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**BRAIN–SPINE INTERFACES AFTER CERVICAL SPINAL CORD INJURY:
BIDIRECTIONAL NEURAL BYPASSES, EPIDURAL STIMULATION, AND
SENSORIMOTOR RESTORATION**

Abstract

Background. Cervical spinal cord injury disrupts descending motor commands, sensory information, and autonomic regulation, producing tetraplegia incompletely reversible with rehabilitation. Brain–spine interfaces seek to re-establish communication across the lesion by decoding cortical intention and delivering patterned spinal stimulation, while bidirectional systems restore somatosensory feedback.

Materials and methods. A structured narrative review integrated trials, prospective cohorts, first-in-human studies, neurophysiological investigations, regulatory documents, and reports published through July 2026. Evidence was organized by biological plausibility, neural-signal acquisition, decoding performance, spinal-target selectivity, sensorimotor integration, safety, durability, rehabilitation dependence, and translational readiness. A prospective multicenter comparative protocol was developed for adults with chronic cervical injury and neurological stability.

Results. The synthesis addresses cortical decoding, epidural and transcutaneous spinal neuromodulation, upper-limb and locomotor restoration, artificial sensory feedback, autonomic effects, and activity-dependent neuroplasticity. Implanted brain–spine systems have enabled intention-driven standing and walking in an individual with chronic tetraplegia, whereas non-invasive cervical stimulation combined with task practice has improved hand strength and sensation in cohorts. A double neural bypass reported in 2026 integrated intracortical decoding, patterned spinal stimulation, and cortical sensory stimulation, producing immediate assistance together with persistent motor and sensory gains in one participant. The proposed primary endpoint is functional independence measured by SCIM III and task-specific upper-extremity performance without device-related morbidity. Secondary endpoints include GRASSP, CUE-T, gait capacity, decoding latency, sensory localization, autonomic stability, quality of life, caregiver burden, durability, and cost-effectiveness.

Conclusion. Brain–spine interfaces are evolving from proof-of-concept bypasses toward restorative neuroprosthetic systems. Multicenter validation, standardized endpoints, transparent algorithms, and long-term surveillance remain essential.

Keywords: cervical spinal cord injury, tetraplegia, brain–spine interface, brain–computer interface, epidural spinal cord stimulation, transcutaneous stimulation, neural bypass, sensory feedback, neuroplasticity.

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**ИНТЕРФЕЙСЫ «ГОЛОВНОЙ МОЗГ–СПИННОЙ МОЗГ» ПОСЛЕ ТРАВМЫ
ШЕЙНОГО ОТДЕЛА СПИННОГО МОЗГА: ДВУНАПРАВЛЕННЫЕ НЕЙРОННЫЕ
ОБХОДЫ, ЭПИДУРАЛЬНАЯ СТИМУЛЯЦИЯ И ВОССТАНОВЛЕНИЕ
СЕНСОМОТОРНЫХ ФУНКЦИЙ**

Аннотация

Актуальность. Травма шейного отдела спинного мозга нарушает нисходящие двигательные команды, сенсорную передачу и автономную регуляцию, вызывая тетраплегию, которая неполностью обратима при реабилитации. Интерфейсы «головной мозг–спинной мозг» восстанавливают связь через зону повреждения, декодируя корковое намерение и передавая паттернированную стимуляцию спинного мозга, тогда как двунаправленные системы также возвращают соматосенсорную обратную связь.

Материалы и методы. Структурированный нарративный обзор объединил клинические исследования, проспективные когорты, первые исследования на человеке, нейрофизиологические работы, регуляторные документы и сообщения, опубликованные до июля 2026 года. Доказательства систематизированы по биологической обоснованности, регистрации нейронных сигналов, эффективности декодирования, селективности спинальных мишеней, сенсомоторной интеграции, безопасности, долговечности, зависимости от реабилитации и трансляционной готовности. Разработан проспективный многоцентровый сравнительный протокол для взрослых с хронической травмой шейного отдела и неврологической стабильностью.

Результаты. Синтез охватывает корковое декодирование, эпидуральную и чрескожную нейромодуляцию, восстановление функции верхних конечностей и ходьбы, искусственную сенсорную обратную связь, автономные эффекты и активностно-зависимую нейропластичность. Имплантированные системы обеспечили управляемые намерением стояние и ходьбу у пациента с хронической тетраплегией, а неинвазивная цервикальная стимуляция с функциональной тренировкой улучшила силу и чувствительность кисти в когортах. Двойной нейронный обход, описанный в 2026 году, объединил интракорткальное декодирование, паттернированную спинальную стимуляцию и корковую сенсорную стимуляцию, обеспечив немедленную помощь и стойкие двигательные и чувствительные улучшения. Первичная конечная точка включает функциональную независимость по SCIM III и выполнение задач верхней конечностью без осложнений, связанных с устройством. Вторичные показатели включают GRASSP, CUE-T, ходьбу, задержку декодирования, локализацию ощущений, автономную стабильность, качество жизни, нагрузку на ухаживающих, долговечность и экономическую эффективность.

Заключение. Интерфейсы переходят от концептуальных обходных систем к восстановительным нейропротезам. Необходимы многоцентровая валидация, стандартизированные исходы, прозрачные алгоритмы и длительное наблюдение.

Ключевые слова: травма шейного отдела спинного мозга, тетраплегия, интерфейс «головной мозг–спинной мозг», нейрокомпьютерный интерфейс, эпидуральная стимуляция спинного мозга, чрескожная стимуляция, нейронный обход, сенсорная обратная связь, нейропластичность.

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SamDTU huzuridagi neyroxirurgiya va neyroreabilitatsiya ixtisoslashtirilgan ilmiy-amaliy markazi

BO‘YIN ORQA MIYA SHIKASTLANISHIDAN KEYINGI “BOSH MIYA–ORQA MIYA” INTERFEYSLARI: IKKI YO‘NALISHLI NEYRON AYLANMA YO‘LLAR, EPIDURAL STIMULYATSIYA VA SENSORIMOTOR FUNKSIYALARNI TIKLASH

Annotatsiya

Dolzarblik. Bo‘yin orqa miya shikastlanishi pastga yo‘naluvchi motor buyruqlar, sezgi uzatilishi va avtonom boshqaruvni buzib, rehabilitatsiya bilan to‘liq qaytmaydigan tetraplegiyani yuzaga keltiradi. “Bosh miya–orqa miya” interfeyslari kortikal niyatni dekodlash va orqa miyaga naqshlangan stimulyatsiyani uzatish orqali shikastlangan soha ustidan aloqani tiklaydi, ikki yo‘nalishli tizimlar esa somatosensor qayta aloqani ham qaytaradi.

Material va usullar. 2026-yil iyuligacha chop etilgan klinik tadqiqotlar, prospektiv kohortlar, insondagi ilk izlanishlar, neyrofiziologik ishlar, regulyator hujjatlar va ma’lumotlarni birlashtiruvchi strukturaviy narrativ sharh bajarildi. Dalillar biologik asoslanganlik, neyron signallarni qayd qilish, dekodlash samaradorligi, spinal nishon selektivligi, sensorimotor integratsiya, xavfsizlik, barqarorlik, rehabilitatsiyaga bog‘liqlik va klinik amaliyotga tayyorlik bo‘yicha tizimlashtirildi. Surunkali bo‘yin shikastlanishi va nevrologik holati barqaror bo‘lgan kattalar uchun prospektiv ko‘p markazli qiyosiy protokol ishlab chiqildi.

Natijalar. Sintez kortikal dekodlash, epidural va transkutan neyromodulyatsiya, qo‘l hamda yurish funksiyasini tiklash, sun‘iy sezgi qayta aloqasi, avtonom ta’sirlar va faollikka bog‘liq neyroplastiklikni qamrab oladi. Implantatsion tizim surunkali tetraplegiyali bemorda niyat bilan boshqariladigan turish va yurishni ta’minlagan, noinvaziv servikal stimulyatsiya funksional mashqlar bilan birga kohortlarda qo‘l kuchi va sezgisini yaxshilagan. 2026-yilda tavsiflangan ikki tomonlama neyron aylanma yo‘l intrakortikal dekodlash, naqshlangan spinal stimulyatsiya va kortikal sezgi stimulyatsiyasini birlashtirib, darhol yordam hamda motor va sezgi yutuqlarini ta’minlagan. Birlamchi yakuniy nuqta SCIM III bo‘yicha funksional mustaqillik va qurilmaga bog‘liq asoratlarsiz yuqori ekstremita vazifalarini bajarishni o‘z ichiga oladi. Ikkilamchi ko‘rsatkichlar GRASSP, CUE-T, yurish, dekodlash kechikishi, sezgini lokalizatsiya qilish, avtonom barqarorlik, hayot sifati, parvarish yuklamasi, chidamlilik va iqtisodiy samaradorlikdan iborat.

Xulosa. Interfeyslar konseptual aylanma tizimlardan tiklovchi neyroprotezlarga o‘tmoqda. Ko‘p markazli validatsiya, standartlashtirilgan natijalar, shaffof algoritmlar va uzoq kuzatuv zarur.

Kalit so‘zlar: bo‘yin orqa miya shikastlanishi, tetraplegiya, bosh miya–orqa miya interfeysi, miya–kompyuter interfeysi, orqa miyaning epidural stimulyatsiyasi, transkutan stimulyatsiya, neyron aylanma yo‘l, sensor qayta aloqa, neyroplastiklik.

Introduction. Cervical spinal cord injury is among the most disabling forms of neurological trauma because it compromises upper-limb function, trunk control, locomotion, respiration, cardiovascular regulation, bowel and bladder control, sexual function, and somatosensory perception. Although early decompression, spinal stabilization, hemodynamic optimization, intensive rehabilitation, tendon transfer, nerve transfer, orthotic support, and assistive technologies improve selected outcomes, severe tetraplegia remains associated with profound dependence in activities of daily living. Restoration of hand function is frequently prioritized above standing or walking because

relatively small improvements in grasp, pinch strength, wrist control, and object manipulation can substantially increase independence in feeding, dressing, hygiene, communication, wheelchair operation, and environmental control. The traditional concept of a completely disconnected spinal cord has been replaced by a more nuanced model. Even clinically motor-complete injuries may retain anatomically spared but functionally silent descending fibers. Below the lesion, spinal interneuronal networks, motor neurons, sensory afferents, propriospinal pathways, and central pattern-generating circuitry may remain excitable. Electrical neuromodulation does not necessarily generate a complete movement independently. Instead, it can move the excitability of these preserved circuits closer to the threshold at which residual supraspinal commands and task-related sensory information become functionally effective [1, 2, 3].

Epidural electrical stimulation of the lumbosacral spinal cord has enabled voluntary lower-limb activation, standing, assisted stepping, and, in selected participants, overground walking after severe chronic spinal cord injury. These effects depend on electrode position, stimulation timing, task-specific programming, residual descending connectivity, proprioceptive input, and intensive rehabilitation [2, 3, 8]. Activity-dependent stimulation targeting specific dorsal roots and spinal segments has improved the selectivity of muscle recruitment compared with conventional tonic spinal cord stimulation. Experimental and clinical observations suggest that dorsal-root afferents are major neural substrates through which epidural stimulation engages spinal motor circuitry [2, 6, 7]. A brain–spine interface extends this concept by creating a digital bypass around the lesion. Neural activity associated with movement intention is recorded from the cerebral cortex, decoded in real time, and converted into stimulation commands delivered below the damaged region. Rather than waiting for weak residual corticospinal signals to cross the injury, the interface transmits intention electronically. A fully implanted system reported in 2023 linked cortical electrocorticographic recordings to analogue modulation of lumbosacral epidural stimulation. The system enabled an individual with chronic tetraplegia to stand, walk, climb stairs, and navigate community environments with voluntary control [1, 2, 3]. The clinical objective is no longer limited to an assistive neuroprosthesis that functions only while switched on. Contemporary systems increasingly combine immediate bypass effects with rehabilitation-induced neuroplasticity. Repeated coupling of cortical intention, spinal-circuit activation, sensory feedback, and successful movement may reinforce residual pathways through activity-dependent synaptic mechanisms. Improvements that persist when stimulation is inactive are interpreted as evidence of therapeutic or restorative effects rather than purely assistive compensation, although the relative contributions of spontaneous variability, training, stimulation, and true circuit reorganization remain difficult to isolate. In 2024, a multicenter study of non-invasive cervical spinal cord stimulation combined with functional task practice demonstrated improvements in hand strength and sensation in people with chronic incomplete cervical injury. The study informed the subsequent United States De Novo classification of a transcutaneous spinal stimulation system intended for use with rehabilitation in adults with chronic incomplete C2–C8 spinal cord injury. The regulatory summary nevertheless emphasized that the open-label, single-arm design could not fully distinguish stimulation effects from intensive rehabilitation and that durability and broader functional benefits remained uncertain [4, 12, 13]. In 2026, a double neural bypass was reported in a participant with chronic, severe motor- and sensory-complete tetraplegia. The system combined intracortical recording

of movement intention, recurrent neural-network decoding, patterned spinal neuromodulation, an active orthosis, and intracortical somatosensory stimulation. The intervention produced immediate assistance for hand movement while also being associated with persistent improvements in elbow flexion and tactile sensation after the system was turned off. This hybrid architecture illustrates the emerging transition from unidirectional motor decoding toward bidirectional and plasticity-oriented neuroprostheses [5, 18, 19].

Despite these advances, current evidence remains dominated by small cohorts, first-in-human trials, and individual cases. Hardware platforms differ in cortical electrodes, signal bandwidth, wireless transmission, decoding algorithms, stimulation arrays, rehabilitation protocols, and outcome measures. Consequently, technical success cannot yet be equated with generalized clinical effectiveness. The present article synthesizes the biological rationale, engineering architecture, clinical evidence, safety requirements, and translational barriers of brain–spine interfaces after cervical spinal cord injury. It also proposes a multicenter prospective protocol linking decoder performance and stimulation selectivity to independence, hand function, gait, sensory recovery, autonomic stability, quality of life, and device burden.

Materials and Methods. A structured narrative review was performed using evidence available through July 2026. Eligible sources included prospective clinical trials, randomized and nonrandomized interventional studies, first-in-human investigations, chronic feasibility studies, neurophysiological experiments, regulatory documents, registered clinical protocols, and relevant translational research. Studies involving cervical spinal cord injury were prioritized. Lower-limb and thoracolumbar stimulation studies were included when they established physiological or engineering principles applicable to brain–spine interfaces. The evidence was organized into eight domains: neural-signal acquisition, movement-intention decoding, stimulation-target selectivity, bidirectional sensory integration, rehabilitation-dependent plasticity, autonomic effects, safety, and translational feasibility. Cortical recording strategies included intracortical microelectrode arrays, electrocorticographic grids, epidural cortical electrodes, and non-invasive electroencephalography. Spinal-output strategies included cervical or lumbosacral epidural electrical stimulation, transcutaneous spinal cord stimulation, functional electrical stimulation of peripheral muscles, active orthoses, and hybrid stimulation systems.

Decoder performance was assessed using classification accuracy, trajectory reconstruction, command latency, false activation rate, stability across sessions, recalibration requirements, and functional task completion. Spinal stimulation was evaluated according to segmental selectivity, recruitment of dorsal-root afferents, muscle-synergy specificity, stimulation amplitude, pulse width, frequency, timing relative to intended movement, and compatibility with sensory feedback. Clinical outcomes included the International Standards for Neurological Classification of Spinal Cord Injury, Spinal Cord Independence Measure III, Graded Redefined Assessment of Strength, Sensibility and Prehension, Capabilities of Upper Extremity Test, upper-extremity motor score, Action Research Arm Test, grasp force, pinch force, walking capacity, autonomic function, quality of life, caregiver burden, and adverse events. A prospective multicenter comparative study is proposed for adults aged 18–70 years with chronic traumatic cervical spinal cord injury of at least 12 months' duration. Eligible neurological levels would range from C2 to C8, with AIS grades A–D considered in predefined strata.

Participants would require stable neurological and medical status, completion of standard rehabilitation, and a functional goal involving upper-limb control, trunk stability, standing, or walking. Exclusion criteria would include progressive myelopathy, unstable spinal instrumentation, active infection, uncontrolled epilepsy, severe cognitive impairment, untreated psychiatric disease, clinically significant coagulopathy, recurrent severe autonomic dysreflexia not controlled by medical management, or inability to participate in rehabilitation. The proposed study would compare three treatment strategies: intensive task-specific rehabilitation alone, spinal neuromodulation combined with identical rehabilitation, and a personalized brain-controlled spinal stimulation system combined with identical rehabilitation. Where randomization to invasive surgery is ethically or practically unacceptable, a prospective matched-cohort design with blinded outcome adjudication and predefined causal-inference methods would be used. Participants receiving an implanted interface would undergo preoperative functional MRI, structural MRI, diffusion imaging, neurophysiological mapping, spinal imaging, and individualized goal assessment.

The primary endpoint would be a hierarchical composite of change in SCIM III and task-specific upper-extremity function at six months, conditional on the absence of serious device-related morbidity. Upper-limb outcomes would be prioritized in cervical injury, although participants with preserved arm function and severe lower-limb paralysis could enter a locomotor stratum. Secondary endpoints would include GRASSP, CUE-T, upper-extremity motor score, grasp force, sensory localization, gait speed, walking endurance, standing duration, autonomic stability, quality of life, caregiver assistance, device-use time, decoder latency, recalibration frequency, and total treatment cost. Assessors would remain blinded to treatment assignment whenever feasible. Motor and functional tasks would be video-recorded and adjudicated centrally. Statistical analysis would use mixed-effects longitudinal models with participant, center, neurological level, AIS grade, time since injury, age, and baseline function incorporated as covariates. Device-on and device-off performance would be separated to distinguish immediate assistive benefit from persistent therapeutic recovery. External validation would require a locked decoding pipeline tested in participants from centers not involved in model development.

Results. Spinal cord injury disrupts long-range communication but does not necessarily eliminate all circuitry below the lesion. Segmental motor pools, proprioceptive afferents, interneurons, propriospinal connections, and autonomic networks may remain structurally present. Their functional output is reduced because descending excitation is insufficient, poorly coordinated, or temporally disconnected from sensory input. Epidural and transcutaneous stimulation can raise the excitability of these networks without directly replacing every descending axon. The most accepted model proposes that stimulation recruits large-diameter posterior-root afferents, which then influence interneuronal and motor-neuron populations trans-synaptically. The resulting state is movement-permissive rather than movement-deterministic. Voluntary intention, loading, joint position, cutaneous input, and rehabilitation-related sensory information shape the final motor response. This explains why identical electrical parameters may produce different movements depending on posture and task context [2, 6, 7]. The spatial organization of cervical motor pools is more complex than a simple rostrocaudal representation. Reaching, grasping, finger individuation, wrist stabilization, elbow flexion, and shoulder control require coordinated recruitment across multiple spinal segments. Cervical epidural

stimulation must therefore target combinations of dorsal roots and spinal circuits rather than a single isolated motor nucleus. Preclinical and translational mapping has demonstrated that stimulation location and current direction can preferentially recruit upper-limb muscle groups, although selectivity decreases when current spreads broadly or stimulation intensity becomes excessive [7, 14, 18].

Acquisition and Decoding of Cortical Movement Intention. The input component of a brain–spine interface must extract stable information from neural activity. Intracortical microelectrode arrays provide high-resolution recordings of single-unit and multiunit activity and can support decoding of finger movements, grasp states, force, movement direction, and continuous trajectories. Their principal limitations include invasive implantation, signal drift, tissue response, connector or telemetry burden, and the need for recalibration. Electrocorticography records population-level activity from the cortical surface. It offers lower spatial resolution than intracortical arrays but may provide greater long-term stability and reduced penetration-related tissue injury. Epidural cortical electrodes reduce direct cortical contact but further attenuate signal amplitude. Non-invasive electroencephalography avoids cranial implantation but has lower signal-to-noise ratio, greater susceptibility to artifacts, and more limited decoding bandwidth. Movement-intention decoders commonly use spectral features, event-related desynchronization, high-gamma activity, threshold classifiers, linear discriminant analysis, Kalman filters, recurrent neural networks, and reinforcement-learning methods. The optimal model depends on the required output. Binary detection of attempted grasp is less computationally demanding than continuous reconstruction of multidimensional hand trajectories. A clinically useful decoder must not only achieve high offline accuracy but also maintain low latency, stable calibration, and a clinically acceptable false-trigger rate during conversation, wheelchair movement, sleep, spasticity, coughing, and involuntary motor activity.

Decoder latency is particularly important when stimulation is intended to generate natural movement. Excessive delay between intention and muscle activation disrupts embodiment and sensory prediction. Variable delay may be more disturbing than a consistently small delay because the central nervous system cannot form a stable internal model. The 2023 implanted brain–spine interface used wireless cortical recordings and real-time decoding to modulate epidural stimulation programs continuously, enabling voluntary initiation, stopping, and adjustment of locomotor activity [1, 2, 3].

Table 1. Principal architectures for neural restoration after cervical spinal cord injury

Architecture	Neural input	Output pathway	Principal advantage	Principal limitation
Conventional rehabilitation	Residual biological pathways	Voluntary muscle activation	Non-invasive and widely available	Limited effect in severe chronic injury
Transcutaneous spinal stimulation	Residual supraspinal intention and sensory input	Cervical or thoracolumbar spinal networks	No implantation and scalable clinical delivery	Limited spatial selectivity and skin discomfort
Epidural spinal stimulation	Residual intention, external	Segment-specific dorsal roots and spinal circuits	Greater anatomical	Requires spinal surgery and

	controller, or sensor input		selectivity and chronic use	implanted hardware
Cortical BCI with functional electrical stimulation	Intracortical, ECoG, or EEG signals	Peripheral nerves or muscles	Direct activation of the patient's limb	Muscle fatigue and limited recruitment naturalness
Brain-controlled epidural stimulation	Cortical movement intention	Spinal motor networks below the lesion	Bypasses the lesion while using intrinsic spinal circuitry	Complex surgery, decoding, telemetry, and calibration
Bidirectional neural bypass	Cortical motor signals plus artificial sensory feedback	Spinal stimulation, orthosis, muscles, and sensory cortex	Integrates intention, movement, perception, and plasticity	Highest hardware, regulatory, and safety complexity

Epidural and Transcutaneous Spinal Neuromodulation. Epidural electrical stimulation places an electrode array within the spinal epidural space, usually over the dorsal aspect of targeted segments. Early systems repurposed pain-stimulation leads, which were not designed for selective recruitment of motor circuits. Newer arrays and programming strategies seek to align electrodes with dorsal-root entry zones and activate functional muscle synergies in task-specific temporal sequences. Lumbosacral epidural stimulation provided critical proof that spinal networks below a severe injury can support voluntary movement, standing, and stepping. In 2018, separate clinical investigations reported recovery of overground walking or independent stepping in selected participants after chronic severe injury when stimulation was combined with intensive locomotor rehabilitation [3, 8, 9]. Subsequent work demonstrated rapid restoration of trunk and leg functions using biomimetic, activity-dependent stimulation programs delivered through purpose-designed arrays [2, 6, 10]. Cervical epidural stimulation seeks to facilitate upper-limb control by targeting neural structures associated with the brachial enlargement. Selective recruitment of arm and hand motor pools has been demonstrated in preclinical and human mapping studies. Cervical stimulation has also improved upper-limb control after stroke, indicating that spinal neuromodulation can amplify residual corticospinal drive even when the primary lesion is supraspinal [7, 14, 18].

Transcutaneous stimulation delivers current through surface electrodes positioned over the spine. High-frequency carrier waveforms may improve tolerability by reducing discomfort associated with activation of cutaneous nociceptors. The technique is less anatomically selective than epidural stimulation but does not require surgery. It may therefore be more suitable for early screening, rehabilitation augmentation, multicenter deployment, and patients in whom implantation is contraindicated. The Up-LIFT investigation evaluated cervical transcutaneous spinal stimulation combined with intensive task practice in chronic tetraplegia. Improvements were reported in upper-limb strength and sensation across a multicenter cohort. The evidence contributed to FDA De Novo classification of the ARCEX system as a Class II transcutaneous electrical spine stimulator intended

to improve hand sensation and strength in adults with chronic incomplete C2–C8 injury when used with functional task practice. The FDA explicitly noted that the study design did not establish which improvements were attributable to stimulation versus rehabilitation and that durable functional recovery had not been demonstrated [4, 12, 13].

Motor Restoration Through Digital Neural Bypasses. A motor neural bypass can route cortical intention to muscles, peripheral nerves, an orthosis, or spinal circuitry. Direct functional electrical stimulation of muscles has enabled grasp and reaching in people with paralysis, but selective stimulation of individual muscles may produce rapid fatigue, nonphysiological recruitment order, and difficulty coordinating multijoint movement. Spinal stimulation may recruit motor pools through endogenous sensorimotor circuitry, potentially producing more coordinated and fatigue-resistant activation. The brain–spine interface described in 2023 consisted of implanted cortical recording systems, a wireless processing unit, and an epidural spinal stimulator. Cortical activity was decoded into probabilities of intended lower-limb movements. These probabilities modulated stimulation programs targeting spinal regions responsible for hip, knee, and ankle control. The participant achieved voluntary standing and walking, including stair climbing and community ambulation. Importantly, the interface provided analogue rather than purely binary control, allowing the intensity and timing of stimulation to reflect movement intention [1, 2, 3]. The report remains a single-participant demonstration and therefore cannot establish population-level effectiveness. The participant had previous experience with epidural stimulation and extensive rehabilitation, which may have facilitated rapid learning. Nevertheless, the study established the feasibility of a fully implanted digital bridge that functioned during everyday activities rather than only under laboratory conditions. For cervical injury, upper-limb restoration imposes greater decoding complexity. Functional grasp requires independent or coordinated control of shoulder, elbow, forearm, wrist, thumb, and individual fingers. The system must also distinguish reaching, grasp opening, grasp closure, force modulation, object release, and corrective movement. Visual feedback can support control, but vision alone is insufficient for natural manipulation because the user must detect contact, slip, object compliance, and applied force.

Bidirectional Interfaces and Artificial Sensory Feedback. A unidirectional BCI can decode intention and produce movement, but the user receives limited information about the resulting action. Artificial sensory feedback seeks to close this loop. Tactile sensors on an orthosis, glove, prosthesis, or limb can be translated into electrical stimulation of peripheral nerves, spinal pathways, thalamus, or somatosensory cortex. Intracortical microstimulation of somatosensory cortex can evoke localized percepts referred to the hand or fingers in people with cervical spinal cord injury. The therapeutic goal is not merely to produce a percept. Sensory feedback should encode location, timing, force, texture, or slip with sufficient stability to improve motor performance. Poorly localized or inconsistent sensations may increase cognitive workload. Biomimetic stimulation patterns that approximate natural temporal dynamics may be easier to interpret than arbitrary stimulation codes, although personalized learning can allow users to exploit nonphysiological signals. The 2026 double neural bypass combined cortical movement decoding with patterned spinal cord stimulation and activity-informed intracortical microstimulation. A recurrent artificial neural network and reinforcement-learning framework supported grasp control, while sensory-cortical stimulation was used to mirror activity associated with

tactile events. In one participant with chronic C4 sensory and C5 motor complete tetraplegia, the system supported self-feeding and manipulation of delicate objects and was associated with persistent improvements in elbow flexion and wrist sensation [5, 18, 19].

This architecture is scientifically important because it combines assistive and restorative objectives. The immediate bypass permits task performance while the system is active. Repeated pairing of motor intention, spinal activation, successful movement, and artificial sensory input may facilitate Hebbian and reinforcement-based plasticity. Nevertheless, the causal contribution of each component cannot be determined from a single-participant multimodal intervention.

Table 2. Candidate endpoints for brain–spine-interface trials

Domain	Recommended endpoint	Clinical interpretation
Neurological impairment	ISNCSCI motor and sensory scores; AIS grade	Standardized neurological change
Upper-limb function	GRASSP, CUE-T, grasp force, pinch force, object-manipulation tasks	Strength, sensation, prehension, and independence
Functional independence	SCIM III	Real-world self-care, mobility, respiration, and sphincter management
Locomotion	10-m walk, 6-min walk, standing duration, transfer performance	Functional mobility and endurance
Decoder performance	Accuracy, latency, false-trigger rate, recalibration frequency	Reliability of cortical intention decoding
Stimulation selectivity	Muscle recruitment map, unwanted co-contraction, movement specificity	Precision of spinal targeting
Sensory feedback	Detection threshold, localization accuracy, force discrimination	Usefulness of artificial sensation
Autonomic function	Blood pressure stability, autonomic dysreflexia frequency, bladder and bowel measures	Nonmotor therapeutic value and safety
Patient-centered outcomes	Quality of life, goal attainment, caregiver burden, device-use preference	Practical relevance to patients and families
Durability	Device-on and device-off performance at 6, 12, and 24 months	Separation of assistance from persistent recovery

Neuroplasticity and Rehabilitation Dependence. Electrical neuromodulation is most effective when paired with task-specific training. Stimulation changes the excitability of neural circuits, but rehabilitation supplies the patterned activity needed to shape these circuits toward meaningful behavior. Repeated coincidence of attempted movement, cortical activation, spinal excitation, sensory input, and task success may strengthen residual pathways through spike-timing-dependent plasticity, Hebbian learning, and reinforcement mechanisms [10, 20, 21]. Device-on improvement should be distinguished from device-off recovery. Immediate performance gains indicate that stimulation enables or assists movement. Persistent gains after stimulation is discontinued suggest training-dependent reorganization, improved voluntary recruitment, strengthened residual descending

pathways, or altered spinal excitability. Both outcomes are valuable, but they represent different therapeutic claims. Closed-loop vagus nerve stimulation provides complementary evidence that precisely timed neuromodulation can enhance rehabilitation after cervical injury. A randomized, double-blinded, sham-controlled study published in 2025 paired vagus nerve stimulation with successful upper-limb movements during task-focused therapy. Nineteen participants with chronic incomplete cervical injury demonstrated beneficial effects on arm and hand strength and activities of daily living. This strategy does not directly bypass the lesion; instead, it reinforces active neural networks during rehabilitation through neuromodulatory mechanisms [15, 20, 21].

The comparison is conceptually important. Brain–spine interfaces increase information transfer across the lesion. Spinal stimulation increases the responsiveness of sublesional circuits. Vagus nerve stimulation promotes plasticity in pathways engaged during successful movement. Future restorative systems may combine all three principles, but component-specific trials will be required to prevent scientifically uninterpretable multimodal interventions.

Autonomic and Cardiovascular Restoration. Cervical spinal cord injury disrupts descending autonomic pathways and can produce resting hypotension, orthostatic hypotension, autonomic dysreflexia, impaired thermoregulation, and reduced cardiovascular adaptability. Restoration of hand or walking function alone may not address these life-threatening and quality-of-life-limiting problems. Targeted epidural stimulation of thoracic spinal circuits has been used to stabilize blood pressure by engaging sympathetic pathways. Neuroprosthetic baroreflex systems can adjust stimulation according to cardiovascular state, illustrating that closed-loop spinal interfaces can restore autonomic as well as motor functions [15, 16, 17]. A comprehensive brain–spine-interface trial should therefore monitor blood pressure, heart rate, orthostatic tolerance, autonomic dysreflexia, bladder and bowel function, respiratory performance, and sexual health. Motor improvement accompanied by increased autonomic instability would not represent acceptable net clinical benefit.

Safety, Reliability, and Human Factors. Brain–spine interfaces combine the risks of cranial implantation, spinal implantation, electrical stimulation, wireless telemetry, machine-learning control, and intensive rehabilitation. Cranial risks include hemorrhage, infection, seizure, cortical injury, cerebrospinal-fluid leakage, wound breakdown, and electrode migration. Spinal risks include epidural hematoma, infection, neurological deterioration, dural injury, lead migration, and hardware erosion. Stimulation can provoke pain, paresthesia, unwanted muscle activation, spasticity, fatigue, autonomic dysreflexia, blood-pressure changes, or interference with implanted cardiac devices. Transcutaneous stimulation may cause skin irritation and discomfort. The FDA regulatory summary for the ARCEX system identifies autonomic dysreflexia, musculoskeletal spasms, stiffness, pain, skin irritation, temporary heart-rate elevation, paresthesia, and neuralgia among relevant risks and precautions [4, 12, 13]. Algorithmic failures create additional hazards. False-positive decoding may trigger unintended movement, whereas false-negative decoding may prevent movement during transfer or standing. Wireless interruption can destabilize control if no safe fallback mode exists. Decoder drift may reduce accuracy gradually and remain unnoticed until a hazardous task is attempted. Safety architecture should include clinician-defined stimulation limits, emergency shutdown, signal-quality monitoring, movement confirmation, state-dependent lockouts, event logging, and predictable fallback programs. Cybersecurity is a component of patient safety. Unauthorized access, corrupted software updates,

telemetry interception, or denial of service could compromise therapy. Systems require encrypted communication, authenticated programming, version-controlled algorithms, access logs, and procedures for restoring safe operation after software failure.

Human factors will influence adoption as strongly as electrophysiological performance. Systems requiring several engineers, daily recalibration, external cables, and prolonged laboratory setup may demonstrate scientific efficacy without achieving clinical scalability. Patients and caregivers must be able to charge, position, activate, troubleshoot, and maintain the system. Clinicians must understand why a decoder or controller produced a particular output. Transparent visualization of neural-signal quality, stimulation state, confidence, and error history is essential.

Table 3. Proposed multicenter comparative study

Component	Proposed specification
Population	Adults with chronic traumatic C2–C8 spinal cord injury and stable neurological status
Stratification	Neurological level, AIS grade, upper-limb versus locomotor goal, time since injury
Comparator 1	Standardized intensive task-specific rehabilitation
Comparator 2	Spinal neuromodulation plus identical rehabilitation
Intervention	Personalized brain-controlled spinal stimulation plus identical rehabilitation
Primary endpoint	Hierarchical composite of SCIM III and task-specific upper-limb performance without serious device morbidity
Secondary endpoints	GRASSP, CUE-T, ISNCSCI, grasp force, gait, standing, sensory localization, autonomic stability, quality of life
Technical endpoints	Decoder accuracy, latency, false-trigger rate, signal drift, stimulation selectivity, recalibration time
Restorative endpoint	Persistent device-off improvement at 6 and 12 months
Safety endpoints	Infection, hemorrhage, neurological deterioration, autonomic dysreflexia, seizures, hardware failure
Blinding	Central blinded video adjudication and blinded neurological assessment
External validation	Locked algorithm tested at independent centers and across distinct hardware environments
Originality	Direct comparison of rehabilitation, spinal stimulation, and brain-controlled stimulation using patient-centered outcomes

Discussion. Brain–spine interfaces represent a convergence of functional neurosurgery, spinal neuromodulation, neurorehabilitation, computational neuroscience, neural engineering, and restorative neurobiology. Their conceptual advantage is straightforward: if biological communication across a lesion is insufficient, cortical intention can be transmitted electronically to excitable spinal circuitry below the injury. The practical implementation, however, requires simultaneous success at every stage of a complex therapeutic chain. The cortical signal must contain stable information about intended movement. The decoder must interpret this information with low latency. The spinal electrode must recruit the appropriate circuits without activating antagonistic muscles or producing autonomic

instability. Sensory feedback must be sufficiently meaningful for corrective control. Rehabilitation must convert assisted performance into repeatable functional behavior. Hardware must remain safe and reliable over years rather than weeks. Current evidence supports the feasibility of each component. Intracortical and electrocorticographic systems can decode intended movement in people with tetraplegia. Epidural stimulation can facilitate voluntary activation, standing, stepping, and selected upper-limb movements. Transcutaneous cervical stimulation can augment rehabilitation without implantation. Intracortical stimulation can evoke localized tactile percepts. Closed-loop neurostimulation can reinforce rehabilitation-induced plasticity. Fully implanted brain–spine interfaces can support intention-driven walking, and a double neural bypass can combine motor decoding with spinal and sensory-cortical stimulation [1, 4, 5].

The evidence does not yet establish which architecture is optimal for a particular patient. An individual with incomplete C5 injury and residual wrist extension may benefit substantially from transcutaneous stimulation and task practice without cranial or spinal implantation. A patient with motor-complete tetraplegia and no functional hand movement may require an intracortical decoder, spinal stimulation, functional electrical stimulation, or an active orthosis. A person whose highest priority is blood-pressure stability may benefit more from an autonomic neuroprosthesis than from a motor BCI. Patient selection must therefore be goal-directed rather than technology-directed. Neurological level and AIS grade are necessary but insufficient. Residual corticospinal connectivity, peripheral nerve integrity, muscle condition, joint contracture, spasticity, neuropathic pain, cognition, motivation, caregiver support, home environment, tolerance of risk, and rehabilitation capacity all influence outcome. The distinction between assistive and restorative benefit should remain explicit. An interface that reliably enables grasp while active may be clinically transformative even if no recovery persists when it is turned off. Conversely, modest device-on assistance may be valuable if repeated training induces durable neurological recovery. Trials should report both effects rather than combining them into a single outcome.

The rapid development of multimodal systems creates a risk of component ambiguity. When cortical recording, spinal stimulation, sensory stimulation, orthotic assistance, rehabilitation, and medication changes occur together, improvement cannot be attributed confidently to any single mechanism. Early feasibility studies may appropriately combine components to demonstrate possibility. Later trials should use factorial, staged, or component-controlled designs. External validation is particularly important for neural decoders. Within-participant models can exploit stable individual neural patterns, but they may require extensive calibration. Algorithms developed from one electrode type or rehabilitation laboratory may not generalize to another center. Evaluation should include day-to-day stability, performance after missed sessions, signal loss, medication changes, fatigue, illness, and unsupervised home use. Outcome selection should reflect patient priorities. Laboratory cursor accuracy and offline decoder performance are not sufficient. The most meaningful outcomes include self-feeding, drinking, grooming, catheter management, wheelchair control, transfers, communication-device use, standing, walking, prevention of falls, autonomic stability, and reduction in caregiver assistance. SCIM III, GRASSP, and CUE-T provide standardized measurement but should be complemented by personalized goal attainment and real-world device-use data. The proposed multicenter study addresses several weaknesses in the existing evidence. It compares brain-

controlled stimulation not only with rehabilitation but also with spinal stimulation using the same rehabilitation dose. This design helps determine whether cortical control provides incremental benefit beyond spinal neuromodulation. It separates device-on assistance from device-off recovery and requires blinded central adjudication. Technical performance, safety, independence, quality of life, and caregiver burden are evaluated together.

Randomization involving invasive surgery remains difficult. Participants may be unwilling to accept assignment to rehabilitation alone after undergoing extensive screening for an implant. Sham cranial or spinal surgery would generally be ethically unacceptable. Adaptive trial designs, randomized activation periods after implantation, delayed-start controls, and prospective matched cohorts may provide more realistic alternatives. Economic and access considerations will become increasingly important. Brain–spine interfaces may require neurosurgeons, rehabilitation physicians, neurologists, engineers, therapists, imaging specialists, and long-term technical support. Concentration in a few specialized centers could widen existing disparities in spinal cord injury care. Scalable systems will require standardized implantation, automated calibration, remote monitoring, interoperable hardware, and training programs for regional rehabilitation centers.

Regulatory evaluation must match the evolving nature of the technology. A software update that changes decoder behavior may materially alter risk and effectiveness even when implanted hardware remains unchanged. Version-specific outcomes, post-market surveillance, and cybersecurity reporting should be mandatory. Device failure plans must address what happens when a manufacturer discontinues hardware or software support. Neuroethical considerations include informed consent, ownership of neural data, privacy, algorithmic agency, identity, reversibility, and expectations of recovery. People with severe paralysis may be especially vulnerable to exaggerated claims. Consent should clearly distinguish experimental feasibility from proven functional restoration and should explain the possibility of infection, hardware removal, declining signal quality, and loss of device support. Several limitations of the present review should be acknowledged. Clinical studies are heterogeneous in injury level, completeness, time since injury, stimulation target, rehabilitation dose, and endpoint selection. Many investigations involve one or a few participants. Publication bias may favor successful cases. Long-term data regarding cortical electrode stability, spinal hardware longevity, home reliability, revision surgery, and sustained sensory integration remain limited. Direct randomized comparisons between transcutaneous stimulation, epidural stimulation, functional electrical stimulation, and brain-controlled spinal stimulation are not yet available.

Despite these limitations, the field has advanced from isolated muscle activation to integrated, intention-driven, bidirectional sensorimotor systems. The central scientific question is shifting from whether communication can be bypassed to how reliably, safely, naturally, and equitably this can be accomplished across diverse patients.

Conclusion. Brain–spine interfaces offer a rational strategy for restoring communication across cervical spinal cord lesions. Cortical signals can encode movement intention, machine-learning algorithms can translate intention into control commands, and epidural or transcutaneous stimulation can place preserved spinal networks into a state that supports functional motor output. Fully implanted systems have enabled intention-driven standing and walking after chronic tetraplegia. Non-invasive cervical stimulation combined with task practice has improved hand strength and

sensation in multicenter cohorts. Bidirectional systems incorporating artificial sensory feedback and patterned neuromodulation have demonstrated the possibility of combining immediate assistive control with persistent sensorimotor improvement. These results remain early and should not be interpreted as evidence of universal neurological restoration. Future research must establish patient-selection criteria, comparative effectiveness, long-term safety, decoder stability, stimulation selectivity, rehabilitation dose, durability, cost-effectiveness, and real-world independence. The next phase of clinical translation should prioritize standardized patient-centered endpoints, separation of device-on assistance from device-off recovery, blinded adjudication, locked external validation, transparent algorithms, cybersecurity, and long-term post-implant surveillance. Brain–spine interfaces will become clinically meaningful only when technical sophistication is translated into durable improvements in independence, safety, participation, and quality of life.

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