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Effectiveness of constraint-induced movement therapy in improving upper limb function among individuals with Hemiparesis: A comprehensive review

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Abstract

Background: Hemiparesis is one of the most common neurological impairments following damage to the central nervous system, particularly after stroke, resulting in significant upper-limb dysfunction and reduced functional independence. Constraint-Induced Movement Therapy (CIMT) has emerged as an evidence-based rehabilitation approach that promotes recovery by overcoming learned non-use and enhancing neuroplasticity.

Objective: This review aimed to summarize the current evidence regarding the mechanisms, clinical effectiveness, applications, and future perspectives of CIMT in the rehabilitation of individuals with hemiparesis.

Methods: A narrative review of the contemporary literature was conducted by synthesizing findings from randomized controlled trials, systematic reviews, meta-analyses, and clinical practice guidelines related to CIMT and upper-limb rehabilitation in patients with hemiparesis.

Results: Available evidence consistently demonstrates that CIMT significantly improves upper-limb motor function, manual dexterity, spontaneous arm use, and activities of daily living, particularly among patients with residual voluntary movement following Stroke. Modified CIMT protocols have improved treatment feasibility while maintaining clinical effectiveness. Furthermore, recent advances integrating CIMT with robotic-assisted rehabilitation, virtual reality, wearable sensors, and telerehabilitation have expanded its clinical applications and may further enhance rehabilitation outcomes. Nevertheless, treatment response remains influenced by factors such as patient selection, intervention timing, treatment intensity, and adherence.

Conclusion: Constraint-Induced Movement Therapy is one of the most effective evidence-based interventions for upper-limb rehabilitation in individuals with hemiparesis. By promoting activity-dependent neuroplasticity and reversing learned non-use, CIMT contributes to meaningful functional recovery and improved quality of life. Future research should focus on standardized treatment protocols, personalized rehabilitation strategies, and the integration of emerging digital technologies to optimize long-term clinical outcomes.

Keywords: Constraint-induced movement therapy, cimt, hemiparesis, stroke rehabilitation, upper limb rehabilitation, neuroplasticity, motor recovery, neurorehabilitation

Introduction

Hemiparesis, a weakness or partial paralysis of one side of the body, is one of the most common and disabling neurologic deficits that are seen in clinical rehabilitation. It is caused by injury to the central nervous system, which interferes with signals that are transmitted down to the voluntary movement pathways [1]. The severity of motor weakness, impaired coordination, loss of dexterity, abnormal muscle tone, sensory abnormality, and compromised postural control in people with hemiparesis depends on the location and size of the lesion. These deficits significantly restrict independence in activities of daily living (ADLs), including mobility, feeding, dressing, self-care and writing, and lead to a reduction in quality of life and burden on caregivers. While most commonly seen after Stroke, hemiparesis may be experienced post-Traumatic brain injury, Cerebral palsy, Multiple sclerosis, brain tumors, intracranial infections or other neurological conditions that interfere with the motor pathways to and from the cortex [2, 3].

Stroke is the most common cause of hemiparesis in adults worldwide and is a significant public health problem. Over the last decades, there have been substantial improvements in the acute care of stroke, which has led to better survival and an increasing number of people with chronic stroke sequelae. This has made rehabilitation an integral part of stroke treatment. Epidemiological studies have shown that around 70–80% of stroke patients have motor disturbances in the upper limbs in the acute phase, with a substantial number of patients having more enduring functional deficits months, or even years, after the stroke [4, 5]. Function of the upper extremity is frequently poor even after the acute stage of recovery, resulting in chronic upper extremity disability affecting vocational, social and psychological functions.

Upper-limb impairment is one of the most difficult effects of hemiparesis as the arm and hand are necessary for complex, coordinated and goal-directed movements [6]. Damage to the corticospinal tract and associated motor networks impairs fine motor control, muscle activation patterns and sensorimotor integration, resulting in weakness, spasticity, loss of grasping ability, decreased manual dexterity and decreased bilateral coordination [7]. This means that patients often end up using the non-affected limb more, and over time, the paretic limb is not used as much when performing normal daily activities. This behavioural adaptation is associated with the phenomenon of 'learned non-use' in which the effected limb gradually becomes underused despite having some remaining functional capacity. Learned non-use, apart from its impact on functional recovery, also reinforces the maladaptive reorganization of the cortex, further limiting motor recovery.

In the last 30 years rehabilitation has moved from compensation to intensive motor training to maximise neuroplasticity. There is growing evidence that rehabilitation programs based on high-intensity, repetitive, task-oriented exercises are more effective than passive exercise programs. One such strategy is Constraint-Induced Movement Therapy (CIMT), which has been investigated and successfully applied to enhance upper-limb function in people with hemiparesis. The CIMT is founded on the principles of: 1) restricting the use of the normal limb, and 2) using intensive, structured repetition of functional tasks with the affected limb. This will directly target learned non-use and encourage use dependent reorganization of the motor system, directly improving motor recovery and functional independence [8].

As the global burden of neurological disability continues to grow, and a greater focus is being put on evidence-based rehabilitation, a thorough knowledge of the principles, mechanisms, clinical efficacy and future directions of CIMT are crucial for all clinicians, rehabilitation experts and researchers. The scientific basis of Constraint-Induced Movement Therapy (CIMT) is therefore discussed, along with its current evidence on effectiveness for various etiologies of hemiparesis, factors that affect therapeutic outcomes and emerging innovations that may further shape the future of neurorehabilitation in the next few years [9].

Causes of Hemiparesis

Hemiparesis is a neurologic syndrome with weakness of one side of the body caused by injury to the motor pathways of the central nervous system. While Stroke is the most common cause, there are many neurological disorders that can give rise to the same motor deficits due to involvement of the corticospinal tract, brainstem, internal capsule or cerebral cortex. The etiology of the hemiparesis affects the motor impairment, its severity, distribution, prognosis, the direction of rehabilitation and the functional outcome. Therefore, it is important to understand the underlying cause in order to design individual rehabilitation programs, such as Constraint Induced Movement Therapy (CIMT) [10].

Stroke

Acquired hemiparesis is the most common problem in which patient needs to receive upper limb rehabilitation and most common cause of hemiparesis is stroke throughout the world. Ischemic and hemorrhagic strokes can involve corticospinal pathways, causing contralateral weakness, coordination problems, spasticity and sensory impairment. The recovery is dependent on the site of the lesions, the size of the infarct, age, and comorbidities and the timing of rehabilitation. Spontaneous recovery of the neurological function takes place in the first weeks following stroke, however intensive rehabilitation is crucial for achieving the best functional outcome in the long term [11].

Traumatic Brain Injury

Causative factors of hemiparesis include other traumatic brain injury, especially in younger adults. Motor deficits are caused by focal cortical contusions, diffuse axonal injury, intracranial hemorrhage or secondary neuroinflammation of motor pathways. The clinical picture is often varied, as cognitive, behavioural and sensory dysfunctions often coexist with motor dysfunctions. Complete neurorehabilitation is thus required that includes both physical and cognitive rehabilitation [12].

Cerebral Palsy

CP is a condition that does not get worse and is caused by damage to the growing brain, either before, during or soon after birth. In hemiplegic cerebral palsy, the motor function is impaired, muscle weakness and spasticity are common, and there is delayed functional development on one side. The developing nervous system has a good amount of neuroplastic potential and intensive motor training programs are effective in this regard, especially with early rehabilitation [13].

Multiple Sclerosis

In MS, the immune system attacks the myelin in the CNS, impairing normal nerve function and movement. Patients may have loss of strength, loss of co-ordination, sensory disturbances, balance disturbance and fatigue on one side. Individualised rehabilitation programs should be tailored to the disease activity and functional status given the inter-individual variability in disease progression [14].

Brain Tumors

As primary and metastatic brain tumors compress or invade motor areas of the brain, a progressive hemiparesis can occur. Other treatments, such as surgery, radiation and chemotherapy, may also affect neurological recovery. The emphasis of rehabilitation is on maximizing residual motor function while treating complications of treatment and maintaining independence [15].

Other Neurological Disorders

Other causes of hemiparesis include intracranial infections, brain abscess, encephalitis, disorders of the descending motor tracts in the spinal cord, vascular malformations, postoperative neurologic disorders and some neurodegenerative disorders. Rehabilitation regardless of etiology, is the same goal: restore functional movement through repetitive task-oriented practice that facilitates adaptive neuroplasticity [16].

Table 1: Major Causes of Hemiparesis

Cause	Pathophysiology	Common Clinical Features	Rehabilitation Considerations
Stroke	Cerebral ischemia or hemorrhage	Contralateral weakness, spasticity, sensory loss	Early intensive rehabilitation, CIMT, task-oriented training
Traumatic brain injury	Direct or diffuse brain injury	Motor weakness with cognitive deficits	Multidisciplinary rehabilitation
Cerebral palsy	Developmental brain injury	Lifelong unilateral motor impairment	Early intervention and pediatric rehabilitation
Multiple sclerosis	CNS demyelination	Weakness, fatigue, impaired coordination	Individualized rehabilitation during stable phases
Brain tumors	Compression or destruction of motor cortex	Progressive unilateral weakness	Combined oncological treatment and rehabilitation
Other neurological disorders	Various CNS lesions	Variable motor deficits	Etiology-specific rehabilitation

Upper Limb Dysfunction in Hemiparesis

The upper-limb dysfunction is one of the most debilitating effects of hemiparesis, as the arm and hand is used for many tasks that require precise coordination, strength, sensory feedback and fine motor control. Even small decreases in strength can significantly impair a person's ability to perform basic tasks, like eating, dressing, writing, taking care of oneself, handling things, and using electronic devices [17]. Therefore, rehabilitation of upper extremity function has become one of the main priorities of neuro-rehabilitation. Motor impairment after hemiparesis is due to disruption to descending corticospinal pathways that control voluntary movements. Patients often have weaker muscles, inability to control movement selectively, abnormal movement synergies, limited range of motion, impaired dexterity and delayed reaction times. Increased muscle tone, spasticity, joint stiffness and abnormal postural patterns often occur in tandem and are additional functional limitations [18].

Sensory deficits are often accompanied by motor deficits and are important factors to consider for upper-limb recovery. Damage to somatosensory pathways can impair their sense of body, tactile sensation, stereognosis and kinesthetic awareness and thus compromise their ability to accurately control reaching, grasping and manipulating objects. Low sensory feedback also hinders motor learning and the effectiveness of repetitive rehab exercises [19]. Learned non-use is one of the key behaviors that follows upper-limb impairment. Following numerous attempts with the affected limb, patients start to use the uninvolved limb to perform tasks more and more frequently [20]. This compensation over time becomes routine so that with remaining motor function, less and less use of the paretic arm occurs. Learned non-use is a factor of maladaptive reorganization of the cortex, and is one of the main therapeutic targets of Constraint-Induced Movement Therapy.

Upper-limb dysfunction is not just a physical problem and has significant psychosocial implications. Loss of functional independence can restrict work, social life, leisure time and social interaction. Many patients report making a lot of people feel frustrated, anxious, depressed, less self-confident and less healthy related to quality of life. Caregivers and family members also face greater physical, emotional and financial strain for long-term care [21].

Table 2: Common Manifestations of Upper-Limb Dysfunction in Hemiparesis

Functional Domain	Common Impairments	Clinical Impact
Muscle strength	Weakness, reduced force generation	Difficulty lifting and carrying objects
Motor control	Poor coordination, abnormal synergies	Reduced movement accuracy
Dexterity	Loss of fine finger movements	Difficulty writing, buttoning clothes, using utensils
Range of motion	Joint stiffness, contractures	Restricted functional reach
Muscle tone	Spasticity or flaccidity	Abnormal movement patterns
Sensory function	Reduced touch, proprioception, kinesthesia	Impaired object manipulation
Functional performance	Reduced spontaneous arm use	Dependence in activities of daily living
Psychosocial function	Anxiety, depression, reduced confidence	Lower quality of life and social participation

Neuroplasticity

Neuroplasticity is the capability of the CNS to adapt its structure and function as a result of injury, learning or environmental stimuli. After neurological injury, the remaining neural circuits change their function in an adaptive way by forming new synapse connections, changing the structure of neural pathways, and reorganizing the areas in the motor cortex [22]. These changes may allow for partial compensation for lost functions and also help to give a biological substrate for functional recovery following hemiparesis. The modern approach to rehabilitation is therefore based on the principle of task-, goal-, and repetitive-based motor practice, which stimulates activity-dependent neuroplasticity [23]. Experimental studies and clinical studies have shown that intensive rehabilitation causes reorganization of the cortex, increase in synaptic efficacy, increase in sensorimotor integration and improvement in motor performance. Structured rehabilitation programs have been associated with increased activation of ipsilesional motor regions with functional imaging techniques such as functional magnetic resonance imaging (fMRI) and transcranial magnetic stimulation (TMS) [24]. The degree of neuroplastic adaptation depends on many factors, including the intensity of exercise, number of repetitions, early intervention, patient motivation and practice. Thus, motor recovery is best achieved by rehabilitation methods that include active movement of the affected limb, rather than passive approaches [25].

Constraint-induced movement therapy (CIMT)

Constraint-Induced Movement Therapy (CIMT) is one of the most widely researched neurorehabilitation interventions to improve upper limb function in hemiparesis patients. The therapy was initially developed by Edward Taub, based on the theory of learned non-use which suggests that patients gradually stop using the affected limb after a repeated series of unsuccessful attempts to engage in daily activities. This is a compensatory use of the intact limb that further inhibits motor recovery even if there is some remaining functional capacity [26].

Learned non-use is prevented with the use of a mitt, sling or splint to limit movement of the unaffected upper arm, combined with intensive/repetitive use of the affected arm or leg. Task-oriented training, shaping techniques and progressively challenging functional activities are used to facilitate motor learning and cortical reorganization. Most commonly, traditional CIMT protocols include restraint of the unaffected limb for the majority of waking time and a number of supervised training sessions for a few hours per day for two to three weeks. Realizing the commitment to feasibility and patient adherence, the modified CIMT (mCIMT) protocols have been widely used in clinical practice that involve less intensity than standard CIMT [27].

There is increasing evidence of the positive effects of CIMT on upper-limb motor function, spontaneous arm use, manual dexterity, and function of activities of daily living in different neurological disorders, especially following stroke. Intensive, meaningful, and repetitive motor practice is thought to be the key to the effectiveness of CIMT, which leads to neuroplasticity, or the brain's ability to change in response to experience [28].

Rationale and Objectives of This Review

This review paper aims to give a focused and comprehensive overview of Constraint-Induced Movement Therapy (CIMT) in hemiparesis. In particular, it reviews the available literature on the clinical effectiveness of CIMT in various etiologies of hemiparesis, identifies factors that can affect motor recovery and points out the differences between CIMT and other rehabilitation strategies, while also identifying novel technological developments that can further improve motor recovery. This review aims to synthesize the most recent scientific evidence in the context of clinical perspectives to offer practical guidance for clinical practice, for rehabilitation experts and specialists, for researchers and healthcare professionals in neurological rehabilitation.

Pathophysiology of Hemiparesis

1. Motor Cortex Injury

Hemiparesis occurs in the presence of upper motor neuron tract dysfunction, most likely affecting the primary motor cortex, the pre-motor cortex, the internal capsule, the brainstem, or the corticospinal tract. Damage to these structures results in disruption of motor command transmission from the cerebral cortex to the spinal cord, with contralateral muscle weakness, delayed coordination, decreased dexterity, and abnormal muscle tone. The degree of motor dysfunction will be determined by the location, extent and type of the neurological lesion. Although Stroke is the most common cause of motor cortex injury, other conditions such as Traumatic brain injury, Cerebral palsy, Multiple sclerosis and brain tumors are also associated with an injury to the motor cortex [29].

2. Learned Non-use

Learned non-use is a behavior that is common to chronic hemiparesis, where patients gradually cease to use the affected limb when they have some function. If the paretic arm is not used successfully during daily activities, the patient may compensate with the use of the other arm in an early stage. This compensatory behaviour over time becomes routine and leads to reduced spontaneous use of the affected extremity and further impairment of motor performance. Learned non-use is a factor in functional disability, as it creates a state of inactivity and decreases the chances for motor relearning. The idea is used as the basis for Constraint-Induced Movement Therapy (CIMT) that is based on the intensive, task-specific use of the affected limb with the goal of reversing learned non-use [30].

After brain injury, the brain goes through a series of adaptive changes—called neuroplasticity. These involve strengthening of existing neural connections, opening up new connections, remodeling of synapses, and reorganization of the cortical maps. These changes enable the remaining neurons to take on some of the functions of the damaged pathways and help restore motor function. Repetitive, goal-directed rehab activities that activate the involved motor networks are especially effective at promoting activity-dependent neuroplasticity. Intensive upper-limb rehabilitation has been shown by neuroimaging to promote activation of ipsilesional motor areas and improved functional connectivity, indicating the critical need for early and prolonged therapeutic interventions [31].

3. Functional recovery mechanisms

Recovery from hemiparesis is a dynamic process of spontaneous biological repair and motor learning due to rehabilitation. In the immediate post-injury period cerebral edema clearance, normalization of blood flow and decrease of inflammation help to restore partial neurological function. During the subacute and chronic phases, motor repetition, sensory feedback, and adaptive cortical reorganization are the most important factors for functional improvement. There are indications that intensive, task-oriented rehabilitation can facilitate motor learning through the reinforcement of neural networks involved in the control of movement and increase the use-dependent plasticity of the cortex. These mechanisms are targeted in interventions like Constraint-Induced Movement Therapy (CIMT), robotic rehabilitation, mirror therapy and training with virtual reality (VR) to enhance the function of the upper limb and increase independence in activities of daily living [32].

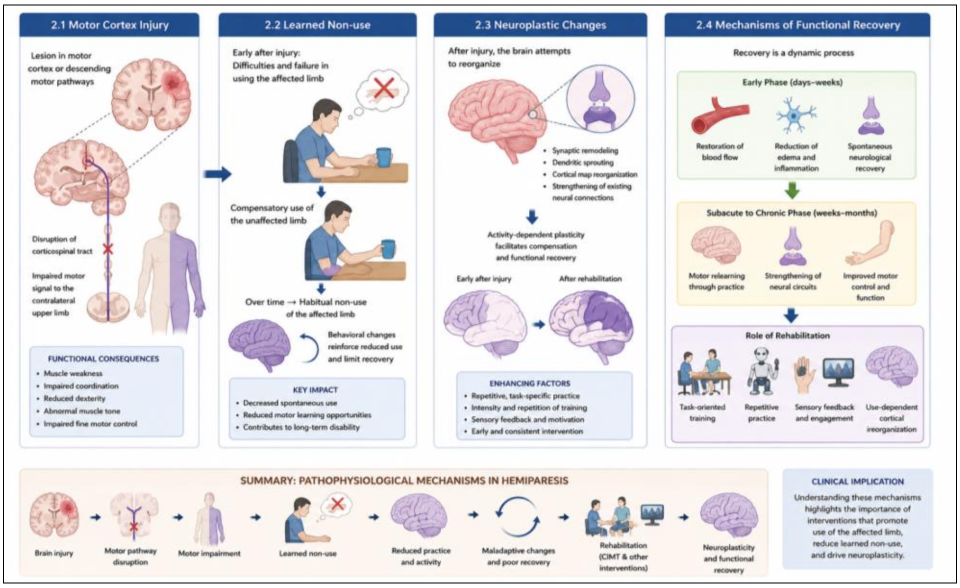

Fig 1: Pathophysiological Mechanisms Underlying Hemiparesis

Table 3: Pathophysiological Mechanisms Underlying Hemiparesis

Mechanism	Pathophysiological Changes	Functional Consequences	Rehabilitation Implications
Motor cortex injury	Damage to corticospinal pathways and motor cortex	Muscle weakness, impaired voluntary movement	Early motor rehabilitation and task-specific training
Learned non-use	Reduced spontaneous use of the affected limb due to compensatory behavior	Progressive decline in functional arm use	Constraint-Induced Movement Therapy to encourage affected limb use
Neuroplasticity	Cortical reorganization, synaptic remodeling, dendritic sprouting	Potential recovery of motor function	Intensive repetitive practice to enhance adaptive plasticity
Functional recovery	Motor relearning through repetitive, goal-oriented activities	Improved coordination, strength, and independence	Multidisciplinary rehabilitation combining physical, occupational, and technology-assisted therapies

Constraint-Induced Movement Therapy

1. Historical Development

Constraint Induced Movement Therapy (CIMT) is a neurorehabilitation technique designed to help restore upper limb function in those with hemiparesis, which is affected by learned non-use. This idea was inspired by experimental research performed by Edward Taub in which he showed that motor function could be restored in an impaired limb after repetitive practice and behavioural conditioning. The results of these studies were then translated into clinical rehabilitation practice, with CIMT being one of the first evidence-based clinical interventions specifically developed for functional recovery of the paretic upper extremity. CIMT has developed from an intensive laboratory protocol to a commonly used rehabilitation program backed by many randomized controlled trials and clinical guidelines over the last 30 years [33].

2. Principles of CIMT

Three key principles in making CIMT effective are: 1) restraining the unaffected limb, 2) intensive task-oriented practice of affected limb, and 3) behavior transferring of acquired skills into daily living. The non-involved upper extremity is immobilized in a mitt, sling or splint during therapy and the patient is instructed to use the affected upper extremity for functional activities. Progressive, repetitive exercises encourage motor learning, enhance spontaneous utilization of the arm, and encourage activity dependent reorganization of the cortex. These principles work together to directly tackle learned non-use and promote long-term functional improvements [34].

Multiple modifications of CIMT have been created to increase patient compliance and clinical practicability. Traditional CIMT requires the use of restraint for the healthy limb for the majority of the waking day and supervised training lasting about six hours per day for two-three weeks. This intensive protocol is not the only one that can be used and modified Constraint-Induced Movement Therapy (mCIMT) lowers the amount of time that the patient is restrained and supervised with therapy being still effective. Other variations include home-based CIMT, pediatric CIMT for children with hemiplegic cerebral palsy, and technology-assisted approaches that combine virtual reality, robotic devices, wearable sensors and telerehabilitation. The modified protocols increase access to this therapy, while maintaining the key concepts of intensive task specific motor practice [35].

3. Clinical Effectiveness

A large number of randomized controlled trials, systematic reviews and meta-analyses have shown that CIMT is an effective intervention for enhancing motor function, manual dexterity and activity of daily living for people with hemiparesis, especially after Stroke. Some benefits have been reported in patients with Cerebral palsy and Traumatic brain injury. Treatment is usually more successful if it is started early in recovery and if patients remain able to move their affected hand and wrist some of the time they do so voluntarily. While treatment intensity and duration vary among studies, available data strongly indicate that CIMT is one of the most effective interventions for enhancing the upper extremity function of patients who are well-matched [36].

Table 4: Summary of Constraint-Induced Movement Therapy

Component	Description	Clinical Significance
Historical basis	Developed from the learned non-use theory by Edward Taub	Foundation of modern CIMT
Core principles	Restraint of unaffected limb, intensive task-oriented practice, behavioral transfer	Promotes repetitive use of the affected limb
Main mechanism	Activity-dependent neuroplasticity and cortical reorganization	Improves motor recovery and functional independence
Major types	Traditional CIMT, modified CIMT, home-based, pediatric, technology-assisted	Increases accessibility and patient adherence
Primary indications	Stroke, cerebral palsy, traumatic brain injury, selected neurological disorders	Restores upper-limb function
Reported outcomes	Improved motor function, dexterity, spontaneous arm use, and activities of daily living	Supported by high-quality clinical evidence

4. Mechanisms of Action of Constraint-Induced Movement Therapy

The most important mechanism through which Constraint Induced Movement Therapy (CIMT) benefits upper-limb function is activity-dependent neuroplasticity, or how neural pathways that control motor control are strengthened with repetitive and task-oriented practice. CIMT involves limiting the use of the unaffected limb and promoting regular use of the paretic limb, thereby promoting activation of the damaged motor cortex and improving motor cortex reorganization. Functional tasks, repeated, promote increased plasticity of the synapses, remodeling of the dendrites, and new neural connections are established, which means better motor coordination and voluntary movement. Another significant mechanism is the learned non-use. Hemiparesis patients tend to overuse the normal side, and this can result in the loss of functional use of the affected arm. CIMT breaks this compensatory behaviour by encouraging the use of the affected limb during activities of daily living. There is evidence of neurophysiology from functional neuro-imaging studies showing higher activation of the motor regions of the ipsilesional hemisphere after CIMT. Together these mechanisms promote better motor behaviour, increased spontaneous arm use and increased functional independence in activities of daily living [37].

5. Clinical Applications of Constraint-Induced Movement Therapy

Constraint-Induced Movement Therapy (CIMT) has been extensively used in rehabilitative treatment of patients with hemiparesis following different neurological diseases. It has been established that CIMT is effective in improving motor function of the upper limb, manual dexterity and performance of activities of daily living in patients with stroke, and the use of CIMT in this patient population has been supported by the strongest evidence. This therapy is effective for patients who have some voluntary movement of the wrist and fingers and can participate in structured rehab programs. In addition to stroke rehabilitation, CIMT has been effective in children with Cerebral palsy with improved hand function, bimanual coordination and participation in everyday activities. There is preliminary evidence to support its use in patients with Traumatic brain injury, and selected cases of Multiple sclerosis, but more quality clinical trials are warranted. The recent development of combining CIMT with robotic-assisted therapy, virtual reality, wearable sensors, and telerehabilitation has further enhanced its clinical applications providing for customized and accessible rehabilitation programs for a wide range of patient groups [38].

6. Evidence from Clinical Studies

In the last 20 years, many randomized controlled trials (RCTs), systematic reviews and meta-analyses have shown that Constraint Induced Movement Therapy (CIMT) is effective for enhancing upper limb function after stroke. In most studies, there are significant improvements in motor performance, manual dexterity, spontaneous use of the affected limb, and independence in activities of daily living compared to conventional rehabilitation. When the greatest benefits are seen, the patients have some voluntary wrist and finger movements and are trained intensively during the subacute or chronic phase of recovery, with training being directed toward specific tasks. There is also clinical evidence that mCIMT, a shorter duration of restraint and shorter sessions of treatment, has similar outcomes to traditional CIMT, with greater patient adherence and feasibility. Long term follow-up studies of these patients indicate that functional improvement may be sustained for months if patients continue to use the involved limb after therapy. While there are differences in the intensity of treatment and selection of patients, overall the body of evidence is consistent and provides strong support for CIMT as one of the most effective evidence-based treatments for upper-limb rehabilitation in hemiparesis [39].

7. Outcome Measures for Assessment of CIMT

The measurement of motor recovery and functional performance are based on standardized clinical assessment tools that will be used to evaluate the effectiveness of Constraint-Induced Movement Therapy. The Fugl-Meyer Assessment is a commonly used instrument for the assessment of motor deficits, the Wolf Motor Function Test for motor activity speed and functional performance, and the Motor Activity Log for quantity and quality of movement of the affected arm during the performance of everyday activities. Hand dexterity and manipulation of objects are often tested with other assessments like the Action Research Arm Test or the Box and Block Test. These outcome measures are reliable and validated tools to measure treatment progress, compare rehabilitation protocols, and to assess long-term functional recovery. Performance-based assessment along with patient-reported outcomes provides a complete assessment of motor function and quality of life, allowing the therapist to tailor rehabilitation programs and assess the overall efficacy of CIMT in various patient populations [40].

8. Factors that affect treatment outcomes, comparative rehabilitation approaches and future perspectives.

Several factors associated with the patient, their clinical status, and therapeutic methods are involved in Constraint-Induced Movement Therapy (CIMT) effectiveness. The most significant factor is the amount of voluntary movement that remains in the involved upper extremity. Improvements in function are usually better in patients with wrist and finger extension intact. There are other factors that play an important role in rehabilitation outcomes such as age, cognitive status, motivation, treatment adherence and time since neurological injury. Early intervention, especially after the subacute phase of Stroke, is related to better recovery and neuroplasticity, and it has been proven that intensive task-oriented rehabilitation is effective in the chronic phase as well [41]. The success of outcomes also relies on the selection of patients, therapist skills, family support and frequent adherence to home exercise programs. CIMT has been one of the most effective evidence-based interventions for the treatment of upper-limb rehabilitation, but is not the sole therapy available for people with hemiparesis. Neurological rehabilitation is still grounded in conventional physical and occupational therapy with muscle strengthening, range of motion exercises, balance training and functional task practice. Other complementary therapies such as bilateral arm training, task-oriented therapy, functional electrical stimulation (FES), robotic-assisted rehabilitation and virtual reality (VR) based training have also proven to be beneficial in motor recovery. These all address various components of motor deficits, and with the patient's clinical status, rehabilitation objectives, and available resources, one may be chosen over another. A comparative study revealed that CIMT may be more effective than traditional rehabilitation in improving spontaneous use of the affected limb, manual dexterity and activities of daily living, especially due to its direct effect on the phenomenon of learned non-use. But it can be difficult to maintain treatment adherence because of the intensive nature of conventional CIMT protocols [42]. For this reason, there is an increasing trend of using modified Constraint-Induced Movement Therapy (mCIMT) that requires less time in restraint and supervised practice and is equally effective. Using CIMT in conjunction with other rehabilitation approaches could further improve functional recovery by adding more motor recovery mechanisms. Recent developments in technology have greatly broadened the scope of application of CIMT. The robotic-assisted rehabilitation systems allow for intensive and repetitive movements training with high intensity, precise control and objective motor performance measures. Likewise, virtual reality environments enhance patient motivation by additionally introducing interactive and task-oriented exercises that mimic real-life activities. In the field of smart rehabilitation, the use of wearable motion sensors and smart devices enables monitoring of the use of the upper limb in the home environment, allowing the therapist to assess the adherence to the therapeutic exercise and the functional outcome in a distant place. Furthermore, the use of a telerehabilitation platform has also helped to increase access to rehabilitation services for people who live in rural or underserved areas and can receive supervised rehabilitation at home. While these improvements have been made, there are some problems still to be addressed. The intensity of treatment, length of intervention, patient selection and maintenance of functional gains remain a topic of continued research. Further research is needed to establish individual rehabilitation plans based on patient characteristics, to include artificial intelligence and digital health technologies within rehabilitation programs, and to assess the long-term clinical effectiveness of these programs in large multicenter randomized controlled trials. As evidence continues to grow, the use of CIMT is likely to continue to be a key resource in the upper-limb rehabilitation arena and is also likely to become a component of a comprehensive, technology-assisted neurorehabilitation program that optimises functional recovery and promotes quality of life for people with hemiparesis [43].

9. Challenges, Future Directions, Clinical Implications:

Despite its proven effectiveness, Constraint-Induced Movement Therapy (CIMT) has several limitations that may affect its clinical implementation. Traditional CIMT protocols require prolonged restraint of the unaffected limb and intensive supervised training, which can reduce patient adherence and increase physical fatigue. In addition, not all individuals with hemiparesis are suitable candidates, particularly those with severe cognitive impairment, profound upper-limb weakness, or significant medical comorbidities. Variability in treatment intensity, intervention duration, and patient selection across clinical studies also highlights the need for standardized rehabilitation protocols. Future research should focus on optimizing individualized CIMT programs by incorporating emerging technologies such as robotic-assisted rehabilitation, virtual reality, wearable sensors, artificial intelligence, and telerehabilitation. These innovations have the potential to improve treatment accessibility, increase patient engagement, and provide objective monitoring of rehabilitation progress. Large multicenter randomized controlled trials with long-term follow-up are also required to establish optimal treatment dosage and identify predictors of successful recovery.

Conclusions

CIMT has emerged as a major component of contemporary neurorehabilitation for hemiparesis, because it undermines the phenomenon of learned non-use and fosters activity-dependent neuroplasticity. A significant clinical proof-of-concept has been established that CIMT enhances upper-limb motor function, manual dexterity, spontaneous use of the affected limb and independence in activities of daily living (ADLs), notably in Stroke patients. The evolution of modified CIMT protocols has also enhanced the feasibility of treatment and adherence to the protocol, making it more applicable to clinical practice. Recent technological developments such as robotic-assisted rehabilitation, virtual reality, wearable monitoring systems and telerehabilitation have broadened the possibilities for CIMT, and have opened new possibilities for personalised rehabilitation. While there are still many issues to be resolved, such as how to optimize treatment intensities, who should be treated, and ensuring long-term maintenance of therapeutic effects, current evidence strongly supports the use of CIMT as a safe, effective, and evidence-based therapy for upper limb rehabilitation. More multi-center and well-designed studies are warranted in the future with standardized clinical protocols, the incorporation of new technologies and the development of personalized therapeutic approaches to optimize the functional outcomes and long-term quality of life of people with hemiparesis.

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