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Systematic Review

Effect of Altered Sensory Input on Motor Relearning in Post-Stroke Rehabilitation: A Systematic Review and Theoretical Synthesis

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Abstract

Background: Stroke is a leading cause of long-term disability in the world that frequently leads toward motor impairment, a lack of independence, and disability in activities of daily living. The regaining of motor functions following a stroke is not solely dependent upon motor practice but also the quality and combination of sensory information. Sensory Related intervention like sensory retraining, mirror therapy, motor imagery, bilateral, electrical, robotic rehabilitation and virtual reality interventions have become promising approaches to improve motor relearning using neuroplasticity processes.

Objective: To conduct a systematic review of the contributions of altered sensory input to post-stroke motor relearning and formulate a theoretical model of the relationships between sensory enhancement, neuroplasticity and functional motor recovery.

Methods: Evidence-based research was presented in the form of a systematic review and theoretical synthesis by the researchers utilizing evidence of clinical trials, systematic reviews, meta-analyses, and rehabilitation-based studies in stroke survivors as adults. The review explored neurophysiological processes, interventions and concluded on their effects on motor recovery outcomes.

Results: The literature review indicates that altered and/or augmented sensory stimuli could potentially contribute to motor relearning poststroke by improving sensory perception, sensorimotor integration, sensorimotor feedback perception, and motor performance. Reported benefit was intervention type-, stroke characteristics-, and outcome assessed dependent. Most consistently found evidence was identified for selected upper limb and hand outcomes, with possible benefits for mirror therapy, bilateral training and feedback based approaches, whilst evidence for gait, activities of daily living, functional independence and specific neurophysiological mechanisms was more heterogeneous. Several possible mechanisms were proposed by the theoretical synthesis which connect changes in sensory input and motor relearning such as increased afferent feedback, sensorimotor integration, error-based learning, internal motor simulation and experience-dependent neuroplasticity.

Conclusion: Modulations or enhancements of sensory inputs could be added to repetitive, taskspecific, active post-stroke rehabilitation for motor relearning. Mirror therapy, sensory retraining, motor imagery, bilateral training, sensory stimulation, robotic rehabilitation and/or virtual reality appear to be beneficial based on current evidence, although evidence varies in strength and consistency for different interventions and outcomes. Research and data support the proposed theoretical framework, which explains the possible interactive role of sensory feedback with motor practice and neuroplasticity, but more and quality research is needed to understand how sensory feedback should be used and to illustrate potential mechanisms.

Keywords: Stroke Rehabilitation; Altered Sensory Input; Motor Relearning; Neuroplasticity; Sensorimotor Integration; Mirror Therapy; Virtual Reality and Functional Recovery

Introduction

Stroke is a leading cause of long-term impairment and it is often linked with chronic motor disability, loss of independence and restriction of activities of daily living. The motor recovery following a stroke is intricate because it depends on the neurological damage, baseline impairment, corticospinal integrity, the intensity of rehabilitation and the ability of the nervous system to restructure following injury [1,30]. Despite the fact that restoring movement is considered to be the main goal of a variety of rehabilitation strategies, motor relearning following a stroke is not reduced to motor practice but also to the quality of sensory input during movement [33,48]. Post stroke somatosensory impairment is frequent and it can include deficits in tactile discrimination, proprioception, stereognosis and sensory awareness. The impairments may include control of upper limbs, hand functions, dexteration, balance, and functional independence [13,36]. The loss of sense can also impair the accuracy of patients to observe errors in movement and in creating motor output when practicing. Research has demonstrated that poorer upper limb functioning and less daily functioning following stroke correlate with proprioceptive as well as tactile deficiency [5,56]. Thus, sensory input can be considered an integral, life-giving component to motor rehab following stroke and is not something that belongs in the back of the line.

Repetition, task specific practice, feedback, attention and neuroplasticity are beneficial to motor relearning. Systematic review has indicated that post stroke training can enhance functional ability particularly when it is systematic and repetitive and the practice has meaning and goal [20,28]. Nevertheless, in most patients, recovery is not complete, which implies that motor practice may not be adequate. Strategies that increase sensory feedback during rehabilitation can boost the brain capacity to correct motor instructions, and fine-tune motor patterns during recovery [21,48].

Distorted the sensory representation could facilitate motor relearning in a number of ways. Sensory stimulation may also induce more attention to the affected limb, sensorimotor integration, and increase the excitability of the cortex in the networks of motor interest [4,47]. It has been proposed that electrical stimulation, vibrotactile feedback, proprioceptive training and sensory retraining might serve as strategies to enhance motor functioning in the post stroke period [33,57]. The rationales behind these interventions are that when the correct afferent information is received, it will enable the central nervous system reengineer movement patterns and revert to more effective motor control [51,65]. Mirror therapy is a popular intervention involving modified visual feedback resulting in motor recovery. Here, the conduction of the unaffected limb causes a perceptual effect of movement in the affected limb, which can stimulate sensorimotor regions and aid cortical restructuring [17,35]. Mirror therapy has been reported to increase hand function, motor performance and sensory recovery in stroke patients [14,34]. Mirror therapy has been used together with other rehabilitation strategies including constraint induced movement therapy, robotic priming and movement-oriented training to improve the recovery of the upper limbs [16,41].

Another strategy is motor imagery, which involves internal sensory-motor simulation, facilitating recovery. In motor imagery, an individual mentally rehearses the movement without executing it, which causes the neural systems of motor planning and execution to be active [6,64]. Kinesthetic motor imagery has been demonstrated to have an impact on corticomotor excitability, and that imagined movement can have an adjusting effect on motor pathways following stroke [8]. It has also been proposed that motor imagery and mental practice can enhance functional recovery through the increase in the strength of the motor representations and the neuroplastic change [18,24]. Bilateral training alters the sensory and motor input in terms of involving both the limbs in co-movement or in a specific coordination. This strategy can facilitate the process of interlimb coupling, better motor network activation, and decrease post-stroke abnormal interhemispheric imbalance [12,55]. Literature (systematic reviews) supports the idea that upper-limb motor recovery in a selected stroke population can be supported using bilateral arm training [25,42]. Bilateral movement with rhythmic auditory cueing or neuromuscular stimulation has also been investigated as a means to improve motor performance in clinical studies [39,68].

Telefacilitated rehabilitation has provided more possibilities to control sensory input in the process of post-stroke motor relearning. The affected limb can receive repetitive, intensive and feedback-based practice via robot-assisted therapy and electromechanical arm training [11,29]. Proprioceptive robotic training has been found to change sensorimotor network connectivity, as well as enhance reaching accuracy during stroke chronicity [51]. In the same way, rehabilitation with virtual reality can offer enhanced visual and auditory feedback, engage the patient more, and train upper-limb functions after the stroke [23,69]. Although the use of sensory-based and feedback-enhanced interventions is on the rise, the importance of altered sensory input in post-stroke motor relearning is a complicated issue. Various methods utilize occurrences of different forms of sensory input which encompass tactile, proprioceptive, visual, electrical, bilateral, robotic and virtual feedback. These interventions too have different levels of intensity, time period, patient population and result measures [45,50]. Consequently, it is not clear what sensory mechanisms play the keys in the recovery of motor functions and what changes to the sensory input are to be incorporated into the practice of rehabilitation. This review thus tries to review the impact of modified sensory input on motor relearning in post-stroke rehabilitation. Synthesising evidence on the use of sensory retraining, mirror therapy, motor imagery, bilateral training, stimulation-based interventions, robotic therapy and virtual reality, the review aims to explain the role of sensorimotor relearning in stroke recovery and the formation of a theoretical perspective of sensorimotor relearning.

Methods

Review design

This paper was planned as the systematic review of literature with the theoretical synthesis that investigates the impact of the manipulated sensory information on post-stroke motor relearning. The review was limited to interventions utilizing change, augmentation or substitution of sensory information during rehabilitation such as sensory retraining, mirror therapy, motor imagery, bilateral training, electrical stimulation, robotic therapy and virtual reality-based rehabilitation. This was not merely an attempt to provide a summary of clinical findings, but also provide an explanation of how the modified sensory input can be used to facilitate sensorimotor recovery and motor relearning following stroke.

Search strategy

An organized search plan was created to find the studies concerning altered sensory input and motor recovery post stroke. The search included the adult stroke survivors whose evidence sources included the interventions aimed to enhance motor performance with the help of sensory, visual, proprioceptive, tactile, bilateral, or technology-based feedback. The search strategy consisted of a combination of the terms associated with stroke, sensory input, motor relearning, neurorehabilitation, and specific intervention methods. To find more studies, reference lists of the relevant reviews and included articles were also screened.

Databases and keywords

Major electronic databases commonly used in rehabilitation and neurological research (such as PubMed, MEDLINE, Cochrane Library, PEDro, Scopus, and Google Scholar) were used to conduct the literature search. Search terms were combined using Boolean operators, e.g., stroke AND sensory input, stroke AND mirror therapy, and post-stroke AND motor relearning. The inclusion and exclusion criteria will be as follows: Articles were considered eligible when all the following conditions were met: 1) the studies must have used adult participants who suffered a stroke, 2) they must have tested an intervention that altered or enhanced sensory input, and 3) they must have reported that the intervention resulted in changes in the level of motor functioning, upper-limb functioning, lower-limb functioning, dexterity, the functioning of movement, or functioning recovery. RCTs, pilot studies, meta-analyses, systematic reviews, theoretical reviews, and clinically relevant rehabilitation studies were taken into consideration. Research articles were filtered out based on their lack of relevance to stroke rehabilitation, lack of sensory or sensorimotor intervention, concentrated on pharmacological therapy, use of non-human subjects and lack of motor or functional outcome data.

Inclusion and exclusion criteria

Studies were included if they were related to how altered or enhanced sensory information influenced motor relearning or functional recovery following stroke. The studies selected were those in which: (1) The participants were adult stroke survivors; (2) An intervention or rehabilitation technique that altered, augmented, or substituted sensory input was studied; and (3) outcomes were reported that were relevant to motor, sensorimotor, or functional recovery. Eligible interventions were sensory retraining, tactile training, proprioceptive training, mirror therapy, bilateral training, electrical stimulation, vibrotactile or touch stimulation, robotic rehabilitation and virtual reality-based rehabilitation. The outcomes were the upper-limb and hand function, lower-limb function, gait, dexterity, activities of daily living, functional independence, sensory recovery, and motor relearning neurophysiological measures.

A variety of outcomes were considered during the review because the purpose was not only to collate the clinical outcomes but also to put forward a theoretical explanation of the sensory-motor relearning. Randomized controlled trials, pilot and other clinical studies for interventions, observational studies and experimental studies evaluated clinical and functional effects. Theoretical, mechanistic, and neurophysiological study was included, and systemic reviews and meta-analyses were used to summarise a broad range of evidence across interventions, where this enhanced interpretation of the studies relative to the sensorimotor integration, neuroplasticity, cortical reorganisations, motor imagery, interlimb coupling or feedback mediated motor learning.

Studies were excluded if they did not include the rehabilitation of stroke patients; included sensory-motor but not motor components involved with motor recovery; were in the main focused on pharmacological administration with no stroke-related rehabilitation component; studied non-human patients; did not report meaningful motor, sensory-motor, functional or mechanistically related outcomes.

Importantly, studies were only deemed equivalent when they used the same methodology. The evaluation of rehabilitation results was mainly achieved by clinical and empirical studies while reviews and theoretical or mechanistic publication were mainly used in order to contextualize the clinical findings and enrich the theoretical synthesis.

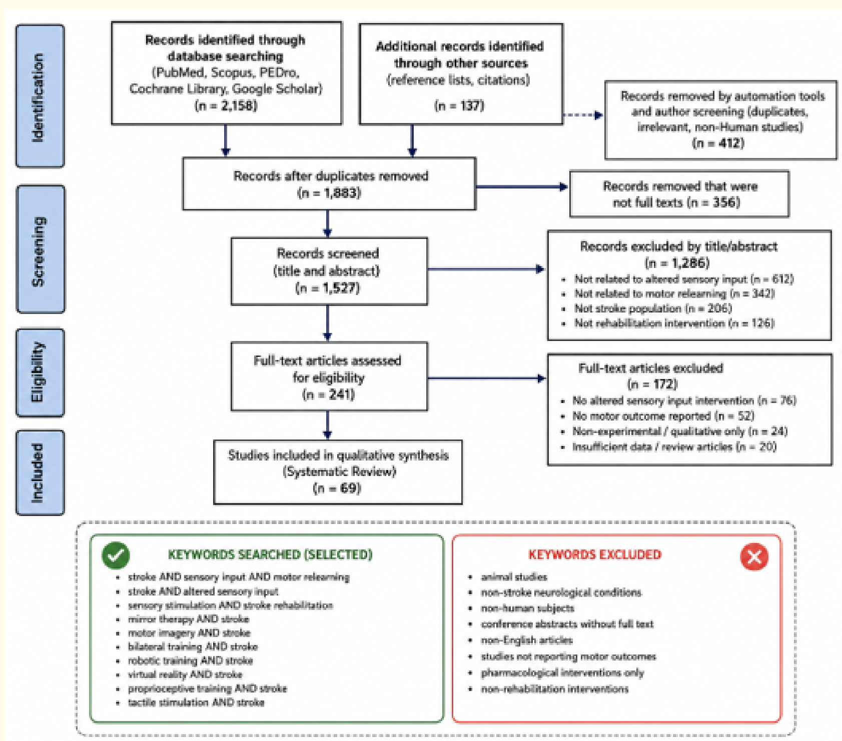

Figure 1: PRISMA 2020 Flow Diagram Showing Study Selection for the Systematic Review on Altered Sensory Input and Motor Relearning in Post-Stroke Rehabilitation.

Study selection process

There were sequential stages of study selection. Records found via the electronic database searching as well as the results from the additional reference-list screening were initially abstracted and duplicate records were eliminated. Title and abstracts were subsequently screened using a pre-defined study selection criterion to exclude clearly irrelevant studies.

Articles were retrieved for full text review if they were potentially eligible. In the full-text review, authors assessed each study for the population, the type of sensory or sensorimotor intervention, the reported motor or functional outcomes and the relevance to the objectives of the review. Articles were excluded at this point if they were not in an appropriate stroke population, investigated a different sensory or sensorimotor component, lacked outcomes for motor relearning or functional recovery, or lacked relevant mechanistic information for the theoretical synthesis.

These selected studies were then divided based on the main intervention, sensory approach, sensory approach with retraining, mirror therapy, motor imagery, bilateral training or sensory input electrical stimulation, robotic rehabilitation and virtual reality. Studies were also sorted by evidence type to separate the primary clinical evidence from systematic reviews and meta-analysis and from the theoretical and mechanistic literature.

The procedures reported in the complete study-selection process should be summarized in a PRISMA 2020 flow diagram, showing the following: Records identified; Duplicate records removed; Records screened; Full-text articles assessed for eligibility; Full-text articles excluded (with reasons); and Full-text articles included in review.

Data extraction

The data of eligible studies were systematically extracted based on structured approach. In primary clinical and empirical studies, the content retrieved involved the author/year published, study design, participant characteristics, stroke recovery stage, type of intervention, intervention length (where applicable), comparison/control condition (where applicable), outcome measures, and major findings.

Motor relearning, functional recovery (upper-limb motor function, hand dexterity, lower-limb function, gait performance, sensory recovery, daily activities and functional independence) was a particular focus. If reported, outcomes pertaining to neurophysiology, including cortical excitability, sensorimotor connectivity, cortical reorganization, and other measures of neuroplasticity were also extracted.

In the case of systematic reviews, meta-analysis, theoretical or mechanistic papers, information pertinent to the proposed mechanisms for sensory-motor relearning was extracted separately. These sources helped to identify and interpret the following mechanisms: sensorimotor integration, sensory prediction, error-based learning, cortical reorganization, internal motor simulation, interlimb coupling, and feedback-mediated neuroplasticity.

Extracted evidence was then categorized by the kind of sensory input modified; the primary motor or functional outcome; and the suggested neuro-physiological mechanism. This enabled the clinical data to be presented separately and then related to the mechanistic data during the theoretical synthesis.

Quality assessment

When interpreting the findings, methodological strengths and limitations of the evidence included were considered. Relevant methodological characteristics of studies were identified as the study design, sample size, clarity of participant selection, description of the intervention, appropriateness of outcome measure, whether there was a comparator or control study group (where applicable), duration of follow up, and potential sources of bias.

The evidence from RCTs and well conducted systematic reviews had a higher weight when conclusions about clinical effectiveness were drawn. Studies with more substantial methodological flaws (including pilot studies, small observational/experimental studies) were interpreted more conservatively. Theoretical/methodological articles were defined as sources of interpretation and used in the creation of frameworks and not as evidence of clinical effectiveness.

Specifically, the interveners' potential limitations that might affect the interpretation of the available evidence, such as small sample size, heterogeneity of intervention protocol, variation in treatment duration and intensity, different levels of stroke severity and stage of recovery, were considered.

Theoretical synthesis approach

The theoretical synthesis was informed by recurring patterns across the studies included, which occurred after the evidence synthesis was completed. Clinical and empirical research was initially discussed in line with the motor or functional outcome and the sensory input that was altered. These techniques involved tactile sensory retraining, modification of the visual sensory feedback with mirror therapy, motor imagery for the internal sensory-motor simulation, sensory motor input bilateral, peripheral sensory stimulation, robotic proprioceptive feedback and virtual and augmented feedback.

Then, the findings were reviewed as to the mechanisms that might reasonably account for the observed association between sensory manipulation and motor learning. Evidence for sensory awareness, peripheral afferent input was associated with sensorimotor integration/neuroplasticity, evidence from Mirror Therapy was considered when speaking about altered visual feedback, action observation, motor reorganization; Evidence of bilateral training was considered with regard to interlimb coupling and coordinated sensorimotor activity; Evidence of robotic rehabilitation, electrical stimulation, virtual reality was considered in the context of feedback mediated, error based motor learning.

The theoretical approach was thus not a different body of evidence to the systematic review. Instead, it was created using an interpretive synthesis to connect the clinical and functional findings with the neurophysiology and motor-learning mechanisms found in the literature. When evidence of the mechanism was indirect, or derived from theory or secondary source was interpreted with some caution and was not used as evidence for a causal mechanism.

Neurophysiological basis of sensory-motor relearning after stroke

Recovery of motor relearning post stroke relies on the interplay of sensory, motor, attention, feedback, and neural plasticity. Movement recovery cannot be isolated of sensory processing although treatment of stroke rehabilitation may be aimed at regaining movement. To plan movement, gauge performance, identify mistakes, and modify the motor output during rehabilitation, the nervous system requires correct sensory data [33,48]. Damage to movement and sensation cortical and subcortical networks can disrupt this sensory-motor system following stroke. Patients could develop a sense of weakness, loss of coordinates, lack of dexterity and balance and difficulty in using the affected limb in their daily life. Such impairments tend to be aggravated when there is reduced or distorted tactile, proprioceptive or somatosensory information [13,36]. It is not just the repeated movement practice that is needed in sensory-motor relearning. It is the healing of the connection between the inputs of the afferent sense organs and the outputs of the motor nerves. Rehabilitation strategies that boost or alter the sensory input can assist the brain to restructure the movement model and facilitate effective poststroke recovery [1,30]. There are the rehabilitation techniques which can deliver altered sensory input. They are sensory retraining, mirror therapy, motor imagery, bilateral training, electrical stimulation, robotic therapy and rehabilitation using virtual reality. Both of these strategies strive to enhance recovery by adding meaningful feedback to the nervous system in the course of motor practice [23,29].

Sensory deficits following stroke

Post-stroke sensory deficits are prevalent and may have a substantial impact on motor outcome. Such deficits can be unilateral or they can accompany motor weakness, spasticity, poor coordination and low level of postural control. Touches can be reduced, proprioception impaired, sensory discrimination poor and differences in the awareness of the body part affected by somatosensory impairment can occur [13,36]. With damaged senses, the patients can struggle to tell the position of the affected limb or its motion. This may complicate such functional activities as reaching, grasping, standing, walking, manipulating objects. Consequently, sensory impairment emerges as a factor that influences the ability to accomplish motor relearning productively following a stroke [5,56].

Tactile impairment

Tactile impairment is a loss of the capacity to sense touch, pressure, vibration, texture and features of objects. This loss is particularly relevant to the use of the hand as proficient use of the hand requires continuous feedback of somatic sensations on the fingers and palm. In the absence of sufficient tactile feedback, patients can difficulty regulate grip force, object shape, or awareness of an object sliding [56,58]. Confidence and limb use in everyday circumstances is also a concern with regard to tactile input. Patients with a hand that is not properly sensationed might avoid using it when they still have motor functioning in it. This decreased utilization could lead to impaired recovery and taught non-utilization of the damaged limb [36,56]. Research has indicated that loss in tactile sensation is associated with lack of prehensile ability following brain injuries. Active discriminative touch has been proposed to associate with dexterity also in post-stroke people. These results imply that there is a strong connection between tactile functioning and skilled upper-limb functioning [56,58]. The objective of sensory relearning interventions is to enhance processing of an individual's sense of touch by means of exposure to repetitive and organized sensations. These can be detection of texture, recognizing objects, localization of touch and graded sensory tasks. These interventions will help enhance sensory awareness and better utilization of the affected limb in functional activity [45,48].

Proprioceptive impairment

Proprioception involves the awareness of the location and movement of joints, limbs, direction and strength. It enables an individual to be aware of where the limb is within space without necessarily relying entirely on that of vision. Proprioception impairment in stroke inaccurately signals a reaching, inept coordination, and requires movement error correction difficulties [5,51]. Proprioceptive feedback is required since motor control relies on the comparison between the planned movement and actual movement. Whenever the nervous system gets the wrong information on the position of the limb, modifying the movement to occur through practice becomes a challenge. This is capable of minimizing the efficiency of rehabilitation in cases where the patient undergoes repeat efforts of performing a motor action [5,48]. Some lack of proprioception has been documented in chronic stroke, which has been linked to impaired upper-extremity performance and daily living limitations. Patients that are impaired in their proprioception could rely more on the eyes to direct movement. Nevertheless, visual compensation might not completely drive out the proprioceptive feedback in skilled motor control [5,51]. Proprioceptive training could be used to recover more precise sensory information when performing a movement. Proprioceptive training Robot controlled training on proprioceptive training has been demonstrated to change sensorimotor network connections and the accuracy of reaching in chronic stroke. This indicates potential benefits of focused proprioceptive stimulation in facilitating neural reorganization as well as in functional motor enhancement [51,65].

Somatosensory loss

Post-stroke somatosensory disorders can involve touch, proprioceptive, vibration, pains, temperature, and enhanced somatic processing. The causes of these deficits can be the destruction of the somatosensory cortex, thalamus, internal capsule, brainstem, or other sensory pathways. Since somatosensory input helps in body awareness and motor planning, its deficit may disrupt functional movement [13,36]. This could be due to somatosensory impairment, which would diminish the cognitions of the affected limb by the patient. When the limb provides the brain with limited information, attention to the limb might be reduced in the course of movement and day to day activity. This may have an impact on motor planning, correction of motion and voluntary functioning of the affected side [36,48]. Stroke has been found to cause somatosensory impairments and these can be of various sensory modalities. Functional problems have also been found to be correlated with sensory loss in stroke patients who have been hospitalized. Thus, sensory testing should be noted as a valuable component of the post stroke rehabilitation planning [13,36]. In case of sensory deficits remain undiagnosed, rehabilitation can be based primarily on observable motor weakness. This can cause incomplete treatment as this may be one of the reasons why there is poor movement since poor movement may not be due to weakness but a combination of weak sensory feedback. To this end, one needs to think about sensory-based rehabilitation as a valuable component of motor relearning following a stroke [33,48].

Neural plasticity and recovery

Neural plasticity means that the nervous system has the capability to restructure during injury and training. Following stroke, recovery could be achieved via spontaneous biological recovery, and experience-based changes that were generated by rehabilitation. These modifications can include cortical regions, regions commonly referred to as the corticospinal pathways, secondary motor as well as sensorimotor networks [1,30]. The variables that determine the recovery of motor functions are the level of impairment at the time of the disease, the nature of the lesions, the integrity of the corticospinal tract, and the rehabilitation contribution. Patients that have preserved motor pathways can demonstrate a higher recovery potential, whereas severe impairment might restrict the voluntary movement and practice. To predict recovery, it is thus necessary to know about the neural injury and plastic reorganization ability of the patient [1,30]. Plasticity can be formed through rehabilitation in the form of repeated meaningful, and task relevant practice. Training of repetitive task has been found to enhance functional post-stroke ability. However, the quality of practice does not go to waste without quality feedback to help correct motor error and learn [21,28]. Practice of tasks without sufficient sensory feedback can inhibit recovery since the brain cannot get clear feedback on movement accuracy. Sensory feedback enables the nervous system to detect errors and compare performance with intention and update motor commands. Thus, the role of sensorial input in the plasticity to experience dependent and post-stroke strokes is significant [33,48]. Neural plasticity is also of value to motor priming in rehabilitation. The purpose of priming techniques is to make the nervous system ready to be trained, that is, to make it more excitable or more responsive to therapy. Sensory stimulation can be a type of priming in enhancing awareness of the involved limb and engaging sensorimotor pathways [9,37]. Plasticity may also be promoted with the electrical and tactile stimulation in order to get more afferent information to the central nervous system. Transcutaneous electrical nerve stimulation has been demonstrated to enable motor performance in the lower limbs in chronic stroke bilaterally. The boost in vibrotactile has also been reported to strengthen sensorimotor brain activity when a hand receives rehabilitation [4,60].

Sensory feedback mechanisms

Sensory feedback is a prerequisite of correct movement since the brain is notified of the position of limbs, force, direction, contact and task outcome using this mechanism. When moving normally, there is continued processing of sensory information of the skin, muscles, joints and the visual system with motor commands. The nervous system is able to do this to rectify mistakes and to enhance future performance [48,65]. Following the stroke, the feedback mechanisms can be weak, slow, distorted, or not well integrated. Patients might be unaware of the movement errors or might struggle to modify their movements in practice. This has the potential to lessen the efficacy of motor relearning and cause long term functional impairment [13,36]. Interventions that attempt to enhance recovery focus on altering feedback to the patient by interfering with altered sensory input. Such interventions can aid in visual, tactile, proprioceptive, electrical, robotic or virtual feedbacks of rehabilitation. They can assist the nervous system to reconstruct more precise movement patterns by strengthening the meaningful feedback [23,33]. A variety of visual feedback This is because mirror therapy is an example of altered visual feedback. In the case of a mirror therapy, the affected limb does not move but the reflection of the normal limb gives the impression that the affected limb is moving normally. This illusion might stimulate sensorimotor formations and aid motor recovery following stroke [17,35]. Mirror therapy in clinical studies has been reported to improve hand function, motor, and sensory recovery. The mirror can give the patient visual feedback that has the potential to assist the patient focus on the affected limb and mentally establish an association between movement intent and actual movement. This could be particularly helpful when there is a restricted movement of the affected limb voluntarily [14,34].

Motor imagery is another form of sensory-motor feedback, which involves internal simulation. In a process called the motor imagery, the patient goes through the process of rehearsing the movement without actually doing the movement. This process triggers the neural processes related to motor planning, action representation and action execution [6,64]. Kinaesthetic motor imagery, in particular, could also be significant to consider as it entails the perception of the sensation of movement. It has been found that corticomotor excitability can be altered by using kinesthetic images. This implies that analog movement may affect motor paths when there is no physical movement of limbs [8,15]. Bilateral training offers feedback in form of the coordinated movement of the two limbs. The free limb can serve as a template of timing, rhythm and coordination of movement. Meanwhile, the simultaneous movement can be used to stimulate common neural processes related to motor control [12,55]. The strategy of upper-limb stroke recovery has been investigated as bilateral movement training. The systematic reviews indicate that the bilateral arm training can be useful in motor improvement in the selected stroke populations. This can be achieved by interlimb coupling, practice, and increased sensory-motor activation [25,42]. There are other types of feedback offered by technology-assisted rehabilitation. During repetitive practice, guided movement, resistance, assistance and proprioceptive feedback can be offered by robotic devices. In an interactive space, virtual reality can potentially offer both visual and auditory feedback which can enhance involvement and practice of tasks [23,29].

Role of sensorimotor cortex reorganization

Motor detoximeter sensorimotor cortex has one of the key roles to play in the recovery of movement following a stroke. There are several key motor regions that help to plan, execute and monitor movement including the primary motor cortex, primary somatosensory cortex, premotor cortex, supplementary motor area, and parietal regions. Damage to them or their connection may interfere with both processing of sensory and motor output [1,30]. The recovery can be in the form of reorganization of the damaged hemisphere, compensatory functions in the intact hemisphere, or differences in connectivity between the sensory and motor regions. Reorganization pattern might be contingent on the lesion location, level of stroke, the duration post-stroke, and experience with the rehabilitation. As rehabilitation has a significant, meaningful, and task relevant input, adaptive reorganization is more likely to occur [30,48]. Mirror therapy can also play a role in sensorimotor cortex reorganization as a result of visual feedback and action observation processes. Mechanisms: it has been reported that mirror therapy can induce motor recovery and reorganization of the cortex in chronic stroke patients. This helps to conclude that neural networks involved in the regulation of movement are capable of being changed by altered visual feedback [35,38]. Motor imagery also could lead to cortical reorganization through stimulating movement planning and simulation brain regions. It is believed that mental imagery in the motor context utilizes inner action representations. These representations can facilitate recovery in case of physical movement which is limited or challenging [6,64].

Repeated afferent input may result in sensorimotor cortex reorganization with proprioceptive and robotic training. Proprioceptive training under control of robots was found to alter functional connectivity of sensorimotor networks. This indicates that neural communication and motor performance can be influenced by sensory-based training [51,65]. This process can be explained with the help of the central-peripheral-central closed-loop model. This model assumes that the interaction of peripheral sensory input, processing in the central nervous system and motor output is an immediate, continuous process. This loop can also be reinforced with repeated sensory-motor practice which might be more effective in rehabilitation [65].

Motor learning theories relevant to stroke rehabilitation

Motor learning is defined as mastering or relearning through practice, feedback, attention and correction of errors in learning a skillful movement. Motor learning takes place at the presence of neural injury, weakness, sensory loss and abnormal movement patterns in stroke rehabilitation. Consequently, the rehabilitation should find a way of adapting principles of motor learning to the neurological and functional limitations in the patient [21,28]. Task-specific poststroke training is among main principles of the motor learning poststroke. According to this theory, patients enhance the type of movements and activities that are frequently practiced. Concrete, purposeful and goal focused practice is thus essential in enhancing post stroke independence [21,31]. Training in operation as a repetitive task has been proven to enhance functional disability following a stroke. But repetition needs to be informed by correct feedback to ensure that learning takes place. With incorrect movements and there is no helpful feedback to the patient, maladaptive movement strategies can form [28,48]. Another principle of stroke rehabilitation is feedback-based learning. Patients should be informed on the movement success, errors, position of limb and performance of tasks. In case of damaged intrinsic sensory feedback, the supplemental feedback provided by mirrors, therapists, robot machines or even computer generated virtual environments can gain particular significance [23,29].

Sensory-motor relearning also relates to motor simulation theory. According to this theory, there are overlapping neural mechanisms between action execution, action observation and motor imagery. Consequently, the mental rehearsal or movement observation could be beneficial in activating the motor networks that play a role in recovery [38,64]. Motor imagery utilizes this theory because it enables the patients to learn movement internally. This can be put into service in patients with severe weakness that cannot engage in complete physical movement. It has been proposed in reviews that motor imagery and mental practice can enhance functional recovery following stroke in cases where this technique is applied in rehabilitation [18,24]. Interlimb coupling theory can be used to support the possible advantages of bilateral training. The coordinated movement of the two limbs could serve as an increase in common neural circuits and enhancement of limb timing. This could enable the un-injured limb to assist the movement organization in the injured limb [12,55]. Various types of training have been investigated as bilateral, such as bilateral arm training, bilateral rhythmic auditory cueing, or a combination of stimulation protocols. The strategies are meant to enhance coordinated sensory-motor input in rehabilitation. There are indications that bi-lateral movement training can enhance motor recovery in the chosen stroke patients [25,49]. Another concept is called enriched sensorimotor practice. This strategy incorporates repetition, task-relevance, sensory feedback, motivation and progressive challenge. This can be facilitated by technology-assisted programs including robotic therapy and virtual reality, which can offer formalized and highly-provided feedback on rehabilitations [23,50]. In general, relearning of the sensory-motor functions in post-stroke recovery, hinges on restoring the connection between sensory input and motor output. Sensory loss might restrain recovery by decreasing the quality of feedback to control motor activity and to learn motor skills. An altered sensory input intervention can enhance recovery, and this intervention can potentially bolster afferent input, reinforce feedback processes, activate sensorimotor networks, and induce adaptive cortical reorganization [33,48].

Altered sensory input used in stroke rehabilitation

In stroke rehabilitation modified sensory input is applied to enhance the quality of feedback supplied to the nervous system in motor practice. The purpose of these approaches is to increase the visual, tactile, proprioceptive, electrical, bilateral, robotic or virtual feedback to enable the patients plan, monitor and correct movements more efficiently. Since stroke motor relearning is reliant on the relationship between sensory and motor outputs, sensory-based interventions can facilitate neuroplasticity and motor function recovery [33,48]. The various types of altered sensory input have different focuses in the sensory-motor system. The visible feedback and the inner sensory simulation are the basis of mirror therapy and bilateral training, respectively; the coordinating input of the two limbs and stimulation techniques, respectively, enhance the peripheral afferent input. Technology-assisted feedback is offered by robotic rehabilitation and virtual reality and can enhance users repetition, task involvement, and sensorimotor learning [23,29].

Mirror therapy

Mirror Therapy is a rehabilitation method in which a mirror is put between the affected and the unaffected limbs. The patient is also able to see how the unaffected limb moves, producing a visual illusion of the affected limb moving normally. This distorted visual feedback can enhance sensorimotor networks and enhance the relation between movement intention and perceived movement [17,35]. Visual substitution is the key process of mirror therapy. Sensory input related to the affected limb is usually diminished and thus the mirror can supply visual information that can substitute missing sensory signals. The illusion can augment attention stimulated to the impacted limb, decrease trained non-use, and encourage more active participation in the rehabilitation [14,34]. Mirror therapy can be also based on action observation and motor imagery mechanisms. The patient experiences movement and might internalize the same movement in the affected limb in even a restricted movement. These proceedings can engage areas of the cortex that are engaged in motor planning, movement execution, and sensory-motor integration [35,38]. Mirror therapy has been found to have clinical effectiveness in terms of enhancing upper-limb motor performance following a stroke. It has been reported in randomized controlled trials, that hand function, motor performance and sensory recovery improves after mirror therapy. Such findings imply that the visual feedback can be a handy technique to help in motor relearning in both subacute and chronic stroke groups [14,43].

Mirror therapy has been also observed in patients with more severe hemiparesis. The intervention can be beneficial in such situations as the patient can feel the visual perception of movement, in spite of limited voluntary movement. This renders mirror therapy particularly pertinent during the initial phases or in cases where the patients are still unable to engage in high- intensive active exercise [17,34]. Cortical reorganization is an important proposed mechanism of mirror therapy. Research has indicated that mirror therapy could be a factor affecting motor recovery because of altering sensorimotor cortical network activity. Cortical reorganization has been shown to positively affect improvement following mirror therapy in chronic stroke patients and this has lent a lot of support to cortical reorganization as a neuroplastic therapy [35]. Other approaches of rehabilitation have also been integrated with mirror therapy. As an illustration, it has been applied in conjunction with constraint-induced movement therapy, robotic priming, arm training, and movement-oriented therapy. The available evidence indicates that MT might be especially effective when added to other rehabilitation programs that emphasize task or sensory-motor strategies, but the evidence presented is no more effective than other rehabilitation strategies [16,41].

Motor imagery and mental practice

Motor imagery refers to rehearsing of a movement mentally without actually performing any physical actions. In motor imagery, the patient envisioned executing a movement and might concentrate on either the visual mental image of the movement or on the kinesthetic sensation of the movement. This method offers an internal simulation of sensory input that may stimulate a motor-related neural circuit [6,64]. The significance of internal sensation simulation is that simulated movement can respond to the part of the brain involved with real movement. Motor imagery enables the patient to rehearse movement in the mind in the presence of physical movement being hard due to weaknesses, lack of coordination or being fatigued. This renders it an effective technique in patients with low voluntary movements post-stroke [15,24]. Kinaesthetic motor imagery can prove to be particularly useful with regard to motor relearning. It includes imagining the experience of movement (including joint movement, muscle effort, and limb position). Studies have also demonstrated that the corticomotor excitability may be modulated through the use of kinesthetic imagery as well as imaging movement is likely to affect motor pathways [8]. Motor imagery has a background in terms of motor representation theory. This school of thought suggests that there overlap of neural representations in movement execution, movement observation, and movement imagination. So recurring mental rehearsal can be useful in preserving or reinforcing motor programs required in functional recovery [38,44].

Motor imagery is also applicable to the general theories of neural simulation. The brain has the ability to communicate action internally, even in cases where the body is not moving. The simulated task can help in motor planning, prediction, and learning by activating the neural process related to the control of actions [6,64]. There is clinical evidence and reviews indicating that motor imagery and mental practice are potentially effective in enhancing functional recovery in the aftermath of stroke. Evidence Systematic review evidence has identified positive impacts of motor imagery on functional outcomes especially when used with conventional therapy. Nonetheless, patient response can be different based on the ability of the patient, quality of imagery, severity of the stroke, and dose of treatment [18,24]. Motor imagery can probably have some specific value as a supplement to physical practice instead of an alternative. It may prime the motor system to move, enhance the paying attention to the affected part, and assist with repetitive movements without relating to physical exhaustion. Motor imagery in this manner, offers some kind of distorted internal sensory input which supplements active rehabilitation [24,63].

Bilateral training approaches

Bi-lateral training implies that one uses both sides or switches between a left and a right limb in a rehabilitation process. It is founded on the principle that interlimb coupling (coordinated movement of unaffected and affected limbs) can be used to enhance motor recovery. The unaffected limb could offer timing, rhythm and sensory cues that assist in movement of the affected limb [12,55]. The mutual coordination of the limbs is known as interlimb coupling. When one moves bilaterally, hemispheres and the two limbs are engaged in a coordinated manner. This can assist in enhancing motor output of the affected side to use common neural connections and lessen subject abnormality between limbs [49,55]. In upper-limb stroke rehabilitation, bilateral arm training has received a lot of research. Systematic reviews article have posited that bilateral training can enhance motor ability in a subset of patients but the effects on different protocols and stroke groups can be inconsistent. The benefits might be dependent on the nature of tasks and intensity of impairment, the intensity of training, and the combination of bilateral training with others [25,42]. There are studies which have compared bilateral and unilateral training of the upper limb. Such comparisons hold significance since unilateral training is more about the affected limb with bilateral training involving the coordinated movement of both limbs. It has been argued that either of these methods can be useful and it is possible that bilateral training can offer more sensory-motor information via interlimb coordination [25,62].

Another type of bilateral training of importance is rhythmic cueing. Rhythmic auditory cued bilateral arm repetition training has been demonstrated as effective in enhancing motor performance in chronic hemiparetic stroke. Audible rhythm could be used to organize the timing of movement, and enhance the quality of repeated bilateral movement practice [68]. Bilateral training has also been combined with neuromuscular stimulation. Combination of bilateral movements with electromyography-delivered neuromuscular stimulation has been shown to help in motor recovery. This method also allows voluntary motor exertion as well as the increased sensory feedback through electrical stimulation [39,57]. Bilateral training is not restricted to the upper limb. Mirror therapy of the lower extremities bi-laterally and arm cycling in a rhythmic way have been investigated in stroke survivors as well. These methods imply that upper-limb and lower-limb recovery process can be affected by bilateral sensory motor input [7,53].

Sensory stimulation techniques

The studies examined outline preliminary to moderate evidence for effects of electrical and vibrotactile stimulation on sensory inputs and possibly provide for selected motor or neurophysiological outcomes. For instance, bilateral TENS was correlated with improved motor performance in the lower limbs during chronic stroke and vibrotactile stimulation with changes in sensorimotor brain activity during hand rehabilitation [4,60].

These results point towards potential sensory-motor effects beyond the classical employment of stimulation but they are not evidence that sensory stimulation always leads to functional rehabilitation on a stroke population.

Transcutaneous electrical nerve stimulation, or TENS is the electrical stimulation of the skin through electrical stimulation to trigger peripheral nerves. TENS, in stroke rehabilitation, can be used to enhance sensory input to the central nervous system and enhance motor control. Bilateral TENS was proven to boost lower-limb motor output in chronically stroke patients [60]. It is said to have the neurobiological mechanisms of TENS, which are often referred to as afferent stimulation and central modulation. TENS is usually related to analgesia, but its sensory activity can also have an impact on sensorimotor processing. TENS can be used to stimulate the neural pathways in movement control and functional recovery by increasing the amount of peripheral input [19,60]. Vibrotactile stimulation is used to induce mechanical vibration of the skin, muscles or tendons. This kind of input can provide more tactile and proprioceptive input and can make a person more aware of their impacted limb. Vibrotactile amplification of hand rehabilitation has been demonstrated to bolster sensorimotor activity of the brain [4].

Muscles can also be stimulated using electricity to enhance movement as well as provide more sensory feedback. The use of electromyography-activated neuromuscular electrical stimulation is especially applicable since it correlates voluntary effort and stimulation. This forms a stronger feedback loop involving movement attempt, muscle activity, sensory input and motor output [39,57]. In cases where voluntary movement is not very strong or complete, neuromuscular electrical stimulation can be implemented.

It could be used to enable patients to associate motor intention with the sensory consequences by generating visible or assisted movement. In combination with bilateral arm exercises, it could also contribute to upper-limb functioning and alleviate hemiplegic shoulder pain following a stroke [57]. The methods of sensory stimulation could thus have peripheral and central effects. They enhance peripheral sensory feedback through muscle, joint and skin input. Core and not peripheral, enhancing sensorimotor integration, cortical excitability, and motor practice preparedness might be enhanced by repetitive stimulation [4,65].

Robotic and technology-assisted sensory feedback

Robotic rehabilitation is based on the mechanical or electromechanical aid, guidance, resistance or sensing of motion during therapy. These systems are able to give high repetition, practice control and even stable sensory feedback. On upper-limb rehabilitation stroke, robots are typically employed to enhance the functioning managed by the higher limb, arm power, and activities of everyday living [11,29]. The benefits of robotic rehabilitation are that good proprioceptive and movement-related feedback can be provided by robotic rehabilitation. Patients can also be helped with the reaching, grasping and arm movement and also be promoted to be active. By providing feedback on movement attempts that are correct, this kind of sensor based training can aid motor relearning [50,51]. Functional connectivity of sensorimotor networks has been shown to be modulated by robot-controlled proprioceptive training. It has also been linked to better accuracy of reaching in chronic stroke. These conclusions indicate that the neural processes and the performance of movement can be affected by robotic sensory feedback [51]. Sensor-based systems which measure the quality, range, speed, and task performance are also part of technology-assisted training. These systems can give both patient and therapist feedback to assist in steering the way and the level of tasks. The design of rehabilitation technology has placed significant emphasis on three aspects which include feedback, specificity of the task and motor control reacquisition [50].

Another concept is closed-loop rehabilitation that is of relevance in technology-assisted therapy. The central nervous system processes sensory input induced by the body in a closed-loop system and produces motor output and obtains updated feedback. This interaction that is continuous as sensory input, central processing and motor response are all focused on the central-peripheral-central model [65]. A closed-loop process can be assisted by sensor-based and robotic systems which give real-time feedbacks. This can assist patients in rectifying errors, movement awareness and training more precise motor patterns. Consequently, sensory feedback aided by technology can prove quite handy in cases where the regular therapy is not able to offer sufficient intensity or accuracy [50,65].

Virtual reality and augmented feedback

Virtual reality offering computer generated settings enables the patients to rehearse movements with enhanced visual, auditory and task related feedback. VR can be employed in the rehabilitation of stroke patients in training and learning: reaching, grasping, balance, bilateral arm movement, and functional training. Immersive VR can enhance interventions by rehabilitating patients more informatively and inspiring [23,69]. The main sensory mechanism of VR is augmented feedback. The patient will be able to view the output of their movement in real time, see, or hear, provide haptic feedback of an object or task, and interact with virtual objects or tasks. Such feedback can enhance movement precision, attention, motivation and repetition in the rehabilitation process [23,26]. Clinical data indicates that upper-extremity post-stroke rehabilitation can be facilitated with the help of immersive VR. A meta-analysis systematic review demonstrated that immersive VR has positive outcomes on upper-limb rehabilitation. These results help to justify the application of VR as sensory-enhanced approach to rehabilitation [23]. The bilateral upper-extremity training in VR has been also reported to be tested on post-stroke patients. This strategy involves visual feedback, bilateral movement, as well as practice of interactive tasks. Research indicates that bilateral training using VR could affect brain functionality and enhance the treatment involvement [26,69].

VR can involve an augmented feedback, which can be especially helpful with patients who have sensory deficits. The use of external visual and auditory feedback can assist patients to learn about movement errors and the success of different tasks when intrinsic sensory feedback is lessened. This may aid motor learning by clarifying and bringing performance information to the forefront [23,50]. In sum, there are alternative methods of supporting motor relearning in a post-stroke environment by using altered sensory inputs methods. Mirror therapy, motor imagery, bilateral training, sensory stimulation, robotic training and virtual reality are all aimed at enhancing the amount of feedback that the recovering nervous system receives. These interventions can also be employed to aid in enhancing sensory-motor integration and adaptive neuroplasticity, thereby supporting functional recovery during post-stroke rehabilitation [33,48].

Evidence Synthesis: Effects on motor relearning

There are a number of studies that have been reviewed as possibly supporting motor relearning post-stroke as a result of altered or augmented sensory input, but the level and consistency of the types of evidence supporting these interventions and outcomes varies widely. There were reports of abnormalities in upper-limb motor function, hand dexterity, lower-limb motor function, sensory function, activities of daily living and selected neurophysiological measures. The findings, however, come from studies with varying methodology, populations, stroke phases, dose and duration of intervention, and evaluation measures. Therefore the results need to be understood as an intervention and outcome, rather than evidence of a consistent effect of changing the sensory input upon post-stroke recovery.

Upper limb recovery

In general, upper-limb evidence was greater than evidence from several other functional areas. Partial evidence of progress within a set of upper-limb measures using mirror therapy was available from clinical studies, and there was some work in systematic review suggesting that bilateral training, involvement with a robot, and virtual reality interventions may all be beneficial [14,42]. However, results were variable for individual procedures and patient groups. The available findings thus indicate that sensory- and feedback-enhanced methods could be used as part of an upper limb rehabilitation program but what is absent is a consistent improvement from a single sensory- and feedback-enhanced method [17,23].

Bilateral training is also a popular upper-limb recovery training therapy. It is a method that entails the coordinated movement of both arms and can encourage inter-limb connection, bilateral cortical reactions and much better movement time. Empirical evidence indicates that bilateral arm exercises are capable of enhancing motor skills of the upper limbs among the chosen stroke patients [25,42]. Robotic rehabilitation is another form of enhancing upper-limb recovery by offering repetitive, assisted and feedback-powered movement practice. The advantages of the electromechanical and robot-assisted arm training could be enhanced arm functions, arm strength, and the activities of daily living in the post-stroke. One area where robotic devices might be particularly helpful is due to their potential to enable intensive practice with consistent proprioceptive and movement related feedback [11,29]. Enriched feedback of the senses can also be found in virtual reality to aid the rehabilitation of upper limbs. Visual and auditory feedback can be used to support the activities of reaching, grasping, and bilateral arm in an immersive and interactive VR system. There is evidence that upper-extremity training using

VR can enhance the level of engagement and recovery following a stroke [23,69].

Hand dexterity and fine motor function

The skill of hands relies on the accuracy of integrating senses and control. The finer motor skills of grasping, pinching, buttoning, writing, and playing with small objects demand precise tactile and proprioceptive information. Voluntary movement together with some dexterity might be too little to restore stroke-related sensory losses [56]. Grip force manipulation (plasticity) and object property recognition can be impaired due to tactile impairment. Patients who exhibit poor tactile discrimination are likely to struggle with detecting texture, shape, pressure, and position of objects within the hand. Research has demonstrated the relationships between impaired tactile sensory and prehensile capabilities as well as poorer dexterity in the aftermath of stroke [58]. Sensory retraining could have a positive effect on hand usage by enhancing awareness of the tactile input and enhancing sensory discrimination. It can be a graded texture recognition, object recognition, localization of touch, and discrimination. The upper-limb rehabilitation intervention has been characterized in a structured sensory relearning intervention whereby sensory practice is directed [45]. Mirror therapy has also demonstrated the advantages of hand functioning improvement as well as fine motor recovery. The mirror could be beneficial, since it gives the patients visual feedback of their normal hand movement, so they might be able to mentally associate movement intent with the realized performance. Mirror therapy has been found to produce positive changes in hand health following subacute and chronic stroke populations under clinical trial [14,43].

Motor imagery can facilitate fine motor recovery through enhancing internal motor representations. The patient rehearses the motor movements in imagination as he or she moves the hand yet is not moving. This has the potential to stimulate neural processes that are related to motor planning and can be applied to situations where there is a limitation of physical movement of the hand [6,64]. The use of kinesthetic imagery can be particularly crucial in the context of hand rehabilitation because the kinesthetic imagery entails imagining the feeling of motion. It has been demonstrated that the motor imagery of a kinesthetic type can be used to adjust corticomotor excitability. This indicates that internal sensory simulation has the potential to help in relearning fine motor skills following stroke [8]. Electric shock and vibrotactile stimulation can also have an effect on the functioning of the hand by raising the sensory input to the damaged limb. Vibrotactile reinforcement of sensorimotor brain activity has been demonstrated to be beneficial in hand rehabilitation. When active movement training is used in combination with neuromuscular electrical stimulation, it can further be used to support hand and arm functions [4,57].

Lower limb function and gait

The evidence pertaining to changes in sensory input for lower-limb function and gait was less extensive than that for upper limb rehab. There was some evidence suggesting possible efficacy of bilateral TENS, rhythmic cycling and LEAME mirror-based intervention in individual studies [54,60]. These findings suggest that abnormalities in sensory and bilateral inputs may be relevant to rehabilitation of the lower limb but the total amount of data available – and their very low level of homogeneity mean that general conclusions cannot be drawn on efficacy for gait recovery.

Bi-lateral sensory-motor input can have special significance to lower limb functions due to the inherent nature of gait as being rhythmic and in a cooperative manner among the two limbs. Interventions that enhance interlimb coordination can aid in enhancing stepping, balance and walking-related motor control. It has proposed the concept of neuromechanical between interlimb interactions to explain how limb-specific coordination can serve to recover walking in stroke patients [32]. Rhythmic arm cycling has been studied as a way of enhancing both the walking performance and neurophysiological integrity in chronic stroke. This intervention relates to walking where although the arms are involved in the intervention, there is the possibility of neuropathological relations between upper and lower limbs. There is some evidence that rhythmic arm cycling training may enhance walking outcomes and neurophysiological processes [53].

Cycling-enhanced training can also cause long-term changes in reflex excitability in the post-stroke period. Cycling training of the arm and leg using bicycles has been linked to plastic alterations in reflex pathways in several weeks. These results indicate that rhythmic bilateral movements can humanely influence spinal and supraspinal processes of gait recovery [54]. Another intervention that has been investigated as an intervention with stroke victims is bilateral lower-extremity mirror therapy. This method can be beneficial in providing motor engagement and/or sensory-motor relearning by generating altered visual feedback during lower-limb movement. The general evidence supporting the use of visual feedback strategies in lower-limb rehabilitation is not as strong as that of upper-limb mirror therapy, though there is evidence suggesting that visual feedback strategies could be of use [7]. The TENS can also play a role in lower-limb motor recovery through augmentation of peripheral sensations. Transcutaneous electrical nerve stimulation has been found to enhance lower-limb motor performance in chronic stroke in a bilateral mode. This suggests that the stimulation-provided sensory input can possibly benefit the functions more than the pain modulation [60].

Activities of daily living

The evidence pertaining to activities of daily living was less direct than the evidence pertaining to impairment-level motor outcomes. Robot-assisted training appears to be the only intervention to show improvement in arm function and activities of daily living in systematic evidence [11], and other approaches, including mirror therapy and virtual reality in general have mostly shown to have beneficial outcomes on upper-limb or task-related outcomes [23,34,43]. Transfer of motor performance to activities of daily living, if not directly observed, may be possible.

Functional relevance may also exist as many daily activities require the coordinated use of both upper limbs during bilateral training. Improved motor coordination, but, should not be confused with direct evidence of improved independence of daily living. Therefore, additional research on the activity and participation levels should be conducted.

Functional independence

Many factors contribute to functional independence, such as motor impairment, sensory function, balance, cognition, the environmental demands, and ability to utilize recovered movements effectively during daily activities. These studies suggest that sensory impairment has an impact on function after stroke [5,13,36] which made it a rationale to address sensory problems during stroke rehabilitation.

Some sensory and feedback interventions have shown benefits in motor or activity outcomes that have the potential to increase independence. But when the evidence for better impairment-level motor performance is found, it does not necessarily mean it is an indicator of better functional independence. An enormous variability was seen regarding the outcome considered in the studies included in this review, and not all the separate types of interventions measured functional independence.

Thus the evidence suggests that using sensory-enhanced rehabilitation along with being active, meaningful and task-specific practice can help with functional recovery, but that relying solely on sensory enhanced practice does not improve independence. Future studies should be conducted to determine if changes in sensory and motor outcomes result in lasting changes in activity of daily living and participation and independent functioning.

Comparison across interventions

None of the sensory strategies were consistently better across all of the stroke survivors evaluated in the interventions reviewed. However, there were some similarities noted. Interventions with tactile-proprioceptive (PT) inputs, with electrical inputs, with vision alteration (mirror), and with internal simulation (motor imagery), with coordinated inter-limb inputs (bilateral) and with structured or augmented feedback (repeated motor practice with robot or VR) provided enhancement of peripheral sensory information [17].

Although they are different, these techniques seem to have a common rehabilitation effect, that is the manipulation of sensory feedback available during attempted or rehearsed movement. This reviewed evidence thus indicates that the potential benefits of their use can be related not only to the type of intervention provided but to how the use of enhanced sensory information is linked to motor intention, movement practice, feedback and task performance [34]. These consistent findings form the basis for the theoretical synthesis which follows. Five highly related processes were deemed especially relevant: sensory driven neuroplasticity, sensory prediction and error-based learning, altered visual feedback and action related neural activation internal motor simulation, closed loop sensorimotor integration. It is important to note that the proposed framework is not meant to be viewed as a single causal progression that is confirmed from findings in multiple interventions, but instead as an evidence-informed explanation of how the findings across interventions might be related [24].

Based on the available evidence, no one sensory-input intervention can be identified commonly to be superior, universally across stroke populations and functional outcomes. The sensory goal, therapeutic intensity, mechanisms and clinical applications of mirror therapy, motor imagery, bilateral training, sensory stimulation, robotic rehabilitation and virtual reality are very different.

In all the methods, there is strong evidence for the use of meaningful sensory feedback coupled with active and repetitive motor training. Differences in study design, participant characteristics, intervention protocols and outcome measures however hamper direct comparisons between interventions. Thus, the results argue for a personalised, impairment-focused sensory-motor rehabilitation and not altogether for a universal recommendation for a particular sensory and/or motor rehabilitation method.

Authors and Year	Methodology/ Study Design	Purpose of Study	Study Area/Intervention Focus	Main Outcome	Future Scope
Bolognini., *et al*. 2016 [48]	Narrative/theoretical review	To describe the sensory input to post-stroke motor recovery.	Sensory input and motor rehabilitation	Complimented the role of sensory systems in motor recovery in post stroke.	Sensory testing and sensory-based practice should be concatenated to a regular stroke rehabilitation in future studies.
Chen., *et al*. 2018 [33]	Clinical research/ therapeutic effects study	To investigate the impacts of the sensory input training on motor stroke recovery rehabilitation.	Sensory input training	Training based on sensory input was the one that was connected with the enhancement in motor-function rehabilitation.	Further controlled trials should be conducted to determine the best dosage and sensory training.
Carlsson., *et al*. 2021 [45]	Intervention development study using TIDieR checklist	To design and write about an upper limb stroke relearning intervention in the upper limb.	Upper-limb sensory relearning	Offers an organized account of relearning in stroke rehabilitation with reference to senses.	The clinical effectiveness in more stroke populations should be tested in future.
Tyson., *et al*. 2008 [36]	Observational clinical study	To characterize the loss of sensors among stroke patients admitted to hospitals and its correlation with functioning.	Somatosensory loss after stroke	Functional limitations following stroke were related to sensory loss.	Long-term effects of sensory loss on recovery should be investigated in future.
Connell., *et al*. 2008 [13]	Clinical observational study	To study the frequency and recovery of somatosensory impairments in poststroke.	Somatosensory impairment	Various sensory impairments had poststroke onset and recovery variability.	Sensory-specific rehabilitation methods should be long-term research.
Rand, 2018 [5]	Cross-sectional/ clinical study	To investigate deficits in proprioception and how it correlates with the functioning in chronic stroke.	Proprioception and upper-extremity function	Deficits of proprioception were connected with upper-extremity functioning and ADL.	Guidance towards influence proprioceptive training needs to be developed in future research.

Wu., *et al*. 2013 [14]	Randomized controlled trial	To investigate the effects of mirror therapy on motor and sensory recovery in chronic stroke	Mirror therapy	Mirror therapy enhanced better motor recovery and sensory recovery.	Additional trials need to be conducted on the way mirror therapy is compared to other type of feedback-based interventions.
Arya., *et al*. 2018 [3]	Randomized controlled trial	To investigate the use of mirror illusion as a sensorimotor training intervention in stroke.	Mirror illusion/sensorimotor training	The sensorimotor recovery after stroke was aided by the Mirror illusion.	Further research must determine the stroke patients who are most likely to respond to the mirror illusion therapy.
Dohle., *et al*. 2009 [17]	Randomized controlled trial	To assess mirror therapy in severe hemiparesis patients.	Mirror therapy for severe hemiparesis	Mirror therapy enhanced motor recovery of severe hemiparesis.	In more severely affected stroke population, bigger trials are required.
Yavuzer., *et al*. 2008 [43]	Randomized controlled trial	To measure hand function after subacute stroke by use of a mirror therapy.	Mirror therapy for hand function	Mirror therapy improved hand function in subacute stroke	The relationship of functional carryover between studies in the future should be studied regarding long-term.
Michielsen., *et al*. 2011 [35]	Phase II randomized controlled trial	To measure post-mirror therapy motor recovery and re-organization of the cortex.	Mirror therapy and cortical reorganization	Mirror therapy brought with it motor recovery and reorganization of the cortex.	Neuroimaging should be used in future studies to shed more light on mirror therapy.
Garcia., *et al*. 2016 [24]	Systematic review	To confirm the motor imagery or mental practice in functional recovery following stroke.	Motor imagery/mental practice	We found that motor imagery might be of useful functional recovery.	Standardization of imagery protocols and outcome measures should be a subject of future trials.
Stinear., *et al*. 2006 [8]	Experimental neurophysiological study	To compare effects of kinesthetic and visual motor imagery on corticomotor excitability	Motor imagery and corticomotor excitability	The kinesthetic image resulted in a greater change of corticomotor excitability compared to the visual image.	The type of imagery in stroke rehabilitation procedures should be studied in the future.
Kimberley., *et al*. 2006 [15]	Neuroimaging/ clinical study	The purpose of the study was to determine neural elements of motor imagery in severe hemiparesis.	Motor imagery in severe hemiparesis	Motor imagery induced neural processes implicated in motor recovery.	Further research is needed into possible motor imagery in severely motor-impaired patients.

Stewart., *et al*. 2006 [49]	Systematic review and meta-analysis	To investigate the effect of bilateral movement training on stroke rehabilitation.	Bilateral movement training	Bilateral training was found to have a positive outcome on stroke motor recovery.	Further studies are needed, comparing bilateral and unilateral protocols by selected subgroups.
Cauraugh., *et al*. 2010 [12]	Structured review and meta-analysis	To study evidence on bilateral movement training and stroke motor recovery.	Bilateral movement training	Bilateral training was an aid to motor recovery.	The best condensing training and patient selection should be established in future research.
Whitall., *et al*. 2000 [68]	Clinical intervention study	To compare the effects of repetitive bilateral arm training with rhythmic auditory cueing in chronic stroke.	Bilateral arm training with rhythmic cueing	Bilateral arm training enhanced motor function through rhythmic bilateral arm training.	Future efforts ought to study rhythm-related cueing with more extensive controlled studies.
Kwong., *et al*. 2018 [60]	Randomized controlled trial	To examine the use of bilateral TENS in lower-limb motor functioning in chronic stroke.	Bilateral transcutaneous electrical nerve stimulation	The TENS used bilaterally enhanced motor performance at the lower extremities.	Future studies are to test dosages, stimulation settings, and gait outcome issues.
Vahdat., *et al*. 2019 [51]	Experimental/ clinical intervention study	To investigate sensorimotor network connectivity and proprioceptive training with the control of robots.	Robotic proprioceptive training	The accuracy of reaching and connectivity modulation was enhanced with proprioceptive robotic training.	Subsequent research ought to subject repeated sessions and recovery outcomes.
Kiper., *et al*. 2023 [23]	Systematic review with meta-analysis	To investigate the effects of the intervention of immersive virtual reality in rehabilitation of upper-extremity stroke.	Immersive virtual reality	Rehabilitation of upper limbs was positively affected by immersive VR.	Future research needs to involve a comparison between immersive VR and traditional and robotic rehabilitation.

Table 1: Summary of Included Studies.

Sensory Intervention	Type of Altered Sensory Input	Target Motor Outcome	Effects on Motor Outcomes are reported.	Possible Mechanism	Clinical Implication
Sensory input training, (Chen., *et al*. [33])	Tactile, proprioceptive, and somatosensory feedback	General motor function after stroke	Improved motor-rehabilitation after a stroke.	Enhances afferent circulation and sensorimotor activities.	The role of sensory training may be as a supplement to the conventional motor rehabilitation.
Sensory relearning, (Carlsson., *et al*. [45])	Tactile discrimination and sensory awareness	Upper-limb sensory-motor recovery	Provides a methodical way of retraining upper limb sensual activity.	Improves tactile and sensory discrimination.	Can be used to formulate systematic rehabilitation programs of the sense.

Active discriminative touch training, (Carlsson., *et al*. [56])	Tactile sensory feedback	Dexterity and hand function	Better active discriminative touch was correlated with an improved dexterity.	Helps appropriately hold and operate items.	The fine motor results can be enhanced with the help of tactile assessment and training.
Proprioceptive-focused rehabilitation, (Rand [5])	Joint position and limb movement feedback	Upper-extremity function and daily living	This proprioception deficiency was associated with a lower functioning and performance in everyday activities.	Enhances awareness of position of limbs and corrects movement.	Proprioceptive training should be applied to the patients when there is sensory loss.
Mirror therapy, (Wu., *et al*. [14])	Visual feedback and mirror illusion	Motor and sensory recovery in chronic stroke	Improved motor recovery processes, as well as sensory recovery processes.	Stimulates motor visual mechanisms and improves attention to affected patients limb.	Useful in the recovery of the upper limbs particularly when there is reduction in the sensory feedback.
Mirror therapy for severe hemiparesis, (Dohle., *et al*. [17])	Visual substitution feedback	Recovery from severe hemiparesis	Greater increase in badly hemiparesic patients.	Develops a visual illusion of mobility; can only be done to a limited degree in a voluntary way.	May be helpful in patients who are too weak.
Mirror therapy for hand function, (Yavuzer., *et al*. [43])	Visual feedback of normal hand movement	Hand function in subacute stroke	Increased hand performance post stroke.	Connections movement will with evident movement.	Has the ability to assist functional hand training in the subacute rehabilitation.
Mirror therapy with cortical reorganization focus, (Michielsen., *et al*. [35])	Visual feedback and sensorimotor activation	Motor recovery and cortical reorganization	Increased motor recovery with evidence of cortical reorganization.	Increases adaptive sensorimotor cortex changes.	Plays a role in the neuroplastic basis of mirror therapy.
Motor imagery, (Garcia., *et al*. [24])	Internal sensory-motor simulation	Functional recovery after stroke	Motor visualization could have been helpful to functional recovery.	Activates motor planning networks and representations.	Can be helpful in addition to a limited physical practice.
Kinesthetic motor imagery, (Stinear., *et al*. [8])	Internal proprioceptive simulation	Corticomotor excitability	The picture that discusses kinaesthetic alters the corticomotor excitability.	Activates motor pathways [controlled] by imagined movement sensation.	Motor relearning might be enhanced by kinaesthetics imagery rather than by visual imagery.
Motor imagery in severe hemiparesis, (Kimberley., *et al*. [15])	Mental practice and motor network activation	Motor imagery capacity in severe hemiparesis	Assign a neural basis to motor imagery in moderate and severe hemiparesis.	Activates the movement related brains without any movement.	May assist patients in doing partial active movement.
Bilateral movement training, (Cauraugh., *et al*. [12])	Coordinated sensory-motor input from both limbs	Stroke motor recovery	Motor recovery was aided by bilateral training.	Increases cross-limb coupling and decerebralization.	Useable in upper-limb rehab co-ordination.

Bilateral arm training, (Stewart., *et al*. [49])	Bilateral limb movement feedback	Upper-limb motor recovery	Bilateral movement training had positive outcome in stroke rehabilitation.	Enhances motor movements.	May could be chosen in patients who gain by practice of symmetrical movements.
Bilateral arm training with rhythmic auditory cueing, (Whitall., *et al*. [68])	Auditory rhythm and bilateral motor feedback	Motor function in chronic stroke	Better chronic hemiparetic stroke motor functioning.	Timing, coordination and movement repetition are enhanced by rhythmic cues.	Rhythmical bilateral training is capable of improving quality of movements.
Bilateral vs unilateral upper-limb training, (Chen., *et al*. [25])	Bilateral sensory-motor feedback	Upper-limb function after stroke	In comparison, the bilateral and unilateral training methods have equal effectiveness.	Engages in interlimb coordination and drill.	They will be selected based on their level of impairment and rehabilitation goal.
Bilateral TENS, (Kwong., *et al*. [60])	Electrical sensory stimulation	Lower-limb motor function	Enhanced lower limb motor performance in chronic stroke.	Specifically augments peripheral afferent and central motor responses.	May facilitates bottom-up rehabilitation and ambulatory recovery.
Vibrotactile stimulation, (Du., *et al*. [4])	Mechanical tactile and proprioceptive stimulation	Hand rehabilitation and sensorimotor brain activity	Increased sensorimotor brain skills in hand recovery.	Enhances tactile-proprioceptive and cortical stimulation.	Could be useful with improving sensory awareness with regard to hand training.
Robot-controlled proprioceptive training, (Vahdat., *et al*. [51])	Robotic proprioceptive feedback	Reaching accuracy and sensorimotor connectivity	More specificity in the modulated functional connectivity that is reached.	Gives feedback proprioceptive supply to sensorimotor systems.	Proponents robotics-assisted special types of sensory-motor training.
Immersive virtual reality, (Kiper., *et al*. [23])	Visual, auditory, and augmented feedback	Upper-extremity rehabilitation	Improved results with regards to rehabilitating upper extremities.	Gives sensorimotor environment where there is feedback and interaction.	VR has the potential to enhance motivation, drilling and functional training of upper limbs.
VR-based bilateral upper-extremity training, (Lee., *et al*. [26])	Virtual visual feedback with bilateral movement	Brain activity and upper-limb training	Altered functioning in the brain of post-stroke patients.	Bicolinear movement is coupled with increased visual stimulation by the couple.	May help in neural activity when conducting upper-limb rehabilitation.
Immersive VR-based bilateral arm training, (Song and Lee [69])	Immersive visual feedback and bilateral arm practice	Chronic stroke upper-limb function	Stroke arm-assisted bilaterally training.	Enhances the involvement, reaction and repetitive arm movement.	Could be applicable to stroke patients with chronic stroke who need motivating practice.

Table 2: Effects of Different Sensory Interventions on Motor Outcomes.

Theoretical synthesis and proposed framework

The mechanisms included in the proposed framework are not necessarily stable causal linkages, but should be read as pathways that are likely based on the evidence and plausible. By themselves, reported clinical improvements after sensory based interventions do not prove that the mechanisms, such as neuroplasticity, cortical reorganization, error-based learning, and otherwise proposed mechanisms, are responsible for the clinical improvements. The framework also draws on literature that supports the mechanism and theory of the work and by combining these with the clinical data provides testable explanations for future research.

The theoretical synthesis was created to visualize how the various intervention strategies might overlap the process of motor relearning. Instead of claiming all instances of sensory-based interventions work in the same way, the framework connects the findings from the systematic review to a number of interacting processes that may be related to recovery: increased sensory input and sensorimotor integration, experience-dependent neuroplasticity, sensory prediction and error correction, activation of brain regions coding action likelihood and internal motor simulation, and repeated closed-loop interactions between sensory input and motor output.

The framework thus suggests the following steps: change or intensification of sensory input, making it easier to receive feedback during motor practice, sensorimotor integration and error correction, repeated use and adaptation of relevant sensorimotor networks, and improvement and achievement of motor performance and potential transfer to functional activity. Its occurrence will depend on the intervention, stroke characteristics, level of sensory impairment, motor ability, level of training and nature of the functional task.

Sensory input as a driver of neuroplasticity

One of the most frequent issues found in the reviewed literature were interventions that increased or modified sensory inputs (e.g., sensory retraining, vibrotactile stimulation, electrical stimulation and robot-controlled proprioceptive training), which were associated with improvement in sensorimotor performance or change in sensorimotor activity. All the above suggest that sensory input may be one factor which contributes to experience dependent neuroplasticity in clinical practice.

Sensory deficits after stroke can diminish amount or accuracy of Afferent information from affected limb. This may affect the ability to perceive the position of the limbs, quality of movement and movement errors. Meanful and repeated sensory input during the rehab phase could lead to greater engagement of the remaining sensorimotor pathways, as well as more association of sensory input with motor output.

This interpretation is aligned the results of sensory input training, input site-specific vibrations, and that robotic provided proprioceptive training can map out new sensorimotor networks and increase reaching accuracy. These findings provide some indication that neural reorganization may be a result of distorted sensory input that is repeatedly related to active motor practice.

But the evidence in hand does not do so as to prove that sensory stimulation is the direct source of adaptive neuroplasticity. It is more in line with the interpretation that sensory enrichment could promote the neural environment for motor learning, especially if the activities involve purposeful and repeated movements.

Sensory prediction and error-based learning

All the findings synthesised in Section 5 also highlight the need for interventions that are feedback rich. Mirror therapy with altered visual feedback, robotic systems for information about trajectory and accuracy of movement and virtual-reality systems for augmented visual or auditory information during task performance. These results corroborate the relevance of sensory prediction error-based learning to post-incidence of stroke rehabilitation [12]. Motor learning involves comparing our intended movement and what our movement, as a sensory effect, creates. Loss of sensory function following stroke may disrupt function of the nervous system to sense mismatches between intended and actual performance. This can restrict the patient's capacity to make adjustments in the next motor attempts [15]. The present challenge might be partially overcome by moving the change or addition of feedback to make the feedback outcomes noticeable. Visual input in connection with movement via mirror therapy, making performance successful or unsuccessful more explicit through the use of virtual reality, and structured feedback on movement-related aspect through robotic systems. Such interventions thus can aid motor relearning by providing increased information for evaluating performance and correcting movement [34]. The systematic findings fail to prove that these interventions follow the error-based learning, only. Instead, error correction is one of the proposed motor learning mechanisms that explains the feedback-based influence of various interventions.

Mirror neuron system and motor recovery

Mirror therapy was one of the most consistently studied types of altered sensory input in the evidence included in this review, and demonstrated improvement in upper-limb, hand, motor and sensory outcomes in several clinical studies. These clinical observations offer the main rationale for taking into account visual feedback and action related neural mechanisms in the proposed framework [22]. The brain receives the visual input that the movement on the non-affected limb provides and perceives the action as somehow occurring on the affected limb, hence the mirror therapy. This altered visual information causes them to focus more attention on the affected side and to enhance the link between intended and perceived movement. Mechanisms that have been suggested to contribute to these effects include action observation, motor representation and cortical reorganization [35]. Some neural plasticity interpretation is given by evidence of the cortical changes evinced with motor improvement through mirror therapy. However, the clinical outcomes reviewed should not be construed as direct evidence for a role of a particular activation of a mirror-neuron system in recovery. Mirror therapy likely engages a number of interrelated processes such as visual feedback, attention, intention to move, body representation, observation of action, and simulation of action [64]. Based on this, altered visual feedback is assumed to be a facilitation of sensorimotor engagement and motor relearning, and is therefore used within the theoretical framework as one of multiple assumptions but not a single known neural mechanism.

Internal models and motor imagery

Systematic evidence about motor imagery indicated it may be beneficial with regard to functional recovery, and as an adjunct to traditional rehabilitation. According to a study in neurophysiology, kinesthetic motor imagery can also influence the excitability of cortico-motor areas. These studies collectively form the groundwork for how to link motor imagination to internal motor simulation - in the theoretical scheme [64]. Motor imagery is internal representation of movement rather than interventions that give other external sensory inputs. In imagery, the patient rehearses an action mentally without actually performing the action. This can still give access to continuation of engagement with movement-related representation despite weakness and/or impaired coordination of movement [56]. Kinesthetic imagery would have relevance since it pertains to the sensory perception of movement – such as the position of the limbs, effort, and movement. Motor imagery could be useful to preserve and/or reinforce representations to be used during movement planning through repeated internal rehearsal [8]. However, it is not recommended to see motor imagery as a substitute for motor practice. There were more supportive pieces of evidence which suggest its use as an adjunct to active rehabilitation. This makes internal simulation an alternative method of involving the sensory-motor processes within the proposed framework when full physical practice cannot be used.

Integrated sensory-motor relearning framework

The combined results of this systematic research indicate that despite the differences in how they are delivered and the sub sensory goals targeted, the various sensory-based interventions may be understood in the same sensory-motor learning model [22]. The first component is sensory modification/enhancement. This can be tactile, proprioceptive, electrical, visual, auditory, bilateral, robotic or virtual information, depending upon the intervention [65]. The other is sensorimotor integration. In order to be meaningful towards motor relearning, the modified sensory information needs to be correlated with motor intention or action. There was a general consensus that sensory-based strategies should not be used alone in rehabilitation but should be integrated with active or task oriented strategies [47]. The third is adaptation and error correction by feedback. The sensory information feeds into the patient and the nervous system giving them information on movement position, direction, accuracy of movement and task success. Comparing desired and actual performance can be repeated, allowing the possibility of sequentially adjusting motor output.

The fourth aspect is the replay of neural activity and the adaptation of neural networks. The conclusions that can be drawn from studies performed on mirror therapy, sensory stimulation, motor imagery and robotic proprioceptive training indicate that the repeated sensory-motor experience can relate to an alteration in the excitability, connectivity or organization of the cortex. The results offer a valid neuro-physiological explanation for the correlation between enriched sensory experiences and motor learning, although there is still incomplete understanding of the mechanisms involved [32]. The 5th component is functional transfer. Sensory-motor control changes are clinically relevant if they affect the use of the hands, the function of the upper limbs, walking, activities of daily living or functional independence. The results presented in Section 5 indicate that evidence for sensory-based interventions is most salient when sensory enhancement is coupled with repetitive meaningful and task specific motor practice [57].

Bilateral training, mirror therapy, or virtual reality can be recommended to patients with chronic impairment of one or both upper limbs as they offer repeated practice that is rich in feedbacks. TENS, rhythmic training, or cycling-related interventions that can boost bilateral and sensory-motor coordination may be helpful with lower-limb deficits in patients. The choice of intervention ought then to be made on the basis of sensory loss, motor, recovery stage and functional objective [42,60]. In general, the suggested framework considers post-stroke motor relearning a process of sensory-motor, as opposed to a motor process. The information provided by sensory input is used to make prediction, correction of errors, reorganization of the cortex, and adaptation of functions. Intervention of altered sensory input can thus be beneficial in recovery as it restores the feedback loops linking perception, intention, action, and function [48,65].

The proposed framework can be summarized as.

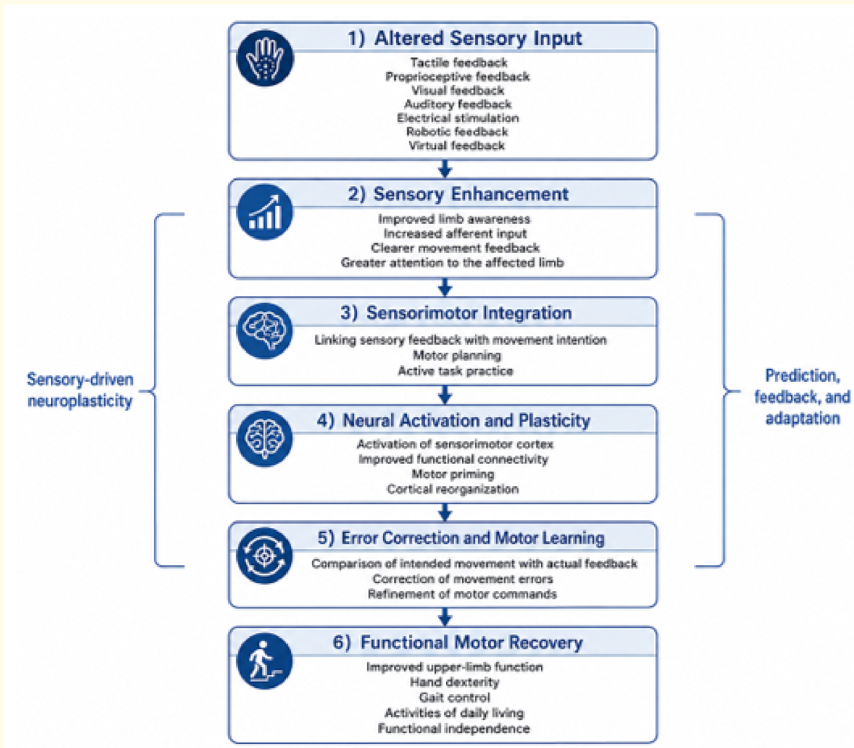

Figure 2: Theoretical Model Linking Altered Sensory Input, Neuroplasticity, and Motor Relearning.

Clinical implications

Implications for physiotherapy practice

The results indicate that sensory function assessments can be used as a complementary evaluation to regular motor assessments in post stroke rehabilitation. As augmentation to the active motor rehabilitation, sensory retraining, mirror therapy, motor imagery, bilateral training, electrical or vibrotactile stimulation, robot feedback or virtual reality-based methods may be considered depending on the clinical appropriateness. The choice should be based on the patient's sensory and motor deficits, recovery stage, functional goals, cognitive abilities, and evidence for the use of the specific selection.

Personalized rehabilitation approaches

An individualized rehabilitation strategy will be required since stroke survivors vary on their sensory loss, motor impairment, progression in recovery, cognitive capacity, and objective in their functions. A mirror therapy, motor imagery, or EMG-triggered stimulation can be useful with patients who are severely weak since they can activate sensory-motor network in response to inability to move freely [15,17]. Proprioceptive impaired patients might respond to proprioceptive training, robotic feedback or sensory relearning to enhance the limb position awareness and accuracy of movement [5,51]. The choice of intervention should also have consideration of the primary aim in which the upper-limb recovery, hand dexterity, gait, or daily life function are intended. Mirror-based therapy and sensory desensitisation may be enhanced to hand function whereas the bilateral training and timekeeping may facilitate coordinated hand-arm or leg movement. Incorporating the intervention in line with the impairment profile of the patient could enhance the effectiveness of the rehabilitation process and carryover of functional performance [25,43].

Integration of technology in stroke rehabilitation

Technology-assisted rehabilitation is offering the introduction of new opportunities of providing intensive, high-feedback, and task-specific therapy. The robotic therapy can also deliver any type of controlled movement and proprioceptive feedback, and the virtual reality can deliver visual and auditory feedback in captivating settings [23,29]. The tools might serve to supplement the intensity of practice, motivation and accuracy of feedback used in rehabilitation. Nevertheless, clinical reasoning should not be replaced by technological means led by therapists. In its place, the integration of robotic devices, virtual reality, and sensor-based systems with individualized goals and active practice of tasks should be applied. Therapist instructions, sensory enrichment, functional training, and technology-aided feedback is likely to provide the most helpful method of aiding motor relearning following stroke [50,65].

Limitations and future directions

Limitations of current evidence

Existing indicators on modified sensory input with regards to post-stroke rehabilitation possess a few limitations. The wide variance in the studies in terms of the type of intervention, length of treatment, level of impairments and level of stroke in terms of stage of stroke are hard to compare. Certain interventions are better supported, like mirror therapy and bilateral training whereas other intervention types need additional high-quality trials [14,25]. Small samples and pilot designs are also many, and restrict the generalizability. The positive responses of some of the reviews indicate the existence of positive effects, yet due to variations in protocols, it is difficult to define the most effective dose and frequency of sensory-based interventions, and the timing. There is also a lack of any long-term follow-up; hence, whether improvements are sustained in the situation following the end of treatment remain unknown [12,24].

Research gaps

There are still critical gaps in the knowledge about the impacts of modified sensory input on neuroplasticity and functional recovery. Additional research is required in order to determine the treatment options that best address individual patients e.g., mirror therapy, motor imagery, sensory stimulation, robotic feedback or virtual reality. Future research should also look into whether a combination of interventions has more effect when compared to one sensory approach [16,23]. The other gap is the scanty utilization of neurophysiological and imaging outputs. Cortical reorganization, functional connectivity, corticospinal excitability and sensorimotor integration have the potential to clarify the mechanisms through which sensory-based interventions are going to effect a clinical change. These results have significance in understanding behavioral recovery in relation to underlying processes [35,51].

Recommendations for future studies

The size of randomized controlled trials conducted in future studies is required to be larger and standardized based on structured intervention protocols and well-defined patient subgroups. The researchers are supposed to deliver the stage of stroke, type of sensory impairment, severity of motor, treatment dose and outcome in the long term. This would enhance cross-study comparisons, which would aid in establishing the best intervention to help particular clinical presentations [20,30]. Further research on combined rehabilitation models involving sensory retraining/ active functional practice also needs to be tested in the future. The interventions are supposed to be tailored to enhance the outcomes at the impairment level and real- world tasks like hand use, movement, personal care, and autonomy. Further emphasis on the idea of functional transfer will contribute to the elucidation of the clinical significance of the modified sensory input in stroke rehabilitation [21,48].

Conclusion

This systematic review indicates that changes in sensory input or augmentation of sensory feedback might play a role in post-stroke motor relearning when combined with motor practice that is active, repetitive, and task specific. There are some potential benefits identified in the reviewed evidence for sensory retraining, mirror therapy, motor imagery, bilateral training, sensory stimulation, robotic rehabilitation and virtual reality, the strength and consistency of which varied based on the type of intervention, study design, characteristics of the stroke and outcome measure [13].

There were more consistent findings for some of the upper-limb and hand issues, with more limited and/or heterogeneous findings for gait, activities of daily living, functional independence and long-term recovery. For this reason, the improvements in the motor outcomes afforded by the impairment level should not be taken to imply improvements in general functional independence [25].

The theoretical synthesis implies that there are possible mechanisms connecting sensory input and motor re-learning by increased sensory feedback, sensorimotor integration, error based learning, internal motor simulation, and by experience-dependent neuroplasticity. They are still not well-documented causal pathways, but mechanisms [28].

Selected sensory enhanced interventions as a result of sensory assessment and their application may thus be regarded as essential in an individualized post-stroke rehabilitation programme along with meaningful functional practice [66]. There is need for further well-designed RCTs with standardized interventions, well-defined patient subgroups, neurophysiology measures as well as functional outcomes and longer follow-up to determine what works for which patients and how.

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