



Case Report

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Sequential Brain-Computer Interface Training Combining SSVEP-Triggered Robotic Exoskeleton and Motor Imagery for Early Paraplegia Rehabilitation Following Spinal Cord Ependymoma Resection: A Case Report and Literature Review

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To Cite This article: Xiangzhu Li, Rui Zhang, Guangmou Cai, Qin Zhang, Xiaoyu Yang, Yuhao Liu, Haojian Mai, Huaxiao Li, Qihui Zhang, Cibo Huang and Li Zhang*, Sequential Brain-Computer Interface Training Combining SSVEP-Triggered Robotic Exoskeleton and Motor Imagery for Early Paraplegia Rehabilitation Following Spinal Cord Ependymoma Resection: A Case Report and Literature Review. *Am J Biomed Sci & Res.* 2026 32(3) AJBSR.MS.ID.004170,

DOI: [10.34297/AJBSR.2026.32.004170](https://doi.org/10.34297/AJBSR.2026.32.004170)

Received: 📅 October 09, 2026 Published: 📅 October 14, 2026

Abstract

Background: Spinal cord ependymomas are the most common intramedullary tumors in adults, accounting for 30–40% of primary spinal cord neoplasms. Despite gross total resection (GTR), up to 60% of patients experience significant postoperative neurological deficits, severely impacting quality of life. Brain-Computer Interface (BCI) technology has emerged as a promising neurorehabilitation tool. However, most existing BCI paradigms rely on either steady-state visual evoked potentials (SSVEP), which lack active patient participation, or motor imagery (MI), which suffers from “BCI illiteracy” and low reliability. A sequential training protocol combining the strengths of both modalities may offer a more pragmatic and effective clinical approach.

Case Presentation: A 33-year-old male presented with progressive thoracic numbness and lower limb weakness. MRI revealed a C7–T5 intramedullary enhancing mass with extensive syringomyelia. He underwent GTR of a cellular ependymoma (WHO grade II, SP-EPN subtype, MYCN non-amplified) under intraoperative neurophysiological monitoring. Postoperatively, he developed chronic paraplegia (T4 sensory level; right lower limb strength 1/5, left 2/5). After 2.5 months of conventional rehabilitation that yielded only minimal improvement (right 2/5, left 2/5), he received 78 days of inpatient sequential BCI training. The protocol consisted of two daily 30-minute stages: (1) an initial SSVEP-based stage using peripheral field high-frequency stimulation (34 Hz left, 35 Hz right) to directly control a lower-limb robotic exoskeleton; followed by (2) a subsequent motor imagery stage to reinforce active cortical participation. Following training, right lower limb strength improved to 4/5 (left lower limb 5/5), enabling assisted standing and stepping. No adverse events, including visual fatigue, occurred.

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Discussion: This is the first report of a sequential BCI training protocol applied in the early post-surgical phase (2.5 months) for spinal ependymoma-induced paraplegia. Unlike synchronous hybrid BCIs that require simultaneous processing of multiple mental tasks, our sequential approach reduces cognitive load, first establishing reliable brain-robot control (SSVEP) to boost patient engagement and self-efficacy, then transitioning to active MI training to maximize Hebbian plasticity. The favorable molecular profile (SP-EPN without MYCN amplification) provided an optimal substrate for neuroplasticity. Early intervention within the subacute plasticity window likely contributed to the favorable outcome.

Conclusion: Sequential BCI training combining SSVEP-triggered robotic exoskeleton with subsequent motor imagery is a feasible, comfortable, and effective early intervention for improving lower limb function after spinal cord ependymoma resection. This patient-centered, two-stage paradigm addresses key limitations of unimodal BCI and holds promise for wider application in neuro-oncology rehabilitation. Larger trials are warranted.

Introduction

Spinal cord ependymomas are rare neuroepithelial tumors originating from ependymal cells lining the central canal of the spinal cord [1]. They constitute the most common intramedullary tumors in adults, representing approximately 30–40% of primary spinal cord neoplasms, with an incidence of <1 per 100,000 population [2,3]. The mean age at diagnosis is approximately 41 years, with no significant gender predilection [4]. The most frequent locations are the cervical and thoracic spinal regions, which together account for over 80% of cases [5,6].

The 2021 World Health Organization (WHO) classification of central nervous system tumors has refined the molecular subtyping of spinal ependymomas, distinguishing spinal ependymoma (SP-EPN) from the rare but aggressive spinal ependymoma with MYCN amplification (SP-MYCN) [7]. SP-MYCN carries a markedly worse prognosis, with recurrence rates of 75–100% and median overall survival of 87 months compared with 180 months for SP-EPN [8,9]. Accurate molecular characterization therefore has important prognostic implications and may influence rehabilitation strategies by identifying patients with longer therapeutic windows. Despite being slow-growing and associated with relatively favorable prognosis, spinal cord ependymomas pose substantial clinical challenges. Gross Total Resection (GTR) is the treatment of choice and is associated with significantly improved Progression-Free Survival (PFS), with 5-year rates reaching 82.6% compared with 41.9% after subtotal resection [10,11]. However, the intimate relationship between tumor and functional spinal cord tissue necessitates surgical manipulation that carries a high risk of neurological compromise. Postoperative neurological deficits

are common, with up to 60% of patients experiencing new or worsened motor, sensory, or autonomic dysfunction [12,13]. These deficits profoundly impact quality of life, independence, and social participation [14].

Brain-Computer Interface (BCI) technology has emerged as a promising tool for neurorehabilitation, translating motor intention into real-time control of external devices [15,16]. Among non-invasive BCI paradigms, Steady-State Visual Evoked Potential (SSVEP)-based BCI offers high signal-to-noise ratio and requires minimal training, making it highly reliable for controlling external devices [17,18]. *Guo et al.* (2022) developed an SSVEP-BCI-controlled soft robotic hand rehabilitation system and demonstrated significant improvement in upper limb function in stroke patients [19]. However, SSVEP exhibits relatively weak correlation with the patient's active motor intention, as it relies on passive visual attention rather than voluntary motor imagery [20,21]. In contrast, Motor Imagery (MI)-based BCI directly engages the patient's active intention and has been shown to promote neuroplasticity and motor recovery [22,23]. *Ma et al.* (2024) demonstrated that MI-BCI rehabilitation combined with conventional therapy significantly improved upper limb motor function in stroke patients, with fMRI confirming enhanced cortical activation [24]. *Wang et al.* (2024) reported in a multicenter randomized controlled trial that MI-BCI training produced significantly greater improvements in Fugl-Meyer Assessment for Upper Extremity scores compared to conventional therapy, with sustained benefits at three-month follow-up [25]. Despite these promising outcomes, MI-BCI faces major implementation challenges: approximately 15–30% of users cannot achieve reliable control—a phenomenon termed “BCI illiteracy”—and it requires prolonged training to obtain stable signal

features [26,27,28]. This is particularly problematic for severely impaired patients who may lack the cognitive reserve or motivation for extended training.

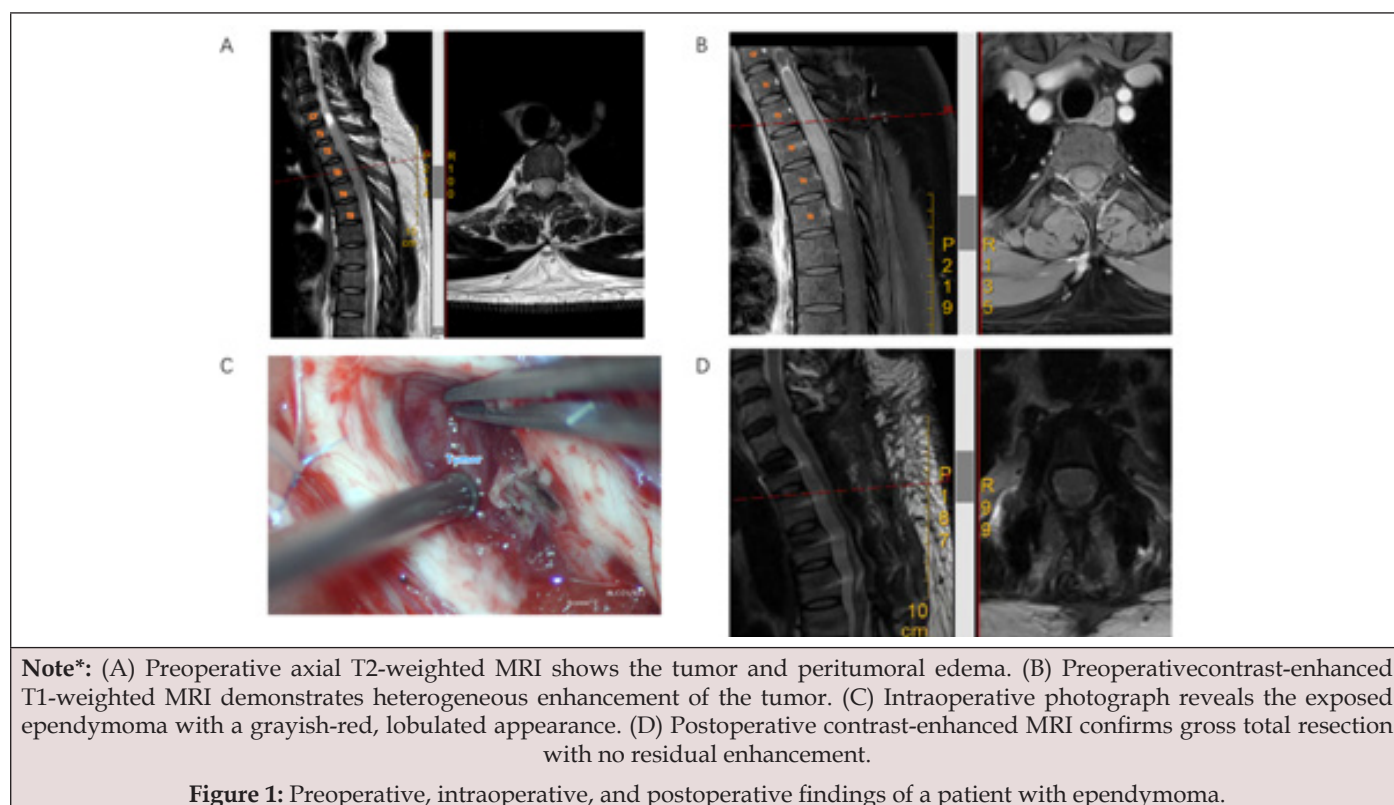
To address these limitations, researchers have proposed hybrid BCI systems that integrate MI and SSVEP simultaneously [29,30]. *Chi et al.* (2022) developed a synchronous hybrid paradigm that achieved 89% accuracy compared to 84% for MI alone and 80.75% for SSVEP alone [31]. However, such synchronous hybrid BCIs require the patient to concurrently process multiple mental tasks, which can be cognitively demanding, especially for patients with neurological injuries or fatigue. This high cognitive load may reduce compliance and real-world applicability [32,33]. A critical but often overlooked factor in BCI design is user comfort. Traditional SSVEP stimuli employ high-contrast, centrally presented flickering stimuli that can cause visual fatigue, drowsiness, and headaches, leading to reduced attention and diminished BCI performance [34,35]. *Lee et al.* (2018) demonstrated that peripheral visual field stimulation can maintain signal recognition accuracy (central: 99%; peripheral: 96.3%) while causing significantly less visual fatigue [36]. *Zhao et al.* (2021) further validated that peripheral stimulation encoding could effectively alleviate visual fatigue while maintaining system feasibility [37]. *Zhang et al.* (2024) recently developed a peripheral field SSVEP stimulation paradigm at 34 Hz and 35 Hz, achieving $97.12 \pm 2.09\%$ online classification accuracy with high user comfort scores (5.36 ± 0.15 on a 6-point scale) [38]. The use of high-frequency stimulation (>30 Hz) also minimizes the risk of photosensitive epilepsy [39,40].

Given these considerations, we hypothesized that a sequential BCI training protocol-separating the high-reliability, low-effort SSVEP control stage from the subsequent, active MI training stage-might offer a more pragmatic and patient-centered approach. This design first establishes a successful brain-robot connection, boosting patient engagement and self-efficacy, then transitions to MI training to maximize Hebbian plasticity. The timing of BCI intervention is also critical. In spinal cord injury, the subacute phase (first 3–6 months after injury) is characterized by heightened neuroplasticity, with increased synaptic receptivity, axonal sprouting, and perilesional reorganization [41,42]. Early application of BCI within this window could optimize recovery. Herein, we report a case of a 33-year-old male who underwent sequential BCI training beginning 2.5 months after resection of a cervical-thoracic spinal cord ependymoma, achieving significant functional improvement. This work was reported in compliance with the SCARE criteria [43].

Case Presentation

Patient History and Initial Presentation

A 33-year-old male with a history of hypertension presented in July 2025 with progressive thoracic numbness for three months and worsening bilateral lower limb weakness for one week. Magnetic Resonance Imaging (MRI) on July 19, 2025, showed a C7–T5 intramedullary cystic lesion with extensive syringomyelia (Fig. 1A). Contrast-enhanced MRI on July 20, 2025, demonstrated a 107×7 mm fusiform mass with marked enhancement, highly suggestive of ependymoma (Figure 1).

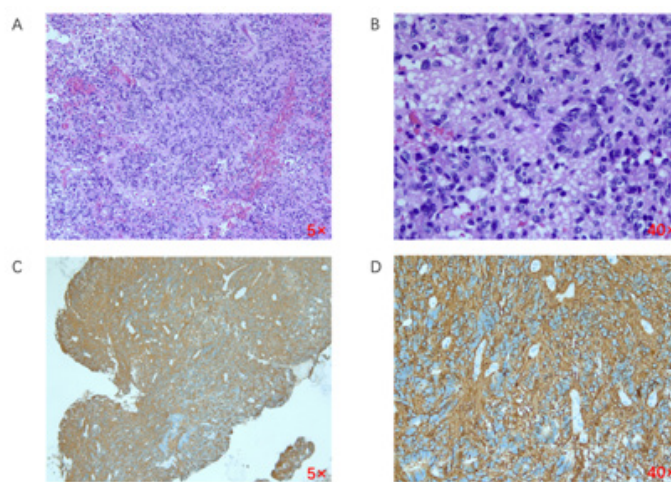


Surgical and Pathological Findings

On July 28, 2025, the patient underwent GTR of the tumor under general anesthesia with Intraoperative Neurophysiological Monitoring (IONM). Anesthesia was maintained with total intravenous anesthesia (propofol and remifentanyl), with a single dose of rocuronium for intubation only, to preserve neurophysiological signal integrity [44]. Baseline Somatosensory-Evoked Potentials (SSEPs) and Motor-Evoked Potentials (MEPs) were recorded before incision and continuously monitored throughout the procedure. Alarm thresholds were set at $\geq 50\%$ SSEP amplitude reduction or $\geq 80\%$ MEP amplitude reduction [45]. No significant signal changes occurred during surgery.

A posterior midline approach from C6 to T4 with laminoplasty and C6–T5 pedicle screw fixation was performed. After durotomy, a reddish, well-circumscribed intramedullary tumor was

identified (Fig. 1C). Using microsurgical technique and continuous IONM, the tumor was completely excised. Intraoperative frozen section suggested ependymoma. Final histopathological examination revealed a cellular tumor composed of ependymal cells with perivascular pseudorosettes and true ependymal rosettes (Fig. 2). Individual tumor cells exhibited round to oval nuclei, fine chromatin, and fibrillary processes. Mitotic figures were rare. Immunohistochemical staining was positive for GFAP (diffuse cytoplasmic), S100 (nuclear and cytoplasmic), and vimentin, with focal positivity for CK. The tumor was negative for EMA, Syn, CgA, and BRAF. The Ki67 proliferation index was 1%+. MYCN amplification was not detected by Fluorescence in Situ Hybridization (FISH). The final pathological diagnosis was cellular ependymoma (WHO grade II), consistent with the Spinal Ependymoma (SP-EPN) molecular subtype [7,46] (Figure 2).



Note*: (A) H&E staining ($\times 5$) demonstrates perivascular pseudorosettes (arrowheads), a diagnostic feature of ependymoma, with tumor cells radially arranged around vessels and separated by an anuclear zone of fibrillary processes. (B) Higher magnification ($\times 40$) shows a true ependymal rosette (arrow). Tumor cells have round-to-oval nuclei, fine chromatin, and scant eosinophilic cytoplasm. Mitoses are rare.

(C) GFAP immunohistochemistry ($\times 5$) reveals strong, diffuse cytoplasmic staining, confirming glial differentiation. (D) S100 protein ($\times 5$) is diffusely positive in both nuclei and cytoplasm, a consistent immunophenotype of ependymoma. Ki-67 immunostaining ($\times 40$) shows a labeling index of approximately 1%, indicating very low proliferative activity (WHO grade II). Fluorescence in situ hybridization for MYCN demonstrates no amplification (red/green signal ratio < 2), classifying the tumor as spinal ependymoma (SP-EPN) subtype and excluding the aggressive SP-MYCN variant.

Figure 2: Histopathological and immunohistochemical features of the spinal cord ependymoma.

Postoperative Course and Initial Rehabilitation

Postoperatively, the patient developed paraplegia with a sensory level at T4 (right lower limb strength 1/5, left 2/5). He was discharged on August 13, 2025, after initial inpatient rehabilitation. He then underwent two months of external conventional rehabilitation (passive and active-assisted range-of-motion exercises, muscle strengthening, and balance training) which yielded only minimal improvement: by early October 2025, his right lower limb strength had improved to 2/5, left to 2/5, but he remained unable to walk independently. A follow-up MRI (December 1, 2025) showed complete resection without residual enhancement (Fig. 1D).

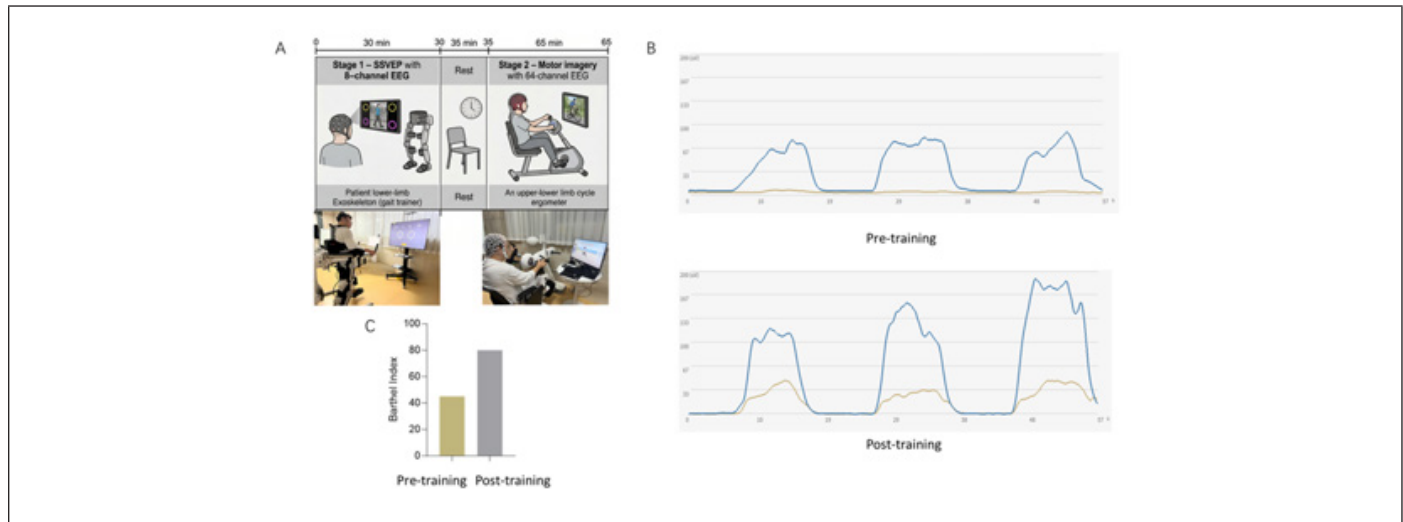
Sequential BCI Rehabilitation Protocol

Given the suboptimal recovery, the patient was readmitted to our center on October 14, 2025, for BCI-based rehabilitation - approximately 2.5 months after surgery, still within the subacute plasticity window. He underwent an intensive 78-day inpatient rehabilitation program (October 14 to December 31, 2025) comprising daily sequential BCI training. The BCI system comprised a 64-channel EEG cap (XY-K-WXND-VII, Sunnyou) with electrodes placed according to the international 10–10 system. For SSVEP signal acquisition, nine occipital channels were used (Pz, PO5, PO3, POz, PO4, PO6, O1, Oz, O2). For MI signal acquisition, 22 channels over sensorimotor areas (FC3, FC1, FCz, FC2, FC4, C3, C1, Cz, C2, C4,

CP3, CP1, CPz, CP2, CP4, P5, P3, P1, Pz, P2, P4, P6) were used, with Pz shared between both modalities [38].

Training was conducted daily in two sequential stages, each

lasting 30 minutes, for a total of 60 minutes per day, with a 5-minute rest between stages (Figure 3).



Note*: (A) Schematic flowchart of the sequential BCI training protocol. The daily 65-minute protocol consisted of two sequential stages separated by a 5-min rest. Stage 1 (SSVEP-driven, 30 min): The patient wore an 8-channel EEG cap (occipital electrodes) and viewed a screen displaying a central walking video with peripheral rings flickering at 34 Hz (left) and 35 Hz (right). Decoded SSVEP signals directly triggered a lower-limb robotic exoskeleton (gait trainer), providing immediate proprioceptive feedback. Stage 2 (MI-driven, 30 min): The patient then wore a 64-channel EEG cap and used an upper-lower limb rehabilitation cycle ergometer. While watching a pedaling video, the patient performed kinesthetic motor imagery of pedaling. Decoded MI signals (μ/β rhythm desynchronization) controlled the resistance or speed of the ergometer. This sequential design allowed progressive training from passive, high-reliability control to active, imagery-based control. (B) Surface electromyography (sEMG) of lower limb muscles before and after training. Representative sEMG recordings from the right Tibialis Anterior (TA) and gastrocnemius (GAS) during voluntary ankle dorsiflexion and plantarflexion attempts. Pre-training (up): minimal or absent EMG activity with low amplitude and irregular bursts, indicating poor voluntary motor drive. Post-training (down): markedly increased EMG amplitude, well-defined burst patterns, and reduced onset latency, reflecting improved corticospinal excitability and neuromuscular recruitment. (Scale bars: horizontal 200 ms, vertical 100 μ V.) (C) Barthel Index scores before and after sequential BCI training. The Barthel Index improved from 45/100 at baseline (pre-training) to 80/100 after 78 days of training. The most notable gains occurred in the transfer (5 $\rightarrow$ 15), mobility/walking (0 $\rightarrow$ 15), and toilet use (5 $\rightarrow$ 10) subscores, reflecting the patient's regained ability to stand, transfer with a cane, and walk independently. These improvements are consistent with the observed clinical transition from bedridden status to community ambulation with a cane.

Figure 3: Sequential BCI training protocol and functional outcomes.

Stage 1: SSVEP-Driven Robotic Gait Training (First 30 minutes)

Following the paradigm validated by Zhang *et al.* (2024) [38] and Zhao *et al.* (2021) [37], a peripheral field SSVEP stimulation interface was presented on a computer screen with a refresh rate of 120 Hz and resolution of 1920 $\times$ 1080 pixels. On both sides of the screen, two videos were displayed symmetrically, each with a size of 304 $\times$ 304 pixels, showing left and right lower limb stepping motions to guide attention. Flicker stimuli were presented on the outside of each video, with an inner eccentricity of 7° and an outer eccentricity of 10°. The outer ring of each video flickered simultaneously at specific stimulus frequencies (left: 34 Hz; right: 35 Hz) using the sampled sinusoidal method [47]. The patient was seated comfortably 50 cm from the screen and instructed to gaze at the central motion video. The system decoded his SSVEP signals in real time, which were used to directly trigger and control a lower-limb robotic exoskeleton (Sunnyou). The goal of this stage

was to establish a reliable, fatigue-resistant brain-robot closed loop, providing immediate positive visual and proprioceptive feedback. This approach capitalizes on the high signal-to-noise ratio and minimal training requirement of SSVEP, ensuring that even severely impaired patients can achieve successful control early in the rehabilitation process [17,36].

Stage 2: Motor Imagery Training with Robotic Assistance (Second 30 minutes)

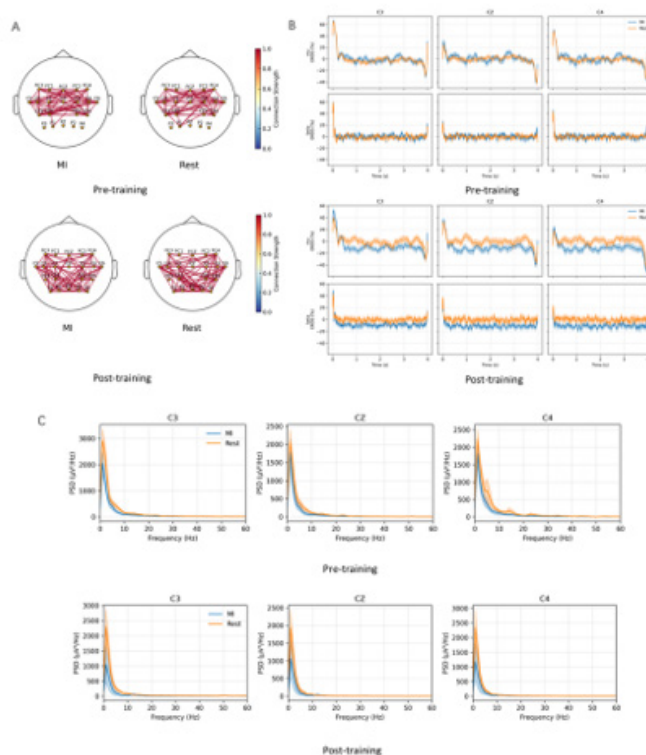
Following a 5-minute rest, the patient proceeded to the MI stage. The SSVEP stimuli were turned off, and the screen displayed only the central motion video. The patient was instructed to perform kinesthetic motor imagery of stepping - imagining the sensation of placing one foot in front of the other. The system decoded MI-related event-related desynchronization (ERD) of μ (8–12 Hz) and β (15–20 Hz) rhythms in real time using the Filter Bank Common Spatial Pattern (FBCSP) algorithm and a support vector machine classifier [38,48]. The decoded intention was

used to guide the upper-lower limb rehabilitation cycle ergometer (Sunnyou), promoting active cortical participation and Hebbian plasticity [49,50]. A neurophysiologist was present throughout all sessions to monitor signal quality and provide real-time feedback adjustment [44]. Training was conducted daily for 78 days (total 78 sessions).

Outcome

After 78 days of sequential BCI training, the patient showed significant functional improvement: Right lower limb strength improved from 2/5 to 4/5 on the MRC scale, and left lower limb strength improved from 2/5 to 5/5. Knee and ankle joint mobility increased, enabling assisted standing and stepping with the exoskeleton; Sensory level remained at L1, with stable light touch and proprioception; No adverse events occurred, including no seizures, visual fatigue, skin breakdown, or falls; The patient reported high comfort with the peripheral field stimulation, consistent with previously published comfort scores [36,37,38]. Neurophysiologically, EEG analysis before and after training revealed significant training-induced plasticity within the motor

imagery networks (Fig. 4). Specifically, post-training functional connectivity, as measured by Phase Locking Value (PLV), was markedly strengthened within the sensorimotor network (e.g., C3-C4, C3-FCz, C4-CPz) during the MI task compared with baseline (Fig. 4A). Time-frequency analysis demonstrated that Event-Related Desynchronization (ERD) in the mu (8–12 Hz) and beta (15–20 Hz) bands became substantially stronger and more sustained during MI, shifting from patchy, low-amplitude ERD to robust, sustained ERD (Fig. 4B). Additionally, Power Spectral Density (PSD) analyses showed a distinct separation between the resting state and MI task in the mu/beta bands post-training, reflecting enhanced task-specific cortical activation (Fig. 4C). These neurophysiological findings indicate that the sequential BCI protocol successfully induced Hebbian plasticity and functional reorganization within the corticomotor pathways. He was discharged on December 31, 2025, to community-based maintenance training with a home exercise program. At the time of this report, the patient continues to perform daily home BCI sessions and has maintained his functional gains (Figure 4).



Note*: (A) Functional connectivity (phase locking value, PLV). Pre-training (left): during MI, connectivity between C3/C4 and other sensorimotor areas was low and not significantly different from rest. Post-training (right): significant strengthening of connectivity within the sensorimotor network (e.g., C3-C4, C3-FCz, C4-CPz) during MI, indicating more efficient information transfer and cortical reorganization. (B) ERDS time-frequency plots (C3, time-frequency representation). Before training: small, patchy ERD (-5% to -10%) lasting about 1-2 seconds. After training: strong, sustained ERD (-20% to -35%) from 0.5 to 5 seconds post-cue, particularly in mu (8-12 Hz) and lower beta (15-20 Hz) ranges. This pattern is consistent with improved motor imagery proficiency and Hebbian plasticity induced by sequential BCI training. (C) Power spectral density at C3 (left hemisphere) and C4 (right hemisphere). Blue line: resting state; red line: motor imagery. Pre-training: minimal separation between rest and MI in mu/beta bands. Post-training: marked power decrease (ERD) during MI in both mu and beta bands, with a larger rest-MI difference, reflecting enhanced task-specific cortical activation.

Figure 4: Training-induced plasticity in motor imagery networks: EEG evidence.

Discussion

Spinal Cord Ependymoma: Epidemiology, Pathophysiology, and Clinical Impact

Spinal cord ependymomas are the most common intramedullary tumors in adults, with an incidence of approximately 5 per 1,000,000 population [1,51]. The cellular subtype (WHO grade II) accounts for approximately 50–60% of spinal ependymomas and typically exhibits indolent behavior [2,52]. In this case, the patient's tumor demonstrated classic ependymoma histology with perivascular pseudorosettes, GFAP and S100 positivity, and a low Ki67 index (1%+), consistent with SP-EPN. The absence of MYCN amplification distinguishes this case from the aggressive SP-MYCN subtype, which carries recurrence rates of 75–100% and median overall survival of only 87 months [8,9,53]. SP-EPN carries a favorable prognosis, with median progression-free survival of 82 months and overall survival of 180 months [54,55].

The location of this patient's tumor (C7–T5) is consistent with the most common presentation of spinal ependymomas, which typically involve the cervical and thoracic regions [5,6]. Thoracic tumor location has been identified as an independent predictor of poorer postoperative functional recovery (hazard ratio 4.7; 95% CI 1.25–17.44; $p = 0.022$), which may have contributed to the severity of postoperative deficits [10]. Despite gross total resection, neurological deficits are common after spinal cord ependymoma surgery. In the cohort study by *Hernandez-Hernandez et al.*, 89.1% of patients experienced some degree of residual neurological deficit postoperatively, with motor weakness persisting in 76.4% [10]. These deficits profoundly affect quality of life, independence, and social participation [14].

Rationale for Sequential BCI Training: A Patient-Centered Approach

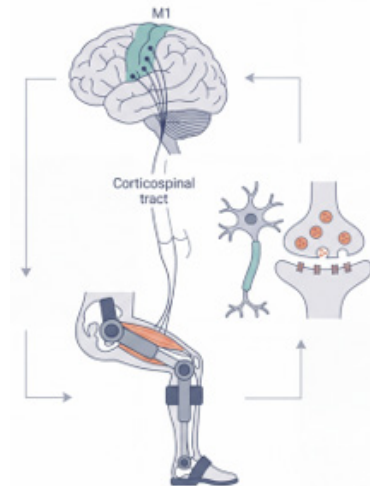
The sequential BCI protocol employed in this case addresses several limitations of both unimodal and synchronous hybrid BCI systems. Addressing “BCI Illiteracy” and Cognitive Load. MI-BCI alone is challenged by BCI illiteracy (15–30% of users cannot achieve reliable control) and requires prolonged training to obtain stable signal features [26,28,56]. Synchronous hybrid BCIs that combine MI and SSVEP simultaneously can achieve high accuracy, but they require the patient to concurrently process multiple mental tasks, which can be cognitively demanding [31,32]. This is particularly problematic for patients with neurological injuries, fatigue, or reduced attention span. Our sequential protocol reduces cognitive load by separating the two tasks in time. In Stage 1, the patient only needs to gaze at the motion video; the SSVEP control is largely passive and requires minimal mental effort. This immediately establishes a successful brain-robot connection, which likely enhances self-efficacy and motivation [57,58]. In Stage 2, the patient can focus exclusively on motor imagery without the distraction of flickering peripheral stimuli.

Peripheral Field Stimulation Reduces Visual Fatigue. A critical innovation in our protocol is the use of peripheral field SSVEP stimulation. *Lee, et al.*, (2018) demonstrated that peripheral

stimulation maintains high accuracy (96.3% vs. 99% central) while causing significantly less visual fatigue [36]. *Zhao et al.* (2021) further validated that peripheral encoding alleviates discomfort [37]. Our patient tolerated 78 daily sessions without any reported visual fatigue or discomfort, confirming the long-term feasibility of this design. The use of high-frequency stimulation (34/35 Hz) also minimizes the risk of photosensitive epilepsy, as frequencies below 30 Hz are more likely to induce seizures [39,40]. Sequential Protocol Aligns with Motor Learning Principles. Our two-stage design aligns well with established principles of motor learning, which advocate for a progression from guided, high-fidelity feedback to autonomous, internalized rehearsal [59,60]. Stage 1 provides the patient with clear, immediate, and reliable feedback via SSVEP-controlled exoskeleton movement. This “closed-loop” reinforcement likely strengthens the association between intention and action, building a foundation for subsequent learning. Stage 2 then challenges the patient to generate the motor command entirely through internal imagery, promoting Hebbian plasticity and cortical reorganization [49,50,61]. This staged approach may be particularly beneficial for severely impaired patients who require a gradual increase in task difficulty. Notably, despite undergoing daily passive joint mobilization and active-assisted physical therapy during the two-month conventional rehabilitation period prior to BCI intervention, the patient's lower-limb muscle strength remained plateaued at 2/5. This clinical plateau strongly indicates that, in the context of severe spinal cord injury (particularly with corticospinal tract disruption), purely passive movement or training lacking central volitional engagement exerts a limited effect on driving neural remodeling. The breakthrough functional gains observed in this case underscore a fundamental neurophysiological dichotomy between intention-driven and passive-execution paradigms. The former, engaging active Motor Imagery (MI) or Visuospatial Attention (SSVEP), recruits residual descending corticospinal pathways and spinal Central Pattern Generators (CPGs). This not only provides top-down central commands but also establishes closed-loop sensorimotor integration through real-time exoskeleton feedback. Such intention-based closed-loop feedback triggers Hebbian plasticity (“neurons that fire together, wire together”), effectively strengthening synaptic connectivity between the cortex and spinal effectors. Conversely, passive movement lacks this intention-related descending drive and the precise temporal coincidence between volitional commands and sensory reafference, thereby demonstrating attenuated efficacy in promoting synaptic plasticity and axonal sprouting. Our findings suggest that rehabilitation for subacute spinal cord injury must incorporate active central volitional components, which may serve as a core mechanism underpinning the superiority of BCI over conventional passive rehabilitation. This proposed mechanism is visually summarized in Figure 5, which illustrates the intention-driven closed-loop pathway. The descending volitional command (blue) activates corticospinal and spinal circuits, while ascending proprioceptive and visual feedback (orange) provides the temporal coincidence required for Hebbian synaptic strengthening. This neurophysiological dichotomy is further corroborated by our EEG data, which demonstrated robust post-training enhancement

of Event-Related Desynchronization (ERD) and sensorimotor connectivity specifically during motor imagery (Fig. 4). These findings provide objective neurophysiological evidence that the

intention-driven closed-loop paradigm effectively reinforced the descending corticospinal drive and Hebbian synaptic strengthening, which are the hallmarks of active, volitional neurorehabilitation.



Note*: Top the primary motor cortex (M1) generates intention-driven efferent commands, characterized by μ/β Event-Related Desynchronization (ERD). Middle: The efferent signals travel down the corticospinal tract (CST) to activate spinal Central Pattern Generators (CPGs). Bottom: The lower-limb exoskeleton executes the intended gait movement. Ascending pathway: Proprioceptive and visual reafference from the moving limbs and exoskeleton is fed back to the sensorimotor cortex.

Central mechanism: The precise temporal coincidence between the descending intention and ascending feedback triggers Hebbian plasticity, driving cortical reorganization and functional recovery. This intention-driven loop is contrasted with passive movement, which lacks descending volitional drive and precise sensorimotor temporal coupling, thereby exhibiting limited efficacy in promoting neuroplasticity.

Figure 5: The intention-driven closed-loop neuroplasticity pathway.

Timing of Intervention: The Window of Neuroplasticity

The timing of BCI intervention is critical for optimizing outcomes. In spinal cord injury, the subacute phase (first 3–6 months after injury) is characterized by heightened neuroplasticity, with increased synaptic receptivity, axonal sprouting, and reduced perilesional inhibition [41,42,62]. Our patient began sequential BCI training at 2.5 months post-surgery, well within this optimal window. The favorable molecular profile (SP-EPN without MYCN amplification) may have further provided an optimal neural substrate for plasticity. Although the patient had already undergone two months of conventional rehabilitation with only minimal improvement, the addition of sequential BCI training produced meaningful functional gains, suggesting that BCI can drive additional neuroplastic changes beyond those achievable with conventional therapy alone.

Evidence for BCI in Spinal Cord Injury Rehabilitation

Landmark studies have demonstrated the potential of BCI in spinal cord injury. *Lorach et al.* (2023) restored walking in chronic tetraplegia using a brain-spine interface [63]. *Ajiboye et al.* (2017)

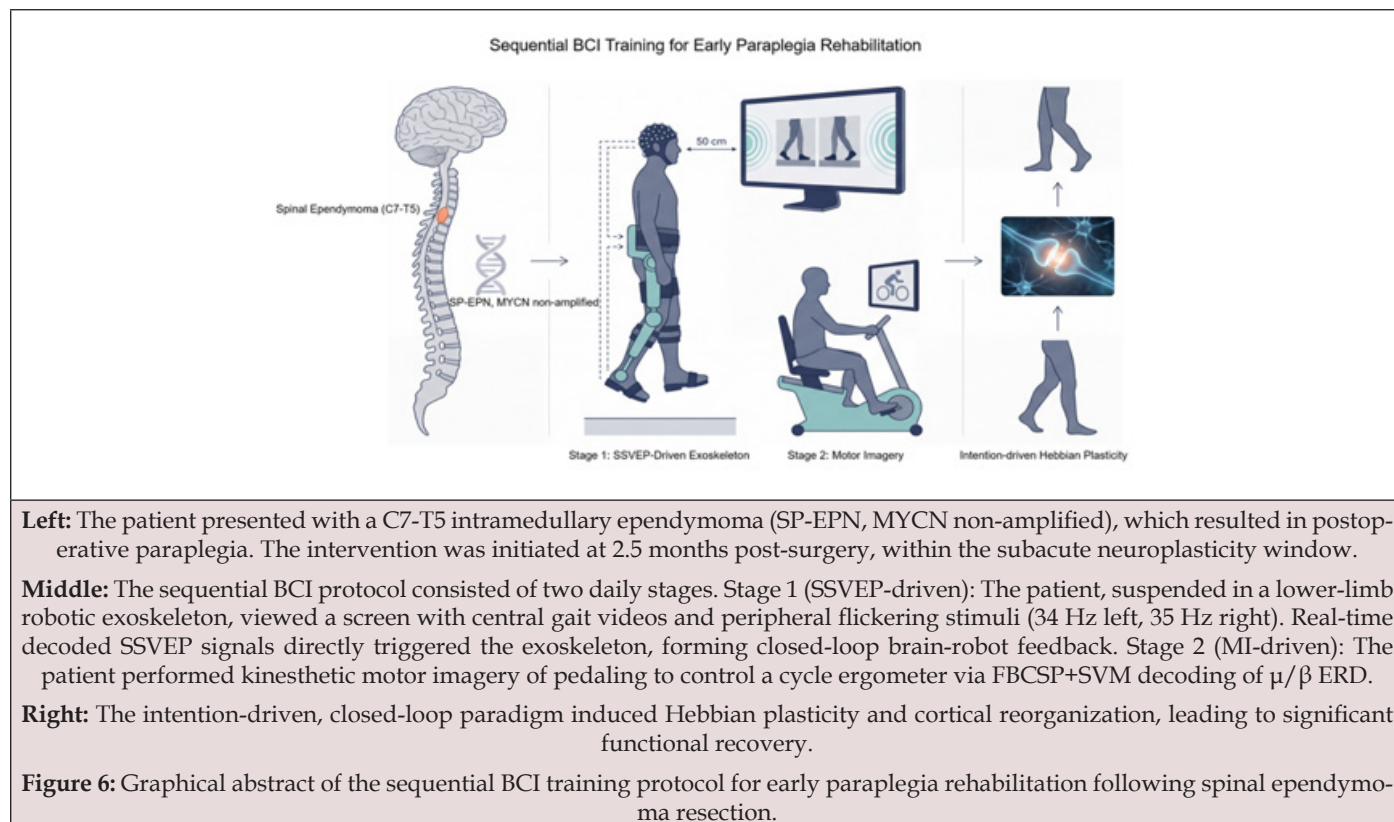
showed that intracortical BCI-controlled functional electrical stimulation could restore reaching and grasping [64]. Non-invasive home-based BCI systems have also proven feasible [65,66]. Our case adds to this literature by demonstrating that a sequential BCI protocol combining SSVEP-triggered exoskeleton with subsequent MI training can achieve meaningful motor recovery when applied early after spinal cord tumor resection. The improvement in lower limb strength and joint mobility enabled assisted standing and stepping - functional gains that directly impact quality of life and independence.

Clinical Implications and Future Directions

This case has several important clinical implications. First, it suggests that sequential BCI training is a feasible and effective early intervention for patients with paraplegia after spinal cord ependymoma resection. Second, the peripheral field stimulation design addresses the critical barrier of visual fatigue, enabling prolonged daily training essential for neuroplastic recovery. Third, the two-stage design may overcome “BCI illiteracy” by first establishing reliable SSVEP control, which builds patient confidence, before transitioning to more challenging MI training.

Fourth, molecular profiling (SP-EPN vs. SP-MYCN) could help identify patients with longer life expectancy who are most likely to benefit from intensive BCI-based rehabilitation. Future research should focus on several key areas: (1) larger prospective trials with control groups to establish efficacy in spinal cord tumor survivors; (2) optimization of training parameters (frequency, duration,

feedback intensity); (3) development of home-based, user-friendly systems to enable long-term community rehabilitation [65,66]; (4) integration of BCI with other neuromodulation techniques (e.g., transcutaneous spinal stimulation); and (5) correlation of molecular subtypes with rehabilitation response to enable personalized treatment planning.



Limitations

This study has several limitations. First, it is a single case report without a control group, which limits generalizability and precludes definitive conclusions about efficacy. However, spontaneous recovery in chronic, complete spinal cord injury is unlikely, and the patient had already plateaued after two months of conventional rehabilitation, suggesting that the observed improvements were related to the BCI intervention [67]. Second, the relative contributions of the SSVEP stage versus the MI stage cannot be separated. Third, we did not perform quantitative gait analysis or urodynamic testing, which would have provided objective measures of functional improvement. Fourth, follow-up was limited to the inpatient period; longer-term durability of gains is unknown but ongoing. Fifth, while the patient reported high comfort with the peripheral field stimulation, we did not systematically administer validated visual fatigue questionnaires. Furthermore, this study acknowledges certain neuroimaging limitations. While we demonstrated functional cortical reorganization and improved motor decoding through EEG-Based Time-Frequency Analysis (ERDS) and Functional Connectivity (PLV), the absence

of structural neuroimaging—such as Diffusion Tensor Imaging (DTI) for corticospinal tract integrity or resting-state fMRI for network topology—precludes direct quantification of white matter restoration or synaptogenesis at the structural level. Nevertheless, it is crucial to underscore that EEG offers an irreplaceable advantage in capturing the transient neural dynamics of lower-limb motor intention, particularly Event-Related Desynchronization (ERD) in the μ and β bands, owing to its millisecond-level temporal resolution. In lower-limb rehabilitation, real-time decoding of volitional intention and subsequent closed-loop feedback are pivotal for driving cortical plasticity. EEG excels at precisely capturing this dynamic process, thereby complementing the temporal resolution constraints of fMRI. Future studies integrating EEG-fMRI fusion techniques hold promise for further elucidating the spatiotemporal coupling between functional and structural remodeling.

Conclusion

Sequential brain-computer interface training combining an initial SSVEP-driven robotic exoskeleton stage with a subsequent motor imagery stage is a feasible, comfortable, and effective early

intervention for improving lower limb function after spinal cord ependymoma resection. Applied within the subacute plasticity window (2.5 months post-surgery), this patient-centered, two-stage paradigm addresses key limitations of unimodal and synchronous hybrid BCIs - namely BCI illiteracy, high cognitive load, and visual fatigue - by separating tasks temporally and leveraging peripheral field high-frequency stimulation. The favorable molecular profile (SP-EPN without MYCN amplification) may have provided an optimal substrate for neuroplasticity. Larger trials are needed to confirm efficacy and establish optimal protocols.

Consent

Written informed consent was obtained from the patient for publication of this case report and accompanying images. A copy of the written consent is available for review by the Editor-in-Chief of this journal on request.

Ethical Approval

Ethical approval was not required for this case report per institutional guidelines.

Funding

Not applicable.

Credit Authorship Contribution Statement

Xiangzhu Li: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. Rui Zhang: Methodology, Software, Validation, Formal analysis, Writing – review & editing. Qin Zhang: Investigation, Resources, Data curation, Writing – review & editing. Xiaoyu Yang: Investigation, Resources, Data curation, Writing – review & editing. Yuhao Liu: Investigation, Data curation, Visualization, Writing – review & editing. Li Zhang: Conceptualization, Supervision, Project administration, Funding acquisition, Writing – review & editing. All authors contributed to the manuscript revision and approved the final submitted version.

Acknowledgement

None.

Conflicts of Interest

The authors declare no competing interests.

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