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Editorial

Technology Enhanced-Neurorehabilitation as a Disease-Modifying Intervention in the Era of Precision Medicine

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Neurorehabilitation has long been viewed mainly as a restorative intervention—an approach intended to reduce disability after neurological injury rather than influence the underlying course of the disease [1]. This distinction has since been transcended. Advances in neuroscience, together with rapid progress in precision neurotechnology, now suggest that contemporary neurorehabilitation can actively shape neural reorganisation and may exert disease-modifying effects across a range of neurological conditions [2].

At a biological level, this shift reflects contemporary concepts of experience-dependent neuroplasticity, which show that neural networks remain modifiable far beyond the acute phase of the injury [2]. Persistent disability is often driven not only by irreversible structural damage but also by maladaptive plasticity, network disconnection, inefficient compensatory behaviours, and other mechanism-level contributors [3]. Rehabilitation strategies targeting these processes therefore have the potential to influence long-term trajectories, rather than merely improve short-term function.

Technological innovation has been central to this transformation in clinical practice. Robotics-assisted rehabilitation enables high-intensity, task-specific, and reproducible training at levels rarely achievable with conventional therapy alone. By offering precise kinematic control, adaptive assistance or resistance, and continuous performance monitoring, robotic systems promote motor relearning and ensure therapy delivery with a degree of quantitative precision that exceeds traditional manual approaches. Evidence indicates that these interventions can induce durable changes in motor control and cortical organisation—effects extending beyond symptomatic improvement [4].

Virtual reality complements this robotics-enabled precision by creating immersive, multisensory environments that enhance engagement, embodiment, and contextual relevance. VR-based rehabilitation enables patients to practice goal-directed actions within ecologically meaningful scenarios, fostering sensorimotor integration and cognitive–motor coupling. These features are especially relevant for addressing learned non-use and altered body representation—factors contributing to long-term disability and potentially shaping disease evolution [5].

At the same time, telerehabilitation has transformed the delivery of neurorehabilitation. Remote platforms allow continuity of care beyond hospital settings, increase cumulative therapy dose, and support sustained engagement over time—key ingredients for durable neuroplastic change. A large multicentre randomized clinical trial (RCT) has shown that structured home-based telerehabilitation can achieve arm-motor outcomes comparable to in-clinic therapy when intensity and dose are matched, supporting its role in extending access and cumulative practice [6]. The integration of wearable sensors, real-time feedback, and adaptive digital therapeutics brings rehabilitation into daily life, where behavioural meaningful learning occurs, and long-term neural adaptation is more likely to consolidate [1].

The convergence of robotics, virtual reality, telerehabilitation, and neuromodulation, understood as non-invasive techniques capable of modulating network excitability and promoting adaptive reorganization within precision-based frameworks, further reinforces the possibility of disease-modifying effects. Evidence syntheses indicate that non-invasive brain stimulation can enhance motor recovery after stroke when embedded in principled programs [7]. Closed-loop combinations (e.g., virtual reality (VR) with non-invasive neuromodulation or stimulation-gated training) illustrate how dysfunctional networks can be down-tuned while adaptive patterns are reinforced, accelerating learning and consolidation [8]. Artificial intelligence now enables more refined patient stratification and dynamic personalization of rehabilitation protocols, including adaptive difficulty, dose titration, and predictive response modelling—key ingredients of precision rehabilitation [9].

Emerging evidence from conditions such as stroke, traumatic brain injury, Parkinson's disease, and disorders of consciousness shows that technology-enhanced neurorehabilitation can produce lasting motor, cognitive, and behavioural improvements that persist beyond the intervention period [3–6]. Although methodological heterogeneity remains a limitation, the overall trend of evidence supports a shift from viewing rehabilitation as purely restorative care to recognizing it as a biologically active intervention.

Important challenges remain. Reliable biomarkers capable of tracking longitudinal neural change are needed, as are adequately powered trials with extended follow-up [10]. Regulatory and reimbursement systems also lag behind scientific progress, often categorizing robotic, virtual, and remote technologies as adjunctive services rather than mechanistically grounded therapeutic interventions. Future priorities should encompass: rigorous validation of disease-modifying effects through research; subsequent formulation and updating of clinical guidelines based on these findings; and eventual integration of these principles into the design and evaluation frameworks of health policy.

Reframing neurorehabilitation as a potential disease-modifying intervention carries significant implications for care pathways, trial design, and policy development, supporting earlier initiation, integration of robotics-assisted therapy, immersive environments, telerehabilitation, and systematic deployment of precision neurotechnologies.

In summary, advances in digital, robotic, immersive, and neuromodulatory technologies are challenging traditional boundaries of neurorehabilitation, shifting it from a predominantly compensatory practice toward a mechanistically informed intervention. This evolution aligns with the paradigm of precision medicine, in which treatments are tailored to an individual's residual neural architecture, network state, and learning capacity rather than applied uniformly across patients. Digital platforms, robotics, immersive environments, and neuromodulation together enable fine-grained control over the type, intensity, mode, and timing of rehabilitation, setting the stage for precision rehabilitation grounded in neural mechanisms.

Author Contributions

RSC conceived and wrote the manuscript. RSC read and approved the final manuscript. RSC has participated sufficiently in the work and agreed to be accountable for all aspects of the work.

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