dual independent review process to ensure accuracy and minimize random error in screening (Stoll et al., 2019): study ID, country/setting, participant characteristics, intervention/technology specifications (sensor type, algorithm/wireless/Bluetooth technology platform), comparator (if present), outcome and measurement window, main results (including 95% CI, if available), funding/conflict of interest (COI), and practical implementation notes (e.g., battery requirements, network connectivity, operational safety). Retraction screening and detection of multiple reports for the same cohort were performed using standard protocols to identify duplicate publications and plagiarism (Minetto et al., 2023; Xu et al., 2025); for overlapping data, the most complete report was prioritized and cross-referenced to avoid data duplication bias in synthesis. Disclosure of conflict of interest and funding sources was systematically documented per International Committee of Medical Journal Editors (ICMJE) guidelines (Solberg, 2023) to evaluate sponsor bias in wearable technology or SAR platform studies.

Risk of bias in individual studies
Given design heterogeneity, risk-of-bias assessments were performed specific to each design by two independent reviewers, with consensus resolution: QUADAS-2 for diagnostic accuracy/wearable device studies (Whiting et al., 2003); ROBINS-I (with JBI quasi-experimental items) for non-randomized pre–post intervention studies (e-learning) (Munn et al., 2019; Sterne et al., 2016); MMAT/JBI for feasibility/prototype studies (UAV). Domain-level summaries are presented in Supplement 2 and narratively in the Results section (Nha HONG et al., 2018)

Synthesis methods

Due to the heterogeneity of interventions, designs, and outcomes, and limited study numbers (k=3), meta-analysis was not performed. Synthesis followed the Synthesis Without Meta-analysis (SWiM) framework with pre-specified clusters: (1) wearable, (2) UAV, (3) e-learning. For each cluster, pre-defined primary outcomes were prioritized; effect direction and magnitude were summarized in tables and narratively. Small-study effects and funnel plots were not conducted (k<10). Where available, study estimates with 95% CI were reported.

Additional analyses (pre-specified)

Sensitivity and subgroup analyses were planned a priori as per protocol to explore sources of heterogeneity and assess meta-analysis robustness, according to (Deeks JJ et al., 2024) in the Cochrane Handbook. If ≥2 studies were available per cluster, planned analyses included: Sensitivity analysis: Following (Higgins, 2012) on "incorporating risk of bias assessments into meta-analyses," studies with high risk of bias (high RoB) would be excluded to assess whether conclusions remain robust to differing methodological quality. This procedure aligns with methodological standards (Rao et al., 2017) emphasizing sensitivity analysis as a key strategy for exploring heterogeneity due to different methodological decisions. Subgroup analysis: (Richardson et al., 2019) provides comprehensive guidance on "interpretation of subgroup analyses in systematic reviews," suggesting that analyses by study characteristics (e.g., professionals vs. volunteers in e-learning) can identify potential effect modifiers. (Rao et al., 2017) likewise emphasize that a priori planned subgroup analysis is a critical strategy to "explore statistically significant heterogeneity based on underlying study level differences." These analyses help explore study heterogeneity and challenge assumptions about effect variation across subpopulations. However, these analyses could not be realized in the final dataset due to insufficient study numbers within each cluster to permit meaningful statistical analysis.

Certainty of evidence

Certainty of evidence was qualitatively evaluated per five core GRADE domains, as described by (Guyatt et al., 2008) in the Cochrane Handbook: risk of bias, inconsistency, indirectness, imprecision, and publication bias. For each cluster, limitations in study design and execution were appraised using the approach developed by (Balshem et al., 2011) in "GRADE guidelines: 3. Rating the quality of evidence." The GRADE framework, adopted by over 110 international academic, professional, and governmental organizations, was followed as described by (Brignardello-Petersen & Guyatt, 2025) in "Assessing the certainty of the evidence in systematic reviews: importance, process, and use." This qualitative evaluation considered risk of bias via methodological appraisal, imprecision in effect estimates, and indirectness in applying results to this context. Formal GRADE tables were not required by the target journal; thus, key considerations from the certainty of evidence assessments are reflected narratively in the Discussion section, per Cochrane Collaboration recommendations. This evaluation process ensures transparency and systematic confidence appraisal in effect estimates, following GRADE's definition that "certainty of evidence reflects the extent to which we are confident that an estimate of effect is correct," as articulated in the GRADE Handbook edited by (Guyatt et al., 2008).

RESULT

Literature Search

An electronic search was conducted in PubMed/MEDLINE, Scopus, and ScienceDirect, yielding 161 unique records. After screening titles/abstracts and full texts, 3 studies met the inclusion criteria: one wearable fall detection study (Tseng et al., 2025), one UAV SAR prototype study (Janovec et al., 2022), and one e-learning intervention for rescuers (Podsiadło et al., 2018). The PRISMA diagram is presented in Figure 1.

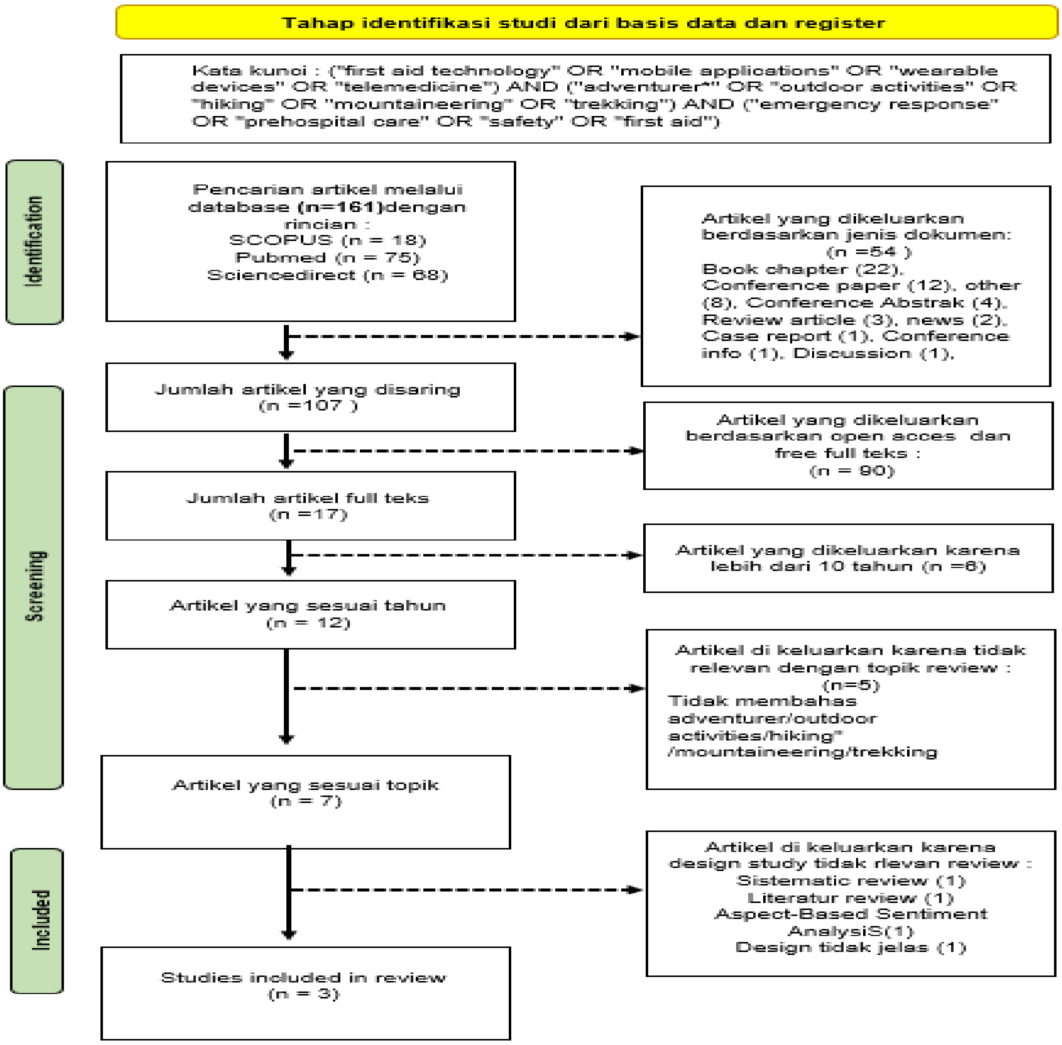

Figure 1. PRISMA Flow Diagram

Study Characteristics

A summary of study characteristics is presented in Supplement 3. The studies originated from diverse contexts: wearable testing was conducted in a simulated environment (Tseng et al., 2025) a UAV SAR prototype was assessed under alpine conditions (Janovec et al., 2022), and a multi-site e-learning module was implemented for rescuers (Podsiadło et al., 2018). All studies employed non-randomized or prototype designs with small to medium sample sizes. Outcomes evaluated aligned with each cluster's focus: sensitivity/specificity (wearables), operational feasibility (UAVs), and Δ knowledge/retention (e-learning).

Risk of Bias

Methodological quality was assessed according to study design:

Wearable: QUADAS-2 → low risk for index/reference; applicability concern due to simulation.

- UAV: MMAT/JBI → low to moderate risk; outcome metrics not reported.
- E-learning: ROBINS-I/JBI → moderate risk due to non-randomized pre–post design and attrition.

Domain-level judgments are available in Supplement 2.

Table 1.
Study Quality Appraisal Table

Study	Design	Appraisal Tool	Domains Evaluated	Summary of Judgement
Tseng et al., 2025 – Wearable Fall Detection System with Real-Time Localization	Diagnostic / Prototype	QUADAS-2	Patient selection; index test; reference standard; flow and timing	Low risk in index test & reference standard; high concern regarding applicability (simulation setting only).
Podsiadło et al., 2018 – Emergency E-learning for Mountain Rescuers	Quasi-experimental (pre–post)	ROBINS-I / JBI Quasi-Experimental	Bias due to confounding; participant selection; classification of intervention; outcome measurement; missing data	Moderate risk overall. Main issues: non-randomized design and lack of blinded outcome assessment.
Janovec et al., 2022 – UAV-based Search and Rescue System	Feasibility / Prototype	MMAT (Mixed Methods Appraisal Tool)	Study rationale; methodological coherence; integration of data sources; interpretation of results	Low–moderate risk; technical feasibility clear; lack of standardized outcome metrics (e.g., no “time-to-locate”).

Narrative Synthesis (SWiM)

Cluster 1: Wearable Fall Detection

(Tseng et al., 2025) employed a wearable prototype with 15 participants and 6,750 labeled windows (6,000 ADL, 750 simulated falls). The wearable system, integrating IMU, GPS, and NB-IoT, demonstrated 97.9% sensitivity, 99.9% specificity, and 99.7% accuracy, including real-time location notification capabilities. These findings indicate effective fall detection in simulation; however, field validation and implementation in target populations, such as older adults, are still required.

Cluster 2: UAV Search-and-Rescue

(Janovec et al., 2022) evaluated a UAV prototype in an avalanche environment. The multirotor UAV was equipped with an avalanche finder and FPV camera. The study demonstrated operational feasibility, but standard performance metrics, such as time-to-locate or search coverage, were not reported. These results highlight the potential of UAVs to accelerate SAR operations, but quantitative evidence is limited and underscores a research gap regarding standardized outcomes.

Cluster 3: E-learning for Mountain Rescuers

(Podsiadło et al., 2018) conducted a quasi-experimental pre–post evaluation among 187 rescuers (136 volunteers, 51 professionals) utilizing an e-learning module on hypothermia. Results showed a significant knowledge increase immediately after training ($p<0.001$), with 12-month retention better among professionals than volunteers. These findings affirm the short-term effectiveness of e-learning, while long-term retention among volunteers suggests a need for reinforcement (booster) interventions.

Cross-Cluster Synthesis

Overall, digital technologies demonstrate potential to support emergency response in outdoor and mountain environments. Wearables are effective in simulations; UAVs have proven operational feasibility but lack standardized quantitative outcomes; e-learning increases rescuer knowledge, with retention depending on professional status. Key evidence gaps include the need for standardized outcomes and field validation for UAVs, real-world validation for wearables, and long-term control and evaluation for e-learning interventions among volunteers. Certainty of evidence was rated low to moderate due to non-randomized/prototype study designs and small sample sizes.

Table 2.
Characteristics of Included Studies

Study (Author, Year)	Country / Setting	Design / Sample	Intervention / Technology	Comparator	Outcomes	Key Findings	Limitations	Risk of Bias
Tseng et al., 2025	Outdoor simulation	Prototype; 15 participants	Wearable (IMU + GPS + NB-IoT, FSM)	None	Sensitivity, Specificity, Accuracy	Sensitivity 97.9%, Specificity 99.9%, Accuracy 99.7%, real-time notification	Simulation-only, small sample, not tested in elderly or real-world	QUADAS-2: Low risk index/reference ; applicability concern
Janovec et al., 2022	Avalanche site, Slovakia	Prototype / feasibility	UAV multirotor + avalanche finder + FPV	None	Operational feasibility	Feasible; improved search speed vs traditional methods	No standardized metrics, small pilot, limited weather testing	MMAT/JBI: Low–moderate concerns (metrics not reported)
Podsiadło et al., 2018	Mountain rescue multi-site	Quasi-experimental pre–post; 187 rescuers	E-learning module (hypothermia)	None	Knowledge, 12-month retention	Knowledge increased ($p<0.001$); retention better in professionals	No control group, attrition, knowledge-only outcomes	ROBINS-I/JBI: Moderate risk (confounding, measurement)

DISCUSSION

This systematic review evaluated three categories of digital technology supporting emergency response in outdoor and mountain activities: wearable fall detection, UAVs for search-and-rescue (SAR), and e-learning for rescuers (Janovec et al., 2022; Podsiadło et al., 2018; Tseng et al., 2025). Wearable devices demonstrated high fall detection effectiveness in simulations (Tseng et al., 2025), UAVs showed operational feasibility but lacked standardized quantitative outcomes (Janovec et al., 2022), and e-learning improved rescuer knowledge with better long-term retention among professionals compared to volunteers (Podsiadło et al., 2018). These findings confirm the potential of digital technologies to enhance safety and response effectiveness in the field, although empirical evidence remains limited.

Across clusters, wearable devices were effective under simulated conditions, UAVs demonstrated operational feasibility without standardized performance metrics, and e-learning significantly increased knowledge, though long-term retention among volunteers indicates a need for reinforcement interventions (Podsiadło et al., 2018). Key evidence gaps include the need for standardized outcomes and field validation for UAVs (Janovec et al., 2022), real-world validation for wearables (Tseng et al., 2025), and long-term controlled evaluation of e-learning, especially for volunteers (Podsiadło et al., 2018). Certainty of evidence was rated low to moderate due to non-randomized or prototype study designs and small sample sizes. Strengths of this review include adherence to PRISMA 2020 standards (Page et al., 2021), use of SWiM for narrative synthesis (Campbell et al., 2020), and risk of bias assessment tailored to study design (Sterne et al., 2016; Whiting et al., 2003)

Limitations: Several limitations should be acknowledged. First, the number of included studies was very small (k=3), limiting generalizability. Second, heterogeneity in design, setting, and outcomes across studies constrained quantitative synthesis or meta-analysis. Third, most studies were simulation- or prototype-based, so real-world evidence remains limited (Janovec et al., 2022; Tseng et al., 2025). Fourth, standardized outcomes were not always available, particularly for UAV studies, limiting objective evaluation of technology effectiveness. From a practical perspective, integration of wearables, UAVs, and e-learning can strengthen triage, monitoring, and coordination of medical or rescue teams in the field (IAEA, 2021; WHO, 2020). Future research should focus on field validation, outcome standardization, and long-term effectiveness evaluation to optimize implementation.

Implications for Nursing Practice

The findings of this review highlight several important implications for nursing practice, particularly for nurses involved in outdoor, remote, and mountain emergency response services. First, the demonstrated accuracy of wearable fall-detection technologies suggests that nurses can benefit from integrating sensor-based monitoring into early triage processes. Continuous physiological monitoring and automated fall alerts with real-time geolocation can reduce the time needed to identify injured individuals, support rapid assessment, and guide targeted deployment of rescue teams. These technologies may strengthen nurses' decision-making in prehospital care by providing objective data related to patients' movement, falls, and potential trauma mechanisms.

Second, the operational feasibility of UAV-based search-and-rescue systems emphasizes the need for nurses to develop competencies in interpreting drone-assisted surveillance data. UAVs can extend the visual and thermal search range in difficult terrains, allowing nurses to collaborate more efficiently with rescue personnel. Incorporating UAV-generated location markers, victim identification cues, and environmental assessments into prehospital triage may reduce delays in patient contact and enable earlier initiation of life-saving interventions such as airway management, bleeding control, or hypothermia prevention.

Third, the demonstrated effectiveness of e-learning for improving knowledge and long-term retention among rescuers underscores the importance of digital learning methods in preparing nurses for emergency situations. Nurses working in mountain rescue contexts require continuous professional development due to the dynamic nature of environmental risks. E-learning allows flexible, scalable, and repeated training on critical topics such as hypothermia management, trauma care in remote settings, communication protocols, and navigation of digital tools (wearables/UAVs). Booster sessions may be particularly important for volunteer rescue nurses to sustain competence over time.Overall, the integration of wearable technologies, UAV systems, and e-learning platforms into nursing roles in mountain and outdoor environments may enhance situational awareness, improve early detection of emergencies, and strengthen the coordination between nurses and rescue teams. As digital technologies continue to evolve, emergency nurses are expected to develop technical literacy, data-interpretation skills, and adaptability to emerging digital tools. These implications support the development of competency-based training frameworks and evidence-based guidelines for digital-assisted rescue nursing practice in remote and high-risk environments.

CONCLUSION

Wearable fall-detection systems, UAVs for search-and-rescue operations, and e-learning for rescuers demonstrate strong potential to enhance safety and improve the effectiveness of emergency response in outdoor and mountain environments. However, the current evidence remains limited and largely indicative. Field validation, the use of standardized performance metrics, and long term evaluation of educational interventions are required to confirm their effectiveness and support the adoption of these technologies in real world practice.

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