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Nörorehabilitasyonda Entegre Teknolojiler: Kanıtlar, Mekanizmalar ve Gelecek Perspektifleri

Integrated Technologies in Neurorehabilitation: Evidence, Mechanisms, and Future Perspectives

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Abstract: This narrative and integrative review examines the role of integrated technologies in contemporary neurorehabilitation, with a primary focus on stroke and other central nervous system injuries. Specifically, it evaluates the clinical and neurobiological effects of robotics, Virtual Reality (VR), and Brain–Computer Interfaces (BCI) in delivering intensive, task-specific, and feedback-rich rehabilitation. Across the reviewed literature, technology-supported interventions enable high-dose training, quantitatively characterized by structured programs involving 20–40 sessions, 300–400 task repetitions per hour, and daily training durations exceeding 60 minutes. These approaches effectively support motor and cognitive recovery; however, clinical outcomes remain heterogeneous based on the recovery stage and functional baseline. Evidence suggests that acute and subacute patients benefit most from intensive robotic-assisted mobilization to exploit the spontaneous neuroplasticity window, whereas chronic populations with moderate-to-severe impairments require higher dosages and hybrid systems to overcome recovery plateaus. Although economic evaluations indicate potential long-term value, current cost-effectiveness evidence is critically limited by small sample sizes, methodological heterogeneity, and a lack of standardized long-term follow-up. Future progress relies on AI-driven personalization and the expansion of scalable home-based systems. Successfully translating these technologies into sustainable solutions requires addressing critical challenges regarding long-term patient adherence, unsupervised safety monitoring, and robust data privacy/security protocols.

Keywords: Neurofeedback, Neuroplasticity, Neurological rehabilitation, Robotics, Virtual reality

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Öz: Bu anlatı ve bütünleştirici inceleme, çağdaş nörorehabilitasyonda entegre teknolojilerin rolünü, öncelikle inme ve diğer merkezi sinir sistemi yaralanmalarına odaklanarak incelemektedir. Özellikle, yoğun, göreve özgü ve geri bildirim açısından zengin rehabilitasyon sağlamada robotik, Sanal Gerçeklik (SG) ve Beyin-Bilgisayar Arayüzlerinin (BBA) klinik ve nörobiyolojik etkilerini değerlendirmektedir. İncelenen literatürde, teknoloji destekli müdahaleler, 20-40 seans, saatte 300-400 görev tekrarı ve 60 dakikayı aşan günlük eğitim sürelerini içeren yapılandırılmış programlarla nicel olarak karakterize edilen yüksek dozlu eğitimi mümkün kılmaktadır. Bu yaklaşımlar motor ve bilişsel iyileşmeyi etkili bir şekilde desteklemektedir; ancak klinik sonuçlar, iyileşme aşaması ve fonksiyonel başlangıç noktasına bağlı olarak heterojen olmaya devam etmektedir. Kanıtlar, akut ve subakut hastaların spontan nöroplastisite penceresini değerlendirmek için yoğun robot destekli mobilizasyondan en fazla fayda sağladığını, oysa orta ila şiddetli bozuklukları olan kronik popülasyonların iyileşme platolarını aşmak için daha yüksek dozajlara ve hibrit sistemlere ihtiyaç duyduğunu göstermektedir. Ekonomik değerlendirmeler potansiyel uzun vadeli değeri gösterse de, mevcut maliyet etkinliği kanıtları küçük örneklem boyutları, metodolojik heterojenlik ve standartlaştırılmış uzun vadeli takip eksikliği nedeniyle ciddi şekilde sınırlıdır. Gelecekteki ilerleme, yapay zeka odaklı kişiselleştirme ve ölçeklenebilir ev tabanlı sistemlerin yaygınlaşmasına bağlıdır. Bu teknolojileri sürdürülebilir çözümlere başarıyla dönüştürmek için, uzun vadeli hasta uyumu, denetimsiz güvenlik izleme ve sağlam veri gizliliği/güvenlik protokolleri ile ilgili kritik zorlukların ele alınması gerekmektedir.

Anahtar Kelimeler: Nöro-geribildirim, Nöroplastisite, Nörolojik rehabilitasyon, Robotik, Sanal gerçeklik

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Introduction

The field of neurorehabilitation is undergoing a profound paradigm shift, moving away from conventional, therapist-led, and time-limited interventions toward technology-enabled training approaches that more effectively leverage experience-dependent neuroplasticity (1, 2). This evolution directly addresses a fundamental limitation of traditional rehabilitation: the restricted capacity to deliver the high therapeutic dose required to induce optimal cortical reorganization (2–4). Functional recovery is primarily driven by high-dose, repetitive, salient, and task-specific practice, which promotes synaptic remodeling and large-scale sensorimotor network reorganization underlying motor learning and functional improvement (1, 3).

In addition to training intensity, motor recovery is critically influenced by key learning mechanisms such as sensorimotor integration, motor imagery, and action observation. These processes can be substantially enhanced through technology-mediated feedback that is precise, consistent, and temporally coupled to patient performance (5, 6). Accordingly, the core value of advanced neurorehabilitation technologies lies in their capacity to exceed the limitations of conventional therapy by systematically delivering both the intensity and specificity required for effective neuroplastic change (4). Robotic rehabilitation systems enable high-dosage, reproducible motor practice with controlled assistance or resistance (e.g., exoskeleton-based devices for joint-specific guidance or end-effector systems for distal limb control); virtual reality (VR) platforms provide immersive, ecologically valid task environments (ranging from non-immersive screen-based tasks to fully immersive head-mounted displays) that enhance motivation and engagement; and brain–computer interface (BCI) technologies facilitate brain-state–dependent neurofeedback (using modalities such as motor imagery or steady-state visually evoked potentials), directly reinforcing motor intent and accelerating neuroplastic reorganization even in individuals with severe motor impairment (7–9).

Despite these advances, clinical outcomes reported across technology-enabled interventions remain heterogeneous, reflecting variability in neurological diagnosis, recovery stage, impairment severity, and delivered training dose. Increasingly, this heterogeneity has prompted a shift toward integrative frameworks that combine advanced hardware with intelligent control strategies. In parallel with developments in robotics, VR, and BCI systems, recent neurorehabilitation research has placed growing emphasis on the integration of artificial intelligence (AI) and tele-rehabilitation models to support individualized therapy planning and scalable delivery. AI and machine learning (ML) based approaches are being explored to optimize dosing, adapt task difficulty in real time, and personalize intervention strategies based on multimodal sensor data, neuroimaging findings, and clinical profiles (10, 11). Concurrently, home-based and tele-neurorehabilitation platforms are emerging as essential tools for extending therapeutic dose beyond the clinic, improving accessibility, and supporting long-term engagement, while also introducing new challenges related to adherence, safety, and data governance (12, 13).

Taken together, contemporary technology-enabled neurorehabilitation is increasingly conceptualized not as a collection of isolated devices, but as an integrated, data-driven ecosystem that combines robotics, immersive environments, intelligent control systems, and remote delivery frameworks. The purpose of this review is to examine how these advanced Technologies both individually and in synergistic combinations enhance functional and neurobiological recovery in individuals with neurological disorders, particularly stroke and spinal cord injury, by optimizing the core principles of neuroplasticity.

Methods

Study Design

This study was conducted as a narrative and integrative review synthesizing current evidence on technology-enabled neurorehabilitation, with a specific focus on robotic rehabilitation systems, VR, BCI, and hybrid technological approaches. The integrative design was selected to allow the joint evaluation of clinical efficacy, neurobiological mechanisms, dosage characteristics, and implementation considerations, which cannot be adequately addressed through a single quantitative synthesis due to substantial methodological heterogeneity across studies.

Research Question

The review was guided by the following research question: How do integrated neurorehabilitation technologies (robotics, VR, BCI, and hybrid systems) influence functional recovery and neuroplasticity in neurological populations, and how do these effects vary according to recovery stage, impairment severity, and training dose?

Literature Search Strategy and Data Extraction

A structured literature search was performed using major scientific databases relevant to neurorehabilitation and biomedical engineering, including PubMed/MEDLINE, Web of Science, Scopus, and IEEE Xplore. The search targeted peer-reviewed articles published between January 2020 and October 2025, reflecting contemporary clinical practice and current-generation technologies. Only English-language publications were included.

The search strategy combined controlled vocabulary (e.g., MeSH terms in PubMed) and free-text terms using Boolean operators (AND, OR) to combine concepts related to:

• Neurological rehabilitation: (neurorehabilitation, stroke, spinal cord injury, multiple sclerosis),

• Rehabilitation technologies: (robot-assisted rehabilitation, robotic therapy, virtual reality, gamification),

• Neural interface systems: (brain–computer interface, motor imagery, neurofeedback),

• Implementation models: (tele-neurorehabilitation, home-based rehabilitation)

The initial database search yielded 412 records. After the removal of duplicates and an initial screening of titles and abstracts, 84 articles were selected for full-text assessment. To ensure literature saturation, the reference lists of key systematic reviews and identified primary studies were manually screened (backward snowballing), identifying 12 additional relevant sources.

Eligibility Criteria

Studies were evaluated based on predefined inclusion and exclusion criteria.

Inclusion criteria:

• Adult neurological populations, primarily stroke, spinal cord injury, and multiple sclerosis (MS)

• Clinical trials, pilot studies, observational studies, systematic reviews, and meta-analyses

• Interventions involving robotics, VR, BCI, or hybrid technology-based rehabilitation

• Studies reporting functional, motor, cognitive, or neurobiological outcomes

• Articles addressing rehabilitation dose, recovery stage, or neuroplastic mechanisms

Exclusion criteria:

• Pediatric-only populations

• Studies unrelated to neurological rehabilitation or purely technical engineering studies without clinical relevance.

• Non–peer-reviewed abstracts or reports without accessible full text

Study Selection and Synthesis Process

Following a rigorous eligibility check, 45 peer-reviewed publications were ultimately included in this synthesis. Rather than aiming for exhaustive coverage, the review focused on methodologically informative and clinically representative publications contributing to the following thematic domains:

1. Clinical efficacy and functional outcomes

2. Dose–response relationships in technology-assisted rehabilitation

3. Neurobiological mechanisms and markers of neuroplasticity

4. Implementation challenges, feasibility, and cost-effectiveness

5. Personalization strategies and future technological directions

Findings were synthesized qualitatively through thematic integration, allowing convergence and divergence across technologies and patient subgroups to be identified.

Methodological Considerations and Limitations

As a narrative and integrative review, this study reflects a selective and concept-driven synthesis of contemporary studies. No formal risk-of-bias assessment or quantitative meta-analysis was performed due to the high heterogeneity in study design, outcome measures, and intervention protocols. These limitations were addressed by prioritizing dose-informed interpretation and mechanistic consistency over effect size comparison.

Neurorehabilitation Technologies and Mechanisms

Technologically-driven neurorehabilitation is progressively supplanting traditional methods due to its superior capacity to deliver the high-dose, multisensory, task-oriented training essential for capitalizing on experience-dependent neuroplasticity (1, 2). This approach is proving particularly critical for managing and recovering function following injuries to the central nervous system, such as stroke and SCI (1, 2).

Robotic Rehabilitation Systems

Robotics plays a critical role in neurorehabilitation by providing the precision, reproducibility, and high-intensity repetition required to drive motor relearning and corticospinal reorganization (Figure 1) (7, 14). Robotic rehabilitation systems can be broadly categorized according to the targeted body region and mechanical design, including upper extremity robots, lower extremity (gait) robots, balance and posture training robots, and, more recently, multifunctional or hybrid robotic platforms. These systems are designed to deliver task-specific, repeatable motor practice while minimizing therapist-dependent variability, thereby creating optimal conditions for use-dependent neuroplasticity.

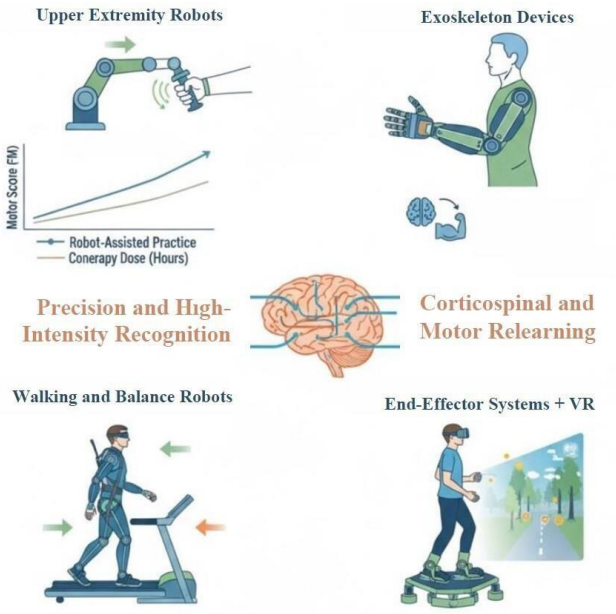

Figure 1. Robotics in neurorehabilitation: mechanisms and applications.

Upper extremity robots are commonly classified as end-effector (devices interacting with the distal segment, e.g., InMotion ARM) or exoskeleton-based (wearable structures aligned with anatomical axes, e.g., ArmeoPower, Exo-Arm) devices. End-effector robots interact with the distal segment of the limb, typically the hand or forearm, whereas exoskeletons provide joint-specific assistance aligned with the anatomical axes of the shoulder, elbow, and wrist. Recent advances have increasingly focused on Assist-as-Needed (AAN) control strategies, which dynamically adjust the level of robotic assistance based on real-time patient performance. By preventing excessive passive movement and encouraging voluntary effort, AAN paradigms promote error-based motor learning and enhance the salience of afferent sensory feedback key drivers of experience-dependent cortical reorganization (15, 16). Although large-scale trials such as the RATULS study highlighted the importance of appropriate patient selection, dosing, and clinical integration to achieve functional gains beyond enhanced conventional therapy, robot-assisted upper limb training has consistently demonstrated improvements in motor impairment outcomes, particularly Fugl–Meyer Assessment (FM) scores, in a highly dose-dependent manner (17, 18).

In addition to upper limb applications, lower extremity robotic systems are widely employed to facilitate locomotor recovery. These include both exoskeleton-based gait robots (e.g., Lokomat, EksoNR) and end-effector devices (e.g., G-EO System), which enable controlled weight-bearing, repetitive stepping, and task-specific gait cycles elements that are essential for relearning walking patterns in neurological conditions such as stroke and MS. Furthermore, robotic platforms targeting balance and postural control, including robotic tilt systems (e.g., Erigo) and perturbation-based trainers, are increasingly integrated into neurorehabilitation programs to address trunk instability and impaired postural responses. Across both upper and lower extremity applications, robotic systems are frequently combined with VR environments to enhance patient engagement, enrich multisensory feedback, and strengthen cognitive–motor coupling during repetitive training (19, 20).

From a neurophysiological perspective, the therapeutic effects of robotic rehabilitation are not merely attributable to increased therapy dose, but are strongly mediated by specific device characteristics. High-precision actuators and anatomically aligned kinematic structures allow for consistent, low-variability movement execution, which is critical for inducing use-dependent corticospinal plasticity. Moreover, adaptive control algorithms particularly AAN strategies continuously modulate assistance intensity in response to patient-generated forces, reinforcing the temporal coupling between motor intent and sensory consequences. This closed-loop interaction enhances sensorimotor integration and supports synaptic strengthening within motor-related neural networks, thereby facilitating functional recovery through targeted neuroplastic mechanisms (15, 16).

Virtual Reality and Gamification

VR–based interventions have emerged as a powerful adjunct in neurorehabilitation by enabling immersive, task-oriented, and ecologically valid training environments that are difficult to replicate in conventional clinical settings (Figure 2). By combining interactive visual scenarios with goal-directed motor tasks, VR systems allow for high-volume, repetitive practice while maintaining patient motivation and adherence two critical determinants of rehabilitation efficacy (21, 22).

From a mechanistic perspective, the physiological impact of VR-based rehabilitation arises from its capacity to deliver enriched multisensory feedback and real-time performance information. The simultaneous integration of visual, auditory, and proprioceptive cues synchronizes afferent sensory input with efferent motor commands, thereby facilitating sensorimotor integration and Hebbian learning processes within motor-related cortical networks. Real-time feedback on movement accuracy and task success enhances error-based learning and supports the refinement of motor representations during repetitive practice (21, 22).

Gamification elements embedded within VR platforms such as adaptive task difficulty, score-based feedback, and reward-driven progression further modulate neurobiological responses to training. These features increase engagement and sustain attention, while also activating dopaminergic reward pathways that are known to support motor memory consolidation and long-term retention of learned motor skills. Clinical studies have demonstrated that VR-based interventions incorporating game-like structures can

positively influence mood, motivation, and emotional state, indirectly facilitating greater training intensity and consistency in individuals with stroke (23).

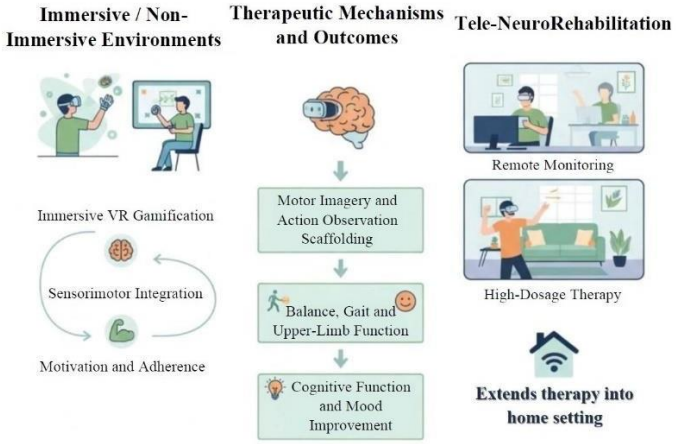

Figure 2. Virtual reality and gamification in neurorehabilitation: benefits in terms of cognitive and motor skills.

Beyond motivational effects, immersive VR environments may directly influence cortical activation patterns by increasing the sense of presence and embodiment during task execution. Functional neuroimaging studies indicate that VR-based motor training can engage widespread sensorimotor and associative cortical regions, suggesting enhanced recruitment of neural networks involved in motor planning, execution, and feedback processing. When combined with robotic devices or other assistive technologies, VR further strengthens cognitive–motor coupling by aligning visual context with physical movement, thereby amplifying the neuroplastic potential of task-specific rehabilitation (19, 21).

Brain-Computer Interfaces and Hybrid Systems

BCIs play a transformative role in neurorehabilitation by translating neural signals most commonly recorded via electroencephalography (EEG) into real-time neurofeedback or control commands that directly link motor intent with task execution (6, 9). This brain-state–dependent, closed-loop architecture enables intention-driven therapy, in which volitional cortical activation is immediately reinforced through congruent sensory, visual, or proprioceptive feedback. By temporally coupling neural activation with movement-related feedback, BCIs amplify experience-dependent neuroplasticity and accelerate motor relearning processes that are often insufficiently engaged by passive or externally driven therapies.

From a mechanistic perspective, the therapeutic efficacy of BCIs arises from their capacity to selectively modulate sensorimotor rhythms and promote task-specific activation within motor and premotor cortical regions. Motor imagery–based BCI paradigms increase corticospinal excitability and contribute to the restoration of interhemispheric balance key neurophysiological mechanisms associated with functional recovery after stroke (5, 10). Concurrent EEG and functional neuroimaging studies further demonstrate that BCI training induces measurable changes in oscillatory power and functional connectivity within sensorimotor networks, providing objective biomarkers of neuroplastic change (10, 24).

Hybrid systems represent a critical evolution of BCI-based rehabilitation by integrating neural decoding with peripheral actuation technologies such as robotics, functional electrical stimulation (FES), and VR. In BCI–FES configurations (where EEG-based motor intent triggers neuromuscular electrical stimulation to the wrist extensors or peroneal nerve), decoded motor intent triggers synchronized electrical stimulation of target muscles, thereby reinforcing correct movement patterns through the precise temporal pairing of cortical activation and peripheral muscle contraction (5, 25). This physiologically congruent coupling between central intent and peripheral execution is particularly beneficial for patients with severe motor impairments, in whom voluntary movement alone fails to generate sufficient afferent feedback to drive adaptive plasticity.

Similarly, BCI–robotic and BCI–VR hybrid platforms extend this principle by aligning neural intent with assisted movement trajectories or immersive task environments (Figure 3). Robotic integration allows graded physical assistance based on real-time cortical engagement, while VR integration enhances task salience, motivation, and multisensory feedback factors known to strengthen motor learning and memory consolidation. These closed-loop hybrid systems are especially valuable in chronic stroke populations, where recovery plateaus and learned non-use limit the effectiveness of conventional high-dose practice alone (25).

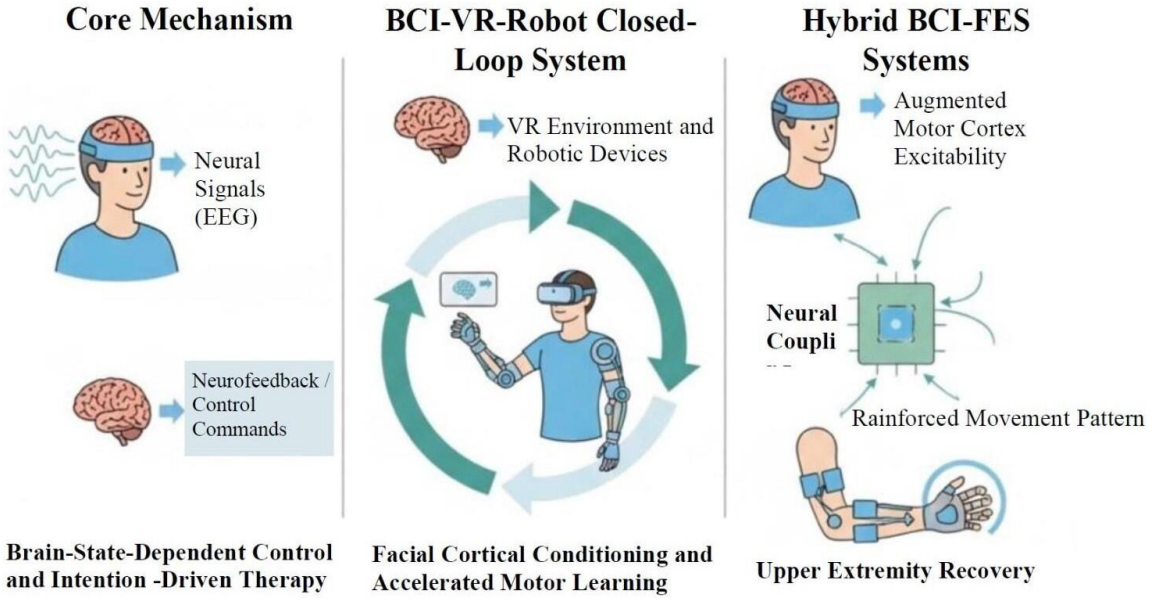

Figure 3. Brain-computer interfaces in neurorehabilitation: mechanisms and therapeutic Systems Efficacy and Implementation.

Figure 3 illustrates the core mechanisms and therapeutic configurations of BCI-based and hybrid neurorehabilitation systems, highlighting how neural signal acquisition, real-time decoding, and feedback delivery converge to optimize cortical conditioning and functional recovery. Collectively, BCIs and hybrid systems shift neurorehabilitation from externally guided repetition toward intention-driven, neurobiologically grounded interventions that directly target the neural substrates of motor recovery.

Collectively, these technological interventions consistently demonstrate positive effects on motor outcomes (including FM scores) and functional independence across diverse neurological conditions such as stroke, SCI, and MS (21, 26). The body of evidence firmly establishes a crucial dose-response relationship, where high intensity and specificity of training are the key drivers of functional gains (21,26). To maximize clinical applicability, however, these interventions must be tailored to the specific recovery stage and functional severity of the patient.

During the acute and subacute stages (0–6 months post-stroke), technology should focus on high-intensity mobilization to capitalize on the peak window of spontaneous neuroplasticity. In these phases, "high-dose" training is quantitatively defined as structured programs comprising at least 20–40 sessions, targeting 300–400 task repetitions per hour, with total cumulative active practice exceeding 30–45 hours over a 4-to-6-week period. Robotic systems are particularly effective here for providing the necessary physical assistance to patients with low functional scores (18, 21, 27).

In contrast, for chronic populations (>6 months post-stroke), therapy aims to overcome recovery plateaus and "learned non-use." Outcomes in these patients are highly dose-dependent and often require the integration of hybrid systems, such as BCI-coupled FES, to achieve measurable cortical reorganization. While individuals with severe impairments require AAN robotic protocols to initiate movement, those with moderate-to-mild impairments derive greater benefit from high-challenge VR environments that prioritize motor precision and cognitive-motor integration.

Despite these clear clinical benefits, successful implementation requires overcoming several logistical barriers, including the high cost of devices, the need for standardized protocols, ensuring strict safety adherence, sufficient clinician training, and seamless integration of devices into existing clinical workflows. Looking ahead, the field is moving toward unprecedented personalization and access. Future directions include the use of AI-driven personalization through the creation of digital twins to model and optimize individual recovery. Furthermore, researchers are exploring the potential of metaverse environments to further customize and extend access to high-quality rehabilitative care (Figure 4) (28-30)

Figure 4. Implementation challenges and future of neurological rehabilitation technology.

The Impact of Technology on Neurobiological Outcomes

Technology-enabled neurorehabilitation, encompassing robotics, VR, BCI and hybrid systems, represents a paradigm shift toward interventions explicitly designed to modulate neurobiological recovery processes rather than solely improve observable motor performance (31, 32). The defining advantage of these technologies lies in their capacity to deliver precisely controlled, high-dose, multisensory, and task-specific training conditions known to drive experience-dependent neuroplasticity at both cortical and subcortical levels (1, 18).

A central determinant of neurobiological impact is training dose. Robotic systems enable this dosage by providing consistent kinematic guidance, adjustable assistance, and fatigue-resistant repetition, which together promote long-term potentiation, synaptogenesis, and reorganization of corticospinal pathways (7, 18). In the acute and subacute phases following stroke, such high-frequency practice is particularly effective in preventing maladaptive plasticity and reinforcing spared motor networks during the spontaneous recovery window.

VR further amplifies neurobiological effects by embedding motor practice within immersive, context-rich environments that enhance salience, motivation, and attentional engagement factors directly linked to dopaminergic modulation of motor learning and memory consolidation (21, 33). Functional neuroimaging studies demonstrate that VR-based interventions increase activation and functional connectivity within sensorimotor, parietal, and prefrontal networks, reflecting enhanced integration of motor planning, execution, and cognitive control processes (33, 34). By coupling visual, auditory, and proprioceptive feedback with goal-directed tasks, VR strengthens sensorimotor integration and supports the formation of more efficient neural representations of movement.

BCI-based and hybrid neurorehabilitation systems exert a more direct influence on neurobiological outcomes by conditioning cortical activity itself. EEG- and fNIRS-guided BCIs enable real-time modulation of sensorimotor rhythms, reinforcing task-specific activation patterns within primary motor, premotor, and

supplementary motor areas (10, 35). Studies combining BCI training with functional neuroimaging reveal adaptive shifts in interhemispheric balance and increased functional connectivity within motor-related networks neural signatures consistently associated with meaningful motor recovery in chronic stroke populations (10, 24). These effects are further strengthened in hybrid BCI–FES or BCI–robotic systems, where decoded motor intent is temporally coupled with peripheral muscle activation or assisted movement, thereby enhancing Hebbian plasticity through synchronized central–peripheral feedback loops (5, 25).

Importantly, the neurobiological impact of technology-mediated rehabilitation is strongly modulated by recovery stage. During early post-stroke phases, high-intensity, technology-assisted practice primarily supports network stabilization and prevention of compensatory maladaptive reorganization. In contrast, in chronic stages, where spontaneous recovery has plateaued, comparable high-dose protocols are required to induce late-phase synaptic remodeling and functional reorganization. In these populations, hybrid systems that integrate neural intent, sensory feedback, and physical assistance are particularly effective in overcoming learned non-use and re-engaging dormant motor circuits (25, 31).

Beyond motor domains, technology-enabled interventions also influence cognitive and affective neural processes. VR- and gamification-based platforms have been shown to modulate neural correlates of attention, motivation, and emotional regulation, which indirectly support motor recovery by improving task engagement and adherence (23, 36). Together, these findings indicate that advanced neurorehabilitation technologies do not merely increase training volume, but fundamentally reshape the neurobiological conditions under which recovery occurs by aligning dose, feedback, and neural activation with the principles governing adaptive plasticity.

Implementation Challenges, Cost Effectiveness, and Personalization

The adoption of advanced neurorehabilitation technologies, including robotics, VR, and BCI, faces significant integration challenges in clinical practice (12, 13). As detailed in Table 1, key barriers to widespread adoption are the substantial upfront costs and continuous maintenance of devices (12).

Table 1. Clinical integration of advanced neurorehabilitation technologies, cost-effectiveness evaluations, and individualized treatment strategies.

Section Title	Core Content and Purpose
I. Clinical Integration and Access Barriers	• High acquisition and maintenance costs limit large-scale adoption of robotics, VR, and BCI systems (12). • Complex setup requirements (space, IT infrastructure, calibration time) increase clinician workload and reduce feasibility in routine practice (38,39). • These constraints contribute to institutional and regional disparities in access to high-dose, technology-assisted rehabilitation (12). • Tele-neurorehabilitation and home-based delivery models represent promising strategies to reduce access barriers and support sustained training dose (13).
II. Cost-Effectiveness and Economic Evaluation	• Existing economic evaluations yield heterogeneous results, largely due to small samples, short follow-up periods (<6 months), and inconsistent methodologies (12,18). • Cost-effectiveness is closely linked to achieving sufficiently high training doses, yet per-patient costs remain elevated due to the need for clinical supervision (12). • Tele-rehabilitation may lower marginal costs, but high-quality studies using standardized health-economic outcomes are required to inform reimbursement and policy decisions (13, 37).
III. Individualized and Adaptive Treatment Strategies	• Optimal outcomes require personalization of technology type and training dose based on neurological severity, cognitive capacity, and patient motivation (29). • Adaptive robotic control strategies (e.g., assist-as-needed) support active engagement while preventing over-assistance (16). • Emerging approaches, including AI-driven dosing models and digital twin frameworks, aim to simulate patient-specific responses and dynamically tailor intervention parameters (29).

Regarding economic viability, while home-based and tele-rehabilitation models hold promise for long-term health-economic benefits by reducing travel burden and marginal costs per session, the current body of cost-effectiveness evidence remains critically limited and fragmented. Most existing economic evaluations are constrained by small sample sizes, a lack of standardized Quality-Adjusted Life Year (QALY) metrics, and significant methodological heterogeneity (12, 13, 37). Furthermore, there is a profound lack of long-term follow-up data (rarely exceeding six months), making it difficult to ascertain whether the high initial investment in technology translates into sustained reductions in long-term care costs or improved social participation. These factors contribute to marked access disparities across institutions, underscoring the necessity of robust, standardized economic evaluations to inform policy and support large-scale clinical adoption (12, 37).

Discussion

The literature on technology-enabled neurorehabilitation presents a complex profile of strengths and weaknesses, with significant inconsistencies regarding which technology is most effective for a given patient group (40, 41). Robotic rehabilitation for upper extremity function shows mixed efficacy; while meta-analyses report gains in impairment, large pragmatic trials like RATULS demonstrated no superiority over enhanced conventional care, highlighting the critical role of patient selection, task specificity, and dose integration (17, 42). The findings of this review underscore that efficacy is highly dependent on the recovery stage. Specifically, in the acute and subacute phases, the primary goal is to harness the peak window of neuroplasticity through high-dose robotic assistance. In contrast, for chronic populations, the focus shifts toward intensive, high-challenge environments and hybrid systems such as BCI-FES to overcome functional plateaus.

VR and BCI contribute meaningful neurocognitive and motivational gains but with variable magnitude; efficacy hinges on task design and effective coupling to motor practice (42). The inconsistency primarily stems from heterogeneity in stroke stage, impairment severity, and a previous lack of standardized dosing. To resolve these inconsistencies, "high-dose" training must be strictly implemented as 20–40 sessions with a target of 300–400 task repetitions per hour. The integration of AI and ML is essential for addressing this heterogeneity. AI/ML holds immense potential for predicting prognosis via data-driven models and imaging-based biomarkers and for personalizing therapy (10, 11). Specifically, ML can be used for real-time dose optimization and adjusting task difficulty by interpreting multimodal sensor streams, thereby aligning the level of robotic assistance with the patient's capability to sustain active motor learning (43, 44).

The development of home-based technologies is integral to realizing the paradigm shift by extending therapeutic dose and access outside the clinical setting (13, 45). However, scaling these remote models requires addressing three critical barriers: long-term adherence, safety, and data governance. First, to prevent the decline in patient engagement after the initial novelty phase, home systems must utilize adaptive gamification and remote monitoring. Second, safety protocols such as automated cut-offs and AI-monitored movement quality are essential for unsupervised settings to prevent injuries. Finally, as these devices collect sensitive physiological and kinematic data, establishing robust end-to-end encryption and compliance with data privacy regulations (e.g., GDPR) is non-negotiable for clinical and legal integration (12, 41).

Furthermore, while tele-rehabilitation holds promise for long-term health-economic benefits, current cost-effectiveness evidence remains critically limited. Existing studies are often weakened by small sample sizes, a lack of standardized quality-of-life metrics (e.g., QALY), and short follow-up periods that rarely exceed six months. Addressing these evidence gaps through rigorous, longitudinal economic evaluations is essential to confirm the long-term value of these technologies and support policy decisions for widespread clinical adoption (12, 13, 37).

Conclusion

Technology-enabled neurorehabilitation represents a definitive paradigm shift, moving recovery from time-limited intervention toward high-dose, intention-driven practice that neuroimaging confirms drives cortical reorganization and motor learning. While significant hurdles remain, including high capital costs,

complex integration challenges, and documented inconsistencies in functional outcomes across heterogeneous patient groups, the path forward rests on two strategic pillars: Personalization and Scalability. The critical role of AI and ML is to resolve current inconsistencies by enabling real-time dose optimization, predicting prognosis, and tailoring task difficulty based on patient-specific neurobiological biomarkers. Concurrently, the robust deployment of home-based technologies and tele-rehabilitation platforms is essential to achieve the necessary dose extension and equitable access required to translate these advanced neurobiological benefits into routine, sustained functional independence outside specialized clinical settings.

Ethical Statement: This study exclusively utilizes publicly available data obtained from open web platforms and, as such, is deemed exempt from formal ethical review processes. However, the research methodology was carefully designed to adhere to the principles of ethical research conduct, respecting the privacy and confidentiality of the data sources.
Authors Contributions: Manuscript concept/design: MCE – Data collecting: MCE – Data analysis/review: MCE – Writing the manuscript: MCE – Critical review of content: MCE – Final approval and responsibility: MCE – Material and technical support: MCE – Supervision: MCE.
Peer Review: External independent.
Conflict of Interest: The authors have no conflicts of interest to declare.
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