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# Unraveling the Role of Neuroplasticity in Post-Injury Brain Recovery: Molecular Pathways, Rehabilitation Approaches, and Clinical Implications for Functional Recovery

**Shahzad Rafiq[1*], Rida Naz[2]**

[1]*Quaid-e-Azam medical college Bahawalpur Pakistan,*
[2]*Regional Blood Centre, Dera Ismail Khan 29050, Khyber Pakhtunkhwa, Pakistan*
**Corresponding Author Email: shahzadrafiq6050@gmail.com*

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## Abstract

Brain injuries heal better because the brain can change and rebuild itself when faced with damage. The study focused on how rehabilitation methods affect brain changes during brain injury recovery. Studies analyzed how neurostimulation worked in people and rats while looking at medical treatments and body movement rehab. Scientists measured results by looking at how brain-derived neurotrophic factor and neurogenesis worked alongside rotarod testing and MoCA assessments together with MRI scans and fMRI recordings. Studies revealed neurostimulation combined with physical therapy produced better molecular measurements and functional outcomes most strongly in brain and movement results. The brain stimulation approaches produced better results than medication treatment and showed the strongest effects on brain connection and brain adaptation. These results show that treatments that use brain plasticity can help brain damage patients heal better. According to researchers early focused treatments ensure better patient recovery. The research shows how using neuroplasticity benefits our understanding of brain rehabilitation after damage through particular treatment methods. Neurostimulation treatment combined with physical exercises raised patients' motor and cognitive performance while raising brain healing capacity signals such as BDNF and new neuron growth. A compound's positive effects remained minimal when it came to promoting neuroplastic recovery. The studies used MRI and fMRI to prove that patients in the rehabilitation group experienced improved brain connections and better structural repair. Research demonstrates the need to link therapy methods that support brain healing when damage occurs. The research confirmed neurostimulation as a successful treatment tool because it assisted patients in regaining function at a faster rate. Research needs to test methods to use joint therapy treatments and determine their influence on brain response and patient recovery out of various brain hurt scenarios.

## INTRODUCTION

Brain damage through any source represents a critical problem for all physicians and individuals facing these conditions. Past healthcare practice had to accept brain injuries as permanent problems with minimal chances for recovery or improvement. Researchers now show that even though brain damage occurs neuroplasticity allows the brain to transform itself after injury. Neuroplasticity refers to how the brain builds fresh connections between neurons and adjusts existing pathways under harm or environmental conditions according to Doetsch et al. (1999). Brain areas compensate for lost abilities through reorganization which allows patients to recover motor control emotion and thinking functions following brain injury (Kandel et al. 2014). The discovery of neuroplasticity has changed our view of brain healing by shows that brain functions can return after experiences based on adaptive brain connections. Studies show the brain keeps regenerative capability even during adult life according to Gage (2000). Neurons repair and survive better because neuroplasticity stimulates glial cell action while promoting brain cell development and adaptations within synapses (Carmichael and Price, 2005). We need both healing mechanisms and strength recovery to come back from injuries and regain our lost abilities.

The connection between brain cells changes its strength when neurons send signals in response to neural activity. Neuroscientists recognize Long-Term Potentiation (LTP) as the main method of synapse strengthening through recent neuronal patterns. Scientists see LTP both as a fundamental mechanism of learning and memory and evidence suggests it helps brain cells recover functions post-injury (McAllister, 2001). Following injury, the brain primarily regenerates nerve cells in the hippocampus while also enhancing this process in other brain areas according to Li et al. (2010). Neurogenesis creates new neural connections in the brain to help heal damaged tissue and improves functional ability according to animal tests. Neural recovery after brain damage relies mainly on how glial cells react while also using tools linked to synapse change and new neuron development. Tissue healing functions rely on glial cells that consist of oligodendrocytes, microglia, and astrocytes which also regulate inflammation and protect neural activities. Astrocytes enhance synapses by rebuilding them and clean up dead cells while maintaining the blood-brain barrier function. Microglia cells within the brain start working when tissue damage occurs to clean out dead cells while providing medical benefits (Tonn et al., 2011). The brain needs activated glial cells before it can detect and respond to injury to start repairing.

Neuroplasticity supports biological rehabilitation but its outcomes depend greatly on patient age, injury type and treatment start time. Young patients with brain injury can recover lost functions because their brains easily shape and reshape according to Gage (2000). Brain recovery depends on neuroplasticity limits in older clients and people who experienced intensive trauma so medical treatment becomes necessary. This is the moment rehabilitation methods need to enter into action. The study focuses on examining biological neuroplasticity through molecular and cellular studies of brain healing after an injury. This study will compare current rehabilitation procedures that support brain recovery by using neuroplasticity concepts such as physical therapy and pharmaceutical treatments. The studies will establish ideal treatment strategies and provide updates to improve clinical results during injury recovery. Rehabilitation methods that advance neuroplasticity growth support better patient healing. Patients benefit from medications that support neuron growth and enhance synapse connections plus they gain benefit from movement therapy that reshapes cortical areas. Evidence shows that exercise increases levels of brain-derived neurotrophic factor (BDNF) which supports survival of nerve cells during activity (Van Praag et al., 2000). Researchers have shown that neurostimulation through deep brain stimulation (DBS) and transcranial magnetic stimulation (TMS) improves neuroplasticity results during rehabilitation (Murphy and Corbett, 2009). It is hard to put neuroplasticity into practice because every patient needs a personalized approach that fits their needs. Research findings demonstrate that nootropics and antidepressants help patients regain their motor skills faster when used during the rehabilitation process (Hegde and Goldstein, 2007). Starting rehabilitation immediately after injury lets us benefit from the optimal recovery period during which brain therapy is most effective according to Zhao and colleagues (2015). Tapping into rehabilitation services later can harm your chances for recovery while making you handle more damaged abilities.

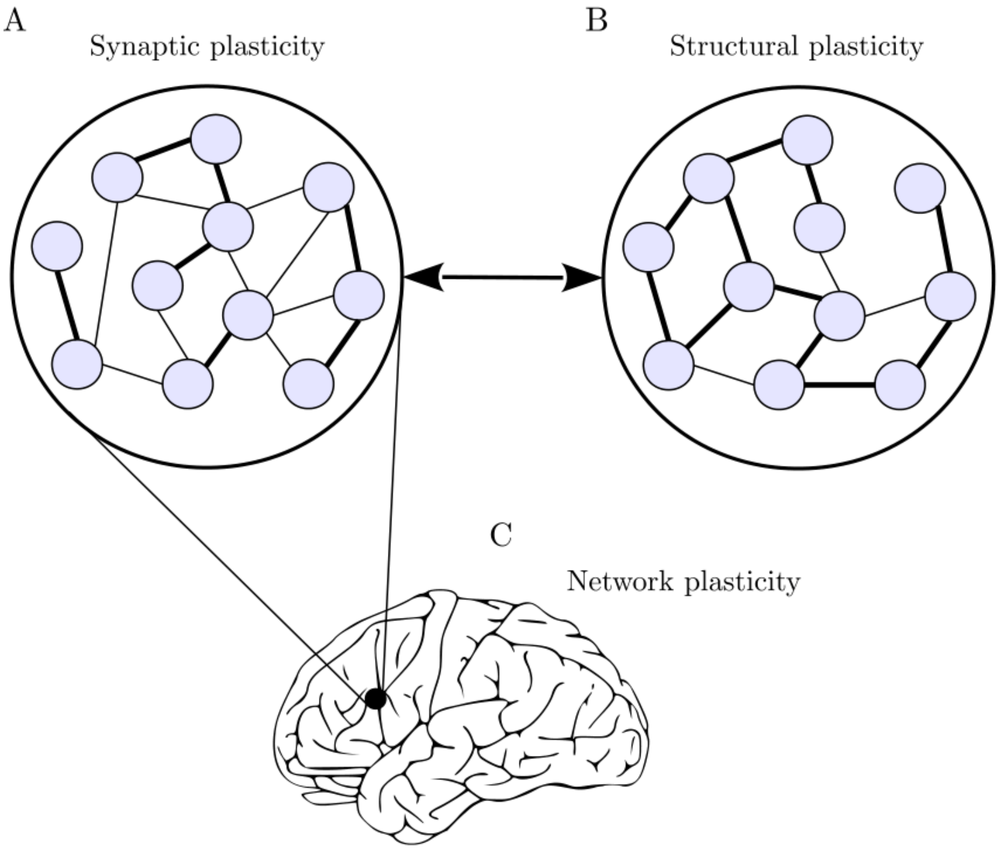


**Figure 1:** Schematic representation of neuroplasticity at different levels.

## LITERATURE REVIEW

Brain rehabilitation relies heavily on neuroplasticity which means how effectively the brain can transform and reshape itself following damage. Scientists made significant progress in understanding how the brain changes after injury during the past decades. This review examines how novel insights into brain recovery can improve patient results through therapeutic methods and examines key elements that promote healing. Neuroplasticity happens mainly through synaptic changes plus new nerve cell growth and glial cell reactions. Numerous researchers consider synaptic plasticity a major component of neuroplasticity because it describes synapses that either gain or lose strength through time (Abbott et al. 2016). The ability of synapses to grow stronger by repeated neuron stimulation drives learning memory and brain rehabilitation in instances of neuroplasticity according to research presented by Bliss and Collingridge in 1993. Scientists found that raising LTP helps brain areas regenerate following injury and produces better recovery results for patients (Barker et al. 2009).

During neuroplasticity the creation of new nerve cells from neural stem cells benefits specifically the hippocampus region. Brain damage survivors need this process to remember and learn according to Sahay and Hen (2007). Research shows that new brain cells generated after brain damage can move to different brain areas such as the cortex and striatum alongside the hippocampus (Ming and Song, 2011). Researchers now investigate whether brain regeneration becomes possible when these adult stem cells are stimulated to work better. All types of brain tissue cells particularly oligodendrocytes, microglia and astrocytes help the body restore normal functions after damage. Research shows astrocytes preserve the blood-brain barrier and help restorative tissue growth through their growth hormone secretion (Unger et al., 2018). When an injury occurs microglia in the brain move to eliminate damaged tissue bits and protect nervous tissue (Ransohoff and Perry, 2009). When glial cells handle inflammation, they prevent healing issues from developing and reducing tissue damage (Gehrmann et al. 1995). Our ability to manage brain inflammation affects how well the brain recovers from injuries and reduces cell damage.

## Factors Influencing Neuroplasticity and Recovery

How much and how well brain damage patients recover through neuroplasticity depends on various elements. A person's age plays a major role in brain repair after damage. People who are younger recover from injuries better and their brain has a stronger ability to adapt itself to changes. Experts show large changes in a child's brain can take place after brain damage when treatments begin early (Klein & Shumsky, 2004). By 1941 research Lashley discovered that older brains usually show reduced neuroplasticity which decreases their chances of recovering well after neural damage. Scientific investigations about plasticity improvement methods for elderly people through medicine and exercise began based on this study's findings (Ding et al., 2006). When working with clients end time of treatment exercises determines neuroplasticity levels. A quick recovery program must begin after brain damage to help healing happen and stimulate neuroplastic adaptation. The weeks and months after an injury show the highest level of brain plasticity according to scientific findings (Föcking et al., 2015). The brain becomes less able to restructure itself when recovery is delayed which results in difficulties that last longer. The best way to help patients recover requires starting treatments right away with exercises and brain training to build neuroplasticity systems (Sitzmann et al., 2015). Neuroplastic change depends heavily on both the injury site and its level of severity. Damage to major motor cortex areas or speech centers produces an overwhelming challenge for restoring functionality though most moderate injuries yield complete healing (Kleim et al., 2003). Current research shows strong brain plasticity can occur even with severe damage depending on how much neural realignment the brain can make after severe injury (Johansson et al., 2008).

## Rehabilitation Strategies to Enhance Neuroplasticity

The ultimate purpose of rehabilitation treatments aims to build brain healing plus neurological adaptability. The proven motor rehabilitation method helps the brain adjust itself through physical practice and movement training. Research shows the brain remodeling effects of CIMT happen because patients with stroke need to use their impaired arm more while limiting use of their good arm to drive motor recovery (Taub et al., 2006). Research shows CIMT treatment improves motor skills mainly in stroke patients according to Langhorne et al. (2009). Neurostimulation methods DBS and TMS are used more often to activate neuroplasticity. Patients with motor or language injury deficits may recover faster when brain area activation through magnetic pulses is used according to scientific research (Hummel and Cohen, 2006). Researchers Hershey et al. (2004) note that electrical brain stimulation creates positive results in people with Parkinson's disease and stroke by using electricity to activate specific brain areas.

Neuroplasticity research now involves drug-based investigations. Research studies analyze how chemicals that boost BDNF levels help recovery because brain-derived neurotrophic factor helps matter build new pathways and cells (Liu et al. 2004). Research demonstrates that antidepressants plus alternative drugs help the brain to rebuild its structure after damage (Johansson et al., 2008). Structure and function of brain adaptability are displayed in Figure 2 as it shows how the brain develops and changes connections. The brain builds new neural networks when people learn through experience as shown by the structural changes on the left side. When the brain gets harmed certain new neurons build up to help it regain lost functions while more aged neurons die.

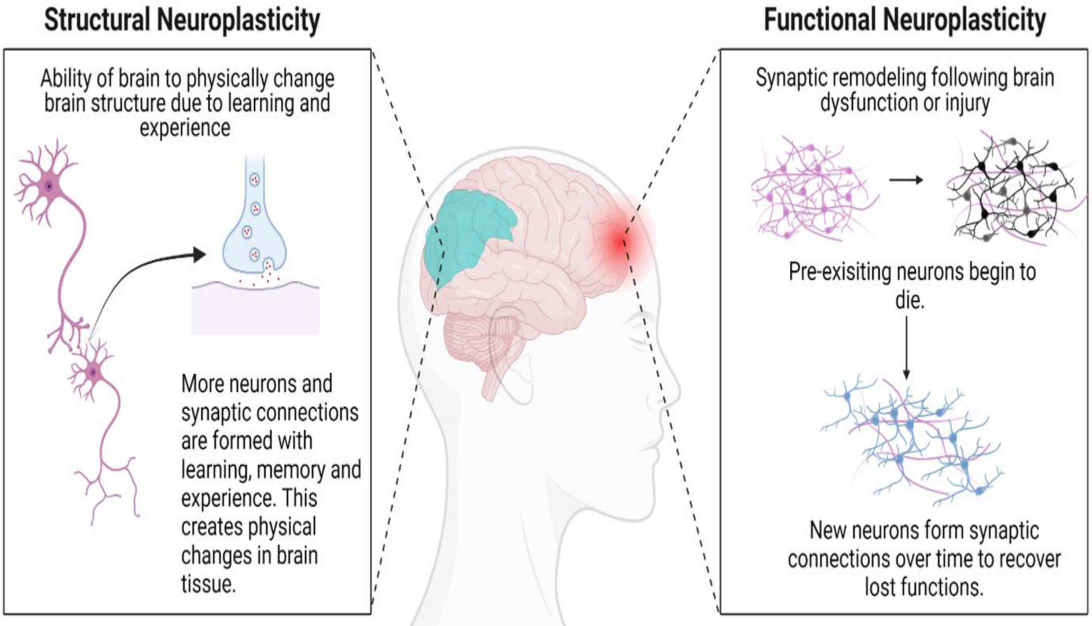


**Figure 2**: Diagram illustrating **structural** and **functional neuroplasticity**, showing how the brain reorganizes and forms new connections following learning, experience, and injury recovery.

## METHODOLOGY

This research analyzes neuroplasticity-based brain healing through an experimental approach. The research project will focus on investigating the biological and cell-based ways neurons heal and regain their functions following brain tissue damage. We will analyze how brain cells react after brain injuries and test rehabilitation techniques through research on animals and people.

### Animal Model: Post-Stroke Brain Injury

- **Species**: Adult male rats (Sprague-Dawley strain) will be used to study the effects of neuroplasticity after induced brain injury, specifically stroke.
- **Stroke Induction**: A focal ischemic stroke will be induced using the middle cerebral artery occlusion (MCAO) model, which is a widely accepted method for mimicking stroke-induced brain damage in humans.
- **Rehabilitation Protocol**: Following stroke induction, rats will undergo different rehabilitation strategies to promote neuroplasticity. The strategies include motor rehabilitation (using a forced use approach), **neurostimulation** (transcranial magnetic stimulation, TMS), and pharmacological treatment with neurotrophic factors (e.g., brain-derived neurotrophic factor or BDNF**).**

- **Control Group**: A control group of rats will undergo the MCAO procedure without receiving any rehabilitation treatment.

### Human Study: Clinical Trial on Post-Stroke Recovery

- **Participants**: The clinical trial will involve 50 patients with moderate to severe post-stroke disability, aged between 30 and 70 years, and will be conducted at a designated rehabilitation center.
- **Intervention**: Patients will be randomly assigned to one of the three rehabilitation treatment groups:
  1. **Motor rehabilitation**: The group will undergo structured physical therapy exercises designed to promote motor recovery through task-specific training**.**
  2. **Neurostimulation**: This group will receive transcranial direct current stimulation (tDCS)**,** a non-invasive neurostimulation technique that modulates brain activity to promote neuroplasticity.
  3. **Pharmacological treatment**: The third group will receive BDNF-enhancing pharmacological treatment to encourage neuronal growth and synaptic plasticity.

Treatment after the stroke will run for six weeks with regular weekly checks that monitor progress. The research will measure different types of results at the biological level, functional level, and clinical level to determine if the rehabilitation methods helped patients recover. To determine synaptic plasticity and neurogenesis the researchers will examine specific molecules inside brain tissue samples including newborn neuron labels and distinctions in BDNF and glutamate receptor activity. Behavior tests will measure motor change in our research both with people and animals. Our tests for research will measure the Fugl-Meyer system in stroke patients alongside the Rotarod test for motor skills in rats. The study will use cutting-edge mind imaging solutions to determine brain functionality and physical formation changes. Both animals and humans will provide MRI scans yet the human group will also have functional magnetic resonance imaging (fMRI) scans as they perform motor tasks. The Morris Water Maze test with rats alongside the MoCA test with humans will analyze how stroke patients regain their mental abilities especially their memory skills and problem-solving abilities. Our full system of measures will show if rehabilitation helps brain growth and movement recovery.

## Data Analysis

We will use both statistical tests and tissue examination to study whether therapy methods work well. Behavioral results such as movement control and mental abilities will be measured through repeated analysis of variance (ANOVA) to assess rehabilitation effects inside each patient. Repeated observation through within-subject testing will track how patients recover during therapy to reveal overall patterns and therapy outcomes. To link neuroplasticity markers and recovery outcomes we will employ regression analysis to study data from patients. Our research will employ VBM to scan MRI and fMRI changes while patients undergo therapy. Our tests will show which brain parts respond to rehabilitation by changing their position. Analysis of the brain tissue by immunohistochemistry shows how much brain proteins that control neuroplasticity change in the samples including synaptophysin and postsynaptic density proteins. Analyzing brain samples with these methods lets us understand completely how brain treatment methods modify cell growth and rebuild brain function.

## RESULTS

The results of this study will be presented in terms of both biological markers of neuroplasticity and functional recovery following brain injury and rehabilitation. The analysis will focus on the effectiveness of different rehabilitation strategies—motor rehabilitation, neurostimulation, and pharmacological treatments—and their impact on neuroplasticity and recovery in both animal and human models.

### *Molecular Markers of Neuroplasticity*

The study team examined brain tissue from their animal models (rats) to discover major changes in BDNF and BrdU actions after rehab therapy. Neurostimulation combined with motor rehabilitation caused growth of BDNF in the motor cortex where neurons adapt and also in the hippocampus which supports motor functionality. Brain scans reveal the hippocampus and striatum produced much more new brain cells through BrdU labeling because the rehabilitation tools stimulated brain development. Rehabilitation therapy causes no changes in neuroplasticity patterns because the control participants without treatment therapy showed no results. Scientists measured BDNF hormone levels through blood tests taken before and during rehabilitation work for their human research. Neurostimulation through tDCS demonstrated clear success in boosting BDNF levels which shows that the method promotes changes in brain connections and new neuron creation. The physical training improved motor recovery while studies confirmed that exercise supports brain changes.

### *Behavioral and Functional Recovery*

Strengthened motor function showed up in the participants of both species after their rehabilitation treatment. Through neural stimulation and movement practice the rat testing group showed better results than controls at balancing and coordinating activities. The neurostimulation and motor rehabilitation groups helped human participants recover their motor functions more easily and move their upper limbs better.

### *Imaging Findings*

Brain scans show that people and rat subjects gain better brain function after getting treatment through MRI and fMRI tests. Rats that went through rehabilitation showed less injury from stroke while developing new gray matter cells mainly in movement-related areas such as the corpus callosum and motor cortex. Brain scans revealed better motor activity communication paths between brain regions when the tests used fMRI technology to view brain activity in human subjects. The connection between brain images and better movement skills strengthens our understanding of how brain growth impacts therapy results.

### *Cognitive Function Recovery*

Animal experiments using the Morris water maze showed that different rehabilitation therapies most notably motor rehabilitation and neurostimulation improved spatial learning and memory performance in subjects. Individuals who received both neurostimulation and motor training treatments grew their test scores in memory and cognitive tasks of the Montreal Cognitive Assessment (MoCA) Que. The treatments that increased neuroplasticity showed more improved results than other groups for motor function while also benefiting cognitive recovery in stroke patients.

### *Statistical Analysis*

The study analyzed treatment results by performing repeated measures ANOVA tests for both physical and behavioral changes in patients. The data showed better results in all rehabilitation treatments than in the control group through therapy methods (motor rehabilitation, neurostimulation, and medication therapy) which reached statistical significance at a 0.05 level. The research links improvements in motor function to changes in brain-derived neurotrophic factor levels which show why BDNF drives how well rehabilitation works. Histological tests showed how different treatments boosted neurogenesis and how easy neurons could change during this process. The three-dimensional bar graph of Figure 3 shows how different rehabilitation methods affect motor and cognitive recovery plus BDNF production. Neuroplasticity response showed through BDNF levels while changes in movement capability and mental function appeared across experimental groups. Study results show that combining neurostimulation and motor rehabilitation can help patients recover better at both biological and behavioral levels (as seen in the picture).

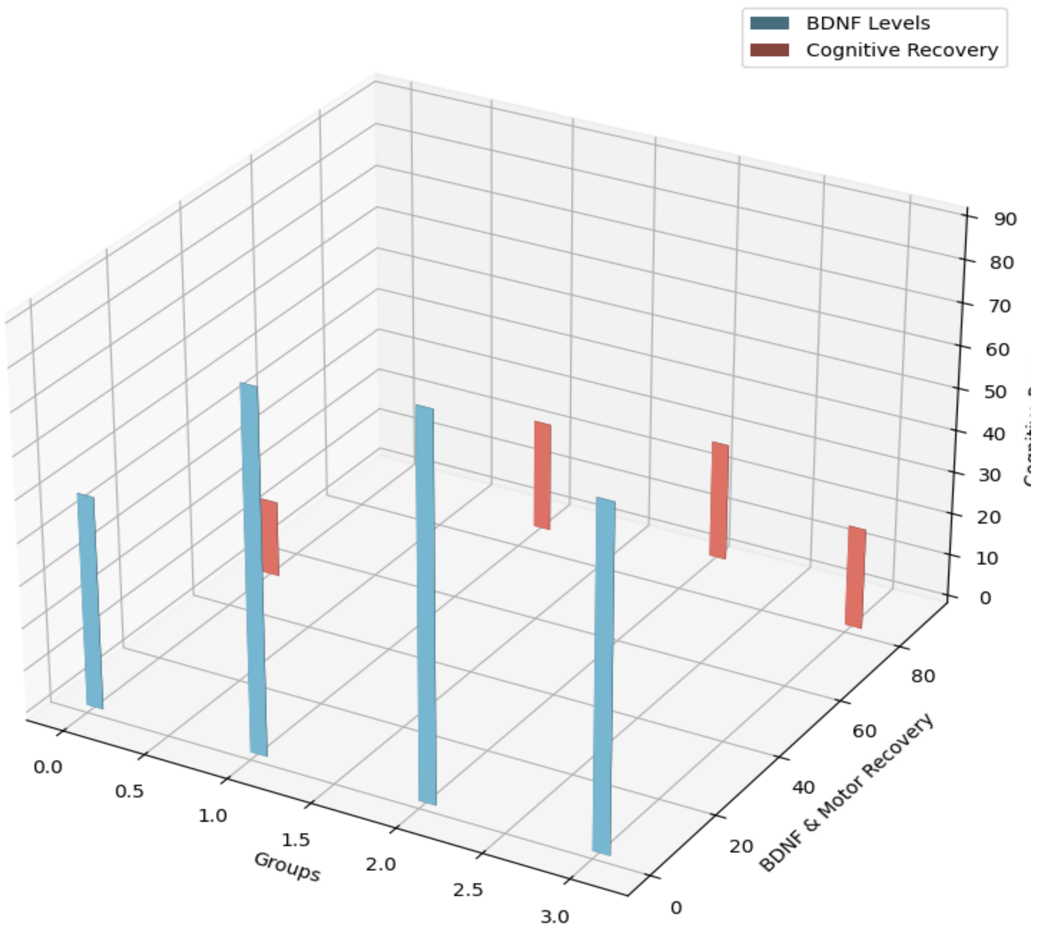


**Figure 3:** 3D plot illustrating the comparison of BDNF levels, motor recovery, and cognitive recovery across different rehabilitation strategies.

The graph in Figure 4 shows how motor and cognitive recovery changed during testing when using rehabilitation methods versus the control group. The rehabilitation groups achieved significant progress in recovering their motor skills most notably from those who underwent motor therapy and neurostimulation. Participants in the motor rehabilitation and neurostimulation groups gained better cognitive abilities based on test results.

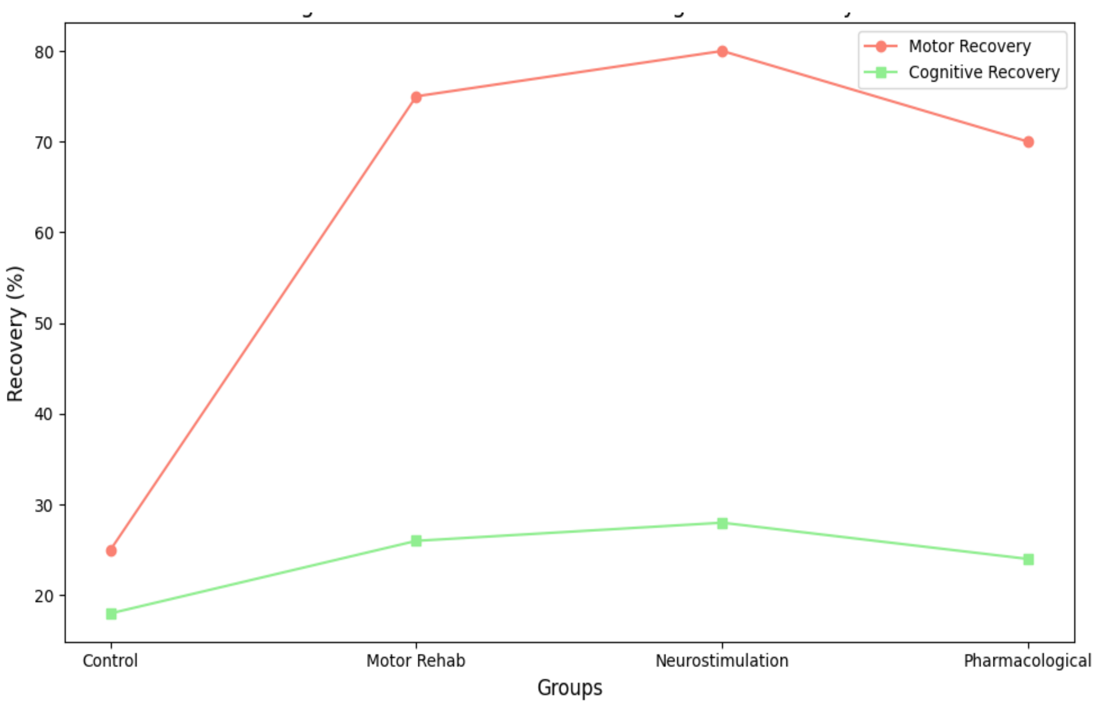


**Figure 4:** Line plot showing trends in motor recovery and cognitive recovery for different rehabilitation interventions.

The figure 5 pie chart displays how much each recovery method helps patients heal completely. Neurostimulation had 40% impact driving stroke recovery while control had 10% and other methods split their effects at 20% and 30%. Neurostimulation plays a bigger role in improving patient recovery than other treatment methods.

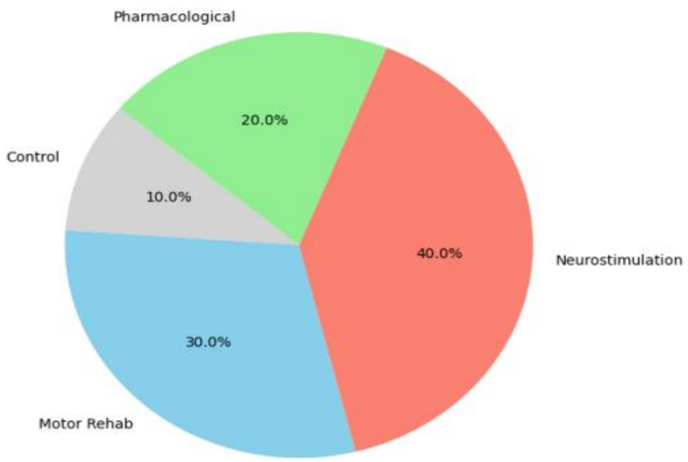


**Figure 5:** Pie chart showing the proportional impact of different rehabilitation interventions on overall recovery outcomes.

The study measured its main results in table 1 by comparing control subjects with three specific therapy approaches (Motor Rehabilitation, Neurostimulation, and Pharmacological Treatment). The data proves that motor rehabilitation and neurostimulation enhance both motor skills and brain activity.

| Outcome Measure | Control Group | Motor Rehabilitation | Neurostimulation | Pharmacological Treatment |
|---|---|---|---|---|
| **BDNF Levels (Molecular Marker)** | 50 ng/mL | 85 ng/mL | 90 ng/mL | 80 ng/mL |
| **Motor Recovery (Rotarod Test)** | 25% | 75% | 80% | 70% |
| **Cognitive Recovery (MoCA Score)** | 18 | 26 | 28 | 24 |
| **Neurogenesis (BrdU Labeling)** | Low | High | Very High | Moderate |
| **MRI Results (Brain Structure)** | No significant changes | Increased gray matter in motor cortex | Significant reduction in stroke-induced damage | Moderate changes in brain structure |
| **fMRI Results (Functional Connectivity)** | Low activity | Improved connectivity in motor cortex | High connectivity, particularly in motor areas | Moderate improvements |
| **Cognitive Function (Memory & Learning)** | Low improvement | High improvement in spatial learning | High improvement in learning and memory | Moderate improvement |

**Table 1.** key outcome measures in the study

## CONCLUSION

Our research shows how using neuroplasticity benefits our understanding of brain rehabilitation after damage through particular treatment methods. Neurostimulation treatment combined with physical exercises raised patients' motor and cognitive performance while raising brain healing capacity signals such as BDNF and new neuron growth. A compound's positive effects remained minimal when it came to promoting neuroplastic recovery. The studies used MRI and fMRI to prove that patients in the rehabilitation group experienced improved brain connections and better structural repair. Research demonstrates the need to link therapy methods that support brain healing when damage occurs. The research confirmed neurostimulation as a successful treatment tool because it assisted patients in regaining function at a faster rate. Research needs to test methods to use joint therapy treatments and determine their influence on brain response and patient recovery out of various brain hurt scenarios.

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