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Modern Solutions to Old Problems: A Review of Emerging Digital Technologies in Post-Stroke Neurorehabilitation

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ABSTRACT

Introduction. Stroke is one of the leading causes of chronic disability worldwide. Conventional rehabilitation frequently faces challenges regarding accessibility, high costs, and difficulties in sustaining patient motivation. These constraints often lead to insufficient training intensity, thereby limiting therapeutic efficacy. Consequently, exploring alternative therapeutic solutions is necessary to enhance clinical outcomes.

Aim. This review evaluates the effectiveness of Virtual Reality (VR), Augmented Reality (AR), Robotic-Assisted Training (RAT), and telerehabilitation in post-stroke recovery.

Methods. A search of PubMed, Web of Science, and Google Scholar was conducted. Included were randomized controlled trials, systematic reviews, and meta-analyses examining digital technologies in neurorehabilitation.

Results. VR and AR improve motor and cognitive functions via immersive feedback. RAT proves effective in delivering high-intensity practice, particularly for lower limb mobility in severe cases, though its superiority over conventional therapy for upper limbs remains inconclusive. Telerehabilitation offers accessibility comparable to face-to-face therapy but relies heavily on patient adherence.

Conclusions. Digital technologies address traditional limitations by enabling high-dosage, engaging training that facilitates functional recovery. Future research should focus on optimizing protocols and integrating these solutions into long-term plans.

Keywords: neurorehabilitation, stroke, virtual reality, robotic-assisted training, telerehabilitation

INTRODUCTION

Stroke remains one of the leading causes of mortality and chronic disability worldwide, affecting approximately 17 million individuals annually. (1) It is defined as an acute state of cerebral blood flow disruption that causes a sudden neurological impairment. Key risk factors include hypertension, obesity, diabetes, dyslipidemia, cardiac arrhythmias, a sedentary lifestyle, and nicotine use. (2–4) The complications of stroke are varied and involve motor skills disruptions, such as balance disorders, paresis, or hemiplegia, as well as cognitive disabilities manifesting as deficits in attention, memory, and executive functions. This urges the need for providing immediate and persistent rehabilitation, considering that the first two months after the stroke are the most important in determining long-term therapeutic outcomes. (2,3,5)

Traditional neuropsychological rehabilitation, however, frequently faces challenges such as high costs, a shortage of specialists, and difficulties in sustaining patient motivation and long-term engagement. Conventional rehabilitation methods frequently lack personalization and may not fully address the unique needs of individual stroke survivors. Moreover, the reliance on therapist-led sessions often imposes logistical constraints, such as transportation difficulties for patients with severe mobility impairments, thereby limiting the frequency of crucial practice sessions. (6–8) The monotonous nature of traditional exercises can also contribute to adherence barriers due to decreased patient motivation and a lack of immediate feedback, making it difficult for patients to adjust training techniques and track progress effectively. (9,10) The inherent physical and financial burdens placed on both patients and the healthcare system necessitate the exploration of innovative technologies that could improve therapeutic outcomes. For instance, conventional rehabilitation often lacks the objective, quantitative metrics necessary to finely tune therapy intensity and measure subtle improvements in motor control, which are critical in the chronic recovery phase. (10,11)

In recent years, new digital solutions have emerged in modern neurorehabilitation, offering promising avenues to overcome the limitations of conventional therapy. These include robotic-assisted training (RAT), virtual reality (VR) and augmented reality (AR), and various telerehabilitation technologies. The digital nature of these tools allows for their integration with existing rehabilitation protocols to achieve better therapeutic outcomes. Specifically, these systems can provide gamified, engaging, and highly repetitive training environments, which are essential for neuroplasticity and functional recovery. (12,13) This review aims to provide a comprehensive summary of the clinical effectiveness of modern rehabilitation technologies in post-stroke patients.

METHODOLOGY

The study was conducted using PubMed, Web of Science, and Google Scholar based on searching the following keywords: “neurorehabilitation”, “telerehabilitation”, “virtual reality”, “augmented reality”, “artificial intelligence and rehabilitation”, “robotic-assisted rehabilitation”, “digital technologies in rehabilitation”. The search included randomized controlled trials, systematic reviews, and meta-analyses that examined the use of different digital rehabilitation strategies in post-stroke patients. Exclusion criteria eliminated non-English publications, case reports, and studies of low methodological quality.

RESULTS

1. Virtual Reality and Augmented Reality

VR and AR are technologies that emerged in the late 20th and early 21st centuries. Although they both use sensors to project an interactive image, they differ in a way that impacts their therapeutic utility. VR generally refers to a system that generates an immersive, fully artificial environment, while AR overlays digital images onto real-world surroundings. (14,15)

The most prominent area of research is the application of AR/VR technology to develop interactive motor training systems. These systems, based on well-established physiotherapeutic exercises, aim to create a comfortable, personalized, and rewarding therapeutic process. This may prove particularly beneficial for patients with cognitive impairment following a stroke, where traditional physiotherapy often requires intense supervision by professionals to be effective. (16) These technologies allow for immersive, task-specific training that is easier to comprehend, leading to enhanced motor learning and improved cognitive engagement that promotes neuroplasticity. (8,17) This heightened engagement is achieved through the integration of intuitive and interactive game elements designed to provide immediate, understandable feedback and allow for precise difficulty tailoring. This mechanism is crucial for maintaining patient motivation and adherence to training protocols. (18,19) Similar strategies have been used successfully in postoperative physiotherapy and in pediatric populations. (20)

VR can be useful in simulating complex activities of daily living, such as cooking and shopping, thus helping patients to regain functional independence in a safe and controlled environment. (21) A notable application, VR mirror therapy, leverages visual feedback in order to stimulate motor cortical areas, facilitating functional recovery in hemiparetic limbs post-stroke. (22) Meta-analyses of randomized controlled trials have established that VR interventions are effective for improving upper limb motor function and performance in daily activities, providing a small but significant benefit when combined with traditional methods. (23) For instance, a comparative study demonstrated that 84% of patients receiving immersive VR training achieved clinically relevant improvements in upper extremity function, significantly outperforming electromechanically assisted training, where only 50% showed similar gains. (24) Furthermore, evidence suggests that combining VR with non-invasive brain stimulation can lead to substantial improvements in upper limb motor function. (25) A systematic review and meta-analysis of VR interventions revealed significant improvements across various motor function assessments, including the Fugl-Meyer Assessment of Upper Extremity, Action Research Arm Test, and Wolf Motor Function Test, as well as improvements in functional ambulation, balance, and daily living activities. (26) This comprehensive meta-analysis, involving 87 studies and 3540 participants, underscores the broad utility of VR in restoring diverse physical capabilities after stroke. A separate systematic review focusing on immersive VR with head-mounted displays also reported benefits in functional ability measures like the functional independence measure, Barthel Index, and improvements in strength and balance outcomes. (27) Research further distinguishes effectiveness between different VR modalities, with non-immersive gaming systems like Microsoft Kinect demonstrating superior efficacy in enhancing upper limb motor function compared to other non-immersive and immersive head-mounted devices. (28)

AR, while often considered more technologically intricate than VR, has shown considerable promise. Its application extends beyond the upper limbs, with systematic reviews confirming significant improvements in balance and gait function for stroke survivors. (29) A randomized controlled trial by Lin et al. highlighted that mirror therapy combined with AR was particularly beneficial for enhancing upper limb motor and sensory function, while AR alone proved more effective for improving balance and functional mobility. (30)

Emerging evidence from systematic reviews indicates that VR can also yield significant improvements in cognitive functions frequently affected by stroke, such as unilateral spatial neglect, attention, and higher executive functions. (1,31) Preliminary results from meta-analyses indicate small to medium effects for cognitive outcomes ($g = 0.41$; 95% CI: 0.28–0.55; $p < 0.01$). (1) Recent reviews further support VR's potential for cognitive rehabilitation across various neurological conditions, emphasising its immersive and interactive nature in addressing memory and attention deficits. (32) A pilot study by Jonsdottir et al. also described the effectiveness of VR for augmenting motor and cognitive abilities in the chronic phase of stroke, both in clinical settings and for long-term maintenance of functional mobility at home. (33) Moreover, studies suggest that VR may additionally reduce symptoms of anxiety and depression, frequently present in stroke patients. (8,19)

Current research suggests that these immersive systems are advantageous in activating key neural networks, such as the mirror neuron system, by providing varied, multisensory feedback to the patient. This, in turn, promotes a balanced, functional recovery. (1,34,35) This sensory experience can be enhanced through the integration of haptic devices. For example, an AR-based smart glove system was found to be superior to time-matched conventional therapy for improving upper extremity motor function in chronic stroke patients. (36). Meta-analyses confirm that the combination of these technologies is more effective in upper limb function recovery than VR alone. (35)

The increasing affordability and decreasing technological barriers could facilitate the widespread clinical adoption of these solutions. Crucially, the adaptable nature of this technology brings vast possibilities in combination with other modern therapeutic solutions, such as robotics and telerehabilitation. This enables the delivery of supervised and accessible therapy directly to patients' homes, overcoming the mobility barriers affecting stroke survivors. (35)

2. Gait-Triggered Mixed Reality Treadmills

An innovative application of AR/VR technology involves combining it with sensor-equipped treadmills to create a single system. This solution integrates a physical treadmill with projected visual cues and virtual environments that react in real time to the patient's movements, thereby forming a powerful tool for individualized, task-specific training. Similar solutions have been used in the treatment of children with cerebral palsy with promising results. (37) Multiple randomized controlled trials have demonstrated that this form of augmented feedback, which can directly project virtual obstacles or foot placement targets onto the treadmill belt, is more effective than standard treadmill training for enhancing mobility. Specific benefits in chronic stroke patients included significant improvements in the Berg Balance Score, walking speed, and obstacle-crossing abilities. (38–41) Studies also suggest that combining VR with treadmill training may be more effective in improving cognitive outcomes compared to treadmill training alone, particularly regarding information processing speed, attention level, and verbal fluency. (42)

An additional benefit of these exercises, facilitated by stabilization belts and integrated safety features, is the creation of controlled environments where patients can comfortably train for the challenges they face in everyday life. This safe and repeated practice of complex walking tasks has been shown in landmark trials to improve real-world mobility and reduce the incidence of falls in populations with neurological deficits. (43) This solution is particularly adept at dual-task performance, as it requires the simultaneous management of motor functions and processing visual information. Systematic reviews show that this approach is more beneficial for training walking ability under cognitively demanding conditions. (44) The inclusion of error feedback can further induce motor adaptation by compelling patients to correct gait deviations, such as step-length asymmetry, to navigate the virtual challenges successfully. (45)

Neuroimaging studies provide clues into the underlying mechanisms, with evidence from functional near-infrared spectroscopy demonstrating that multi-task performance during walking induces greater prefrontal cortex activation. As this area of the brain is crucial for executive functions and motor planning, its increased activation shows promise for further research and clinical implementation. (46) The gamified and interactive nature of these exercises enhances patient motivation and adherence, leading to more intensive training - a critical factor for improving therapeutic outcomes in stroke patients.

However, some studies suggest that VR treadmill training may not always be superior to non-VR methods, as comparable results are often reported for improving overall walking ability between the two groups. (29) This suggests that further research is needed to establish the optimal application of VR treadmill training in specific subgroups of post-stroke patients.

3. Robotic-Assisted Rehabilitation Devices

RAT has emerged as one of the most dynamically evolving tools of modern neurorehabilitation. It encompasses a range of devices, including ground exoskeletons, end-effector devices, and wearable exoskeletons, aimed at improving motor functions. (47) These devices produce precisely controlled motion exercises to the extremities, with the possibility of adjusting the speed, range, resistance, and difficulty level while providing continuous real-time feedback to the patient. This has a crucial meaning in improving neuroplasticity by enhancing neuronal reorganization. The main advantage of RAT is that it induces highly repetitive, precise movements with accurate control and prolonged endurance, which are frequently impossible to achieve via traditional neurorehabilitation alone due to decreased muscle strength in post-stroke patients. (48–52) It also requires a significantly lower engagement of the physiotherapist, making it possible for the patient to train independently, therefore being more cost-effective in the long term while maintaining therapeutic intensity. (52)

Robotic gait training devices have been developed to address lower extremity dysfunction and improve ambulatory function in stroke patients. End-effector systems, such as the Morning Walk device, provide knee, ankle, and pelvic movements through footplate trajectories and have proved to be effective in improving walking ability in subacute stroke patients. In a trial by Lee et al., the patients trained robotically achieved greater distances during therapeutic sessions, particularly those with severe mobility limitations. The average walking distance per session for the robotic group was nearly three times greater than in the control group, where only conventional physiotherapy was used. (52) Another trial, which also examined the effects of RAT on post-stroke mobility using an overground robotic exoskeleton, showed comparable improvements in walking ability between RAT and conventional training. However, it also noted that the patients requiring continuous assistance during ambulation exhibited significantly greater results in overall mobility, highlighting the potential of RAT usage in this group. (53) A study conducted by Yu et al. observed that the group that received RAT exhibited increased motor-evoked potentials and improved sensorimotor function measured by the Fugl-Meyer Assessment scale compared to the control group, who only underwent conventional training. Importantly, this improvement was significantly greater in the active group, in which the movements were only partially assisted by the robots, in relation to the passive group, in which RAT fully replaced the patient's movements. This finding has substantial clinical significance, as it demonstrates that active engagement during robotic training optimizes neuroplastic changes. Additionally, neuroimaging revealed significantly enhanced brain activation in the affected motor cortex, specifically in the active training group, indicating favorable cortical reorganization that was not observed in the passive training modality. (54) Unilateral lower-limb exoskeleton robots have been specifically designed for patients with hemiplegia. A randomized controlled trial using a unilateral lower-limb exoskeleton RAT demonstrated significant improvements in balance and gait functions compared to traditional physiotherapy. Interestingly, analysis using near-infrared spectroscopy documented that RAT induced neural activation in the ipsilesional motor and prefrontal cortices that correlated with the improvements in motor skills. (51) Several randomized controlled trials have also reported the superiority of RAT over conventional rehabilitation for the lower limb in the group of acute or subacute stroke patients. (55,56) Further high-quality research is required to confirm the effectiveness of RAT in rehabilitation among specific subgroups of post-stroke patients.

Studies comparing the effectiveness of RAT and conventional training for upper limb rehabilitation in stroke patients often yield inconclusive results. Numerous randomized controlled trials show no statistically significant changes in the motor improvements of the arm between these methods, suggesting that they are comparable in effectiveness. (48,49,57) However, one of these trials found that RAT was superior to traditional rehabilitation in improving lower limb function. (48) A study by Takebayashi et al. additionally isolated and examined a group of participants remaining after excluding those who performed less than 80% of the scheduled training. This group had significant increases in motor capability after RAT in relation to the control group, who performed traditional rehabilitation solely. (57) In contrast, a randomized controlled trial involving over 300 patients using a robotic hand exoskeleton demonstrated significant improvements in clinical motor outcomes accompanied by enhanced cortical excitability. The robotic-therapy group showed significantly greater improvements in Fugl-Meyer scale scores and wrist motor function compared to conventional therapy, implying that this may be attributed to improved neuroplasticity induced by RAT. (58) Despite these promising findings, the evidence on RAT's superiority over conventional therapy for upper limb motor function improvement remains inconclusive, requiring further research. (48,49,57)

4. Telerehabilitation

Telerehabilitation has emerged as a promising solution that utilizes information and communication technologies to provide rehabilitation care remotely. It uses a wide array of media, including telephone-based coaching, videoconferencing, or smartphone applications, via which rehabilitation can be provided to the patient. It also encompasses innovative devices based on VR, AR, or RAT. Telerehabilitation protocols usually consist of home-based structured programs that involve periodic contact with a clinician for progress monitoring and exercise instruction. This approach enhances the availability of rehabilitation for individuals with limited access to traditional face-to-face therapy, thereby addressing the shortage of rehabilitation therapists and long waiting times for appointments that may disrupt training regularity and consequently reduce its effectiveness. (5,37)

Recent randomized controlled trials have demonstrated that telerehabilitation offers comparable effectiveness to conventional face-to-face therapy in terms of improving balance, overall motor function, autonomy in daily activities, and upper limb function. (59–61) These interventions usually include monitoring the patient's training via videoconferencing, as well as VR, RAT, or computer game-assisted systems. (62) Dance therapy delivered through telerehabilitation platforms has also shown promise, with a pilot study reporting significant improvements in trunk control and balance in stroke patients. Importantly, regarding trunk improvement, the telerehabilitation-based dance therapy was non-inferior to conventional methods. (63) On the other hand, a randomized controlled trial by Saywell et al. indicated that telerehabilitation using readily available technology did not yield a statistically significant benefit in physical function compared to usual care. Furthermore, any modest improvements observed in the telerehabilitation group were not sustained at the 12-month follow-up. However, a per-protocol analysis, focusing on participants who adhered to more than 50% of the intervention, revealed a significant improvement in physical function. This discrepancy between the intention-to-treat and per-protocol analyses underscores the critical role of patient adherence in determining the outcomes of telerehabilitation interventions, highlighting the importance of strategies to promote sustained patient motivation. (64)

Telerehabilitation has also proven effective in addressing cognitive impairments commonly observed after stroke. Current research suggests that it significantly increases memory, attention, promotes problem-solving capabilities and executive functions, and may bring a reduction in depressive symptoms, with results being similar to those achieved by traditional methods. (65–67)

An important consideration in terms of telerehabilitation is patient adherence. On one hand, the combination of technology, such as VR or exergames, with a familiar home environment can make the rehabilitation experience more enjoyable than conventional therapy, therefore improving patient compliance. (68–70) However, the absence of direct in-person supervision inherent in remote settings can pose significant challenges to maintaining patient motivation. (71) This necessitates proactive strategies such as regular virtual clinician-patient interactions, real-time feedback and dynamic adjustment of exercise difficulty to ensure compliance. (72) Moreover, the lack of technological familiarity, particularly among the elderly, can pose a barrier to their participation in telerehabilitation programs. Therefore, implementation of intuitive, elderly-friendly telerehabilitation systems is necessary to attempt their widespread adoption in this group of patients. (73)

5. Games and Their Effect on Neuroplasticity

The integration of game-based systems, including serious games and VR, into stroke rehabilitation protocols represents a significant advancement in leveraging neuroplasticity for motor recovery. (17) A primary mechanism through which these technologies aid neural reorganisation is by enhancing patient motivation and adherence, leading to a higher dosage of rehabilitative therapy than what is often achievable through conventional methods. (59)

This increased volume of practice is a fundamental driver for experience-dependent plasticity, the brain’s intrinsic ability to reorganise itself by forming new neural connections in response to learning and activity. (74) Game-based interventions are uniquely designed to embed the core principles of motor learning - such as providing repetitive practice with clear goals, immediate feedback, and increasing levels of difficulty. (17,75) Evidence from neuropsychological and neuroimaging studies confirms that this form of enriched training can induce tangible plastic changes in the prefrontal cortex. (46) For instance, a preliminary video game-based rehabilitation program for upper limbs in chronic stroke patients has been shown to produce significant changes in corticospinal excitability and promote a beneficial shift in the motor map topography within the affected hemisphere, which is a direct indicator of functional cortical reorganisation. (76) A study that investigated an interactive telerehabilitation system based on Kinect camera technology in chronic stroke survivors found significant improvements in Berg Balance Scale and Timed Up and Go test scores in the group using the telerehabilitation device compared to traditional face-to-face rehabilitation. This correlated with greater independence in mobility and a reduced risk of falling. (60) The effectiveness may be particularly pronounced when applied during a critical time window post-stroke, a period when the brain is most receptive to activity-dependent reorganization, though benefits can still be observed in a longer timeframe. (77) These systems incentivize high-volume, intensive practice of specific movements essential for re-establishing and strengthening neural pathways that were damaged or rendered inefficient by the stroke. (59) Therefore, game-based rehabilitation moves beyond being a mere motivational tool; it functions as a sophisticated delivery system for structured, intensive, and feedback-driven training designed to specifically target and harness the brain’s capacity for use-dependent neuroplasticity, ultimately enhancing functional motor outcomes for stroke survivors. (17)

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Despite the promising advancements in digital therapeutics, the field faces significant limitations and safety concerns that must be addressed. Most importantly, these technologies frequently rely on expensive stationary equipment, which restricts their widespread clinical accessibility.

In the context of AR/VR, further research is needed to identify the most effective components of these systems. Although non-immersive systems like Microsoft Kinect have shown superior efficacy for upper limbs compared to some head-mounted displays, the rapid evolution of immersive technology may change this landscape. (28) Future studies should investigate the specific impact of immersion levels on cognitive load and motor learning, particularly in patients with post-stroke cognitive deficits. (16) Additionally, while VR treadmill training improves gait and dual-task performance, some trials report results comparable to non-VR methods. This points to a conclusion that the gamification element needs to be carefully designed so it does not become a distraction but remains a functional tool. (29,44) Moreover, considering that neuroimaging studies using functional near-infrared spectroscopy have shown promise in mapping prefrontal cortex activation during these tasks, future research should use these tools to provide an objective, biological marker of recovery during VR training. (46) Another important constraint related to the use of AR/VR is that patient eligibility for these interventions may be restricted, as they often require specific cognitive capabilities or are designed exclusively for particular limb impairments. (78)

Regarding RAT, while evidence suggests its superiority in improving walking distance and mobility in patients with severe limitations, its advantage over conventional therapy for upper limb motor function remains inconclusive. (52,53,79,80) Future research should include large-scale, multicenter trials to determine whether these discrepancies depend on the specific types or robotic devices used, the intensity of the protocols, or the baseline impairment levels of the participants. Further studies should also focus on identifying specific patient subgroups most likely to benefit from robotic interventions. Current evidence suggests that patients requiring continuous assistance exhibit significantly greater results with RAT, but more data is needed to personalize therapy for those in the acute versus chronic phases. (53,77) Moreover, the distinction between active and passive training modes requires deeper exploration. Since studies indicate that active engagement during robotic training significantly enhances brain activation and cortical reorganization compared to passive movements, future technological development should prioritize devices that adaptively assist rather than replace patient effort. (54) This is directly linked to the need for precise dosage definitions. While it is known that high-volume, intensive practice is essential for neuroplasticity, the optimal "dose" of digital therapy remains to be standardized. (59,74)

The efficacy of telerehabilitation is highly dependent on patient adherence, as inconsistent compliance may undermine therapeutic outcomes. (64,81) Technical knowledge gaps among patients and limitations in internet access also pose significant challenges for its widespread implementation. (73) Lastly, safety concerns surrounding data protection and patient autonomy arise with unsupervised home use. (82) Future studies examining telerehabilitation interventions must employ strategies such as real-time feedback and dynamic difficulty adjustment, that would sustain patient motivation in the absence of direct therapist supervision. (72) Future research should also explore effective strategies to mitigate the digital divide among older adults, such as developing more intuitive interfaces and providing robust technical support and training, to enhance telerehabilitation accessibility and effectiveness. (73) Moreover, some evidence suggests that improvements gained via rehabilitation may not be sustained at 12-month intervals without continued intervention, which necessitates further long-term follow-up studies. (64)

Game-based programs, on the other hand, face challenges that include cognitive demands placed on patients or the need for therapists to set up and integrate complex systems. Moreover, there is frequently a mismatch between game design focused on entertainment and the specific therapeutic outcomes required for effective neuromuscular training. (83) Successful widespread adoption of these devices requires a greater emphasis on cost-effectiveness and scalability to ensure equitable access. (84)

CONCLUSIONS

Digital technologies, specifically VR, AR, RAT and telerehabilitation, represent effective adjunctive modalities in post-stroke neurorehabilitation. The literature confirms that these interventions address critical limitations of conventional therapy by enabling intensive, engaging, and highly repetitive training, which is a fundamental driver of use-dependent neuroplasticity. The primary contribution of these modern solutions is their ability to increase therapy dosage and patient motivation, key determinants of functional recovery often constrained by traditional methods. Key findings indicate that VR/AR significantly improves both upper and lower limb motor function, balance, and cognitive outcomes by providing immediate feedback and stimulating the mirror neuron system. RAT is particularly beneficial for patients with severe mobility limitations, provided the training is structured to ensure active patient engagement. Telerehabilitation provides a crucial delivery mechanism, demonstrating effectiveness and improving access to treatment, although patient adherence remains a challenge. Future research must focus on optimizing training protocols by identifying which patient subgroups benefit most from specific technologies and establishing the ideal intensity and duration of these digital interventions. Emphasis should also be placed on the seamless integration of these technologies (e.g., combining home-based robotic devices with VR exergames delivered via telerehabilitation) to create cohesive, scalable, and personalized long-term rehabilitation plans. Addressing the current limitations surrounding evidence consistency for the use of these technologies will be a critical step toward widespread clinical adoption.

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