Advances and Challenges in Sensory Retraining and Neurorehabilitation for Post-Stroke Arm Dysfunction: Integrating Neuroplasticity and Personalized Approaches

Tailai Cong (从泰来)

High School Affiliated to Renmin University of China, Beijing, China

Abstract

This paper explores the efficacy of sensory retraining therapy (SRT) and advanced neurorehabilitation strategies, such as virtual reality (VR) and non-invasive brain stimulation (NIBS), in promoting neuroplasticity and functional recovery post-stroke. This highlights the critical role of personalized rehabilitation approaches, addressing gaps in current methodologies, and underscores the need for integrating emerging technologies with tailored therapeutic protocols to optimize recovery. Key challenges, including standardization and patient selection, are discussed, alongside future directions for research and clinical application.

1 Introduction

Stroke poses a formidable global health challenge, ranking as a leading cause of death and disability worldwide [42, 43]. Ischemic stroke, its most prevalent form, imposes substantial global health and economic burdens [42, 43]. Projections indicate a sustained increase in the global age-standardized incidence rate of ischemic stroke through 2030, suggesting an expanding affected population [43]. Nevertheless, overall death and disability-adjusted life years (DALYs) rates are anticipated to decline, potentially reflecting advancements in acute care and improved survival outcomes [43]. However, significant disparities in stroke burden persist. Countries with a low socio-demographic index (SDI) may continue to experience rising death and DALY rates due to persistent challenges in healthcare access, health literacy, and service quality [42, 43]. This highlights a critical tension between global health progress and persistent regional inequities [42, 43].

2 Post-Stroke Arm Dysfunction

A profound and highly prevalent consequence of stroke is post-stroke arm dysfunction, which encompasses a spectrum of severe motor and sensory deficits [24, 59]. Motor impairments, such as unilateral arm paresis, are observed in a high percentage of acute stroke cases, significantly impeding a survivor's ability to perform self-care and diminishing overall quality of life [59, 60]. Beyond overt motor weakness, subtle proprioceptive deficits—a crucial sensory impairment—are also common, profoundly affecting motor performance and hindering functional recovery [24].

Contemporary understanding of motor recovery from stroke increasingly acknowledges its complexity, challenging the long-held ”proportional recovery rule” by suggesting that recovery is not solely determined by initial motor function loss [3]. Instead, it is significantly influenced by spared function and a confluence of other demographic, clinical, imaging, and physiological factors, underscoring the need for more nuanced recovery models [3].

3 Rehabilitation Approaches

Given these pervasive functional challenges, effective post-stroke rehabilitation is paramount for improving upper limb function and facilitating a return to daily living activities [59]. Rehabilitation approaches encompass a range of interventions, from central strategies like repetitive transcranial magnetic stimulation (rTMS) to peripheral interventions, such as robotic therapy [59]. Nevertheless, a notable gap remains in identifying optimal, evidence-based rehabilitation strategies, particularly for patients with severe upper limb dysfunction [59].

While general sensory stimulation has been explored, specific interventions like proprioceptive training with visual feedback present a promising, yet under-researched, avenue to address the profound impact of sensory deficits on motor function and overall recovery [24]. This highlights a broader tension in stroke rehabilitation research, where enhanced methodological rigor, particularly in the design of control comparators, is essential to ensure the validity and generalizability of findings and ultimately accelerate the translation of effective interventions into widespread clinical practice [23].

4 Upper-Limb Dysfunction and Sensory Deficits

Stroke often results in significant upper-limb dysfunction, characterized by intricate neurological underpinnings involving damage to specific brain regions that disrupt both motor and sensory pathways, profoundly impacting an individual’s self-care ability and overall quality of life [2, 6]. A critical aspect of post-stroke impairment is the high prevalence of somatosensory deficits, affecting a substantial proportion of survivors [8]. For instance, leg somatosensory impairment can be observed in up to 89% of cases [8].

These deficits are not confined to the contralesional side but are also frequently present in the ipsilesional hand, with tactile impairment reported in 83% of contralesional and 42% of ipsilesional hands [35]. Specific types of sensory impairments include proprioception, light touch, tactile discrimination, stereognosis, two-point discrimination, and temperature sensation [8, 35], encompassing superficial, deep, cortical, and subjective sensations [18]. The primary motor cortex (M1), conventionally associated with motor control, also plays a crucial role in somatosensation through its extensive connections with somatosensory cortices and the thalamus, making it a critical area where damage or dysfunction can contribute to sensory loss [18].

5 Impact of Sensory Deficits

These pervasive sensory deficits directly impair motor control, fine motor skills, and the ability to perform daily activities. The loss of proprioception, for example, significantly hinders effective motor learning and balance training [36]. Furthermore, tactile sensory feedback is indispensable for precise initial force scaling and ongoing finger force control during gripping tasks [14].

Stroke survivors with sensory deficits frequently exhibit a greater phalanx force deviation during power grip, meaning forces are directed more tangentially to the object surface, consequently elevating the risk of finger slippage and object dropping [14]. This altered gripping strategy is often accompanied by aberrant muscle activation patterns, such as reduced activity in the first dorsal interosseous (FDI) and extensor digitorum communis (EDC) muscles relative to the flexor digitorum superficialis (FDS) [14]. Such observations highlight that sensory deficits independently and significantly contribute to impaired hand motor control post-stroke, extending beyond the impact of motor impairment alone [14].

While sensory retraining interventions have demonstrated improvements in somatosensory function and balance, their consistent impact on complex motor outcomes like gait remains less clear [8, 36], underscoring the multifaceted challenges in full functional recovery.

6 Neuroplasticity and Recovery

The brain's inherent capacity for neuroplasticity plays a pivotal role in both the manifestations of impairment and the potential for recovery of sensorimotor function post-stroke. Cortical reorganization is a dynamic process where damage to primary motor areas can induce compensatory sensory responses in adjacent premotor regions, such as the rostral forelimb area (RFA) in experimental models [22]. Intriguingly, the RFA can then modulate activity in the primary somatosensory cortex (S1), signifying a functional connectivity aimed at restoring sensorimotor integration [22].

This reorganization is further reflected in changes in corticospinal excitability [18]. While a larger ipsilesional motor cortex evoked potential (MEP) can correlate with worse somatosensory function, an increased MEP ratio (ipsilesional vs. contralesional) is paradoxically associated with better somatosensory function in well-recovered patients, suggesting a complex, non-linear relationship crucial for recovery [18]. Even in the chronic phase, neuroplasticity can be leveraged for recovery, as evidenced by hyperbaric oxygen therapy (HBOT) leading to improvements in motor function, increased functional MRI activation in key motor-related regions like the supplementary motor area (SMA) and premotor cortex (PMA), and enhanced brain connectivity [6]. This suggests a shift towards more bilateral and balanced brain activity, with increased inter-hemispheric connectivity supporting motor recovery [6].

Despite these advancements, a persistent gap exists in standardizing quantifiable and precise somatosensory assessment measures to effectively diagnose impairment and evaluate treatment efficacy

[8, 35], and there is a continued need for the development of consistent, replicable sensory retraining methods for widespread clinical application [8].

7 Conventional Rehabilitation Approaches

Conventional approaches to upper limb rehabilitation in stroke patients predominantly focus on improving motor output through intensive, repetitive practice, aiming to restore functional movement and minimize disability. Constraint-Induced Movement Therapy (CIMT), for instance, directly addresses ”learned non-use” by constraining the unaffected limb, thereby compelling the use of the paretic extremity [55]. While CIMT has demonstrated positive impacts on upper limb motor function, its effectiveness in improving broader functional mobility or balance can be less pronounced, highlighting a specific focus on motor execution rather than integrated functional gains [55].

Similarly, task-specific training (TST) and the Motor Relearning Program (MRP), a form of task-oriented rehabilitation, emphasize repetitive practice of functional movements to promote neuroplasticity and motor recovery [39, 52]. These approaches generally show effectiveness in enhancing upper limb function and reducing impairment; however, systematic reviews often find moderate evidence and note methodological limitations, suggesting that their superiority over other interventions is not definitively established [39].

The Neurodevelopmental Treatment (NDT) or Bobath approach, widely applied in stroke rehabilitation, focuses on facilitating normal movement patterns, posture, balance, and coordination [1]. Despite its widespread use, the robust evidence supporting NDT’s specific efficacy also remains a subject of ongoing discussion in the literature [1].

8 Technological Advancements in Rehabilitation

Technological advancements have integrated robot-assisted therapy (RT) into conventional care, offering intensive, repetitive, and measurable motor training [32, 61]. RT has shown a statistically significant, albeit small, effect in improving upper extremity motor impairment, particularly for patients in the late subacute or chronic stages and those with moderate to severe deficits [61]. Interestingly, unilateral RT appears more effective than bilateral RT, and end-effector devices tend to outperform exoskeleton devices in motor function improvement [61].

Beyond singular modalities, emerging strategies explore combining conventional therapies with priming techniques, which aim to enhance the brain’s receptiveness for subsequent training [32, 52]. For example, movement-based priming has been shown to significantly augment the benefits of task-specific training in early stroke recovery, suggesting a role for preparing the motor system beyond mere repetition [52]. Furthermore, novel hybrid approaches, such as robotic priming combined with mirror therapy (MT) or bilateral arm training, are being investigated to potentially improve both sensorimotor and daily functions [32].

Mirror therapy itself, through the visual illusion of movement, inherently bridges sensory input with motor output, fostering motor functions and movement control strategies [32]. Despite the established benefits of these conventional and technologically augmented motor-focused therapies in improving motor output, a critical tension arises from their typical emphasis. Many approaches, by primarily targeting motor execution, often under-emphasize or implicitly address the crucial role of sensory integration in comprehensive recovery. This gap, particularly concerning the intricate interplay between sensory feedback and motor learning, highlights the imperative need for dedicated sensory retraining strategies to fully optimize upper limb recovery in stroke patients.

Even advanced approaches like Brain-Computer Interface (BCI) training, while exploring direct neural pathways for motor control, have shown no statistically significant superiority over conventional therapy in improving severely impaired upper limb function, especially if cortico-spinal tract integrity is compromised, further underscoring the complexities and the ongoing search for more holistic and effective rehabilitation paradigms [4].

9 Sensory Impairments and Functional Independence

Stroke survivors frequently experience profound sensory impairments that critically undermine motor function, compromise motor learning, and ultimately diminish functional independence. Upper limb impairments, prevalent in a substantial majority of stroke survivors, are intricately linked to a diminished ability to perceive and execute movements, significantly impacting daily living activities [48, 53]. Specifically, the widespread manifestation of impaired grip force directional control impedes successful object manipulation, leading to compromised dexterity and self-care abilities [48].

Similarly, balance impairments, a common and significant consequence of stroke, are directly tied to the disruption of effective sensorimotor integration [25]. These pervasive sensory deficits contribute to a complex sensorimotor dysfunction wherein the central nervous system struggles to accurately regulate muscle contraction, underscoring the critical necessity of addressing sensory deficits in rehabilitation [28].

10 Sensorimotor Integration

Intact and accurate sensory feedback is indisputably crucial for the precise planning, execution, error correction, and adaptation of movement. Sensorimotor integration, defined as the nervous system's capacity to unify sensory information with motor commands for coordinated action, underpins dynamic motor control [25]. This integration is particularly vital for online adjustment of motor output based on continuous sensory feedback, as observed in the intricate control of grip force direction [48].

While historically, impaired grip force control has been linked to peripheral tactile sensory deficits and altered muscle activation patterns, contemporary research indicates that cortical sensorimotor integration, rather than solely peripheral sensory impairment, serves as a primary driver of these motor control deficits [48]. Notably, a significant tension exists in the literature, as studies have demonstrated a robust association between impaired grip force direction control and cortical sensorimotor integration, even independently of the level of peripheral sensory impairment [48]. This underscores a critical gap in understanding the intricate interplay between peripheral sensory input and central processing in driving post-stroke motor deficits, suggesting that a more nuanced approach is required beyond merely addressing peripheral sensation [48].

11 Sensory Retraining in Rehabilitation

Given the profound impact of sensory disruption on motor function and the central role of sensorimotor integration, it is imperative that addressing sensory impairment directly receives equal emphasis alongside motor retraining for comprehensive stroke recovery. The concept of sensorimotor integration, which is consistently disrupted post-stroke, necessitates therapeutic strategies that actively target and restore this critical neural function [25].

Neglecting sensory retraining, particularly proprioception and kinaesthesia, represents a significant oversight in traditional rehabilitation paradigms [53]. Evidence suggests that synchronously combining motor and proprioceptive retraining leads to stronger connections between sensorimotor regions, indicating a synergistic effect that surpasses sequential or isolated approaches [53]. This integrated approach is supported by findings demonstrating that sensorimotor integration exercises significantly enhance balance by increasing muscle activity and improving limits of stability in stroke patients [25].

Furthermore, novel interventions utilizing real-time tactile discrimination feedback have shown promising results in reorganizing sensorimotor areas, improving deep sensation, and enhancing hand movement quality, which are attributed to the re-establishment of a sensory information integration system that facilitates error detection and online adjustments [28]. Beyond limb function, the critical role of sensory input extends to broader neurological recovery, as illustrated by spinal cord injury models where sensory input rerouting proved more crucial than motor axon reinnervation in reactivating neurocircuits and central pattern generators for locomotor recovery, emphasizing the profound and often underestimated role of afferent feedback in neuroplasticity and functional restoration [63].

Therefore, the rationale for prioritizing sensory retraining is firmly grounded in its capacity to drive neuroplastic changes essential for motor relearning and ultimately, functional independence.

12 Theoretical Underpinnings of Sensory Retraining

Sensory retraining therapy is fundamentally underpinned by the principle of neuroplasticity, positing that the brain's inherent capacity for reorganization can be harnessed to improve somatosensory function following neurological injury [26, 44, 57]. This process involves targeted and repetitive sensory input inducing beneficial cortical reorganization within the somatosensory cortex and broader sensorimotor networks [26, 41, 44]. Studies consistently demonstrate that rehabilitation can lead to structural brain changes, such as increased cortical thickness, which correlates with enhanced sensory function after stroke [44]. Furthermore, these interventions can restore cortical responsiveness, as evidenced by improved somatosensory evoked potentials and modulated alpha power activity in sensory discrimination tasks [26, 41].

The mechanisms driving sensory retraining can be broadly categorized into bottom-up and top-down processes. Bottom-up approaches primarily involve direct peripheral stimulation to enhance somatosensory input and induce cortical plasticity. Examples include repetitive sensory stimulation (rSS) to the paretic hand, which has shown considerable improvements in sensory and motor abilities in chronic cerebral lesion patients, with effects developing over weeks to months [26]. Similarly, sensory electrical stimulation (SES) and repetitive peripheral sensory stimulation (RPSS) directly target peripheral nerves to promote rapid plastic changes in both motor and somatosensory cortices [29, 41].

Focal muscle vibration (fMV) also exemplifies a bottom-up approach, inducing multisite neuroplasticity in both the brain and spinal cord, thereby modulating cortical and motoneuron excitability to improve motor function and reduce spasticity [57]. Conversely, top-down mechanisms emphasize cognitive and attentional modulation of sensory processing. Research indicates that strategies enhancing attentional resources and motivation can significantly influence rehabilitation outcomes [41, 66]. For instance, reward strategies, whether fixed or probabilistic, are hypothesized to improve rehabilitation motivation and motor learning, thereby indirectly facilitating sensory processing through enhanced engagement and salience [66].

Moreover, sensory training, particularly when combined with peripheral stimulation, can modulate attentional resources and neural plasticity, potentially leading to improved task performance and increased confidence in sensory discrimination [41]. The involvement of higher-order association sensory cortices, such as the posterior parietal cortex and occipital pole, in sensory recovery further underscores the role of integrative and potentially top-down modulated processing [44].

These theoretical underpinnings are operationalized through key principles of motor learning and neurorehabilitation, including specificity, intensity, repetition, and salience. Interventions like sensory reeducation are designed to be specific to the targeted sensory modality, incorporating repetitive and intensive practice to drive neuroplastic changes [26, 44]. The duration of stimulation, varying from single sessions to many months, as well as its intensity (suprasensory versus subsensory), are crucial parameters currently under investigation to optimize outcomes across different stroke phases [26, 29, 41].

Despite these advancements, several gaps and tensions persist within the field. A notable tension lies in the relative focus on motor versus sensory recovery; while rehabilitation often improves motor function, sensory acuity improvements may be less pronounced and driven by distinct structural changes, suggesting the need for more targeted sensory interventions [44]. Furthermore, the optimal parameters for sensory retraining—including the frequency, amplitude, duration, and timing of intervention across subacute and chronic phases—remain largely unclear, with studies often employing variable protocols [15, 29, 57]. The generalizability of findings is also limited by small sample sizes and single-case study designs in some research [26, 41, 44]. Addressing these gaps through standardized treatment protocols, clear reporting of patient characteristics, and robust outcome measures is crucial for advancing the efficacy and clinical applicability of sensory retraining therapies [15].

13 Specific Techniques and Modalities

Specific techniques and modalities employed in sensory retraining for arm dysfunction span a spectrum from traditional hands-on approaches to advanced technology-assisted interventions, often emphasizing a graded and repetitive nature to foster neuroplasticity. Foundational to sensory retraining are methods that target tactile and proprioceptive discrimination. For instance, goal-oriented proprioceptive training, which can involve single or dual-task exercises, has been demonstrated to improve balance and, to some extent, autonomy in subacute stroke patients [9].

Similarly, sensory training programs specifically focusing on finger perception, incorporating discrimination tasks performed under blind conditions, have been shown to enhance tactile sensitivity, such as tactile-pressure threshold, and improve fine motor skills like manipulating middle and small objects [56]. This approach contrasts with motor-focused rehabilitation alone, suggesting that a combined motor and sensory emphasis is critical for optimal recovery [56]. A more cognitively integrated approach includes proprioceptive training combined with exercise imagery, where patients imagine movements without physical action, leading to significant improvements in balance ability and joint position sense error through exercises on balance pads and boards [33].

Expanding on cognitive engagement, visual movement-discrimination exercises, often involving the discrimination of dim test patterns, serve as a unique sensory retraining modality by enhancing visual timing and potentially improving broader cognitive functions like reading fluency, attention span, and memory retention, highlighting the interplay between different sensory systems and higher-level cognitive abilities [30].

Advancements in technology have introduced sophisticated modalities for sensory retraining, particularly for severe or chronic impairments. Robotic devices, such as the Hand-Wrist Assisting Robotic Device (HWARD), are designed to assist functional grasping and releasing movements, enabling interaction with real objects during therapy to stimulate sensorimotor integration and enhance motor learning [54]. While some robotic interventions, like treadmill-integrated robot-assisted ankle dorsiflexion training (TMR), have not consistently demonstrated superiority over conventional treadmill training for general gait improvement, they hold potential for specific subgroups with pronounced deficits, underscoring the ongoing tension in determining the added value of complex technological interventions [12].

Moreover, the integration of robotic assistance with neurofeedback systems, such as Motor Imagery (MI)-based Electroencephalogram (EEG) Visual Neurofeedback (VNFB) coupled with Lokomat, allows individuals with complete spinal cord injuries to modulate brain rhythms while imagining gait movements, leading to improvements in sensory sensitivity and brain connectivity [50]. Beyond direct motor assistance, neurostimulation techniques are also emerging as powerful tools for sensory restoration.

Closed-loop stimulation of the lateral cervical spinal cord (SCS) in upper-limb amputees has enabled the discrimination of object size and compliance by providing somatotopically-matched tactile feedback via sensorized prosthetic hands [37].

Additionally, Proprioceptive Body Vibration Rehabilitation training (PBVT), involving vibration platforms, provides a multimodal sensory input that has shown superior effectiveness over conventional physical therapy in improving motor function, balance, and activities of daily living for stroke patients with impaired sensory function [62]. Despite the promising results, many of these interventions are limited by small sample sizes, retrospective designs, or focus on specific sensory aspects, highlighting a consistent gap in large-scale, double-blind randomized controlled trials and comprehensive evaluations of various sensory modalities or detailed upper extremity function [9, 33, 37, 50, 56, 62]. Furthermore, while some techniques demonstrate improved balance, the challenge remains in translating these gains to enhanced autonomy or reduced fall risk [9].

14 Clinical Efficacy and Evidence-Base

Converging evidence suggests that sensory retraining plays a crucial role in post-stroke rehabilitation, addressing sensory impairments that profoundly impact motor function and daily living. A systematic review and meta-analysis indicates moderate support for passive sensory training techniques, such as thermal stimulation, pneumatic compression, and peripheral nerve stimulation, in enhancing activity measures in stroke survivors [51]. However, the evidence for active sensory training remains limited yet promising [51].

Beyond these general approaches, various specialized interventions contribute to the evidence base, albeit with differing levels of rigor and scope. Traditional Chinese Medicine, specifically acupuncture combined with rehabilitation training, has shown significant efficacy in alleviating sensory disorders and improving self-care abilities in stroke patients. A network meta-analysis by Li et al. (2024) found that acupuncture combined with rehabilitation, particularly when augmented with massage, led to substantial improvements in Numbness Syndrome Scores, Sensory Impairment Scores, and daily living abilities [58]. This integrative approach is posited to accelerate sensory recovery by functionally reconstructing the central nervous system and increasing cerebral blood flow in the sensorimotor area [58].

Similarly, non-invasive brain stimulation techniques like transcranial direct current stimulation (tDCS) have demonstrated effectiveness in improving motor deficits, including upper and lower limb function, mobility, and activities of daily living (ADLs), highlighting their potential for motor rehabilitation, especially in subacute stroke when applied anodal in the affected area and cathodal in the unaffected [47].

Furthermore, technological advancements offer novel avenues for sensory retraining. Robotic rehabilitation, for instance, is explored for its ability to provide high-intensity, repetitive interventions for upper limb function. Kim et al. (2024) are investigating the comparative efficacy of proximal versus distal priority robotic priming combined with impairment-oriented training on sensorimotor impairment, upper limb function (e.g., Fugl-Meyer Assessment Upper Extremity subscale, Wolf Motor Function Test), and functional independence in chronic stroke [31].

In parallel, novel sensory stimulation devices like the TheraBracelet, which delivers imperceptible vibration during hand task practice, aim to enhance hand function and ADLs (e.g., Wolf Motor Function Test, Action Research Arm Test) by augmenting afferent input to the motor cortex without impeding natural movements [49]. Mirror therapy (MT), a simple visual feedback approach, also demonstrates potential for improving upper extremity function and ADLs, particularly when combined with other therapies or applied in a task-oriented manner, by activating mirror neurons and promoting motor recovery [10].

Emerging exergaming systems, originally investigated for conditions like multiple sclerosis, have also shown promise in improving sensorimotor upper limb function post-stroke, offering engaging and motivating avenues for intense rehabilitation [20]. Despite these encouraging findings, the current evidence base for sensory retraining exhibits several gaps and tensions. A significant limitation is the considerable heterogeneity across study protocols, encompassing varying intervention intensities, application parameters, and outcome measures, which complicates direct comparisons and meta-analyses, often leading to inconsistent findings [10, 47, 51].

Many studies are characterized by small sample sizes, single-center designs, and moderate methodological quality, particularly within specific intervention areas such as acupuncture-related treatments, underscoring a pressing need for higher-quality, standardized randomized controlled trials to validate and strengthen conclusions [47, 51, 58]. Furthermore, issues of generalizability arise from study populations that are often geographically limited, as seen in the predominantly Chinese cohorts in some acupuncture research [58]. The optimal timing and severity of stroke for intervention, as well as the long-term durability of effects, remain areas requiring further exploration.

While many interventions aim for sensorimotor integration, a tension exists in the primary outcome focus of some studies, which may emphasize motor outcomes more directly than primary sensory function, potentially highlighting a gap in comprehensive sensory assessment across the field [51].

15 Clinical Implementation Challenges

Clinical implementation of sensory retraining interventions for stroke survivors faces numerous practical challenges, primarily stemming from a pervasive lack of standardization and comprehensive reporting in research. For instance, a systematic review of somatic sensory training (SST) interventions revealed that reporting quality is suboptimal, with a median adherence of only 33% to the TIDieR checklist, thereby hindering the replication and widespread clinical adoption of these therapies [16]. This insufficient detail often means interventions are described merely by a label or a basic ”ingredient list,” which is inadequate for clinicians and researchers to accurately reproduce them [16].

Compounding this issue is the general insufficiency of high-quality evidence to definitively guide practice. A Cochrane review analyzing interventions for upper limb function post-stroke found that while some sensory interventions showed moderate-quality evidence of effectiveness, overall evidence quality for most interventions was low or moderate due to small sample sizes, methodological limitations, and heterogeneity [38]. This, in turn, does not support a change in routine clinical practice without continued personalized care [38]. This gap in evidence quality makes it difficult to ascertain which interventions are most beneficial, at what doses, and for which patient populations [38].

Patient motivation and adherence represent significant barriers to consistent therapy engagement. Repetitive sensory retraining tasks can lead to decreased motivation [70], underscoring the need for engaging approaches. Virtual reality (VR) systems, leveraging multisensory feedback and gamification, are proposed as a means to enhance motivation and engagement in stroke rehabilitation, thereby potentially improving adherence to often lengthy and intense therapy regimens [70].

However, even promising home-based interventions, such as sensory amplitude electrical stimulation (SES) via a sock electrode, grapple with challenges in formal adherence tracking and variability in patient activity, which can obscure the true impact and sustainability of benefits [34]. Furthermore, the required intensity and duration of therapy, alongside the need for specialized therapist training, pose practical constraints. While advanced modalities like powered exoskeletons can significantly improve gait performance and induce beneficial neurophysiological changes [5], their implementation necessitates specialized equipment, considerable resources, and expert training for clinicians.

Similarly, novel approaches like Acupuncture Synchronized Rehabilitation Therapy (ASRT) require adherence to specific guidelines and skilled practitioners, demanding further verification of their clinical efficacy and safety in rigorous trials before widespread adoption [64]. Patient-specific factors, such as the severity of impairment or cognitive status, also influence the feasibility and potential outcomes of sensory retraining, as evidenced by exclusion criteria in clinical trials that stipulate a minimum cognitive score for participation [64].

Collectively, these multifaceted challenges highlight the complex path from research discovery to effective, accessible, and standardized clinical implementation of sensory retraining for stroke survivors.

16 Integrated Approaches

The imperative for comprehensive recovery post-stroke has increasingly underscored the significance of integrating sensory retraining with established motor-focused rehabilitation techniques to achieve synergistic benefits. This integration acknowledges the fundamental role of sensorimotor processing in promoting functional restoration and adapting to neurological impairment. For instance, the combination of Action Observation Therapy (AOT) with Sensory Observation Therapy (SOT) is being explored, grounded in mirror neuron and embodied cognition theories, which posit that observing both actions and sensory experiences can activate neural pathways critical for sensorimotor integration and improved motor output [68].

This approach, while innovative, highlights ongoing debates regarding the ideal timing of AOT and the need for further research into neural mechanisms [68]. Beyond observation-based therapies, various studies delineate the benefits of combining physical stimulation with methods that augment sensory input. For example, Functional Electrical Stimulation (FES), which provides direct muscle activation and proprioceptive feedback, is being synergistically combined with Robotic-Assisted Therapy (RAT) to improve complex reach-to-grasp movements, acting on distinct aspects of motor relearning [67].

Similarly, repetitive peripheral magnetic stimulation (rPMS), which influences peripheral motor nerves and potentially modulates central motor cortical excitability, shows synergistic efficacy when combined with central intermittent theta burst stimulation (iTBS) for enhancing grasp function and daily activities in stroke patients [7]. While both real and sham rPMS combined with iTBS improved overall motor function and self-care, only the real rPMS combination significantly improved grasp, suggesting a targeted synergistic effect [7].

These findings illustrate how peripheral and central stimulation can be integrated to foster neuroplasticity. Concurrently, the effectiveness of combining electrical stimulation (EMS) with Mirror Therapy (MT) has been demonstrated, where EMS enhances muscle activation and strength, laying a foundation for MT's visual sensory feedback to further improve motor function [40]. However, a comparative analysis suggests that Constraint-Induced Movement Therapy (CIMT, primarily motor-focused) still demonstrates superior overall efficacy in improving upper extremity function compared to EMS+MT or MT alone, indicating the powerful impact of intensive use-dependent plasticity, implicitly requiring sensory processing during the constrained movement [40].

Technological advancements further facilitate integrated sensorimotor rehabilitation by creating immersive and interactive environments. EEG-based Brain-Computer Interfaces (BCIs), for instance, are being integrated with Functional Electrical Stimulation (FES), Augmented Reality (AR), Virtual Reality (VR), and robotic systems [69]. The BCI-FES integration targets muscle strength and coordination through direct stimulation and feedback, whereas BCI-AR/VR systems leverage immersive training environments to enhance motor learning and cognitive engagement by robustly engaging both sensory and motor systems [69].

BCI-robotic systems, on the other hand, offer closed-loop feedback, translating brain signals into physical movements and providing a blend of physical support and mental engagement [69]. These technological integrations underscore a shift towards personalized and adaptive interventions, though challenges such as signal processing complexity and cost persist [69]. Moreover, telerehabilitation systems, such as the HoMEcare aRm rehabiLItatioN (MERLIN) device utilizing serious games, exemplify how technology can deliver high-intensity, repetitive, and task-specific training at home, with the sensory-rich game environments enhancing patient motivation and adherence, demonstrating lasting improvements in chronic stroke patients' arm function [46].

Collectively, these integrated approaches underscore the critical interplay between sensory input and motor output in optimizing neurological recovery, highlighting a diverse landscape of strategies for promoting comprehensive sensorimotor integration in stroke rehabilitation.

17 Emerging Technologies and Future Directions

The evolving landscape of sensory retraining in rehabilitation is characterized by the rapid integration of cutting-edge research and emerging technologies, promising a paradigm shift towards more precise, engaging, and personalized interventions. Wearable sensors, such as inertial measurement units and ground reaction force sensors, are transforming gait analysis by offering low-cost, near real-time assessment capabilities for temporal dynamic synergies, providing detailed therapy follow-up information beyond conventional measures [19].

Complementing this, portable, minimally-actuated haptic devices are being developed to facilitate unsupervised home rehabilitation, addressing both motor and sensory deficits by combining active movements with passive range of motion and haptic feedback [45]. This development aims to significantly increase training dosage and accessibility for stroke patients, although clinical validation with patient populations and refinements in usability are still crucial [45].

Further advancing immersive rehabilitation, virtual reality and augmented reality platforms are increasingly being integrated with sensory stimulation to enhance therapeutic outcomes. For instance, combining virtual reality training with sensory stimulation has demonstrated significantly greater improvements in upper limb strength, active joint range of motion, and hand function compared to virtual reality alone in chronic stroke patients, bridging a critical gap in somatosensory rehabilitation within virtual environments [27].

The efficacy of these platforms is further amplified by artificial intelligence and gamification. Artificial intelligence applications in hand rehabilitation robots range from gesture recognition algorithms and robot control to interactive game design and personalized training program development, offering potential for heightened precision and effectiveness [21]. Moreover, machine learning models, particularly recurrent neural networks like LSTM, are now being employed to predict errors during robot-mediated gamified training [65].

This predictive analysis enables proactive adaptation of game difficulty or robotic assistance, thereby optimizing the challenge level to maintain patient engagement and prevent frustration, and potentially identifying the optimal timing for assistive interventions [65]. A pivotal area of innovation lies in the realm of neuromodulation, where brain-computer interfaces and neurofeedback are unlocking new pathways for direct brain-driven therapy. Motor-imagery-based brain-computer interfaces, when coupled with hand exoskeletons, have demonstrated significant improvements in specific hand functions like grasp and pinch by translating imagined movements into contingent haptic and kinesthetic feedback [17].

This approach highlights the potential for personalized rehabilitation based on individual brain activity and suggests that the ability to control a brain-computer interface may serve as a key indicator for identifying patients with the greatest rehabilitation potential [17]. Building upon this, combining motor imagery-based neurofeedback training with bilateral repetitive transcranial magnetic stimulation has shown synergistic effects, leading to superior improvements in upper limb motor and sensory function compared to repetitive transcranial magnetic stimulation alone [13].

Beyond these technological advancements, emerging conceptual frameworks, such as a four-level model of music therapy mechanisms, underscore the multifaceted impact of sensory input at neural coherence and even cellular/genetic levels, suggesting new avenues for understanding and optimizing therapeutic responses [11].

Despite these promising advancements, several key areas require further research and development. A significant gap exists in biomarker discovery for predicting treatment response, which could be informed by insights from brain-computer interface control ability [17] and predictive error analysis [65]. Optimizing the dosage and intensity of therapy remains crucial, with current research highlighting the importance of increased training dosage in home settings [45] and the impact of training intensity on outcomes [17].

Technical limitations, such as the accuracy and reliability of wearable devices compared to optoelectronic systems [19], the need for improved wearing comfort in portable devices, limited tactile feedback in virtual environments, and instability in physiological signal acquisition, call for continued engineering innovation [21]. Future efforts must also focus on developing closed-loop control networks, achieving complete human-machine integration, and integrating multi-information fusion to enhance precision and adaptability [21].

Methodological rigor, including the implementation of more robust randomized controlled trials and addressing challenges like skewed datasets and generalization across patient variability, is essential to validate these emerging technologies and facilitate their widespread clinical translation [13, 65]. Ultimately, fostering interdisciplinary collaboration among engineers, clinicians, and neuroscientists is paramount to realizing the full potential of these technologies in revolutionizing sensory rehabilitation [11].

18 Conclusion

In conclusion, the overarching findings of this review underscore the significant and multifaceted role of sensory retraining therapy in ameliorating arm function and enhancing the quality of life for stroke survivors. This body of literature consistently posits that targeted sensory interventions can facilitate neuroplastic changes, thereby improving somatosensory discrimination, proprioception, and tactile sensation, which are critical precursors to functional motor recovery.

Clinically, these findings bear substantial implications: therapists and healthcare providers are strongly encouraged to integrate sensory retraining as an early, integral component of post-stroke rehabilitation protocols, recognizing its potential to complement and augment traditional motor therapies. Practical recommendations include implementing individualized, task-specific sensory training, fostering multi-sensory integration approaches, and leveraging emerging technologies to optimize patient engagement and therapeutic outcomes.

However, despite these promising advancements, a notable gap persists in the current evidence base, highlighting the ongoing need for robust, large-scale randomized controlled trials to further solidify efficacy, define optimal intervention parameters such as intensity and duration, and explore the long-term sustainability of gains. Future research should also systematically investigate the comparative effectiveness of different sensory retraining modalities and their synergistic potential when combined with pharmaceutical or neuromodulatory interventions, thereby paving the way for more refined, evidence-based, and innovative approaches in sensory rehabilitation.

References

[1] Md. Abdul Alim et al. "Neurodevelopmental Treatment (NDT) Approach for Improving Balance in the Hemiplegic Stroke Patient: A Comprehensive Case Study". In: *Journal of Clinical and Healthcare Research* (2024). DOI: 10.53555/jchr.v14i01.2822.

[2] Saba Anwer et al. "Rehabilitation of Upper Limb Motor Impairment in Stroke: A Narrative Review on the Prevalence, Risk Factors, and Economic Statistics of Stroke and State of the Art Therapies". In: *Healthcare* (2022). DOI: 10.3390/healthcare10020190.

[3] A. Bonkhoff et al. "Bringing proportional recovery into proportion: Bayesian modelling of post-stroke motor impairment". In: *Brain* (2020). DOI: 10.1093/brain/awaa146.

[4] I. Brunner et al. "Brain computer interface training with motor imagery and functional electrical stimulation for patients with severe upper limb paresis after stroke: a randomized controlled pilot trial". In: *Journal of NeuroEngineering and Rehabilitation* (2024). DOI: 10.1186/s12984-024-01304-1.

[5] R. Calabró et al. "Shaping neuroplasticity by using powered exoskeletons in patients with stroke: a randomized clinical trial". In: *Journal of NeuroEngineering and Rehabilitation* (2018). DOI: 10.1186/s12984-018-0377-8.

[6] Merav Catalogna et al. "Functional MRI evaluation of hyperbaric oxygen therapy effect on hand motor recovery in a chronic post-stroke patient: a case report and physiological discussion". In: *Frontiers in Neurology* (2023). DOI: 10.3389/fneur.2023.1233841.

[7] Chieh Chang et al. "Synergistic efficacy of repetitive peripheral magnetic stimulation on central intermittent theta burst stimulation for upper limb function in patients with stroke: a double-blinded, randomized controlled trial". In: *Journal of NeuroEngineering and Rehabilitation* (2024). DOI: 10.1186/s12984-024-01341-w.

[8] Fenny Sf Chia, S. Kuys, and N. Low Choy. "Sensory retraining of the leg after stroke: systematic review and meta-analysis". In: *Clinical Rehabilitation* (2019). DOI: 10.1177/0269215519836461.

[9] R. Chiaramonte et al. "The Effectiveness of Goal-Oriented Dual Task Proprioceptive Training in Subacute Stroke: A Retrospective Observational Study". In: *Annals of Rehabilitation Medicine* (2024). DOI: 10.5535/arm.23086.

[10] J. Chrastina and Hana Svízelová. "Mirror therapy in adult stroke patients: a review of possible applications and effectiveness with an emphasis on activities of daily living". In: *Central European Journal of Nursing and Midwifery* (2021). DOI: 10.15452/CEJNM.2020.11.0026.

[11] Amy Clements-Cortés and L. Bartel. "Are We Doing More Than We Know? Possible Mechanisms of Response to Music Therapy". In: *Frontiers in Medicine* (2018). DOI: 10.3389/fmed.2018.00255.

[12] Susan S Conroy et al. "Treadmill Integrated Robot-assisted Ankle Dorsiflexion Training for Stroke Rehabilitation: A Pilot Randomized Controlled Trial". In: *Journal of Rehabilitation Medicine* (2024). DOI: 10.29011/2688-8734.100170.

[13] Francisco José Sánchez Cuesta et al. "EFFECTS OF MOTOR IMAGERY-BASED NEUROFEEDBACK TRAINING AFTER BILATERAL REPETITIVE TRANSCRANIAL MAGNETIC STIMULATION ON POST-STROKE UPPER LIMB MOTOR FUNCTION: AN EXPLORATORY CROSSOVER CLINICAL TRIAL". In: *Journal of Rehabilitation Medicine* (2024). DOI: 10.2340/jrm.v56.18253.

[14] Leah R. Enders and N. J. Seo. “Effects of Sensory Deficit on Phalanx Force Deviation During Power Grip Post Stroke”. In: *Journal of Motor Behavior* (2017). DOI: 10.1080/00222895.2016.1191416.

[15] S. J. Eskildsen et al. “Scoping review to identify and map non-pharmacological, non-surgical treatments for dysphagia following moderate-to-severe acquired brain injury”. In: *BMJ Open* (2021). DOI: 10.1136/bmjopen-2021-053244.

[16] D. Feller et al. “The Reporting of Somatic Sensory Training Interventions in Individuals After a Stroke Is Suboptimal”. In: *American Journal of Physical Medicine Rehabilitation* (2023). DOI: 10.1097/PHM.0000000000002188.

[17] A. Frolov et al. “Post-stroke Rehabilitation Training with a Motor-Imagery-Based Brain-Computer Interface (BCI)-Controlled Hand Exoskeleton: A Randomized Controlled Multicenter Trial”. In: *Frontiers in Neuroscience* (2017). DOI: 10.3389/fnins.2017.00400.

[18] Zhongming Gao et al. “Evaluation of Relationships between Corticospinal Excitability and Somatosensory Deficits in the Acute and Subacute Phases of Stroke”. In: *Journal of Integrative Neuroscience* (2023). DOI: 10.31083/j.jin2203061.

[19] Marija M. Gavrilović and M. Janković. “Temporal Synergies Detection in Gait Cyclograms Using Wearable Technology”. In: *Sensors* (2022). DOI: 10.3390/s22072728.

[20] Dr. Onno van der Groen et al. “Motor Improvement in Neurological Conditions (MINC): Multiple Sclerosis Design and methods of a single-arm feasibility study”. In: *bioRxiv* (2023). DOI: 10.1101/2023.07.30.23293287.

[21] Yuexing Gu et al. “A Review of Hand Function Rehabilitation Systems Based on Hand Motion Recognition Devices and Artificial Intelligence”. In: *Brain Sciences* (2022). DOI: 10.3390/brainsci12081079.

[22] P. Hayley et al. “Post-ischemic reorganization of sensory responses in cerebral cortex”. In: *Frontiers in Neuroscience* (2023). DOI: 10.3389/fnins.2023.1151309.

[23] KS Hayward et al. “Control intervention design for preclinical and clinical trials: Consensus-based core recommendations from the third Stroke Recovery and Rehabilitation Roundtable”. In: *International Journal of Stroke* (2023). DOI: 10.1177/17474930231199336.

[24] Jieying He et al. “Proprioceptive Training with Visual Feedback Improves Upper Limb Function in Stroke Patients: A Pilot Study”. In: *BioMed Research International* (2022). DOI: 10.1155/2022/1588090.

[25] Sang-hun Jang and Onseok Lee. “Effect of Sensorimotor Integration Exercise on Balance Among Patients with Stroke”. In: *International Journal of Biology and Biomedicine* (2016). DOI: 10.11159/ICBB16.111.

[26] J. Kattenstroth et al. “Long-term sensory stimulation therapy improves hand function and restores cortical responsiveness in patients with chronic cerebral lesions. Three single case studies”. In: *Frontiers in Human Neuroscience* (2012). DOI: 10.3389/fnhum.2012.00244.

[27] Dong-Hoon Kim and Sukmin Lee. “Effects of sensory stimulation on upper limb strength, active joint range of motion and function in chronic stroke virtual reality training”. In: *Physical Therapy Rehabilitation Science* (2020). DOI: 10.14474/ptrs.2020.9.3.171.

[28] Ken Kitai et al. “Evaluation of Intervention Effectiveness of Sensory Compensatory Training with Tactile Discrimination Feedback on Sensorimotor Dysfunction of the Hand after Stroke”. In: *Brain Sciences* (2021). DOI: 10.3390/brainsci11101314.

[29] J. Kroth et al. “Effects of Repetitive Peripheral Sensory Stimulation in the Subacute and Chronic Phases After Stroke: Study Protocol for a Pilot Randomized Trial”. In: *Frontiers in Neurology* (2022). DOI: 10.3389/fneur.2022.779128.

[30] T. Lawton. “Increasing visual timing by movement discrimination exercises improves reading fluency, attention span, and memory retention in dyslexics”. In: *Neurology and Neuroscience Reports* (2019). DOI: 10.15761/NNS.1000118.

[31] Yi-Chen Lee et al. “Effects of proximal priority and distal priority robotic priming techniques with impairment-oriented training of upper limb functions in patients with chronic stroke: study protocol for a single-blind, randomized controlled trial”. In: *Trials* (2021). DOI: 10.1186/s13063-021-05561-6.

[32] Yi-Chen Lee et al. "Effects of robotic priming of bilateral arm training, mirror therapy, and impairment-oriented training on sensorimotor and daily functions in patients with chronic stroke: study protocol of a single-blind, randomized controlled trial". In: *Trials* (2022). DOI: 10.1186/s13063-022-06498-0.

[33] H. Lee et al. "Effects of proprioception training with exercise imagery on balance ability of stroke patients". In: *Journal of Physical Therapy Science* (2015). DOI: 10.1589/jpts.27.1.

[34] Roberto López-Rosado et al. "Sensory Amplitude Electrical Stimulation via Sock Combined With Standing and Mobility Activities Improves Walking Speed in Individuals With Chronic Stroke: A Pilot Study". In: *Frontiers in Neuroscience* (2019). DOI: 10.3389/fnins.2019.00337.

[35] Yvonne Y K Mak-Yuen, T. Matyas, and L. Carey. "Characterizing Touch Discrimination Impairment from Pooled Stroke Samples Using the Tactile Discrimination Test: Updated Criteria for Interpretation and Brief Test Version for Use in Clinical Practice Settings". In: *Brain Sciences* (2023). DOI: 10.3390/brainsci13040533.

[36] Shobhna Mishra et al. "Effects of Lower Limb Proprioceptive Training on Balance and Trunk Control Among the Adult Stroke Population". In: *Cureus* (2024). DOI: 10.7759/cureus.64554.

[37] A. Nanivadekar et al. "Closed-loop stimulation of lateral cervical spinal cord in upper-limb amputees to enable sensory discrimination: a case study". In: *Scientific Reports* (2022). DOI: 10.1038/s41598-022-21264-7.

[38] Liliana Sousa Nanji et al. "Analysis of the Cochrane Review: Interventions for Improving Upper Limb Function after Stroke". In: *Acta Médica Portuguesa* (2015). DOI: 10.20344/AMP.7049.

[39] Claire O'Rourke and David Edwards. "The effectiveness of the motor relearning program on upper limb function post-stroke: a systematized review". In: *Physical Therapy Reviews* (2024). DOI: 10.1080/10833196.2024.2362045.

[40] Ghada S M Omar et al. "Effectiveness of Mirror Therapy, Electrical Stimulation, and CIMT in Restoring Upper Extremity Function after Stroke". In: *Southeast European Journal of Public Health* (2024). DOI: 10.70135/seejph.vi.1542.

[41] Eduardo Villar Ortega et al. "Enhancing touch sensibility with sensory electrical stimulation and sensory retraining". In: *Journal of NeuroEngineering and Rehabilitation* (2024). DOI: 10.1186/s12984-024-01371-w.

[42] Raju Paudel et al. "Stroke epidemiology and outcomes of stroke patients in Nepal: a systematic review and meta-analysis". In: *BMC Neurology* (2023). DOI: 10.1186/s12883-023-03382-5.

[43] Liyuan Pu et al. "Projected Global Trends in Ischemic Stroke Incidence, Deaths and Disability-Adjusted Life Years From 2020 to 2030". In: *Stroke* (2023). DOI: 10.1161/STROKEAHA.122.040073.

[44] S. Pundik et al. "Greater Cortical Thickness Is Associated With Enhanced Sensory Function After Arm Rehabilitation in Chronic Stroke". In: *Neurorehabilitation and Neural Repair* (2018). DOI: 10.1177/1545968318778810.

[45] Raphael Rätz et al. "Designing for usability: development and evaluation of a portable minimally-actuated haptic hand and forearm trainer for unsupervised stroke rehabilitation". In: *Frontiers in Neurorobotics* (2024). DOI: 10.3389/fnbot.2024.1351700.

[46] S. Rozevink et al. "HoMEcare aRm rehabiLItatioN (MERLIN): telerehabilitation using an unactuated device based on serious games improves the upper limb function in chronic stroke". In: *Journal of NeuroEngineering and Rehabilitation* (2021). DOI: 10.1186/s12984-021-00841-3.

[47] Raynara Fonsêca dos Santos et al. "THE INFLUENCE OF TRANSCRANIAL DIRECT CURRENT STIMULATION ON FUNCTIONAL RECOVERY AFTER STROKE: A SYSTEMATIC REVIEW". In: *Journal of Health Sciences* (2024). DOI: 10.36557/2674-8169.2024v6n2p2279-2284.

[48] Christian Schranz and Na Jin Seo. "Cortical Sensorimotor Integration as a Neural Origin of Impaired Grip Force Direction Control following Stroke". In: *Brain Sciences* (2024). DOI: 10.3390/brainsci14030253.

[49] N. J. Seo et al. "Concomitant sensory stimulation during therapy to enhance hand functional recovery post stroke". In: *Trials* (2022). DOI: 10.1186/s13063-022-06241-9.

[50] Ericka Raiane S. Serafini et al. “Gait Training-Based Motor Imagery and EEG Neurofeedback in Lokomat: A Clinical Intervention With Complete Spinal Cord Injury Individuals”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* (2024). DOI: 10.1109/TNSRE.2024.3400040.

[51] Ines Serrada, B. Hordacre, and S. Hillier. “Does Sensory Retraining Improve Sensation and Sensorimotor Function Following Stroke: A Systematic Review and Meta-Analysis”. In: *Frontiers in Neuroscience* (2019). DOI: 10.3389/fnins.2019.00402.

[52] Damayanti Sethy et al. “Effect of movement-based priming combined with task specific training on upper limb recovery in patients after stroke”. In: *Journal of Applied Medical Sciences* (2024). DOI: 10.12982/jams.2024.009.

[53] Ananda Sidarta. “Revisiting sensory impairment: a robotic-based training approach with chronic stroke survivors”. In: *Proceedings of the ACM on Human-Computer Interaction* (2023). DOI: 10.1145/3628228.3628495.

[54] Craig D. Takahashi et al. “A robotic device for hand motor therapy after stroke”. In: *IEEE International Conference on Rehabilitation Robotics* (2005). DOI: 10.1109/ICORR.2005.1501041.

[55] J. Tedla et al. “Effectiveness of Constraint-Induced Movement Therapy (CIMT) on Balance and Functional Mobility in the Stroke Population: A Systematic Review and Meta-Analysis”. In: *Healthcare* (2022). DOI: 10.3390/healthcare10030495.

[56] N. Umeki, J. Murata, and M. Higashijima. “Effects of Training for Finger Perception on Functional Recovery of Hemiplegic Upper Limbs in Acute Stroke Patients”. In: *BioMed Research International* (2019). DOI: 10.1155/2019/6508261.

[57] A. Viganó et al. “Focal Muscle Vibration (fMV) for Post-Stroke Motor Recovery: Multisite Neuroplasticity Induction, Timing of Intervention, Clinical Approaches, and Prospects from a Narrative Review”. In: *Vibration* (2023). DOI: 10.3390/vibration6030040.

[58] Jiaqi Wang et al. “Effect of acupuncture combined with rehabilitation training on sensory impairment of patients with stroke: a network meta-analysis”. In: *BMC Complementary Medicine and Therapies* (2024). DOI: 10.1186/s12906-024-04401-9.

[59] Taotao Wang et al. “Effectiveness of soft robotic glove versus repetitive transcranial magnetic stimulation in post-stroke patients with severe upper limb dysfunction: A randomised controlled trial”. In: *Frontiers in Neurology* (2023). DOI: 10.3389/fneur.2022.887205.

[60] J. Wassélius et al. “Detection of Unilateral Arm Paresis after Stroke by Wearable Accelerometers and Machine Learning”. In: *Sensors* (2021). DOI: 10.3390/s21237784.

[61] Jingyi Wu et al. “Robot-assisted therapy for upper extremity motor impairment after stroke: a systematic review and meta-analysis”. In: *Physical Therapy* (2021). DOI: 10.1093/ptj/pzab010.

[62] Hyun-seok Yoon and Chanhee Park. “Effectiveness of Proprioceptive Body Vibration Rehabilitation on Motor Function and Activities of Daily Living in Stroke Patients with Impaired Sensory Function”. In: *Healthcare* (2023). DOI: 10.3390/healthcare12010035.

[63] Dou Yu et al. “T12-L3 Nerve Transfer-Induced Locomotor Recovery in Rats with Thoracolumbar Contusion: Essential Roles of Sensory Input Rerouting and Central Neuroplasticity”. In: *Cells* (2023). DOI: 10.3390/cells12242804.

[64] Zifu Yu et al. “Effects of acupuncture synchronized rehabilitation therapy on upper limb motor and sensory function after stroke: a study protocol for a single-center, 2 × 2 factorial design, randomized controlled trial”. In: *Frontiers in Neurology* (2023). DOI: 10.3389/fneur.2023.1162168.

[65] Nihal Ezgi Yücetürk et al. “Predictive Analysis of Errors During Robot-Mediated Gamified Training”. In: *IEEE International Conference on Rehabilitation Robotics* (2022). DOI: 10.1109/ICORR55369.2022.9896589.

[66] Jingwang Zhao et al. “Improving rehabilitation motivation and motor learning ability of stroke patients using different reward strategies: study protocol for a single-center, randomized controlled trial”. In: *Frontiers in Neurology* (2024). DOI: 10.3389/fneur.2024.1418247.

[67] Huan-xia Zhou et al. “Synergy-based functional electrical stimulation and robotic-assisted for retraining reach-to-grasp in stroke: a study protocol for a randomized controlled trial”. In: *BMC Neurology* (2023). doi: 10.1186/s12883-023-03369-2.

[68] Zhiqing Zhou et al. “Effects of integrated action and sensory observation therapy based on mirror neuron and embodied cognition theory on upper limb sensorimotor function in chronic stroke: a study protocol for a randomised controlled trial”. In: *BMJ Open* (2023). doi: 10.1136/bmjopen-2022-069126.

[69] Zhengyu Zhuang. “Advancements in EEG-Based Brain-Computer Interface Integrations for Stroke Rehabilitation”. In: *Journal of Biomedical Engineering and Medical Imaging* (2024). doi: 10.54254/2755-2721/106/20241113.

[70] Fatin Shamimi Mohd Zuki et al. “Sensory Feedback and Interactivity: Enhancing Motivation and Engagement for VR Stroke Rehabilitation”. In: *IEEE International Conference on Computing, Informatics and Mathematics* (2021). doi: 10.1109/ICCOINS49721.2021.9497200.