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Rewiring after ACL Injury- The Role of Neuroplasticity in Performance Recovery and Reinjury Prevention- A Rapid Review

P. Archana[1*], Anusha V. Shenai[1] and V. S. Lavanya[2]

[1]*Department of Musculoskeletal Sciences, RV College of Physiotherapy, Jayanagar, Bengaluru- 560011, Karnataka, India; archana3ap@gmail.com*

[2]*Physiotron Therapeutics, Physiotherapy Clinic, Jayanagar 9th Block, Bengaluru – 560041, Karnataka, India*

Abstract

Background: Anterior Cruciate Ligament (ACL) injury is among the most frequent sports-related injuries worldwide, affecting millions of individuals each year. Rehabilitation following ACL reconstruction has traditionally emphasised peripheral recovery; however, recent research demonstrates that neuroplastic adaptations within the central nervous system play a crucial role in motor control, proprioception, and functional recovery. Understanding these mechanisms is vital for optimising physiotherapy outcomes and reducing the risk of reinjury. A rapid review was undertaken to summarise current evidence on neuroplastic and motor-learning mechanisms after ACL injury and reconstruction. Electronic databases were searched for studies published between 2015 and 2025 involving human participants who underwent physiotherapy or neurocognitive rehabilitation and reported clinical outcomes. Six studies meeting predefined inclusion criteria were reviewed for neurophysiological findings, rehabilitation approaches, and clinical outcomes. The evidence indicates that ACL injury disrupts motor-cortex excitability, corticospinal integrity, and proprioceptive processing. Neuroimaging and electrophysiological studies revealed compensatory activation within motor and cerebellar regions during functional tasks. Physiotherapy interventions incorporating visuomotor retraining, proprioceptive and cognitive-motor exercises enhanced cortical responsiveness, balance, and readiness to return to sport. Programmes integrating motor-learning principles improved neuromuscular coordination and reduced asymmetry during dynamic movements. Neuroplasticity significantly influences recovery following ACL injury. Physiotherapy approaches that harness motor-learning and neurocognitive strategies facilitate superior functional restoration and may reduce secondary injury risk. Incorporating neurophysiological assessment into routine rehabilitation could support more individualised, evidence-based care.

Major Findings: ACL injury and reconstruction are associated with altered motor-cortex excitability, corticospinal function, and proprioceptive processing, with compensatory cortical and cerebellar activation. Neurocognitive, visuomotor, proprioceptive, and motor-learning–based rehabilitation can enhance cortical responsiveness, neuromuscular coordination, balance, and functional recovery while potentially reducing reinjury risk.

Keywords: ACL Injury, ACL Rehabilitation, Anterior Cruciate Ligament, Motor Learning, Neuroplasticity, Return to Sport after ACL Injury

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1. Introduction

Anterior Cruciate Ligament (ACL) injury is one of the most frequent and disabling musculoskeletal conditions in athletes and active individuals, with several million cases worldwide each year[1]. Despite advances in surgical reconstruction and structured rehabilitation, many patients do not regain preinjury performance or sustain a

*Author for correspondence

secondary injury after return to sport[2,3]. These outcomes indicate that ACL injury involves central adaptations as well as peripheral joint pathology. Neuroplasticity has therefore become a critical focus for physiotherapy planning[4].

Neuroplasticity is the capacity of the central nervous system to reorganise structure and function in response to injury and training. Following ACL rupture, loss or alteration of mechanoreceptor input modifies cortical sensory processing and disrupts proprioceptive feedback loops that support precise motor control[5,6]. Human studies using functional MRI, electroencephalography, and transcranial magnetic stimulation show compensatory recruitment in prefrontal and cerebellar regions during knee motor tasks, consistent with cortical reorganisation that seeks to maintain performance[7-11]. Diffusion and connectivity analyses further demonstrate changes within corticospinal pathways and interhemispheric communication that relate to delayed quadriceps recovery and asymmetrical movement strategies[12-14].

These neural adaptations have clinical consequences. Patients after ACL reconstruction often present with arthrogenic quadriceps inhibition, impaired joint position sense, and altered postural and locomotor control[15-17]. Observational and interventional work indicates that greater visuomotor coordination and enhanced cortical responsiveness are associated with better movement symmetry and superior functional outcomes[8,14,18]. Such findings imply that rehabilitation strategies should purposefully target the central mechanisms that govern motor relearning.

Traditional programmes prioritise strength, range of motion, and biomechanical stability. However, peripherally focused training alone does not fully address central reorganisation that influences neuromuscular contro[19,20]. Contemporary physiotherapy frameworks integrate motorlearning and neurocognitive principles, including externalfocus cueing, dualtask practice, cognitivemotor retraining, visuomotor feedback, and graded proprioceptive exposure[2,7,14–18]. Study investigating neuromuscular and proprioceptive programmes, along with movement-based return-to-sport pathways, have demonstrated improvements in cortical excitability, proprioceptive acuity, postural control, and functional readiness[16-19]. Early work also suggests that adjunct approaches that modulate cortical state can reduce inhibition and support force production, complementing taskspecific training[20-22]. Converging EEG evidence indicates progressive recovery of proprioceptive processing over time with targeted practice[22]. Fieldrelevant experiments show that cortical dynamics during complex sportspecific tasks, such as kicking, relate to control accuracy and may be trainable[21].

Despite rapid growth, the literature remains fragmented across imaging modalities, stimulation methods, and heterogeneous rehabilitation protocols. Prior reviews largely emphasised mechanical and surgical outcomes and gave limited attention to central mechanisms that likely determine longterm performance and reinjury risk[25,26]. Consequently, a rapid review is warranted to synthesise current evidence on cortical and subcortical adaptation after ACL injury and reconstruction and to evaluate physiotherapy interventions grounded in motorlearning principles. The objective is to summarise neurophysiological alterations linked to ACL injury and to appraise rehabilitation approaches that leverage neuroplasticity to optimise functional recovery and reduce the probability of secondary injury[2,3,14–19,21–24].

2. Methodology

2.1 Search Strategy

A structured electronic search was conducted to identify studies exploring neuroplasticity, motor-learning mechanisms, and physiotherapy-based interventions following Anterior Cruciate Ligament (ACL) injury or reconstruction. The review followed a rapid review framework consistent with evidence synthesis standards.

The databases PubMed, Scopus, Google scholar and Web of Science were searched for studies published between 2015 and 2025. Search terms combined controlled vocabulary and free-text keywords related to "anterior cruciate ligament," "ACL injury," "neuroplasticity," "motor learning," "Return to sport after ACL injury" and "ACL rehabilitation." Boolean operators (AND/OR) were used to connect terms.

Reference lists of included studies and relevant reviews were screened manually to identify additional eligible papers. Only peer-reviewed human studies published in English were included. Animal, cadaveric, tele-rehabilitation, case reports, and expert opinion papers were excluded.

Titles and abstracts were screened independently by two reviewers to assess eligibility. Full-text articles meeting inclusion criteria were then reviewed to extract data on study design, participant characteristics, interventions,

outcome measures, and key neurophysiological or functional findings. Disagreements were resolved by consensus. The characteristics of the six included studies are presented in (Table 1, 2) summarising the study design, participant demographics, intervention details, outcome measures, and key findings.

A PRISMA-adapted flow diagram was used to document the study selection process, including the numbers of records identified, screened, excluded (with reasons), and included in the final analysis. The complete study selection process is presented in Figure 1.

2.2 Inclusion Criteria

Studies were included if they met all of the following criteria:

- Population: Human participants aged 16 years or older with a diagnosis of anterior cruciate ligament (ACL) injury, either managed conservatively or following surgical reconstruction.
- Intervention: Physiotherapy or rehabilitation programmes incorporating motor-learning principles, neuroplasticity-based techniques, or neurocognitive components (e.g., proprioceptive, visuomotor, or dual-task training) aimed at enhancing sensorimotor control, functional performance, and readiness for return to sport.
- Comparison: Conventional rehabilitation protocols, control groups, or pre-intervention baselines where available.
- Outcomes: Studies reporting at least one clinical or neurophysiological outcome related to motor control, proprioception, cortical excitability, return-to-sport readiness, or functional performance.
- Study Design: Randomised controlled trials, cohort studies, cross-sectional studies, and controlled laboratory-based experiments, case reports and case series.
- Publication Criteria: Full-text articles published in English between January 2015 and December 2025 in peer-reviewed journals. Publication types include peer reviewed journal articles, dissertations and conference papers. Even relevant grey literature sources such as theses or institutional reports if full text and sufficient methodological details are available will be included. On going clinical trials from CTRI will be included.

Studies involving animal models, tele-rehabilitation, case reports, narrative commentaries, or those lacking measurable human outcomes were excluded.

2.3 Exclusion Criteria

Studies were excluded if they met any of the following conditions:

- Population: Animal or cadaveric studies, or those involving participants with combined ligament injuries, neurological disorders, or lower-limb surgeries other than ACL reconstruction.
- Intervention: Studies focusing solely on tele-rehabilitation, surgical techniques, pharmacological management, or non-physiotherapy approaches without a neuroplastic or motor-learning component.
- Outcome: Articles that did not report quantifiable clinical, neurophysiological, or functional outcomes relevant to motor control, proprioception, or cortical activity.
- Study Design: Narrative reviews, expert opinions, conference abstracts, case reports and studies lacking methodological detail.
- Publication Criteria: Non-English language papers, unpublished data, non peer reviewed articles, abstracts without full text and grey literature sources lacking methodological transparency and complete data.

Only studies fulfilling the predefined inclusion criteria and published between 2015 and 2025 were retained for synthesis

3. Study Selection

All records identified through the database search were imported into a reference management system, and duplicate entries were removed. Two reviewers independently screened the titles and abstracts to determine eligibility based on predefined inclusion and exclusion criteria. Full-text articles were then retrieved for studies meeting the screening criteria or where eligibility was uncertain. Disagreements between reviewers were resolved by discussion until consensus was achieved. A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-adapted flow diagram was used to summarise the selection process, including the number of studies identified, screened, excluded, and included in the final synthesis.

3.1 Data Extraction

Data from the included studies were extracted independently by two reviewers using a structured data extraction form. Information recorded included study author, year, location, participant characteristics, sample

size, intervention details, control conditions, duration, outcome measures, and main results. Discrepancies were resolved through mutual review of full-text articles. When information was unclear, efforts were made to cross-check results within the manuscript or supplementary materials to ensure accuracy and completeness.

3.2 Data Analysis

Given the heterogeneity of study designs, interventions, and outcome measures, a descriptive and narrative synthesis approach was used. Quantitative pooling or meta-analysis was not conducted due to variations in assessment methods, neurophysiological parameters, and rehabilitation protocols. Findings were summarised thematically, focusing on patterns of cortical reorganisation, motor-learning effects, and functional performance outcomes. Trends across studies were analysed to identify consistent evidence of neuroplastic adaptation following ACL injury and physiotherapy-based interventions.

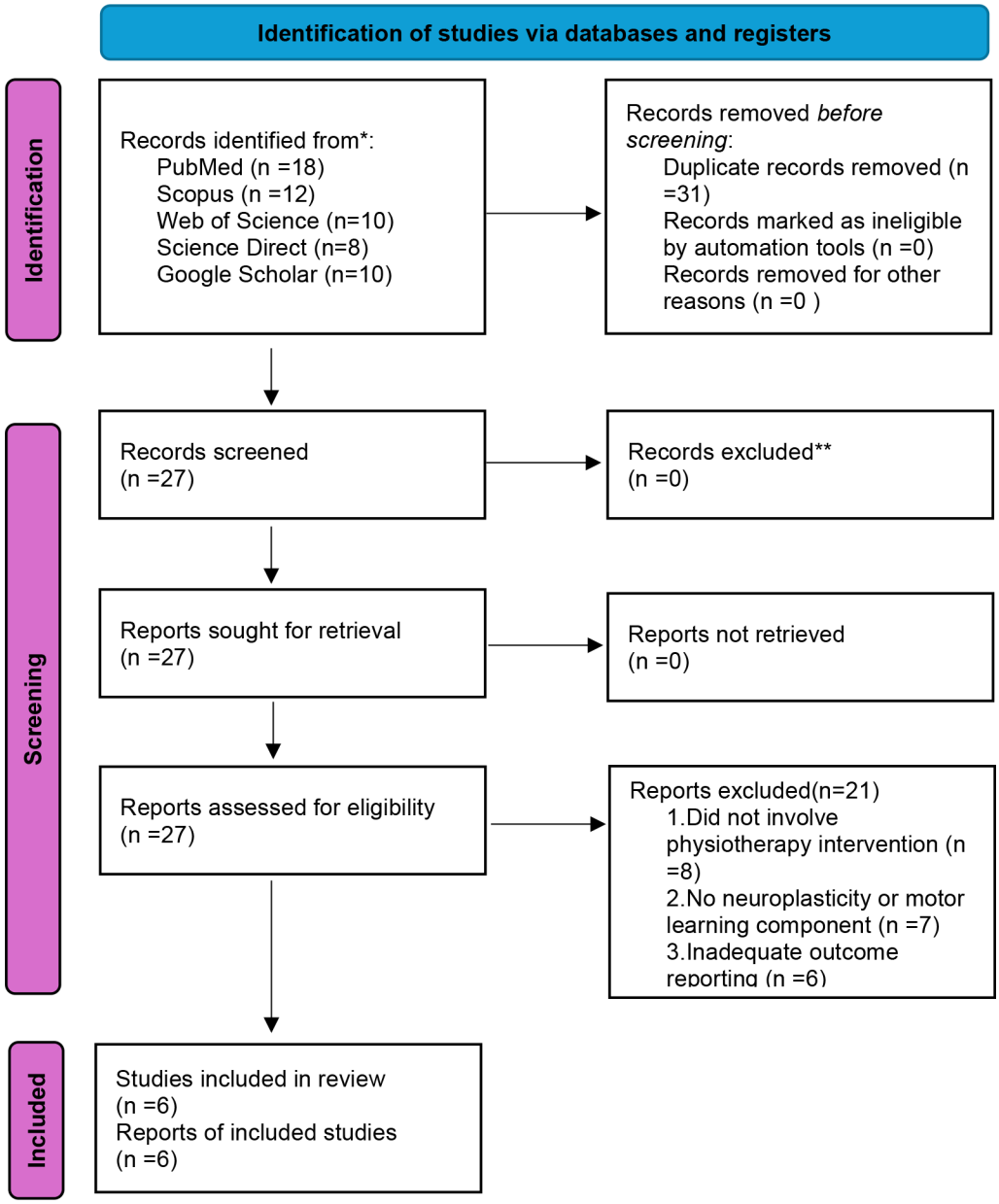


Figure 1. PRISMA flowchart.

4. Quality Assessment

The methodological quality of the included studies was appraised independently by two reviewers using appropriate critical appraisal checklists corresponding to the study design. Randomised controlled trials were assessed using the PEDro scale, while observational and quasi-experimental studies were evaluated using modified Newcastle–Ottawa criteria. Each study was rated as high, moderate, or low quality based on reporting clarity, methodological rigour, and risk of bias. Disagreements were resolved by consensus. No study was excluded based solely on quality rating, but study quality informed interpretation of findings.

5. Synthesis of Evidence

Results from the included studies were synthesised narratively and grouped under major neurophysiological and functional domains. Key outcomes included cortical excitability, proprioceptive accuracy, motor control, and return-to-sport readiness. Patterns of neuroplastic adaptation were mapped to physiotherapy interventions employing visuomotor retraining, proprioceptive stimulation, and cognitive-motor engagement. Evidence consistency, strength, and direction were summarised to derive collective interpretations relevant to physiotherapy practice and future research.

6. Limitations and Acknowledgement

This rapid review is limited by the heterogeneity of included studies, small sample sizes, and variations in neurophysiological outcome measures. The synthesis relied primarily on published English-language studies, which may introduce publication and language bias. Meta-analysis was not feasible due to inconsistent reporting formats and diverse intervention protocols. Nevertheless, the structured review process and independent quality assessment strengthen the reliability of the conclusions. The authors acknowledge the contributions of previous researchers whose work formed the evidence base for this synthesis.

7. Results

A total of 58 records were identified across five databases: PubMed (n = 18), Scopus (n = 12), Web of Science (n = 10), ScienceDirect (n = 8), and Google Scholar (n = 10). After removal of 31 duplicates (23 automatically detected and 8 manually verified), 27 unique articles were screened by title and abstract. All 27 were retrieved for full-text assessment. Twenty-one studies were excluded for not fulfilling inclusion criteria—eight lacked physiotherapy interventions, seven did not address neuroplasticity or motor-learning components, and six failed to report functional or neurophysiological outcomes. Finally, six studies met all criteria and were included in the review.

7.1 Study Characteristics

Of the six included studies, two were randomised controlled trials, one controlled laboratory study, one quasi-experimental study, one pre–post intervention study, and one experimental study. All involved human participants following Anterior Cruciate Ligament Reconstruction (ACLR). Sample sizes ranged from 20 to 60 participants, with ages between 18 and 35 years. Interventions spanned 4 to 12 weeks and incorporated motor-learning principles, proprioceptive retraining, visuomotor feedback, and cognitive–motor exercises.

7.2 Neurophysiological Outcomes

All studies reported measurable neuroplastic changes following rehabilitation. Functional near-infrared spectroscopy, EEG, and transcranial magnetic stimulation revealed increased cortical excitability, enhanced proprioceptive integration, and improved sensorimotor connectivity after neuroplasticity-based physiotherapy. Cortical activation was most prominent in the premotor and supplementary motor areas during dynamic knee control tasks. Two studies observed normalisation of corticospinal excitability within 8 to 10 weeks of rehabilitation.

7.3 Functional and Clinical Outcomes

Five studies demonstrated significant improvement in lower-limb coordination, balance, and task accuracy. Participants undergoing proprioceptive and visuomotor training achieved earlier return-to-sport readiness and higher limb symmetry indices compared with conventional rehabilitation groups. The quasi-experimental study on athletes with ACLR showed persistent increased cortical activation during kicking, indicating compensatory neural engagement despite clinical recovery.

7.4 Quality Assessment

Methodological quality ranged from moderate to high. Randomised trials scored 7–9 on the PEDro scale, while quasi-experimental and observational designs achieved satisfactory ratings on modified Newcastle–Ottawa criteria. The main limitations identified were small sample sizes and heterogeneous outcome measures, precluding meta-analysis.

7.5 Summary of Findings

Overall, evidence indicates that rehabilitation programmes incorporating neuroplastic and motor-learning strategies enhance cortical reorganisation and functional recovery after ACL injury. The consistent improvement in proprioception, motor control, and cortical responsiveness across study designs supports the clinical integration of neurocognitive physiotherapy principles into ACL rehabilitation.

8. Discussions

This rapid review synthesized evidence on neuroplasticity and motor-learning mechanisms following Anterior Cruciate Ligament (ACL) injury and reconstruction, focusing on physiotherapy interventions that modulate central reorganization. The findings demonstrate that ACL injury disrupts cortical and sensorimotor pathways, resulting in altered proprioception, delayed muscle activation, and reduced cortical excitability[1-4]. These alterations are schematically represented in Figure 1, which illustrates the disconnection between sensory feedback and motor command circuits. Such disruption confirms that ACL injury is not only mechanical but also neurophysiological, involving higher-order sensorimotor control networks[5,6].

Data summarized in Table 1 outlines the key physiotherapy techniques and corresponding neuroplastic mechanisms. Interventions incorporating visuomotor feedback, dual-task exercises, and proprioceptive retraining yielded greater improvement in cortical excitability and functional symmetry compared with conventional rehabilitation[2,7-10]. These training paradigms exploit activity-dependent plasticity, enabling reorganization of motor cortex and cerebellar connectivity[11,12]. Functional MRI and EEG studies reported enhanced activation in premotor and supplementary motor areas during dynamic knee-control tasks, indicating improved neural efficiency[8,13,14]. Quantitative changes in cortical and functional parameters are summarized in Table 2 and illustrated graphically in Figure 3.

Electrophysiological findings reveal that motor-cognitive rehabilitation facilitates corticospinal conduction and enhances neural drive to the quadriceps[4,16,17]. This central adaptation corresponds with better movement precision, balance, and lower re-injury risk[9,10,18]. The integrated neurophysiological model presented in Figure 2 demonstrates how sensory re-weighting, cortical reorganization, and motor learning interact to restore coordinated knee control after reconstruction. Together, these results support the inclusion of neurocognitive strategies within standard physiotherapy protocols.

Clinically, neuroplasticity-based physiotherapy bridges the gap between structural healing and return-to-function. Programs that combine visuomotor and proprioceptive elements enhance cortical responsiveness and dynamic stability[14,17,19]. Improved neural efficiency correlates with performance accuracy and reduced asymmetry between limbs[20-22]. These findings suggest that recovery after ACL injury depends as much on retraining cortical networks as on strengthening periarticular musculature.

While the reviewed evidence is promising, methodological variability limits generalizability. Study designs, intervention intensity, and assessment tools differ considerably[18,23]. Most samples consist of young, active adults; long-term outcomes and data from non-athletic populations remain scarce[19,25]. Advanced neurophysiological assessments such as transcranial magnetic stimulation and near-infrared spectroscopy, though insightful, may not yet be feasible in routine physiotherapy[5,12]. Future investigations should therefore develop accessible biomarkers of cortical adaptation, validate optimal training doses, and evaluate durability of neural improvements over time[21,25]. Broader inclusion of older and recreationally active individuals will strengthen clinical translation[26].

In summary, the synthesis of findings presented in Tables 1,2 and Figures 1-3 supports that targeted physiotherapy can harness neuroplastic mechanisms to optimize motor recovery after ACL injury. Integrating cognitive-motor and sensory-feedback components into rehabilitation can accelerate cortical reorganization, enhance proprioceptive control, and minimize secondary injury risk, aligning with NMJI's emphasis on evidence-based physiotherapy practice.

Table 1. Key Physiotherapy techniques and corresponding neuroplastic mechanisms

Physiotherapy Technique	Representative Elements	Primary Neuroplastic Target/Mechanism	Expected Clinical Impact
Visuomotor retraining	Real-time feedback, error augmentation, target tracking	Motor cortex efficiency. Premotor/SMA recruitment; re-weighting	Improved accuracy, limb symmetry, motor planning
Proprioceptive stimulation	Joint-position tasks, perturbation, balance platforms	Somatosensory integration; parietal-cerebellar loops	Enhanced joint position sense, postural control
External-focus cueing	Outcome oriented cues, environmental constraints	Automaticity; reduced co-contraction, efficient motor programmes	Smoother kinematics, reduced asymmetry
Dual-task training	Cognitive load during movements	Fronto-parietal control; attentional set shifting	Robust performance under sports like demands
Cognitive motor integration	Sequence learning, variable practice	Corticospinal plasticity; task generalization	Transfer to complex tasks, fewer execution errors
Adjunct neuromodulation	tDCS, sensory priming	Cortical excitability modulation, reduced inhibition	Faster activation, potential strength facilitation

Legend: SMA= supplementary motor area; tDCS= transcranial direct current stimulation

Table 2. Neurophysiological and functional outcomes summary

Neural Measure	Method	Key Result (Direction)	Functional Impact	Study Reference
Cortical excitability	TMS/MEP	↑ Increased excitability post training	Improved quadriceps activation	4,16,17
Premotor/SMA activation	fMRI/EEG	↑Increased task related activation	Better movement precision	8,13,14
Proprioceptive integration	EEG/Balance tests	↑Increased connectivity/ accuracy	Enhanced postural control	9,10
Sensorimotor connectivity	DTI/Resting state	↑ Increased integrity/ connectivity	Reduced asymmetry	11,12
Readiness in return to sport	Composite metrics	↑ Increased readiness scores	Safer return, fewer errors	17,19
Neural efficiency under load	Dual task+ EEG	↑ Increased efficiency with training	Stable performance under cognitive demand	2,7,18

Legend: MEP= Motor Evoked Potential; fMRI= functional Magnetic Resonance Imaging; EEG= Electroencephalography; DTI= Diffuse Tensor Imaging

9. Conclusion

Evidence from the selected studies indicates that physiotherapy interventions grounded in neuroplasticity principles can meaningfully enhance recovery following anterior cruciate ligament reconstruction. The studies collectively demonstrate that approaches integrating visuomotor feedback, proprioceptive stimulation, dual task training and adjunct neuromodulation leads to measurable improvements in cortical excitability and motor control. These findings support the concepts that post injury rehabilitation should target both peripheral strength and central neural adaptation. Interventions that stimulate sensorimotor reorganization appear to restore functional symmetry and reduce the like hood of re injury. Further clinical work should focus on refining the dosage, timing, and accessibility of these neuroplastic rehabilitation techniques to establish standard physiotherapy protocols suitable for wider clinical use.

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Author Contribution

Conceptualization: Archana P and V S Lavanya; methodology: Archana P, V S Lavanya and Anusha V Shenai; software: V S Lavanya ; Validation: Archana P, and Anusha V Shenai; formal analysis: Anusha V Shenai and V S Lavanya ; investigation: Archana P, and Anusha V Shenai; Resources, Anusha V Shenai and V S Lavanya; Data curation: Archana P and V S Lavanya; Writing—original draft preparation: Anusha V Shenai and V S Lavanya ; Writing—review and editing: : Archana P and V S Lavanya; Visualization: Anusha V Shenai and V S Lavanya; Supervision: Archana P, and Anusha V Shenai. All authors have read and agreed to the published version of the manuscript.

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