ORIGINAL ARTICLE

Mapping of the Sensory Circuits in the Spinal Cord: A Literature Review

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ABSTRACT

Recent advancements in neuroscience have profoundly enhanced our comprehension of the organization of sensory circuits within the spinal cord. These developments are primarily attributed to significant breakthroughs in intraoperative neurophysiological monitoring (IONM) techniques, which have been instrumental in uncovering the intricate anatomical, functional, and neurophysiological complexities associated with spinal pathways.

This literature review examines the multifaceted role of various IONM modalities, including somatosensory evoked potentials (SSEPs) and electromyography (EMG), in accurately mapping sensory circuits. It assesses their clinical practicality, particularly in guiding surgical interventions for spinal cord injuries, where precise mapping is critical to minimize damage and maximize recovery potential.

Furthermore, the review highlights the impact of neuroplasticity, the spinal cord's ability to reorganize and adapt following injury, on recovery outcomes. It examines how neuroplastic mechanisms can be harnessed to improve rehabilitation strategies, potentially leading to enhanced recovery in patients.

The discussion also highlights the growing importance of computational modeling as a valuable tool in deepening our understanding of spinal function. By simulating various scenarios, these models can provide valuable insights into the dynamics of neural circuits and inform targeted rehabilitation strategies, thereby contributing to the development of effective therapeutic approaches for spinal cord injury recovery.

INTRODUCTION

The broad understanding of the spinal cord's functions has remained relatively stable throughout history. Given the consistency of the spinal cord's structure, as well as its ability to be manipulated, historical

understandings of its functional properties have been surprisingly stable. Early physicians have noted intricate accounts, with great accuracy, including that of Ibn Jazlah, a physician from the 11th century, who posited that diseases of the spinal cord often led to paralysis and numbness [1]. Experimental manipulations were pioneered by Galen, who practiced in the first century, leading to the conclusion that damage to the spinal cord at a particular level results in dysfunction of the sensory and motor counterparts below the level of the lesion [1]. Physiological knowledge about the spinal cord has expanded dramatically, from Blasius' differentiation of gray and white matter in 1666, to the localization of the laminal layers of the spinal cord by Bror Rexed in the early 1950s [2].

Wilder Penfield and his colleagues are credited as the first people to use direct cortical stimulation for the mapping of intraoperative cortical functions during epilepsy surgeries, with the first instance being in 1937 [3]. The use of spinal instrumentation, as well as aggressive surgical techniques, was widely adopted by the early 1970s. Intraoperative neurophysiological monitoring (IONM) was thus expanded from works such as those of Brown & Nash, who were the first to describe the monitoring of spinal cord function using cortical somatosensory evoked potentials during surgeries to correct scoliosis in children. Many pioneers of this field, such as Aage Møller, were audiology professionals who performed the majority of monitoring during the 1980s and 1990s in the United States [4].

The expanding body of research in this field has led to the development of various monitoring methods, including somatosensory cortical evoked potentials, spinal somatosensory evoked potentials, muscle evoked potentials, and motor evoked potentials, among others. These techniques have been enhanced through multiple pathways, such as the creation of specialized hardware for stimulation and recording, the development of software tailored for monitoring and data analysis, and advancements in anesthesiology.

While pioneers in Japan and the United States, such as Tamaki and Kurokawa, invented methodologies for spinal cord-evoked potentials, and Nash and Brown contributed to the field of somatosensory-evoked potentials, the use of transcranial stimulation was not reported until the 1980s by Merton and Morton.

The expansion of IONM has been pivotal to the field of Neuroscience, due to its enduring impact on our understanding of complex systems interwoven by neurons in the sensory, motor, and interneuron networks. Such innovative approaches have also had transformative implications for clinical applications, including those involving invasive treatments. On the matter of high-risk surgical treatments for disorders of the spinal cord, intraoperative monitoring has been a vital aid to the surveillance of neurological functions, preventing possible iatrogenic injuries [6]. Intraoperative neuromonitoring can be of essential value, providing real-time feedback to surgical personnel regarding a patient's neurological functioning, and it can produce indispensable support of anatomical localization via mapping [6]. The mapping of the dorsal column and midline is of the utmost value for patients with spinal cord distortions caused by tumors, which can be challenging to navigate otherwise. The identification of essential structures aids in the accurate implementation of many surgical approaches [7]. Most importantly, the mapping of the spinal cord through intraoperative methods has been crucial for understanding the inner workings of the sensory system, as it

identifies structures of ascending and descending sensory pathways via the mapping of the dorsal columns [6].

In this literature review, we will explore the complexities of using intraoperative monitoring for the functional mapping of the spinal cord's sensory system. We will examine methodologies such as Somatosensory Evoked Potentials (SSEPs) and Motor Evoked Potentials (MEPs), with a particular focus on the Bulbocavernosus Reflex (BCR) and the Hoffman Reflex (H-reflex). Additionally, we will consider the role of computational modeling and briefly discuss the potential for neuroplasticity in the context of spinal cord injuries.

Interneuron Network

Mapping the sensory circuits of the spinal cord involves identifying and understanding the pathways through which sensory information travels from the peripheral nervous system (PNS) to the central nervous system (CNS) (Figure 1) [8]. Between the sensory and motor neurons are interneurons that integrate all functions [8,9]. The five sensory functions are mechanosensation, proprioception, stereognosis, vibration, weight discrimination, and tactile discrimination, all of which are sensory inputs that form part of the functional network. Additionally, nociception (the perception of pain) and temperature are also affected. Different intraoperative neurophysiological monitoring (IONM) techniques are utilized to assess these sensory inputs during surgeries, such as somatosensory evoked potentials (SSEP) and motor evoked potentials (MEP). Mapping the sensory circuit may provide a deeper understanding of how the nervous system processes different inputs and develop essential treatments for sensory disorders, spinal cord injuries, and diseases affecting the nervous system [10].

The dorsal column-medial lemniscus (DCML) pathway transmits mechanoreception and proprioception from the skin and joints to the brain [10]. The anterolateral system (ALS) carries pain and temperature signals through the spinothalamic tract [11,12]. Nerve fibers in the corticospinal tract (CST) travel from the cerebral cortex to the spinal cord to produce movement-related signals [9,13]. For example, Takeoka and Arber [14] concluded that the roles of proprioception in mice after injury were age-dependent and task-specific. Comparing juvenile circuits and mature circuits in mice showed an increased level of malleability at the synaptic level. Considering the movement of the mice and their performance on the treadmill differed. In the spinal cord, sensory signals travel through the dorsal columns [13,15]. Depending on whether the touch is fine or crude, mechanosensation may be processed by either DCML or ALS [13]. Pain and temperature are conveyed through specialized nerve endings (nociceptors and thermoreceptors) through the anterolateral system and lateral spinothalamic tract [11]. While the CST, DCML, and ALS serve distinct functions, their integration occurs at multiple levels, contributing to sensory-motor coordination [16]. Proprioceptive feedback from the DCML and sensory inputs from the ALS allow motor actions via the CST, making these pathways interconnected in sensory-motor functions [14].

The fundamental IONM techniques used to assess the functional integrity of sensory and motor pathways during surgery are Somatosensory Evoked Potentials (SSEPs) and Motor Evoked Potentials (MEPs).

Somatosensory Information travels from the peripheral nerves to the cortex and is measured through SSEPs. The descending motor pathways are measured through motor evoked potentials (MEPs) from the motor cortex to peripheral muscles [17,18]. Damage to upper motor neurons leads to spastic paralysis or central paralysis, while injury to lower motor neurons results in flaccid paralysis or peripheral paralysis [11]. Additionally, motor impairment is possible after spinal cord lesions due to the disruption of descending pathways [14]. A research study analyzed how proprioceptive afferent neurons interact with the spinal cord circuit to maintain locomotion post-injury. Utilizing kinematic behavioral analyses and circuit tracing experiments, the researchers' findings supported that proprioceptive feedback below the injury is critical for initiating locomotor recovery and descending circuit rearrangements [14].

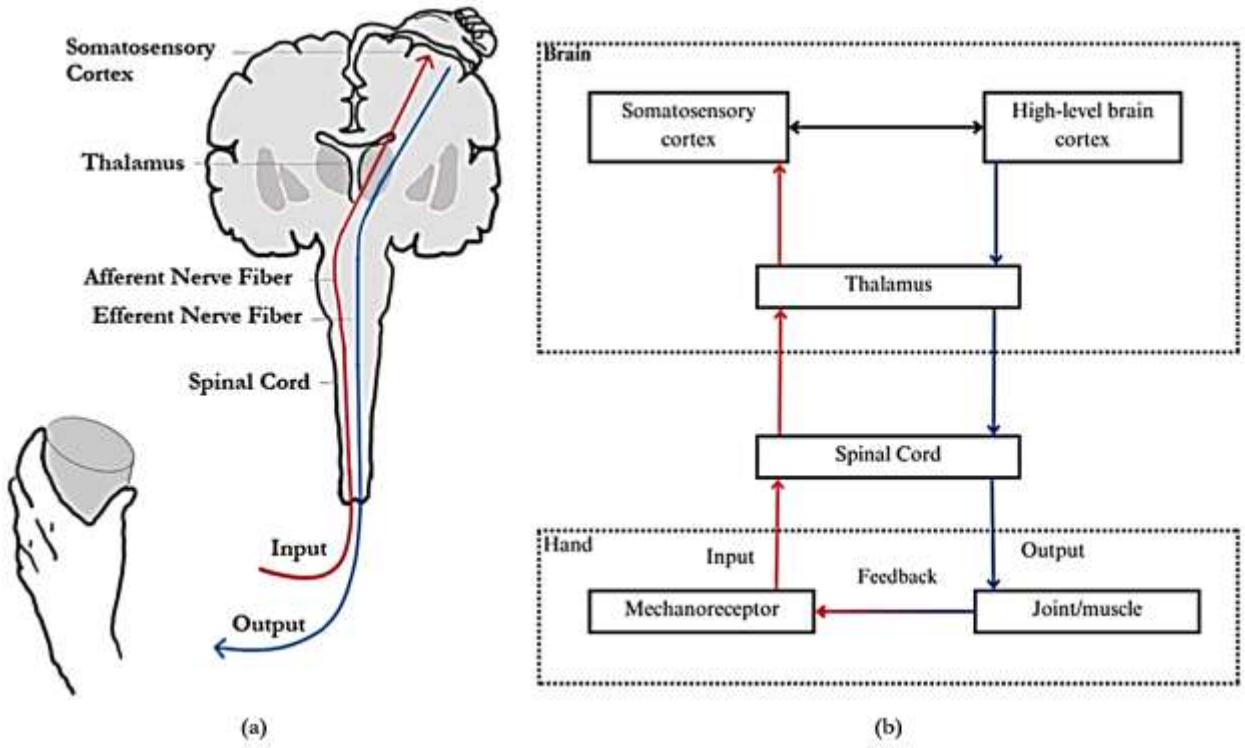

Figure 1. Human somatosensory pathway. (a) Schematic diagram. (b) Flow chart. The red line is the ascending somatosensory pathway, and the blue line is the descending motor pathway. *(Illustrated by Asma Mohammed and Cherrender Brown).*

Additional modalities are employed in clinical studies to elucidate further the sensory circuit map and the benefits of spinal cord surgeries. Transcutaneous spinal cord stimulation (tSCS) was previously utilized for mapping the spinal sensorimotor network [19]. In intramedullary spinal cord tumors (IMSCTs), multimodality is used in cases where SSEPs or MEPs are lost, and the D-wave (direct wave) stimulation is present, which provides precise accuracy and predictability in monitoring [20]. In a ten-year single-sentence experience, Tropeano et al. [20] studied how D-wave monitoring was reliable in instances where

SSEPs or MEPs were lost in intramedullary spinal cord tumors (IMSCTs). In addition, postoperative neurological deficits were predicted with higher accuracy in D-wave monitoring compared to SSEP and MEP alone. Multiple modalities could be beneficial by providing a more precise perspective on spinal cord surgeries and outcomes.

Considering the clinical approach to mapping the sensory circuit, additional measures are incorporated. Quantitative Sensory Testing (QST) may measure psychophysical thresholds for sensory nerve function [17]. QST can facilitate sensory loss or gain in nociception, temperature, mechanosensation, and vibration in specific sensory functions, such as nociceptive responses along different afferent nerve fibers and central pathways [17]. Although QST is not an IONM modality, it provides valuable insights into sensory nerve function in clinical and research settings by measuring patient responses to controlled stimuli.

Spinal Segment Mapping

As sensory input is carried through spinal segments, segment-specific mapping of these pathways determines how and where signals engage with interneuronal networks for processing (Figure 2). Although the same sensory pathways may pass through all segments, the neurons that process sensory signals are activated only in specific segments based on where the input originates. There are three main ascending tracts, which are the dorsal column-medial lemniscus tract, the spinothalamic tract, and the spinocerebellar tract.

The spinal cord is divided into 31 segments corresponding to the vertebral levels: 8 cervical, 12 thoracic, five lumbar, five sacral, and one coccygeal. Each segment gives rise to a pair of spinal nerves, which innervate specific dermatomes or regions of the skin. These segments exhibit specialized functions depending on their anatomical location.

The cervical spinal segments (C1-C8) process sensory input from the neck, shoulders, arms, and hands. For instance, when you touch something with your hand, the tactile stimulus, such as pressure or touch, is processed by sensory neurons located in the cervical spinal segments (C5 to C8). This signal is then transmitted upward through the dorsal columns (specifically, the fasciculus cuneatus) of the spinal cord to higher segments. It ultimately reaches the brainstem, particularly the medulla, before continuing to the somatosensory cortex in the brain.

The thoracic spinal segments (T1-T12) are responsible for processing sensory input from the chest, back, and parts of the abdomen. For instance, when you feel pain or touch your chest or back, this sensory information is processed in the thoracic segments (T1-T12). From there, the signals travel along two main pathways: the spinothalamic tract, which conveys pain and temperature sensations, and the dorsal column pathway, which transmits information about touch and proprioception. These signals ultimately reach the brainstem, thalamus, and then the somatosensory cortex in the brain [22,23].

The lumbar spinal segments (L1-L5) are responsible for processing sensory input from the lower back, hips, thighs, knees, and feet. For instance, if you stub your toe or feel pain in your lower leg, sensory neurons in

the lumbar spinal segments (L4 to L5) will process this pain signal. The signal is then transmitted through the spinothalamic tract or the dorsal columns to higher spinal segments, continuing up to the brainstem (medulla) before reaching the thalamus and the somatosensory cortex [13,22].

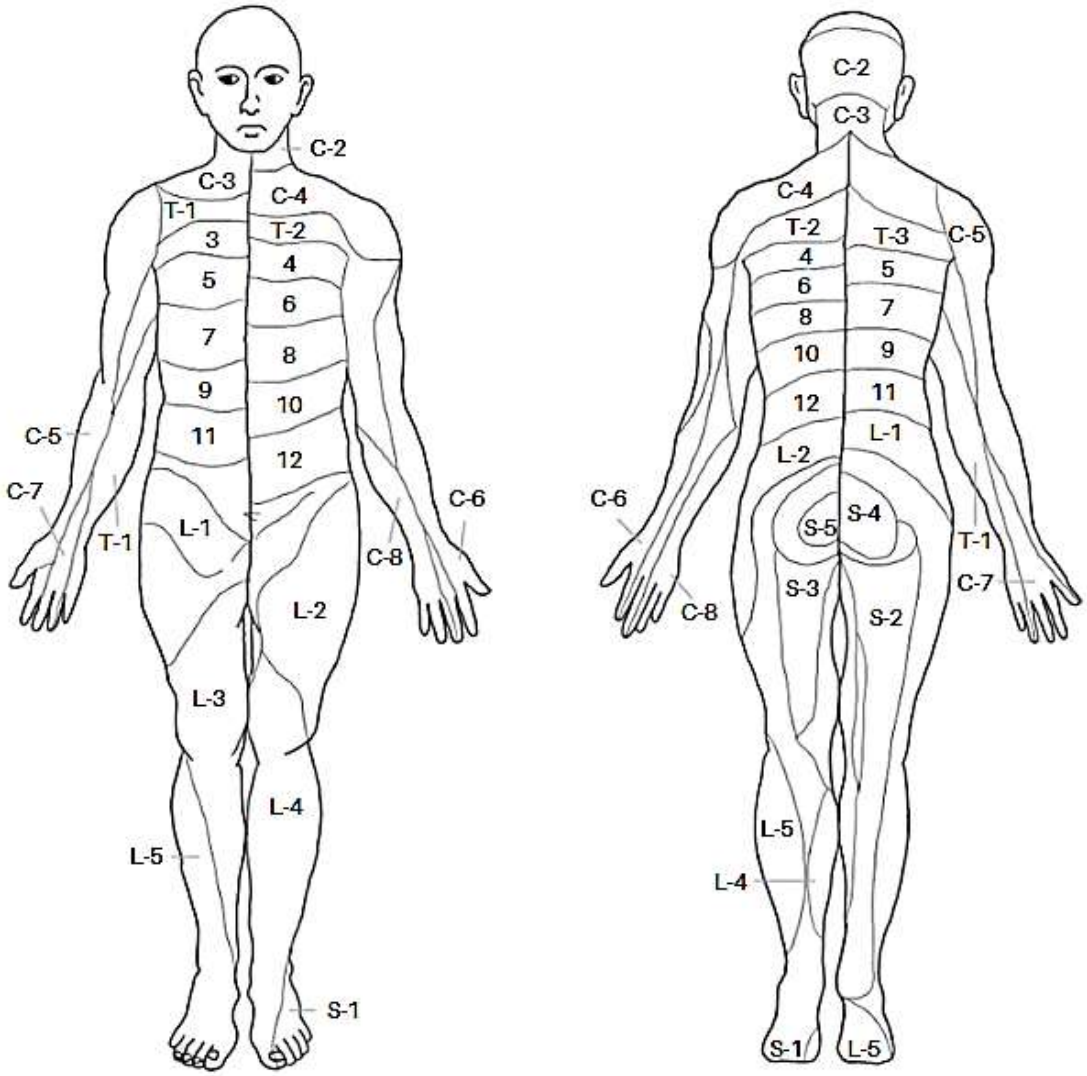

Figure 2. Map of Spinal Dermatomes. Labeled by the innervating dorsal root of the vertebra. *(Illustrated by Asma Mohammed).*

The sacral spinal segments (S1-S5) are responsible for processing sensory input from the pelvis, buttocks, genitals, and parts of the lower legs [21]. For instance, when you feel sensations such as pressure or discomfort in the pelvic area (for example, due to bladder or bowel distension), these signals are processed by neurons in the sacral spinal segments (S2 to S4) [21]. The sensory information is then transmitted

upward through the spinothalamic tract or dorsal columns to higher spinal segments. Eventually, it reaches the brainstem and continues to the somatosensory cortex, where it is consciously perceived. [13,24].

Spinal dermatomes are distinct regions of the skin that receive sensory innervation from the dorsal roots of the spinal cord [25]. Each of these dermatomes corresponds to specific vertebrae that emerge from the spinal column, with identifiable labels indicating their association. Although the boundaries of these dermatomes are often depicted in diagrams, it's important to note that they are not rigidly confined within these lines. Instead, dermatomes typically encompass broader areas, overlapping with adjacent regions and exhibiting variability among individuals. This intricate mapping highlights the complex relationship between the spinal cord and the sensory perception of the skin across the body.

Different reflexes are tied to specific spinal segments. These reflex arcs are confined to specific segments because each segment has connections to sensory neurons, interneurons, and motor neurons that control the muscles and corresponding regions of the body. Cervical reflexes control the muscles in the arms and shoulders, lumbar reflexes control leg muscles, sacral reflexes govern pelvic functions, and thoracic reflexes, less involved in limb movement, control muscles involved in posture, breathing, and autonomic responses [26]. Thus, while the same pathways may technically pass through all segments, the neurons that process or relay sensory information are specific to each segment, depending on the source of the sensory input.

Bulbocavernosus Reflex (BCR) and Hoffmann reflex (H-reflex)

The Bulbocavernosus Reflex (BCR) is an oligosynaptic spinal reflex arc mediated by the S2-S4 sacral segments, elicited through precise pudendal nerve stimulation and recorded from the external anal sphincter (EAS) via electromyography (EMG) [27]. When integrated with multimodal neuromonitoring, BCR monitoring provides real-time evaluations of sacral afferent and efferent pathways and becomes an indispensable tool in surgeries involving the conus medullaris and cauda equina, where sacral neural integrity is significantly at risk [28]. Continuous monitoring of sacral reflex circuits serves as a cornerstone in preventing postoperative urogenital and EAS dysfunction [29].

Intradural surgeries for tumors such as schwannomas, ependymomas, and meningiomas benefit from BCR monitoring by enhancing surgical precision, minimizing nerve injury risk, and improving postoperative. BCR monitoring is equally pivotal in posterior lumbar fusion surgeries for spinal stenosis, kyphosis, scoliosis, and vertebral fractures, as it helps preserve sacral reflex integrity and mitigate postoperative voiding dysfunction [30]. For optimal BCR monitorability, stimulation parameters include a train of 4 pulses, a 0.5 ms pulse duration, 40 mA intensity, and an inter-stimulus interval (ISI) of 3 ms, as determined by Skinner and Vodušek [31]. Earlier studies by Deletis and Vodušek [27] recommended double pulses with a 0.5 ms duration, 20 mA intensity, and an interstimulus interval (ISI) of 3 ms; however, trains of 4 or 5 pulses were later found to be more effective [32]. While there is no universally "optimal" standard, these parameters, combined with appropriate anesthesia, enhance monitorability and efficiency in intraoperative BCR monitoring. BCR is an efficient multimodality neuromonitoring tool for reducing postoperative genitourinary complications in pediatric and adult patients undergoing surgery involving cauda equina. We

found consistent efficacy of BCR in multiple studies, including Cha et al., Sala et al., and Nonaka et al. [33–35].

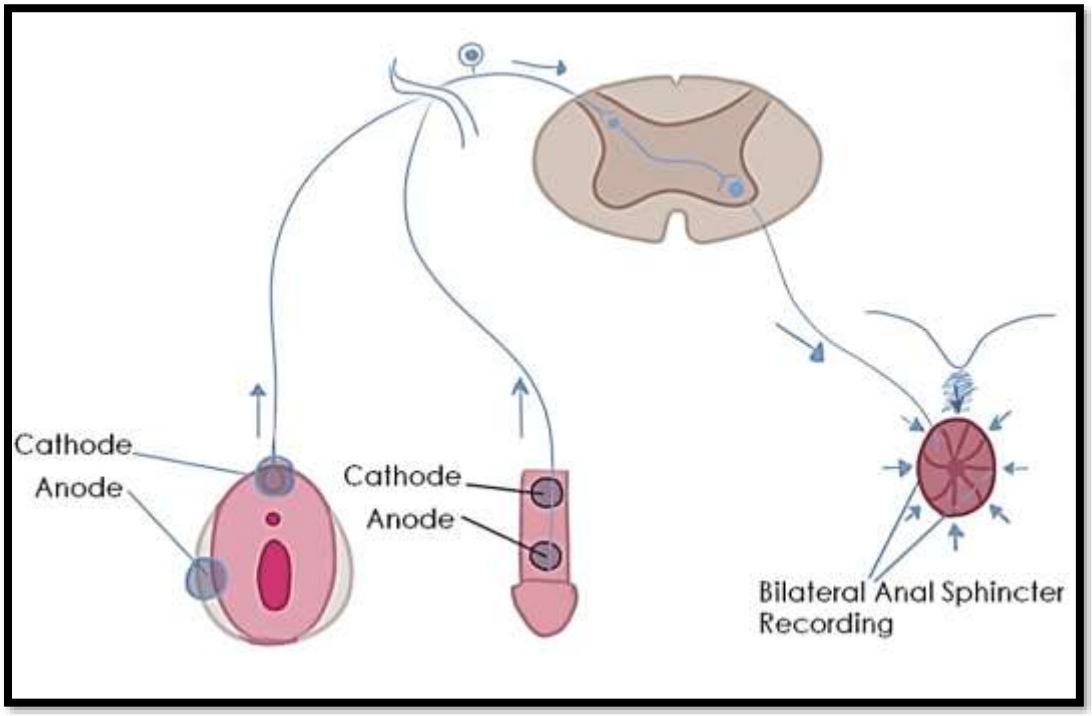

Figure 3. Schematic representation of the BCR stimulation & recording: sacral segment of spinal cord, male and female anatomy (lower left), and anal sphincter (lower right). *(Illustrated by Ayesha Ahmed).*

The Hoffmann reflex (H-reflex) is a monosynaptic spinal reflex used to assess the functional integrity of nerve roots and motor pathways at both lumbar (S1-S2) and cervical levels (C6-C7). It is elicited by electrically stimulating the tibial nerve for the soleus muscle at the lumbar level and the median nerve for the flexor carpi radialis at the cervical level [36]. Intraoperative neurophysiological monitoring (IONM) of the H-reflex is particularly effective in lumbar decompression, sacral nerve procedures, and cervical laminectomies, preserving nerve root function [37]. In cervical cases, the C6-C7 H-reflex provides precise feedback on nerve root integrity by stimulating the median nerve and recording from the flexor carpi radialis [38].

The M-wave, a direct motor response from electrical stimulation of motor neurons, serves as a baseline measure to ensure consistent stimulus intensity and distinguish reflex activity from direct motor activation [39]. The H-reflex is elicited with a stimulation intensity that activates Ia afferents, maintaining a small M-wave for submaximal responses. A pulse duration of 0.5–1 ms is used, with an interstimulus interval (ISI) of 80–120 ms for presynaptic inhibition studies and 8–10 seconds to prevent post-activation depression, ensuring reliable reflex measurements [40]. In trauma cases involving cervical or lumbar regions, the H-

reflex detects early functional deficits with high specificity, even when structural imaging appears normal [36]. It also facilitates motor recovery through neurophysiological tracking, while operant conditioning protocols enhance neuroplasticity and functional rehabilitation [41]. The H-reflex is a valuable diagnostic tool that assesses the integrity of the S1 spinal segment, along with multimodality monitoring, for rehabilitation in prosthesis applications [42].

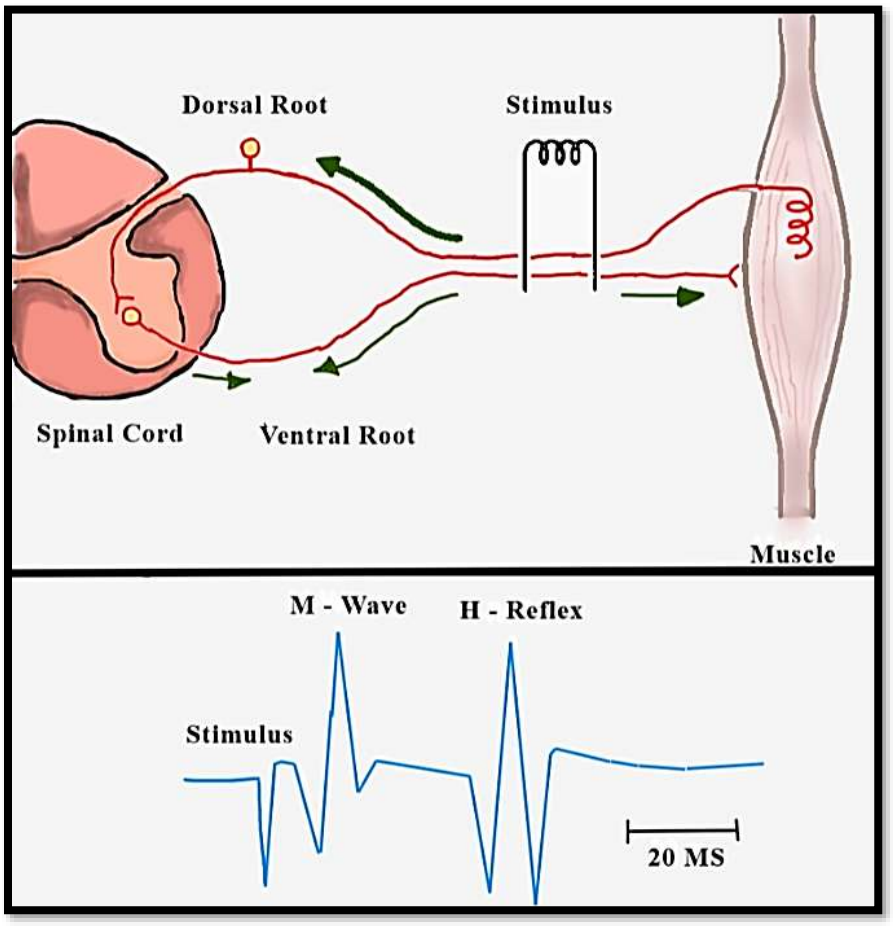

Figure 4. Low-intensity tibial nerve stimulation generates the H-reflex, whereas higher-intensity stimulation recruits motor fibers, producing the M-wave. As intensity increases, the H-reflex diminishes and disappears above 20 mA. *(Illustrated by Husna Ahmed).*

Distal tibiofibular joint manipulation significantly increased soleus muscle activation by elevating the H/M ratio, demonstrating the therapeutic potential of manual therapy to enhance motoneuron pool excitability in chronic ankle instability [43]. This application complements the H-reflex's role in rehabilitation, where it tracks progress and enables individualized therapy adjustment [40]. Its high specificity for differentiating central and peripheral motor dysfunctions and sensitivity to subtle impairments make it invaluable for diagnosing radiculopathy, spasticity, and nerve root injuries [37].

Plasticity

The mechanisms by which the nervous system spontaneously reorganizes structures, functions, or connections in response to intrinsic or extrinsic stimuli are known as plasticity. The functions of motor, sensory, and autonomic systems can spontaneously return or recover to varying degrees, depending on the severity of the lesion. Plasticity can also be described as short-distance sprouting above and below a lesion, accompanied by changes in synaptic strength, thus enabling the change in connectivity of the CNS [44]. Although there is no conclusive definition of the underlying mechanisms for plasticity, numerous well-documented examples exist. An example included the reappearance of electromyographic (EMG) activity in human leg muscles during assisted locomotion only a few months after complete cervical or thoracic spinal cord injury (SCI). Other studies have demonstrated that the enhancement of axonal regrowth can be made possible through constraint-induced movement therapy taken by individuals with unilateral corticospinal tract injuries [45]. It has been proved that corticospinal tract fibers can regrow or be reorganized with intraspinal neurons after incomplete SCI, to reestablish functional motor circuits [46].

It is postulated that the onset for the return of spontaneous function after complete SCI could be driven by the restoration of excitability of motoneurons via constitutive expression of 5-HT2C receptors, as well as adaptations in polysynaptic flexor reflexes that aid in locomotor circuits, and the rearranging of synapses which might contribute to the initial phases of recovery [47]. Animal studies have also shown that fibers of the reticulospinal tract can sprout below a lesion site after an incomplete SCI, as well as relay cortical commands and induce locomotion after rehabilitation [46].

The understanding of the plasticity of ascending tracts has been less prevalent than that of descending tracts, primarily because such tracts convey unconscious information, such as proprioception, which can be challenging to investigate in animal models. In one study, however, investigators concluded that the lemniscal tracts can sprout and form functional synapses after a dorsal column injury [48].

The use of facilitators that aid in this systematic reorganization has been long explored, including treatments such as the use of axon growth-promoting cell types to stimulate regeneration through the site of injury [44]. Some treatments may affect the signaling of proteins such as Nogo-A, which is responsible for the inhibition of neurite outgrowth, thus leading to the potentiation of axon regeneration and growth [46,49].

There are some complications with plasticity, including that of difficulties experienced by sensory axons attempting to regenerate into the spinal cord, which may result in such axons getting stuck during at the scar-like interface between Schwann cells of the peripheral nervous system and astrocytes of the central nervous system at the dorsal root entry zone [44]. The system used for rehabilitation can have a lot of effects on whether recovery is achieved, and previous studies with animals have shown that antibody treatments used to potentiate plasticity after SCI injury may lead to anatomically abnormal sprouted connections [44,50]. Furthermore, a similar study investigating the combination of a rehabilitation regimen (locomotor training) with antibody treatment led to the conclusion that new neuronal connections potentiated by

antibody treatments may cause disturbances in previously normal behavior, such as abnormal stepping performance in mice. Animals subjected to a locomotive rehabilitation regimen without antibody treatment, however, did not exhibit such abnormalities in locomotive behavior [51]. Such results highlight the importance of further research and the implementation of rehabilitation regimens or plasticity-focused treatments that do not cause further constrictions and do not prove to be suboptimal. As the risk of such interventions producing abnormal behaviors in humans may limit the adaptation of helpful research in animal models into clinical settings, this is crucial.

There is still much to explore regarding the plasticity of the spinal cord. Although current understanding suggests that some level of plasticity is achievable, a host of factors and variables remain either unaccounted for or not entirely understood.

Computational Modeling of the Spinal Network

Computational models of spinal neural networks are essential for simulating the intricate interactions between neurons, synapses, and circuits, offering valuable insights into both normal and pathological spinal cord functions. These models have proven essential in advancing our understanding of spinal cord injury recovery and facilitating the development of more precise therapies [52]. They are particularly effective at replicating motor control circuits, such as reflex pathways, and analyzing sensory information processing, which aids in predicting recovery outcomes and optimizing rehabilitation strategies [53]. Additionally, these models simulate neuroplasticity, offering guidance for treatment planning focused on enhancing spinal cord injury recovery [54]. Computational models are also pivotal in the development of neuromodulation therapies, such as spinal cord stimulation, which provide precise, individualized treatments by mimicking neural activity, ultimately improving therapeutic outcomes [55].

Recent advances have led to the development of direct spinal cord-computer interfaces, enabling improved control of paralyzed limbs in patients with spinal cord injuries. This innovative approach has proven to be a groundbreaking method for restoring functionality and control, demonstrating the significant potential of combining computational modeling with neurostimulation in spinal cord injury recovery [52]. Furthermore, research has emphasized the spinal cord's critical role in facilitating cerebellar motor learning and control, suggesting that computational models incorporating neuromusculoskeletal simulation can further enhance our understanding of spinal-cerebellar interactions [53].

The sheer complexity of spinal neural networks, with their dense synaptic connections and dynamic interactions, presents a significant challenge for comprehensive physiological mapping. Computational models, grounded in mathematical algorithms, offer an invaluable solution by simulating these circuits and providing insights that surpass what can be achieved through direct physiological techniques. Advances in Artificial Intelligence (AI)-assisted modeling have further refined these capabilities, enabling the processing of vast datasets that improve predictions for interventions such as spinal cord stimulation and injury rehabilitation [55]. As these technologies evolve, they promise more personalized and effective

treatments for spinal cord injuries, though fully mapping the spinal cord remains a long-term goal for both science and technology [54].

MATERIALS AND METHODS

Protocol

To develop a comprehensive literature review on sensory circuit mapping in the spinal cord, we organized the sensory circuit components into five main categories: interneuronal functions, spinal segment mapping, the blink reflex and H-reflex, plasticity, and computational modeling of the spinal network. Each member of our team conducted a literature search focusing on one of these categories. Together, we established inclusion and exclusion criteria to ensure a robust understanding of the relevant literature on sensory circuit mapping in the spinal cord.

To synthesize our findings, we combined the individual research results into a unified PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram, providing a clear overview of our collective results. Additionally, we created a separate table to highlight the intraoperative neuromonitoring (IONM) modalities commonly used in sensory mapping, showcasing their prevalence across the selected articles for review. This approach enabled us to systematically present the diverse aspects of spinal cord sensory circuit mapping and IONM techniques(Figure 5).

Study Search

A comprehensive literature search was conducted using PubMed, UT Dallas Library Database, and Google Scholar, and additional references were sourced from other publications. The PRISMA flow diagram was used to outline the study selection process, including identification, screening, eligibility assessment, and inclusion, as illustrated in Figure 5. The titles and abstracts were each independently reviewed and selected based on inclusion and exclusion criteria. Articles that met these criteria underwent a full-text review.

Study Selection & Eligibility Criteria

In conducting this literature review, a systematic approach was adopted to select relevant studies. Keywords used in the search included “mapping the sensory circuit,” “spinal reflexes,” “neuronal plasticity,” and “computational modeling,” along with terms related to BCR, H-reflex, spinal segment mapping, spine anatomy and physiology, spinal cord function, spinal segments, neural pathways, neuronal circuits, neuronal wiring, plasticity, adaptation, neuronal changes, pain, temperature, neuromodulation, mathematical modeling, pathways, synapses, and circuitry gates. The inclusion criteria consisted of studies that addressed the specific research question, employed recognized methodologies, and were published in English. Exclusion criteria included studies that did not provide full text, were not peer-reviewed, were not

written in English, or focused on unrelated topics. A total of 519 studies were initially identified, and through a detailed screening process, 55 studies met the eligibility criteria for this review.

Assessment of Bias

To mitigate bias, each project member independently reviewed and selected articles, analyzed the data, and resolved discrepancies through discussion and consensus.

RESULTS

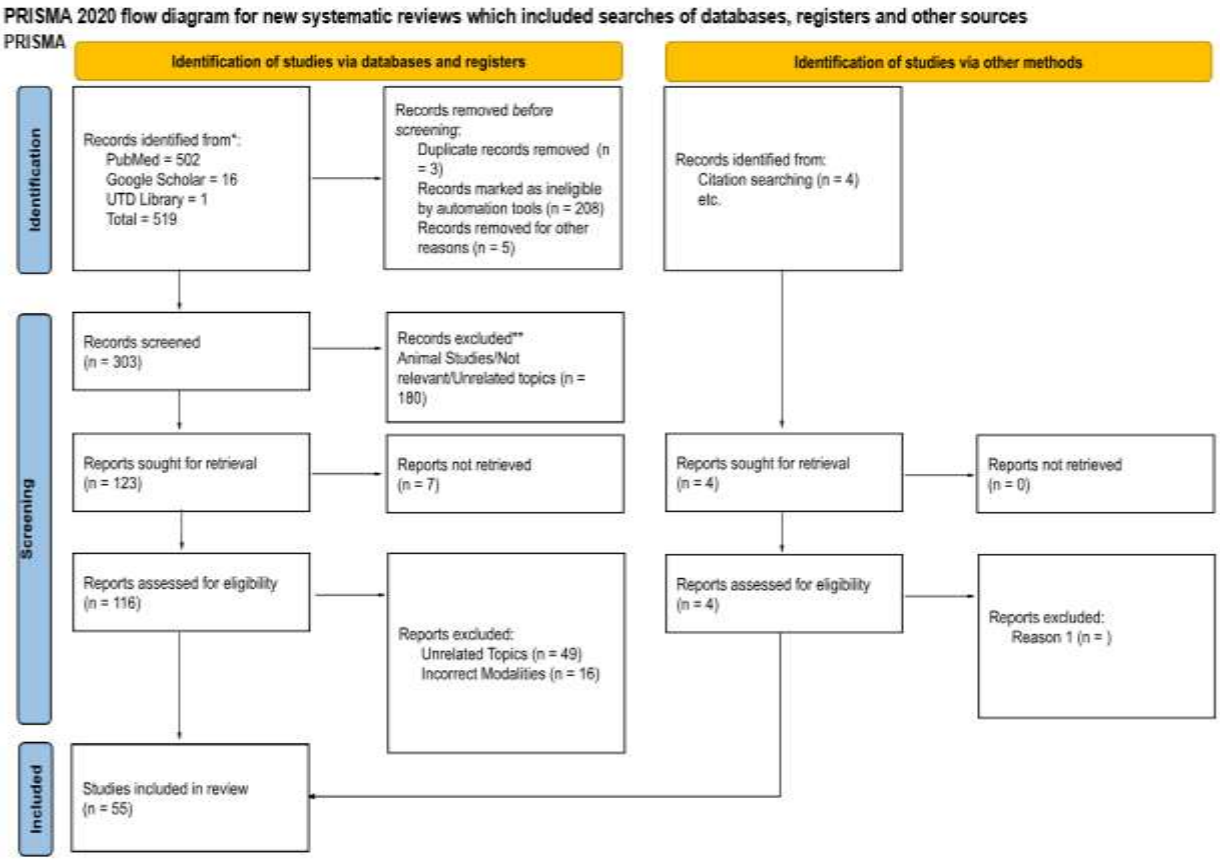

Figure 5. PRISMA Flow diagram of the study selection. Identification, screening, and inclusion of studies.

Literature Search (Results in numbers)

Articles	MEP	SSEP	CHEP	LEP	EMG	BAEP	VEP	D-Wave	BCR	TCeMEP	TOF	H Reflex	M wave	Other
Calderone et al., 2024	X	X	X	X										
Todd, 2022	X	X			X	X	X							
Takeoka & Arber, 2019														
Hofstoetter et al., 2021					X									
Levine et al., 2012														X
Barolat et al., 1993														X
Quinones-Hinojosa et al., 2002		X												
Mazzola et al., 2012														X
Cadotte et al., 2012														X
Guérout, 2021														X
Oudega & Perez, 2012	X				X			X						
Tropeano et al., 2024	X	X						X						
Morota et al., 2019	X	X			X				X					
Choi et al., 2022	X	X			X				X					
Deletis and Vodusek, 1997	X	X			X				X					
Skinner et al., 2007		X			X				X	X	X			
Nonaka et al., 2023	X	X			X				X					X
Cha et al., 2018	X	X			X				X					
Sala et al., 2002	X	X			X				X	X		x		X
Grindstaff et al., 2011					X							x	x	
Nishikawa & Grabiner, 1999					X							x	x	

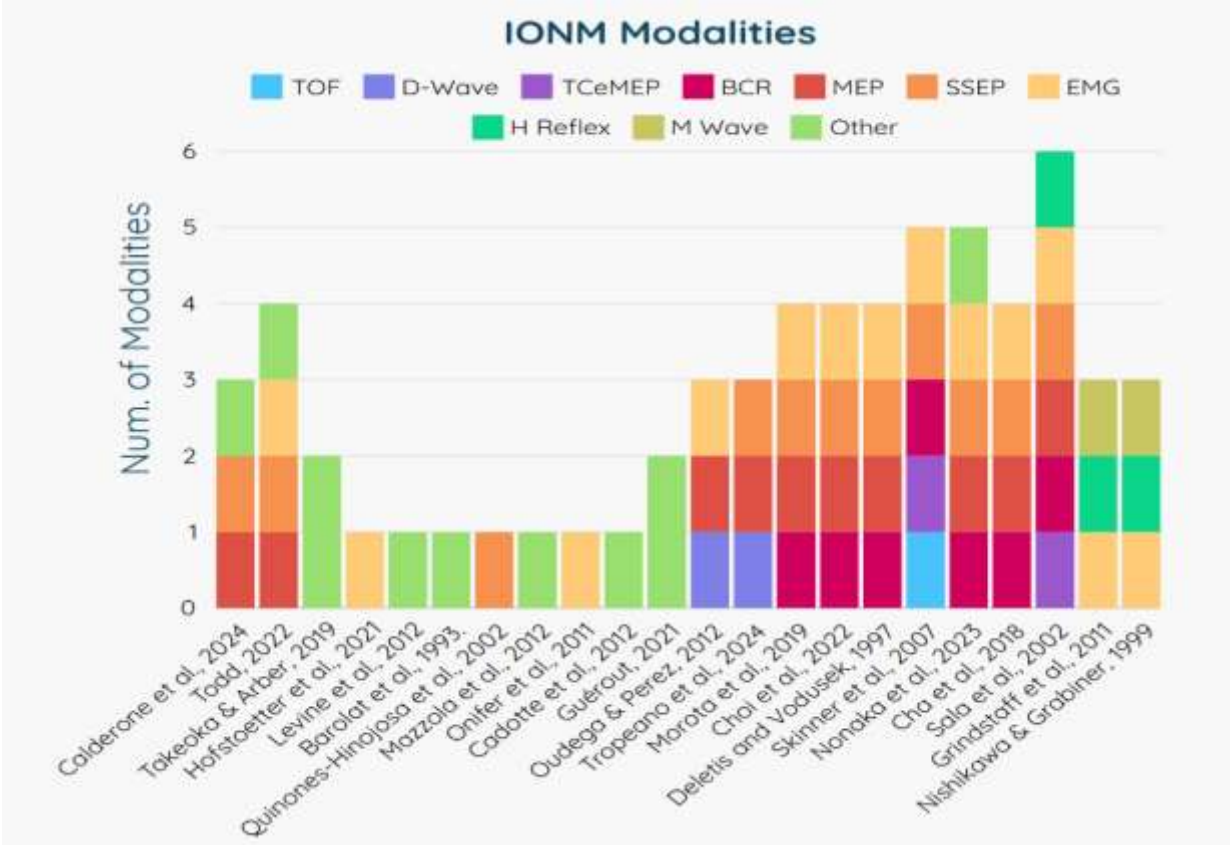

Figure 6. The bar chart illustrates the number and types of intraoperative monitoring modalities mentioned. Twenty-two articles were analyzed, revealing over nine distinct modalities. TOF: Train of Four, D-wave: Direct Wave, TCeMEP: Transcranial Electrical Motor Evoked Potential, BCR: Bulbocavernosus Reflex, MEP: Motor Evoked Potentials, SSEP: Somatosensory Evoked Potentials, EMG: Electromyography, H Reflex: Hoffmann Reflex, M Wave: Motor Wave.

Other modalities include Brainstem Auditory Evoked Potentials (BAEP), Contact Heat Evoked Potential (CHEP), Laser Evoked Potentials (LEP), Repetitive Trans-Spinal Magnetic Stimulation (rTSMS), and Epidural Electrical Stimulation (EES).

DISCUSSION

Interneurons in the sensory circuit integrate information from both the peripheral and central nervous systems. Through research and clinical trials that analyze the five sensory functions, in addition to pain and temperature, researchers have gained more insight and provided validity in mapping the sensory circuit. In highlighting the surgeries, strides are being made to increase patient rehabilitation efforts. Multiple spinal cord mapping modalities, such as somatosensory evoked potentials (SSEPs), motor evoked potentials (MEPs), and D Wave, continue to advance surgical and rehabilitation techniques. Future research might consider the endogenous responses to sensory stimuli and utilize in vivo imaging tools to monitor active circuit changes [10].

Mapping sensory circuits at the spinal segment level provides critical insights into how sensory information is processed across different regions of the spinal cord. While major sensory pathways, such as the spinothalamic tract and dorsal column-medial lemniscus (DCML), extend through all spinal segments, the activation of segment-specific neurons is determined by the location of sensory input. This highlights the regional organization of sensory processing rather than a purely linear transmission model.

Techniques such as somatosensory evoked potentials (SSEPs) are instrumental in identifying the precise sites of sensory reception and tracing the pathways through which signals ascend. A deeper understanding of segmental sensory integration could refine neuromonitoring approaches, optimize interventions for spinal cord injury, and enhance computational modeling of spinal sensory networks. Future research should aim to delineate further the specific structural and functional characteristics of ascending sensory pathways within individual spinal segments, thereby contributing to more precise neurophysiological assessments and therapeutic advancements.

The H-reflex and Bulbocavernosus Reflex (BCR) serve as valuable tools in intraoperative neurophysiological monitoring (IONM), each targeting distinct aspects of neural function. The H-reflex primarily evaluates the integrity of lumbar and cervical motor pathways, offering essential information regarding nerve root functionality during decompression or trauma surgeries. In contrast, the BCR assesses sacral reflex circuits, crucial for preserving pelvic function during procedures involving the conus medullaris and cauda equina [30]. The integration of these reflexes in multimodal monitoring enables comprehensive neural protection by addressing both motor and sacral pathways, which are frequently at risk during complex spinal surgeries. This synergy contributes not only to the preservation of limb motor control but also to the prevention of postoperative urogenital and sphincter dysfunction, thus improving

surgical precision and functional outcomes [32,36]. Despite the recognized importance of these reflexes in safeguarding neural integrity, their routine use in intraoperative neurophysiological monitoring (IONM) remains unsystematic, suggesting a potential for further refinement and standardization in surgical protocols.

Mechanisms for axon regeneration and functional reorganization following spinal cord lesions remain an area of active investigation. While plasticity in descending motor pathways is relatively well characterized, emerging evidence suggests that ascending sensory pathways, including the lemniscal tracts, also exhibit potential for sprouting and structural adaptation.

Various therapeutic interventions have demonstrated efficacy in promoting axonal regrowth in humans, including constraint-induced movement therapy, which enhances neuroplasticity through targeted functional rehabilitation. Additionally, experimental approaches with antibody-mediated therapies have shown promise in preclinical models, though their translational applicability requires further validation.

Despite these advancements, several challenges hinder progress. The monitoring of proprioception in animal models remains a significant limitation, necessitating innovative strategies for assessing plasticity in sensory pathways. Moreover, post-lesion axonal growth is often constrained by scar tissue interfaces, resulting in aberrant connectivity that may lead to maladaptive sensory processing and abnormal behavioral responses. The optimization of therapeutic combinations, such as antibody treatments alongside locomotive training, presents additional complexity, requiring precise modulation to achieve functional recovery without unintended neurological consequences.

Future research should aim to refine strategies for enhancing ascending pathway plasticity, address the barriers posed by inhibitory extracellular environments, and develop integrative therapeutic models that maximize neurophysiological adaptation while minimizing maladaptive outcomes.

CONCLUSION

This literature review analyzed the intraoperative monitoring for functional mapping of the spinal cord's sensory circuit. Research highlights the role of IONM modalities such as SSEPs, MEPs, BCR, and H Reflex in ensuring accurate and precise techniques during spinal cord surgeries and advancing clinical applications. Standardizing the integration of H-reflex and BCR monitoring in spinal surgeries has the potential to significantly enhance neural protection and promote better recovery and functional outcomes. Additionally, literature covering neuroplasticity reveals the recovery mechanisms and therapeutic interventions for spinal cord injuries and sensory disorders.

Spinal segment mapping plays a crucial role in understanding how sensory pathways are organized across different regions of the spinal cord. By identifying the specific segments involved in processing sensory signals, we gain valuable insight into how sensory input is integrated and transmitted. This mapping not only enhances the accuracy of spinal surgeries but also aids in identifying pathways at risk during interventions.

Spinal segment mapping and reflex assessments, such as the Bulbocavernosus reflex and H-reflex, are techniques that have contributed to enhancing our understanding of the sensory pathways. Significant contributions are being made to comprehend the sensory circuit. Future studies that integrate computational modeling with clinical approaches have the potential to advance mapping techniques and improve overall outcomes for patients undergoing spinal interventions. This additional insight provides a foundation for the approaches that are taken to preserve and restore neuronal function.

Spinal cord injuries present significant challenges; however, the potential for neuroplasticity to mediate functional recovery and promote axonal regeneration offers a promising avenue for adaptation and rehabilitation. Research suggests that the inherent capacity for reorganization within sensory and motor pathways could facilitate the restoration of function, even in cases previously considered irreversible.

Despite this potential, critical questions remain regarding the translational applicability of findings from animal models to human clinical practice. The complexity of neurophysiological remodeling, inhibitory extracellular environments, and systemic factors poses substantial challenges that must be addressed to optimize therapeutic interventions.

While limitations persist, the intrinsic resilience of the human nervous system highlights the body's profound ability to adapt and heal. Advancing our understanding of plasticity-driven recovery mechanisms will be essential in refining clinical strategies aimed at maximizing functional restoration and improving long-term outcomes in individuals with spinal cord injuries.

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