Vol. 18 (2026): Proceedings of 2026 International Conference on Smart Healthcare and Biomedical Engineering (ICSHBE 2026)
E-ISSN: 3105-0522 P-ISSN: 3105-0514
DOI: https://doi.org/10.70267/shbe.2026320328

Sensorimotor Closed-Loop Control in Post-Stroke Wrist-Hand Rehabilitation Robots: A Structured Narrative Review

Shengwei Chai*

School of Safety Science and Engineering, Anhui University of Science and Technology, Huainan, Anhui, China

**Corresponding author: Shengwei Chai.*

Abstract

Post-stroke wrist-hand rehabilitation robots can increase training intensity, repetition, and measurement. Still, systems centered mainly on mechanical assistance may not fully address the sensorimotor impairments that constrain functional recovery. This structured narrative review examines how sensorimotor closed-loop control may reshape wrist-hand robotic rehabilitation by linking somatosensory feedback, voluntary motor effort recognition, and home-based translation. The review was informed by a PubMed-based literature pool and organized around three interrelated themes rather than a meta-analytic effect estimate. Current evidence suggests that proprioceptive, tactile, vibrotactile, and electro-vibro-feedback strategies may support sensorimotor integration. At the same time, EMG-, EEG/BCI-, and CMC-informed approaches can help detect residual motor intention or effort and trigger robotic, FES, or NMES assistance. Home-based and telerehabilitation systems also show potential to improve access, training dose, and therapist-supported monitoring. However, the evidence remains heterogeneous, often limited by small samples, pilot designs, mixed devices, and incomplete validation of long-term home use. Future wrist-hand systems should integrate somatosensory feedback, voluntary effort recognition, adaptive robotic/FES/NMES assistance, objective neurophysiological and kinematic assessment, home monitoring, and therapist-in-the-loop supervision, while avoiding claims of clinical superiority before stronger controlled evidence is available.

Keywords

post-stroke rehabilitation, wrist-hand robot, sensorimotor integration, voluntary motor effort recognition, telerehabilitation

1. Introduction

Post-stroke wrist-hand impairment remains a major rehabilitation target because distal upper-limb function is closely linked to grasp, release, object manipulation, and self-care. Robotic devices, wearable gloves, and digital training platforms can increase practice opportunities and make movement more measurable, but the clinical problem is not only whether a device can move the paretic hand. Wrist-hand recovery also depends on how sensory input, residual voluntary activation, task engagement, and feedback are coupled during training. For that reason, robotic rehabilitation should be interpreted cautiously: higher repetition and mechanical assistance may be useful, yet they do not by themselves establish sensorimotor recovery or superiority over well-designed conventional practice [1-7].

This distinction is particularly important for the wrist and hand because distal movements require coordination among small muscles, sensory discrimination, anticipatory control, and error correction during object interaction. A robot that repeatedly opens and closes the hand may increase dose, but it may still fail to train the patient to perceive joint position, generate timely effort, or adapt movement to task demands. The central question is therefore not whether robot assistance is useful in general, but how assistance can be made contingent on the patient's sensorimotor state. This is why the review focuses on closed-loop control rather than on mechanical design alone, and why evidence is interpreted through a functional recovery lens.

A sensorimotor closed-loop perspective reframes the robot from a movement provider into an interactive rehabilitation system. Somatosensory feedback, including proprioceptive, tactile, vibrotactile, and electro-vibro feedback, may help patients connect movement attempts with their sensory consequences. Voluntary motor effort recognition, using EMG, EEG/BCI, CMC, or related signals, can help distinguish passive limb displacement from active participation and can trigger assistance when the patient attempts to move. These two elements are complementary: sensory feedback without active effort can become mere stimulation. In contrast, intention recognition without meaningful feedback may remain a signal-processing exercise rather than a rehabilitation mechanism [8,11,15-19,23-30].

A third issue is translation beyond the supervised clinic. Home-based and telerehabilitation systems may expand access, increase self-directed practice, and support remote monitoring. Still, home deployment also exposes weaknesses in donning and doffing, calibration, safety monitoring, adherence, movement quality, troubleshooting, and long-term robustness. These issues are not secondary implementation details; they determine whether a technically promising system can be used safely and repeatedly by patients with variable impairments, varying levels of caregiver support, and varying levels of digital literacy. This structured narrative review was informed by a PubMed-based literature pool and organized around somatosensory feedback and sensorimotor integration, EMG/EEG/CMC-based voluntary motor effort recognition, and home-based translation with therapist-supported deployment [10,17,37-39].

2. Somatosensory Feedback and Sensorimotor Integration

2.1 Somatosensory Feedback as a Recovery Mechanism

Somatosensory feedback is not a decorative add-on to wrist-hand robotic training; it is one pathway through which movement assistance may become sensorimotor learning. After a stroke, impaired proprioception, tactile processing, and sensory-motor coupling can limit how patients perceive hand position, correct errors, and use residual motor output during practice. Representative evidence supports this mechanism at several levels. The AMES randomized clinical trial combined assisted movement with proprioceptive stimulation during the subacute period and reported clinically relevant signals of upper-limb recovery, making it one of the strongest clinical examples for this theme [8]. WristBot-based sensorimotor training and vibrotactile glove studies further suggest that robot-guided practice paired with sensory feedback can improve proprioceptive or sensorimotor behavioral measures. However, these studies are smaller and more exploratory [19,23].

These studies also clarify why feedback must be considered in relation to the task context. Proprioceptive stimulation during assisted movement may reinforce the temporal relation between joint motion and sensory inflow. At the same time, vibrotactile or tactile feedback can make otherwise weak or poorly perceived hand movements more salient. In robotic wrist-hand training, such feedback may support error detection, body awareness, and attention to the paretic limb. The evidence does not show that one feedback modality is universally best. Still, it does suggest that a device designed only for range of motion or repetition misses a clinically important layer of recovery. For patients with sensory impairment, this layer may influence whether practice is perceived, corrected, and incorporated into motor relearning. It may also help explain why patients with similar motor impairment can respond differently to the same robotic protocol. The most relevant mechanistic evidence comes from studies that connect sensory feedback to active muscle or neural signals. EMG-driven electro-vibro-feedback in robot-assisted wrist-hand rehabilitation links residual muscle activation, NMES or FVS timing, and CMC/dCMC-related indicators, illustrating how peripheral effort and sensory feedback may be temporally coupled [15]. Other work indicates that baseline somatosensory system integrity can help explain differences in treatment response, while NMES-enhanced rehabilitation has been associated with somatosensory cortical plasticity and SEP-related changes [24-25]. Together, these findings support the plausibility that wrist-hand recovery is shaped by the integrity and training responsiveness of somatosensory pathways, rather than solely by repeated mechanical movements.

2.2 Evidence Boundaries

The RQ1 evidence should still be interpreted conservatively. The strongest clinical support comes from assisted movement with proprioceptive stimulation, but it does not prove that vibration or any single sensory component is independently effective [8]. WristBot, vibrotactile, and electro-vibro-feedback studies are important because they align closely with sensorimotor closed-loop concepts, yet several are pilot, proof-of-concept, or single-arm investigations [15,19,23]. SEP, CMC, and dCMC findings provide useful mechanistic indicators, but they do not establish a universal causal mechanism for all robot-assisted rehabilitation systems [15,24-25]. Another limitation is heterogeneity: studies differ in stroke stage, impairment severity, target joints, sensory modality, device assistance, training dose, and outcome measures. Some outcomes reflect clinical performance, while others reflect neurophysiological association or sensorimotor behavior. This makes cross-study comparison difficult and prevents a simple ranking of feedback modalities. It also means that patient selection may be as important as device selection. Thus, current evidence supports somatosensory feedback as a plausible and clinically relevant target for sensorimotor integration, while larger controlled studies and component-separation designs are needed before claiming general efficacy across devices, stroke stages, and impairment levels.

3. Voluntary Motor Effort Recognition and Closed-Loop Control

3.1 EMG and EMG-triggered Assistance

Voluntary motor effort recognition addresses a central limitation of mechanically assisted robots: the device must identify when the patient is attempting to move, rather than merely imposing motion. EMG is the most immediately practical route because it can capture residual muscle activation and can be integrated with robot hands, NMES, or FES. The AI-integrated EMG-driven robot hand trial directly illustrates how multi-muscle EMG and classification can drive hand-oriented assistance after stroke [9]. EMG-triggered FES-robot systems also show how a detectable contraction can be converted into stimulation and robotic assistance, potentially reinforcing active participation [29]. In practice, EMG can support threshold triggering, proportional assistance, pattern classification, or adaptive control, depending on the number of muscles recorded and the device's signal-to-movement mapping. These systems are clinically attractive because they are relatively wearable and interpretable, but EMG remains sensitive to weakness, spasticity, fatigue, electrode placement, co-contraction, and compensatory movement. Importantly, detecting an EMG pattern is not the same as demonstrating durable functional benefit.

3.2 EEG-BCI and CMC-informed Control

EEG-BCI approaches shift the control signal toward central motor intention and may be particularly relevant when overt movement is limited. Motor-imagery BCI with a hand exoskeleton provides a clear example of EEG-based intention driving hand-oriented feedback, while multimodal BCI-FES and related trials show how central signals can be paired with peripheral feedback or assistance [18,26,30]. However, BCI evidence must be handled carefully. Classification stability, cognitive load, fatigue, calibration time, and patient selection can limit real-world use, and controlled trials do not justify broad claims that BCI systems clearly outperform sham or conventional therapy across outcomes. EEG can support intention-driven training, but it is not yet a universal clinical control standard.

CMC-informed control occupies a mechanistically appealing middle ground by linking cortical activity and muscle output. The corticomuscular integrated representation study is especially relevant to voluntary motor effort recognition in wrist-hand robotic control, as it combines central-peripheral coupling with EMG information rather than treating either signal stream in isolation [16]. This route is conceptually closer to voluntary effort than to simple movement-onset detection, but it is also technically demanding. CMC estimation can be affected by signal quality, task constraints, real-time computation, and small sample validation. It may be useful for understanding whether central drive is effectively coupled to target muscles, but the measurement is more complex than surface EMG triggering and less mature for everyday clinical deployment. At present, CMC+EMG should be viewed as a promising pilot-level control strategy, not as evidence that this route is superior to EMG-only, EEG-only, or conventional robotic control.

3.3 Technical and Clinical Limitations

Across EMG, EEG-BCI, CMC, and EMG-triggered FES-robot systems, the main advantage is that assistance can be tied more closely to patient participation. The main limitation is that signal detectability, classifier accuracy, or trigger reliability does not automatically translate into clinical efficacy. Some EMG-triggered FES-robot studies include clinical trial evidence, but not all are strictly wrist-hand-specific; several are broader upper-limb or arm-oriented systems [29]. AI-EMG robot hand evidence is encouraging, yet sample size, transparency, and generalizability remain limited [9]. BCI and CMC studies strengthen the rationale for closed-loop control, but the field still lacks a unified, robust, and deployable standard for voluntary motor effort recognition. A mature control standard would need to remain stable across sessions, impairment levels, fatigue, tone changes, and home environments while still being simple enough for therapists and patients to use. It would also need clinically meaningful thresholds for when assistance should increase, decrease, or switch modes, and it should report failures as carefully as it reports successful detections. These requirements are essential if effort recognition is to guide therapy rather than only demonstrate technical feasibility. Future systems should compare signal routes directly, separate the effects of assistance and feedback, and validate whether effort-sensitive control improves movement quality and function rather than only improving system responsiveness.

4. Home-Based Telerehabilitation and Translation Challenges

4.1 Value of Home-based Systems

Home-based rehabilitation systems are valuable because they may extend practice beyond short clinic sessions, reduce access barriers, and support self-directed training. For wrist-hand rehabilitation, this value is especially relevant because distal motor recovery often requires repeated, task-related practice that is difficult to deliver at high doses in routine care. Soft robotic gloves, portable hand devices, and digital platforms can record training dose, guide practice, and connect patients with remote therapist oversight [1,6,7,37-39]. They may also help bridge the gap between clinic-based impairment training and daily hand use by encouraging practice in a familiar environment. In principle, home systems can make rehabilitation more continuous, but continuity depends on whether patients can actually wear the device, understand feedback, complete sessions, and receive timely support. However, home-based delivery should not be equated with unsupervised care. The more complex a closed-loop system becomes, the more it depends on reliable setup, safe assistance, usable interfaces, and mechanisms for clinicians to review performance and intervene when needed.

4.2 Current Evidence and Unresolved Barriers

Current evidence supports the feasibility more clearly than it does the long-term efficacy. A soft robotic glove with cloud monitoring shows how telerehabilitation can combine hand assistance, home practice, and remote data review [37]. An EMG-driven wrist-hand exoneuromusculoskeleton extends this idea by combining effort-sensitive control, NMES, wrist-hand assistance, and home-based self-help telerehabilitation [17]. The HAAPI home robotic trial is important because it shows that home robotic delivery is possible, but also cautions that a robotic program may not necessarily outperform dose-matched home practice [10]. Neurofenix and MusicGlove illustrate the contribution of gaming or sensor-based systems to engagement, dose, acceptability, and hand-oriented practice, while remaining different from fully sensorimotor closed-loop wrist-hand robots [38-39].

The unresolved barriers are shared across platforms. Patients and caregivers must manage donning and doffing, calibration, fatigue, skin comfort, device alignment, and safety events. Clinicians need interpretable data on adherence, movement quality, compensatory patterns, and progression rather than only raw minutes or repetitions. Remote troubleshooting, software updates, sensor drift, network reliability, cost, maintenance, and long-term durability also matter. These requirements become more demanding when a device includes sensors, stimulation, adaptive assistance, or cloud monitoring, because errors may affect both training quality and safety. Evidence from gaming and sensor-based platforms is useful because it highlights engagement and acceptability, but these systems should not be treated as equivalent to fully closed-loop robotic rehabilitation. Future home trials should therefore report not only clinical scales, but also setup failures, missed sessions, adverse events, therapist contact, and whether recorded movements represent useful hand practice. They should also specify which patients can manage the system independently and which need assistance from a caregiver or therapist. Therefore, RQ3 evidence supports home-based translation as a necessary direction, but feasibility is not efficacy, dose recording is not clinical superiority, and home use is not proof of fully independent rehabilitation. Therapist-in-the-loop supervision remains central to responsible deployment.

5. Discussion

The three themes of this review converge on a single argument: post-stroke wrist-hand robots should move from mechanical assistance toward sensorimotor closed-loop control. Mechanical assistance can increase repetition and reduce physical burden, but it does not guarantee that training engages the impaired sensorimotor system. A robot that assists without sensing effort may promote passivity, while a system that detects effort without useful feedback may fail to shape motor learning. The goal is not to make every device more complex, but to ensure that added complexity serves a clear therapeutic function. RQ1 evidence indicates that somatosensory feedback and sensory integrity are relevant to treatment response and neural plasticity; RQ2 evidence shows that EMG, EEG/BCI, and CMC-based signals can make patient effort more visible to the device; and RQ3 evidence shows that translation requires systems that remain usable and safe outside specialized laboratories [8-10,15-17,23-25,37-39]. A key implication is that somatosensory feedback and voluntary motor effort recognition should not be developed as isolated modules. Feedback without active effort risks becoming passive stimulation, while effort recognition without meaningful sensory consequences risks becoming only classification. A more coherent closed-loop system would link attempted movement, detected effort, adaptive robotic/FES/NMES assistance, and sensory feedback in time, while using neurophysiological and kinematic assessment to monitor whether training is changing movement quality or only device behavior [15-18,26,29,30]. This architecture is evidence-informed, not already validated, and should be tested against simpler interventions with component-separation designs to identify which element contributes to recovery. This integration also helps avoid two common overstatements. First, adding a sensory stimulus does not automatically produce sensorimotor integration; the timing, target muscle, task relevance, and patient sensory integrity matter. Second, detecting an EMG, EEG, or CMC pattern does not automatically prove that a patient is learning a more functional movement. A closed-loop system should therefore be evaluated at multiple levels: signal reliability, assistance timing, movement quality, clinical function, safety, adherence, and patient usability. Such layered evaluation is especially important for wrist-hand systems, where small changes in alignment or compensation can make device performance appear better than functional hand recovery. It also supports more precise patient stratification, because patients with different sensory loss, residual EMG activity, attention, and tolerance for technology may need different control routes. Without such stratification, negative trials may hide responsive subgroups and positive feasibility studies may overstate generalizability. Home deployment adds a second layer of requirements. A laboratory prototype can rely on expert setup, immediate troubleshooting, and controlled supervision; a home system must tolerate variable placement, fatigue, caregiver support, internet instability, and inconsistent adherence. For that reason, therapist-in-the-loop supervision should be considered part of the intervention rather than an optional service feature. Remote monitoring should help clinicians evaluate safety, dose, and movement quality, rather than simply counting repetitions. Future studies should move beyond demonstrating that a device can be used at home and test whether it can maintain calibration, promote useful practice, and support clinical decisions over weeks or months. Larger controlled trials, patient stratification, transparent AI models, long-term robustness testing, and cost-aware service models are needed before sensorimotor closed-loop wrist-hand robots can be treated as mature home-based rehabilitation solutions [10,17,37-39].

6. Conclusion

Post-stroke wrist-hand rehabilitation robots are most promising when they are designed not only to assist movement, but also to support sensorimotor closed-loop training. Current evidence suggests that somatosensory feedback, Voluntary Motor Effort Recognition, and home-based monitoring are key directions for future systems. Proprioceptive, tactile, vibrotactile, EMG-driven, EEG/BCI-informed, and CMC-related approaches provide mechanistic plausibility and early clinical support, but the evidence remains heterogeneous and device-specific. Home-based systems may improve access, dose, and continuity of care, yet feasibility should not be interpreted as established clinical superiority. Future work should use larger controlled samples, component-separation designs, patient stratification, transparent signal-processing methods, objective movement-quality assessment, and long-term home-deployment validation. The most defensible direction is therefore an integrated, therapist-supported system that combines sensory feedback, voluntary effort recognition, adaptive assistance, objective assessment, and safe home monitoring, while keeping clinical claims in line with current evidence and the practical limits of home use. This direction is promising, but it remains a research and translation agenda rather than a settled standard of care. Careful validation should precede broad clinical implementation and guide later manuscript refinement for future submission preparation.

References

[1] Doumas I, Everard G, Dehem S, Lejeune T. Serious games for upper limb rehabilitation after stroke: a meta-analysis. Journal of neuroengineering and rehabilitation. 2021;18:100. doi:10.1186/s12984-021-00889-1. PMID:34130713.

[2] Liu LY, Li Y, Lamontagne A. The effects of error-augmentation versus error-reduction paradigms in robotic therapy to enhance upper extremity performance and recovery post-stroke: a systematic review. Journal of neuroengineering and rehabilitation. 2018;15:65. doi:10.1186/s12984-018-0408-5. PMID:29973250.

[3] Seo NJ, Ramakrishnan V, Woodbury ML, Bonilha L, Finetto C, Schranz C, Scronce G, Coupland K, Blaschke J, Baker A, Howard K, Meinzer C, Velozo CA, Adams RJ. Concomitant sensory stimulation during therapy to enhance hand functional recovery post stroke. Trials. 2022;23:262. doi:10.1186/s13063-022-06241-9. PMID:35382902.

[4] Tsai MF, Wang RH, Zariffa J. Validity of Novel Outcome Measures for Hand Function Performance After Stroke Using Egocentric Video. Neurorehabilitation and neural repair. 2023;37(2-3):142-150. doi:10.1177/15459683231159663. PMID:36912468.

[5] Gu Y, Xu Y, Shen Y, Huang H, Liu T, Jin L, Ren H, Wang J. A Review of Hand Function Rehabilitation Systems Based on Hand Motion Recognition Devices and Artificial Intelligence. Brain sciences. 2022;12:1079. doi:10.3390/brainsci12081079. PMID:36009142.

[6] Tseng KC, Wang L, Hsieh C, Wong AM. Portable robots for upper-limb rehabilitation after stroke: a systematic review and meta-analysis. Annals of medicine. 2024;56(1):2337735. doi:10.1080/07853890.2024.2337735. PMID:38640459.

[7] Fardipour S, Hadadi M. Investigation of therapeutic effects of wearable robotic gloves on improving hand function in stroke patients: A systematic review. Current journal of neurology. 2022;21(2):125-132. doi:10.18502/cjn.v21i2.10496. PMID:38011474.

[8] Cordo P, Wolf S, Rymer WZ, Byl N, Stanek K, Hayes JR. Assisted Movement With Proprioceptive Stimulation Augments Recovery From Moderate-To-Severe Upper Limb Impairment During Subacute Stroke Period: A Randomized Clinical Trial. Neurorehabilitation and neural repair. 2022;36(3):239-250. doi:10.1177/15459683211063159. PMID:35067125.

[9] Murakami Y, Honaga K, Kono H, Haruyama K, Yamaguchi T, Tani M, Isayama R, Takakura T, Tanuma A, Hatori K, Wada F, Fujiwara T. New Artificial Intelligence-Integrated Electromyography-Driven Robot Hand for Upper Extremity Rehabilitation of Patients With Stroke: A Randomized, Controlled Trial. Neurorehabilitation and neural repair. 2023;37(5):298-306. doi:10.1177/15459683231166939. PMID:37039319.

[10] Wolf SL, Sahu K, Bay RC, Buchanan S, Reiss A, Linder S, Rosenfeldt A, Alberts J. The HAAPI (Home Arm Assistance Progression Initiative) Trial: A Novel Robotics Delivery Approach in Stroke Rehabilitation. Neurorehabilitation and neural repair. 2015;29(10):958-968. doi:10.1177/1545968315575612. PMID:25782693.

[11] Gassert R, Dietz V. Rehabilitation robots for the treatment of sensorimotor deficits: a neurophysiological perspective. Journal of neuroengineering and rehabilitation. 2018;15:46. doi:10.1186/s12984-018-0383-x. PMID:29866106.

[12] Bai J, Zhu R, Jiang Y, Du X. Robot-Assisted Dynamic Interaction of Hemiplegic Upper Limbs with Complex Objects Based on Enhanced Feedforward-Impedance Control. Biomimetics (Basel, Switzerland). 2025;10:815. doi:10.3390/biomimetics10120815. PMID:41439883.

[13] Ben Abdallah I, Bouteraa Y, Alotaibi A. AI-driven hybrid rehabilitation: synergizing robotics and electrical stimulation for upper-limb recovery after stroke. Frontiers in bioengineering and biotechnology. 2025;13:1619247. doi:10.3389/fbioe.2025.1619247. PMID:40635696.

[14] Bhagat NA, French J, Venkatakrishnan A, Yozbatiran N, Francisco GE, O'Malley MK, Contreras-Vidal JL. Detecting movement intent from scalp EEG in a novel upper limb robotic rehabilitation system for stroke. Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference. 2014;2014:4127-4130. doi:10.1109/EMBC.2014.6944532. PMID:25570900.

[15] Lin L, Huang Y, Qing W, Kuet MT, Zhao H, Ye F, Rong W, Li W, Hu X. Sensorimotor Integration by Targeted Priming in Muscles with Electromyography-Driven Electro-vibro-feedback in Robot-Assisted Wrist/Hand Rehabilitation after Stroke. Cyborg and bionic systems (Washington, D.C.). 2026;7:0507. doi:10.34133/cbsystems.0507. PMID:41608594.

[16] Guo Z, Zhou S, Ji K, Zhuang Y, Song J, Nam C, Hu X, Zheng Y. Corticomuscular integrated representation of voluntary motor effort in robotic control for wrist-hand rehabilitation after stroke. Journal of neural engineering. 2022;19:026004. doi:10.1088/1741-2552/ac5757. PMID:35193124.

[17] Nam C, Zhang B, Chow T, Ye F, Huang Y, Guo Z, Li W, Rong W, Hu X, Poon W. Home-based self-help telerehabilitation of the upper limb assisted by an electromyography-driven wrist/hand exoneuromusculoskeleton after stroke. Journal of neuroengineering and rehabilitation. 2021;18:137. doi:10.1186/s12984-021-00930-3. PMID:34526058.

[18] Remsik AB, van Kan PLE, Gloe S, Gjini K, Williams L Jr, Nair V, Caldera K, Williams JC, Prabhakaran V. BCI-FES With Multimodal Feedback for Motor Recovery Poststroke. Frontiers in human neuroscience. 2022;16:725715. doi:10.3389/fnhum.2022.725715. PMID:35874158.

[19] Zhang W, Lai J, Xu B, Zeng H, Wu T, Hu H, Song A. The Role of Vibrotactile Stimulation in Soft Rehabilitation Glove-Assisted Hand Rehabilitation Training: A Pilot Study. IEEE transactions on neural systems and rehabilitation engineering: a publication of the IEEE Engineering in Medicine and Biology Society. 2026;34:149-162. doi:10.1109/TNSRE.2025.3639490. PMID:41329575.

[20] Hoh JE, Scott SH, Dukelow SP, Semrau JA. Proprioceptive Thresholds Are Indicators of Upper Limb Perception After Stroke. Neurorehabilitation and neural repair. 2025;39(11):931-944. doi:10.1177/15459683251363245. PMID:40842407.

[21] Bustamante C, Brevis F, Canales S, Millón S, Pascual R. Effect of functional electrical stimulation on the proprioception, motor function of the paretic upper limb, and patient quality of life: A case report. Journal of hand therapy: official journal of the American Society of Hand Therapists. 2016;29:507-514. doi:10.1016/j.jht.2016.06.012. PMID:27665394.

[22] Du Q, Luo J, Cheng Q, Wang Y, Guo S. Vibrotactile enhancement in hand rehabilitation has a reinforcing effect on sensorimotor brain activities. Frontiers in neuroscience. 2022;16:935827. doi:10.3389/fnins.2022.935827. PMID:36267238.

[23] Elangovan N, Yeh IL, Holst-Wolf J, Konczak J. A robot-assisted sensorimotor training program can improve proprioception and motor function in stroke survivors. IEEE ... International Conference on Rehabilitation Robotics : [proceedings]. 2019;2019:660-664. doi:10.1109/ICORR.2019.8779409. PMID:31374706.

[24] Ingemanson ML, Rowe JR, Chan V, Wolbrecht ET, Reinkensmeyer DJ, Cramer SC. Somatosensory system integrity explains differences in treatment response after stroke. Neurology. 2019;92(10):e1098-e1108. doi:10.1212/WNL.0000000000007041. PMID:30728310.

[25] Tashiro S, Mizuno K, Kawakami M, Takahashi O, Nakamura T, Suda M, Haruyama K, Otaka Y, Tsuji T, Liu M. Neuromuscular electrical stimulation-enhanced rehabilitation is associated with not only motor but also somatosensory cortical plasticity in chronic stroke patients: an interventional study. Therapeutic advances in chronic disease. 2019;10:1-13. doi:10.1177/2040622319889259. PMID:31798821.

[26] He J, Yuan Z, Quan L, Xi H, Guo J, Zhu D, Chen M, Yang B, Cui Z, Zhu S, Qiao J. Multimodal assessment of a BCI system for stroke rehabilitation integrating motor imagery and motor attempts: a randomized controlled trial. Journal of neuroengineering and rehabilitation. 2025;22:185. doi:10.1186/s12984-025-01723-8. PMID:40859358.

[27] Pichiorri F, Toppi J, de Seta V, Colamarino E, Masciullo M, Tamburella F, Lorusso M, Cincotti F, Mattia D. Exploring high-density corticomuscular networks after stroke to enable a hybrid Brain-Computer Interface for hand motor rehabilitation. Journal of neuroengineering and rehabilitation. 2023;20:5. doi:10.1186/s12984-023-01127-6. PMID:36639665.

[28] Mashayekhi M, Moghaddam MM. EMG-driven fatigue-based self-adapting admittance control of a hand rehabilitation robot. Journal of Biomechanics. 2022;138:111104. doi:10.1016/j.jbiomech.2022.111104. PMID:35561557.

[29] Ambrosini E, Gasperini G, Zajc J, Immick N, Augsten A, Rossini M, Ballarati R, Russold M, Ferrante S, Ferrigno G, Bulgheroni M, Baccinelli W, Schauer T, Wiesener C, Gfoehler M, Puchinger M, Weber M, Weber S, Pedrocchi A, Molteni F, Krakow K. A Robotic System with EMG-Triggered Functional Electrical Stimulation for Restoring Arm Functions in Stroke Survivors. Neurorehabilitation and neural repair. 2021;35(4):334-345. doi:10.1177/1545968321997769. PMID:33655789.

[30] Frolov AA, Mokienko O, Lyukmanov R, Biryukova E, Kotov S, Turbina L, Nadareyshvily G, Bushkova Y. Post-stroke Rehabilitation Training with a Motor-Imagery-Based Brain-Computer Interface (BCI)-Controlled Hand Exoskeleton: A Randomized Controlled Multicenter Trial. Frontiers in neuroscience. 2017;11:400. doi:10.3389/fnins.2017.00400. PMID:28775677.

[31] Cantillo-Negrete J, Rodríguez-García ME, Carrillo-Mora P, Arias-Carrión O, Ortega-Robles E, Galicia-Alvarado MA, Valdés-Cristerna R, Ramirez-Nava AG, Hernandez-Arenas C, Quinzaños-Fresnedo J, Pacheco-Gallegos MDR, Marín-Arriaga N, Carino-Escobar RI. The ReHand-BCI trial: a randomized controlled trial of a brain-computer interface for upper extremity stroke neurorehabilitation. Frontiers in neuroscience. 2025;19:1579988. doi:10.3389/fnins.2025.1579988. PMID:40606836.

[32] Guo L, Wang J, Wu Q, Li X, Zhang B, Zhou L, Xiong D. Clinical Study of a Wearable Remote Rehabilitation Training System for Patients With Stroke: Randomized Controlled Pilot Trial. JMIR mHealth and uHealth. 2023;11:e40416. doi:10.2196/40416. PMID:36821348.

[33] Laver KE, Adey-Wakeling Z, Crotty M, Lannin NA, George S, Sherrington C. Telerehabilitation services for stroke. The Cochrane database of systematic reviews. 2020;(1):CD010255. doi:10.1002/14651858.CD010255.pub3. PMID:32002991.

[34] Li L, Fu Q, Tyson S, Preston N, Weightman A. A scoping review of design requirements for a home-based upper limb rehabilitation robot for stroke. Topics in stroke rehabilitation. 2022;29(6):449-463. doi:10.1080/10749357.2021.1943797. PMID:34281494.

[35] Proulx CE, Higgins J, Vaughan T, Hewko M, Gagnon DH. Poststroke Neurorehabilitation Using a Soft Robotic Glove Combined With a Virtual Environment: Preliminary Study on Feasibility, Safety, Effects, and User Satisfaction. JMIR neurotechnology. 2025;4:e69750. doi:10.2196/69750. PMID:41341419.

[36] De Bartolo D, De Pasquale P, Russo M, Berger DJ, Maselli A, Borzelli D, Nissler C, Nowak M, Castellini C, Morone G, d'Avella A. Usability, Acceptability, and Feasibility of a Personalized Adaptive Mirror Therapy for Upper-Limb Poststroke Rehabilitation Using Immersive Virtual Reality and Myoelectric Control: Single-Arm Pre-Post Study. JMIR rehabilitation and assistive technologies. 2026;13:e81894. doi:10.2196/81894. PMID:42082173.

[37] Proietti T, Nuckols K, Grupper J, Schwerz de Lucena D, Inirio B, Porazinski K, Wagner D, Cole T, Glover C, Mendelowitz S, Herman M, Breen J, Lin D, Walsh C. Combining soft robotics and telerehabilitation

for improving motor function after stroke. Wearable technologies. 2024;5:e1. doi:10.1017/wtc.2023.26. PMID:38510985.

[38] Kilbride C, Scott DJM, Butcher T, Norris M, Warland A, Anokye N, Cassidy E, Baker K, Athanasiou DA, Singla-Buxarrais G, Nowicky A, Ryan J. Safety, feasibility, acceptability and preliminary effects of the Neurofenix platform for Rehabilitation via HOMe Based gaming exercise for the Upper-limb post Stroke (RHOMBUS): results of a feasibility intervention study. BMJ Open. 2022;12:e052555. doi:10.1136/bmjopen-2021-052555. PMID:35228279.

[39] Zondervan DK, Friedman N, Chang E, Zhao X, Augsburger R, Reinkensmeyer DJ, Cramer SC. Home-based hand rehabilitation after chronic stroke: Randomized, controlled single-blind trial comparing the MusicGlove with a conventional exercise program. Journal of rehabilitation research and development. 2016;53(4):457-472. doi:10.1682/JRRD.2015.04.0057. PMID:27532880.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgment

This paper is an output of the science project.

Open Access