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Intelligent integration of assessment tools for specialized prognosis in spinal cord injuries: A scoping review

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Abstract

Spinal cord injury is a life-threatening condition resulting from spinal cord trauma, leading to paralysis, loss of sensation, bowel and bladder control. Accurate assessment tools are crucial for diagnosing and treating spinal cord injuries, and various scales have been developed for this purpose. Additionally, electrophysiological measures, including somatosensory evoked potentials, motor evoked potentials, and nerve conduction studies, can aid in patient stratification. Recent developments in spinal cord injury assessment have shown promise, particularly with the use of advanced imaging techniques and artificial intelligence. Neuroimaging and molecular biomarkers combined with electrophysiological measures, promise to predict outcomes and guide treatment decisions. Machine learning and Artificial intelligence have revolutionized the healthcare industry, including the field of spinal cord injuries, as they can facilitate personalized medicine by accurately predicting. Challenges remain in validating machine learning models and ensuring they are safe and effective for clinical use. Quality data and expertise are crucial for accurately interpreting and applying machine learning results in spinal cord injury management. Moreover, due to artificial intelligence entering healthcare to assist in processing data, electrophysiology can eventually meet the high-quality information it can provide, as it is easier to analyze data recordings from somatosensory evoked potentials and other electrophysiologic measures. Summing up, the integration of advanced imaging techniques, biomarkers, and machine learning leading to maximizing the use and importance of electrophysiology as far as the information it can reveal, has the potential to revolutionize the diagnosis, prognosis, and treatment of spinal cord injuries, leading to improved patient outcomes and personalized care.

Keywords: Spinal Cord Injuries – SCI; Assessment Tools; Evaluating Tools For SCI; Prognosis In SCI; Diagnosis In SCI; Machine Learning In SCI

1. Introduction

Spinal cord injury (SCI) is a severe condition caused by damage or trauma to the spinal cord. SCIs can result in a range of symptoms, including paralysis, loss of sensation, and loss of bowel and bladder control (Nas et al. 2015). Accurate and reliable assessment tools are essential for diagnosing and treating SCIs. Over the years, various assessment scales have been developed to help healthcare professionals diagnose and monitor SCIs, assess the severity of the injury, and develop effective treatment plans, as these types of injuries vary to a great extent (Kirshblum et al. 2011). The rehabilitation and recovery of individuals with SCIs are usually complex and require collaboration among numerous medical professionals, physical therapists, psychologists, and social workers, aiming to improve the function and quality of life (Behrman and Harkema 2007). This review provides a comprehensive guide to these assessment tools, including their purpose, scoring system, and limitations.

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1.1. Spinal Cord Injuries and Classifications

The SCI classification is based on anatomical and functional criteria. The neurologic level of injury is the most caudal neurologic segment with intact motor and sensory function. Good motor function is considered when the most caudal myotome has a muscle strength grade of three on a five-point scale (Nas et al. 2015).

Traumatic SCIs are classified as incomplete and complete. An injury is considered incomplete when some non-reflexive neurological activity is observed below the level of partial preservation of functionality (i.e., the region immediately below the neurological level of injury where some degree of motor or sensory function is retained). A complete injury is when no motor or sensory function is preserved below the neurological level of injury. The injury is considered complete even in cases where the zone of partial preservation of functionality extends up to three neurological levels below the neurological level of injury. Furthermore, based on the affected areas of the body, SCIs are classified into topographic categories such as Paraplegia, loss of sensation and mobility in the lower extremities, and Tetraplegia, loss of sensation and mobility in all four limbs and the trunk (Kirshblum et al. 2011).

1.2. Evaluating Scales and Tools for Spinal Cord Injuries

Standardized assessment tools have been developed and subsequently validated for accurately estimating and evaluating the neurological conditions of patients with SCI. Every SCI patient admitted to an emergency department should undergo an immediate standardized assessment (Pinchi et al. 2019). Following this, a comprehensive neurological examination is performed to assess sensory, motor, and reflex functions. This examination includes muscle strength, sensation, coordination, and reflexes in several parts of the body. It includes evaluations such as the International Standards for Neurological Classification of Spinal Cord Injury, which measures basic motor and sensory elements (Kirshblum et al. 2014). Below is a list of all the scales used to describe a SCI case (table 1).**Table 1** Evaluating scales used in defining Spinal Cord Injuries.

Table 2 Evaluating scales used in defining Spinal Cord Injuries

Authors	**Date**	**Rating Scale**	**Scale characteristics**	**Assessment of Functional Abilities**	**Restrictions**	**Diagnostic/ Prognostic Value**
Frankel et al.	1969	Frankel Scale	5-point SCI assessment scale	Not assessing functional abilities/ Acts predictive of skill acquisition only in perfect CSI	Evaluates limited data/ Requires patient to have consciousness & communication skills	Diagnostic & Prognostic
Waters et al.	19821992199 620002006	ASIA Impairment Scale (AIS)	5-point scale for SCI/ assessment of 28 dermatomes & myotomies for movement of 10 key joints, assessment of clamps	Not assessing functional abilities/ giving data on expected recovery of functional abilities especially in complete SCI lesions	Requires the patient to have consciousness & communication skills	Diagnostic & Prognostic
Mahoney & Barthel	1965	Barthel Scale	Evaluation of 10 variables	Specialized in the assessment of activities	Not specific to SCI/ more ideal for incomplete SCI	Diagnostic

				of daily living		
Ottenbacher et al.	1996	Functional Independence Measure Scale	Evaluation of 18 variables	Specialized in self-care & mobility assessment	Higher scores due to insufficient grading, unrepresentative scores on cognitive & social variables	Diagnostic
Catz	1997	Spinal Cord Independence Measure Scale	Assessment of 3 subscales and 19 variables	Assesses self-care ability	Not evaluating the gradation in movement quality	Diagnostic
Waters et al.	1994	Lower Extremities Motor Score	AIS scale subcategory for lower extremity scoring	Assesses the likelihood of gait recovery	Ideal only for incomplete SCI lesions	Diagnostic & Prognostic
Ditunno et al.	2000 2001	Walking Index for Spinal Cord Injury Score	Assessing the need for an aid to achieve walking in 21 levels	Assesses functional activities & provides data on the patient's degree of autonomy	Not suitable for quadriplegic patients & muscle strength less than 3 in triceps	Diagnostic
Bohannon & Smith; Dunning et al.	19872011	Ashworth Scale	5-point muscle tone assessment scale (0 to 4)	Evaluates according to the degree of spasticity, the chances of recovery of functional activities	Stretch application may vary from therapist to therapist/ differences in score	Diagnostic

Additionally, a wealth of information for more precise localization and description of the injury is provided by various imaging techniques. These techniques are described in the following table (table 2).

Table 3 Evaluating tools used in assessing Spinal Cord Injuries

Authors	**Date**	**Assessment Tool**	**Usefulness**
Guarnieri et al.	2016	X-rays in SCI	To diagnose the traumatic abnormality, characterize the type of injury & assess the severity to avoid neurological deterioration.
Freund et al.	2019	Magnetic resonance	MRI of the spine is the gold standard for evaluating any damage to the disc and neural structures caused by mechanical trauma.
Goldberg & Kershah	2010	Computed Tomography	A CT scan of the spine is a diagnostic imaging test used to help diagnose damage to the spine in injured patients. It is a quick, painless, non-invasive, and expensive solution. In emergencies, it can reveal internal injuries and bleeding fast enough to help save lives.

Singh et al.	2020	Electromyogram/ Neural Conduction Studies	There is a strong connection between electrodiagnostic findings and the ASIA scale in predicting neurological deficit and subsequent recovery after acute traumatic SCI.
Jamison et al.	2011	Urodynamics - Gastroenterology Examinations	In SCI, disorders in the functioning of the gastrointestinal and urinary systems coexist, so a diagnosis must be made for proper bladder and bowel management.
Ji et al.	2013	Somatosensory Evoked Potentials	Somatosensory evoked potentials assess the nerve pathway from the arms and legs through the spinal cord to the brain and are used to identify spinal cord injuries or diseases.

1.3. Application of Electrophysiological Measures in Spinal Cord Injury

The use of electrophysiology in diagnosing SCI can facilitate patient stratification, evaluation of adverse events, and prediction of therapeutic outcomes (Korupolu et al. 2019). However, various issues arise regarding the establishment of protocols, as electrophysiological studies require specialized, costly equipment and well-trained staff to ensure reliable data acquisition with standardized recording configurations, test conditions, protocols, and data processing/analysis. The effort to standardize environmental conditions, especially for multicenter studies, may limit the selection of participating centers to those with the required technical capabilities and expertise. Discussion is being made in various electrophysiological evaluations that can be used in clinical trials for SCI, with the most prevalent being somatosensory evoked potentials, motor evoked potentials, and nerve conduction studies (Curt and Ellaway 2012). These assessments examine large, myelinated nerve fibers by applying artificial electrical or magnetic stimuli.

According to neurophysiology, the term "evoked potential" is used to describe the electrical potentials recorded in humans or animals following the application of a stimulus, differentiating it from spontaneous potentials such as electroencephalograms or electromyograms (Fustes et al. 2021). Evoked potentials (EPs) are classified as a subcategory of potentials, known as event-related potentials (ERPs). ERPs are essentially potential differences that are directly or preparatorily elicited by a specific event in the human brain, which can be cognitive, sensory, or motor-related, and are usually measured on the scalp surface. The event that can trigger a potential difference can be any external stimulus, concerning the subject's environment (evoked potentials) or may represent an endo-psychological process of it (emitted potentials). EPs provide non-invasive methods for assessing the neural activity of the nervous system. Given the anatomical characteristics of sensory and motor pathways and their relationship to areas associated with physical, conscious, and cognitive processes, EPs can represent a significant source for detecting neurological disorders. They can reveal nervous system disorders that may not be detected by conventional methods. The use of EPs is a non-invasive method of studying brain activity during cognitive processes (All and Al-Nashash 2021).

In the last fifty years, with the development of informatics and computers, the use of EPs has evolved from research laboratories to clinical neurology applications. These stimuli are commonly used for clinical studies. The clinical evaluation of the level, extent, and severity of SCI can be complemented by electrophysiological recordings. These techniques provide an early diagnosis of neurological diseases in patients with acute SCI and have prognostic value in patients who are unable to cooperate. Electrophysiological recordings and SSEPs have similar significance in predicting gait ability, hand function, and bladder function as clinical examination according to American Spinal Injury Association (ASIA) standards. Neuro-electrophysiological evaluations using SSEPs are employed to provide a comparative analysis of functional changes among different SCI cases (Hubli et al. 2019).

Specifically, ASIA scores and SSEPs are associated with the outcome of walking ability in patients with acute SCI. In cases where patients are non-compliant or uncooperative, SSEPs have supplementary value for clinical examinations (Singh et al. 2020). Therefore, the combination of clinical and electrophysiological examinations can be of additional diagnostic value in assessing acute SCI. Searches about *Somatosensory Evoked Potentials in Spinal Cord Injuries* are shown in the table below (table 3).

Table 4 Studies where Somatosensory Evoked Potentials were used in evaluating Spinal Cord Injuries

Authors	Date	Background	Results
Fustes et al.	2021	Utilization of SSEPs in neurological conditions, including Chronic SCI, affecting central & peripheral nervous systems. Role in demyelinating diseases, monitoring coma & trauma patients. Assessing sensory pathways during surgical interventions.	The advent of information technology has facilitated digital analysis, resulting in a significant increase in the clinical application of SSEP and other EP studies. Still, there is the necessity to define the practical boundaries and appropriate utilization of Eps.
All & Al-Nashash	2021	Comparison of the SSEP & motor behavioral assessments of 2 commonly used rodent SCI models (contusion & transection). Understanding functional similarities & differences during the acute phase.	Despite having distinct pathophysiologies, contusion, and transection SCIs display similar trends in injury progression during the acute phase.
Li et al.	2021	Electrophysiological recordings conducted on the brachial muscles of rats to investigate the involvement of spinal cord pathways in motor function.	Suggesting that changes in SSEPs & MEPs can reflect alterations in gross and fine motor functions after mild spinal cord contusion injury. Change in SSEP amplitude may serve as an indicator of fine motor function after severe SCI.
All et al.	2020	Behavioral evaluation with Basso, Beattie, and Bresnahan scoring, is subjective. Neuro-electrophysiological monitoring (SSEP assessment) offers an objective and continuous approach for longitudinal studies.	Incorporating SSEP monitoring & conventional BBB scoring in SCI research to effectively standardize injury progression & obtain comprehensive insights into the injury mechanisms.
Korupolu et al.	2019	Electrophysiological outcome measures, including SSEP, are reported in clinical trials for SCI, with the goal of informing a future consensus study.	Need for the development of standardized reporting guidelines for electrophysiological outcome measures in SCI clinical trials.
Hubli et al.	2019	Electrophysiology to future clinical trials in SCI, specifically in terms of enhancing SCI diagnosis, patient categorization, & determining exclusion criteria; evaluating adverse events; assessing therapeutic effects post-intervention.	Tailored electrophysiological measures can characterize the location & completeness of SCI & reveal the integrity of neurons below the injury site, which is crucial for the success of any interventional trial.
Cheng et al.	2019	Assessing alterations in SEP & the impact of decompression timing on spinal cord recovery and evoked potentials in rats with SCI, by measuring SEP at various time points.	SEP is a reliable indicator of the severity of SCI. Prolonged spinal cord compression leads to more significant changes in SEP. Changes in SSEP amplitude are more sensitive than latency changes for early diagnosis and prompt assessment of SCIs.
Bazley et al.	2014	Cortical somatosensory evoked potentials were utilized to assess changes in the intact forelimb pathways in rats.	SSEPs detect significant enhancements in the activation of forelimb sensory pathways following both midline and unilateral contusive SCI at T8. Suggesting the possibility of forelimb pathway reorganization after thoracic SCI, which SSEPs can monitor, potentially aiding the development of future therapeutic approaches.
Ji et al.	2013	Use SSEP detection technology to monitor spinal cord ischemia-reperfusion injury, in rabbits.	Changes in SSEP latency reflect the extent of SCI, whereas variations in amplitude serve as indicators of late spinal cord reperfusion injury. Valuable for assessing limb motor function & avoiding iatrogenic SCI.

Mutoh et al.	1991	SEPs resulting from stimulation of the posterior tibial nerve (PTN) in 8 infants and children diagnosed with focal spinal cord disorders.	PTN-SEPs have the potential to aid in diagnosing focal spinal diseases, particularly in infants and young children who may not be able to cooperate with detailed neurologic examinations.

2. Subject and Methods

For this review article, a comprehensive search was conducted in the period of time from 01/12/2022 until 30/7/2023, on published medical literature using several electronic databases including Medline, Google Scholar, Science Direct, Sci-Hub, and PubMed. The research used keywords such as *spinal cord injuries, spinal cord injury scales, evaluating tools for spinal cord injuries, somatosensory evoked potentials, and neurophysiology in spinal cord injuries, artificial intelligence, machine learning in SCI*. A flowchart describing the process of searching articles is presented below (figure 1).

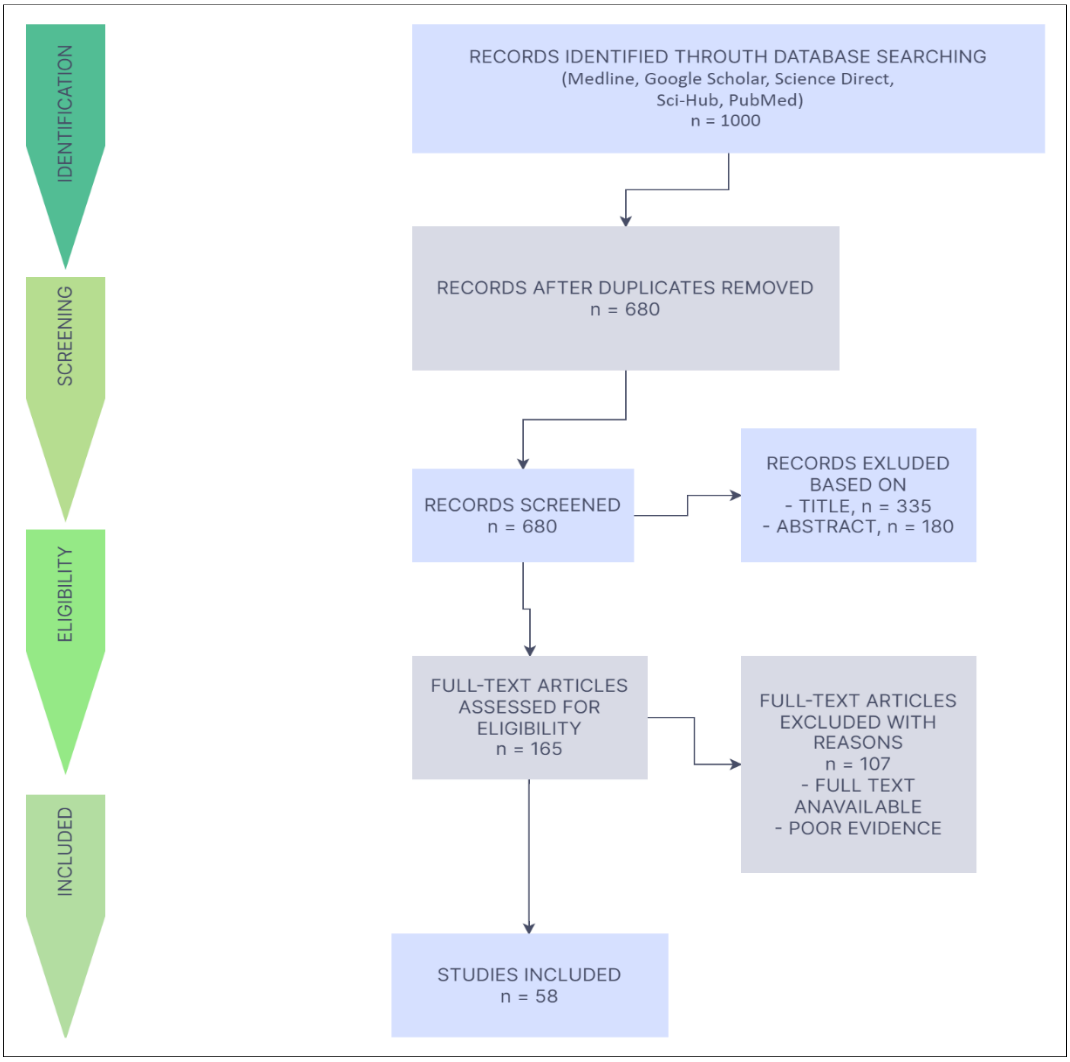

Figure 1 Flowchart

3. Results

Regarding the diagnostic and prognostic value of other imaging techniques in the field of SCI, diffusion imaging is a promising technique that can offer more detailed imaging of the injury compared to conventional magnetic resonance imaging (Middendorp et al. 2011). Additionally, the neurological examination according to the International Standards for Neurological Classification of Spinal Cord Injury has become the cornerstone for assessing the severity and level of injury. As for treatment, it has been noted that despite promising progress in basic research for spinal cord restoration, there is currently no effective treatment leading to significant neurological or functional recovery after SCI. Nevertheless, significant advances have been made in the care of patients with SCI during the 21st century, including the prevention of complications and the introduction of specialized care by pioneers in SCI rehabilitation, such as Dr. Donald Munro and Sir Ludwig Guttmann, which has led to increased survival rates in the SCI population.

However, in the current, there have been tremendous strides in the field of assessment, diagnosis, and prognosis of SCIs. Compared to established predictive steps, the last five years have witnessed real progress, with significant contributions from technology and Artificial Intelligence. An excellent example is the Spinal Cord Injury Risk Score - SCIRS, which was developed to estimate the mortality risk for patients who have suffered thoracic SCIs compared to the Injury Severity Score - ISS, a general trauma measurement (Fallah et al. 2022). The analysis showed that age, American Spinal Injury Association Impairment Scale (AIS) classification, neurological level of injury, spinal column morphology, and associated injuries were significant predictors of early mortality after tSCI. The ability to predict mortality using a simple, fast, and reliable assessment tool upon a patient's admission to the healthcare setting would greatly assist in making timely clinical decisions and improving the outcome of incidents.

Thus, current prognostic tools, such as the Injury Severity Score, which predicts mortality after trauma, do not adequately consider the unique characteristics of traumatic SCIs. Fallah et al., in a study conducted in 2021, used machine learning techniques on patient data to develop the Spinal Cord Injury Risk Score (SCIRS) that can predict mortality based on age, neurological level and type of injury, SCI, and Abbreviated Injury Scale scores in comparison to the performance of the Injury Severity Score (ISS), a measure used for predicting mortality after general trauma. The results showed that SCIRS can predict in-hospital mortality and one-year mortality after SCI with higher accuracy than ISS. SCIRS can be used in research to reduce bias in parameter estimation and can help in adjusting coefficients when developing models (Fallah et al. 2022).

It is worth mentioning that developing a mortality prediction model poses challenges due to the complex interactions of factors contributing to patient outcomes. Models based on generalized linear models have been used in the past to develop predictive tools in various clinical studies (Kirshblum et al. 2011; Frankel et al. 1969). Nevertheless, despite the advantage of simplicity with directly available and interpretable parameters, these models may not capture the possible interactions and complex behavior of variables often present in biological conditions. Acute traumatic SCI involves primary and secondary injury mechanisms (Witiw and Fehlings 2015). The primary mechanism is related to the initial traumatic damage caused by the catastrophic impact, and this damage is irreversible. The secondary mechanisms, which start a few minutes after the initial injury, include processes such as ischemia of the spinal cord, excitotoxicity, ionic dysregulation, and oxidative stress caused by free radicals (Eckert and Martin 2017). SCI is characterized by different forms of injury, where the exploration of pathology and clinical diagnosis, therapeutic strategies, animal models that have allowed for a better understanding of injury mechanisms, and finally, the role of new diagnostic and prognostic tools, such as miRNA, could improve the management of this traumatology (Pinchi et al. 2019; Yong et al. 2019).

3.1. Predictive Value of Biomarkers

Due to a recent review by Schading et al., published in July (2021), developments in the search for clinically significant biomarkers in SCI are presented. SCI is a complex and heterogeneous condition that can lead to a wide range of functional impairments. The current clinical evaluations of SCI are limited in their ability to predict outcomes and guide therapeutic decisions. As a result, there is an increasing need for more sophisticated assessments and the development of biomarkers that can complement current clinical measurements (Schading et al. 2021). Further studies have identified several potential biomarkers for SCI, including advanced neuroimaging techniques and molecular biomarkers. These biomarkers promise to predict outcomes, monitor disease progression, and guide therapeutic decisions. However, further validation is required before these biomarkers can be applied in clinical practice. The term "biomarkers" in the field of SCI refers to advanced neuroimaging and molecular biomarkers that are sensitive to the detection of this condition (Rodrigues and Moura-Neto 2018). To elaborate, these biomarkers range from advanced neuroimaging techniques to neurophysiological indicators and molecular biomarkers that identify concentrations of various proteins in the blood and cerebrospinal fluid (Leister et al. 2020).

Clinical assessment with standardized neurological examination is the gold standard for assessing the severity of the injury and predicting functional outcomes in SCIs as revised by ASIA and ISCoS International Standards Committee (2019). Thus, these models can be improved by including advanced diagnostic methods, indicating that a multiparametric approach—including neuroimaging and cerebrospinal fluid/ blood biomarkers—improves the accuracy of predicting individual recovery trajectories. In other words, these biomarkers can complement current clinical evaluations by providing additional information that can enhance the accuracy of predicting individual recovery trajectories (Schading et al. 2021). Biomarkers, in general, can be categorized into structural and inflammatory factors, as well as indicators measured in routine blood analyses. Structural biomarkers are mostly cell-type-specific proteins from neural tissue that leak into the cerebrospinal fluid and blood after injury. These tissue-specific proteins are produced by different cells, such as neurons or glial cells. Following SCI, changes in the concentrations of several of these proteins have been observed in both blood and cerebrospinal fluid. Inflammatory biomarkers include cytokines, chemokines, and other factors related to the immune system and are produced in response to injury. Routine blood analysis indicators include the number of white blood cells, C-reactive protein, and the erythrocyte sedimentation rate (Schading et al. 2021).

Furthermore, neurophysiological techniques such as measuring nerve conduction, motor evoked potentials, and SSEPs provide objective measures of neural integrity and allow differentiation between demyelination and axonal damage (Li et al. 2021; Abdelkader et al. 2019). Their value as independent tools for stratifying patients with SCI into subgroups and their prognostic utility have already been demonstrated and validated several years ago. Thus, some have questioned whether these electrophysiological parameters could add valuable information to improve the prediction of functional outcomes. In summary, recent developments in identifying reliable biomarkers for traumatic SCI and improving prognostic models are promising. Clinical evaluation with standardized neurological examination remains the mainstay for assessing the severity of the injury and predicting functional outcomes. However, these models can be improved by including advanced diagnostic methods, indicating that a multiparametric approach—including neuroimaging and blood indicators—enhances the accuracy of predicting individual recovery trajectories (Freund et al. 2019). A plethora of studies exploring the exact potential of this approach with multivariable models capable of accommodating multimodal data to demonstrate the usefulness of these advanced biomarker combinations is deemed necessary.

According to Schading et al., the inclusion of electrophysiological multiparametric parameters in the prediction model leads to better accuracy in forecasting. The research suggests that the assessment of neurological function and prognostic accuracy in patients with SCI can be improved by adding neurophysiological methods to standardized clinical evaluation (Schading et al. 2021). Regarding electrophysiological outcome measures in clinical trials for SCI, in 64 articles that met eligibility criteria, assessing 877 individuals with SCI who received various interventions and 324 individuals with and without SCI who served as controls, five types of clinical trial study designs were identified, with hybrid designs that included both controls and crossover interventions (Korupolu et al. 2019). The use of the Delphi method to develop consensus on standardized guidelines for collecting and reporting electrophysiological results in SCI clinical trials stood out. The Delphi method is a process of achieving group consensus by providing experts with questionnaires and group responses before each subsequent round. Examples of electrophysiological measurements used in SCI clinical trials include cortical somatosensory evoked potentials, motor evoked potentials and spinal reflexes. The results are based on the significance of reporting parameters such as amplitude, latency, and optimal stimulus intensity for obtaining motor-evoked potentials (Korupolu et al. 2019).

Electrophysiological measures have many benefits in SCI clinical trials (Sand et al. 2013). They are largely objective, independent of patient cooperation, and unbiased, as the results do not depend on subjective patient responses. Electrophysiological measures can also provide information about the neurophysiology of SCI, which can guide future therapies that may subsequently achieve clinically significant results. Additionally, electrophysiological measures can be used in combination with conventional clinical outcome measures to provide a more comprehensive assessment of treatment efficacy. Therefore, the literature suggests that future studies should use standardized protocols for data collection and analysis, such as the Delphi method, and report parameters such as amplitude, latency, and optimal stimulus intensity for proper EP acquisition.

3.2. Evidence of Somatosensory Evoked Potentials in Spinal Cord Injuries

According to the literature, the majority of the studies regarding the prognostic value of SSEPs in SCIs show a positive correlation with patient recovery (Fustes et al. 2021). It has been found that the contribution of SSEPs is particularly significant in predicting recovery after SCI, either independently or in conjunction with other examinations (ASIA), or as a specialized tool occasionally used for objective differentiation of SCIs, aiding in distinguishing incomplete from complete injuries, especially in patients who are comatose or uncooperative (Li et al. 2021). It has been demonstrated that changes in SSEPs can reflect changes in gross motor function and fine motor function after mild SCI and that changes in the EP amplitude may also reflect changes in fine motor function after severe SCI (Li et al. 2021).

Patients with acute SCI in spinal shock are more sensitive to the assessment of relative damage to the peripheral motor pathways, i.e., the motor neurons and nerve roots (Singh et al. 2020). Recordings from electromyography, nerve conduction studies, and reflex reproduction allow for predicting increased muscle tone or muscle atrophy in comparison to clinical examination. The evaluation of damage to the autonomic nervous system after SCI with clinical examination is limited. Conversely, recordings of Sympathetic Skin Response - SSR can provide information about the extent and level of damage to the sympathetic nervous system related to autonomic dysfunction (Kumru et al. 2009). Responses recorded from the scalp hair are absent in complete cervical SCIs, while incomplete injuries produce various abnormalities in SSEPs. SSEPs can help localize the sensory level in cases of injury and moreover aid in determining the prognosis for functional outcomes. Furthermore, early recording of an SSEP from the tibia has been associated with favorable functional and neurological status and outcome after SCI (Chawla et al. 2019). Therefore, electrophysiological recordings, as complementary to the clinical examination, are useful for designing and selecting the appropriate therapeutic approach for the rehabilitation program. Additionally, they allow for predicting functional outcomes and providing objective assessment regarding spinal and peripheral pathway recovery.

3.3. Somatosensory Evoked Potentials in the Diagnosis of Spinal Cord Injuries

As established above, SSEPs are neurophysiological tests used in the assessment and prognosis of SCI (Mauromatis 1996). SSEPs measure electrical activity as a response to sensory stimulation and can provide information about the integrity and function of sensory pathways. Therefore, they are used directly for the diagnosis of the injury and indirectly as a prognostic factor (Kakulas 2004). Regarding the prediction of sensory recovery, SSEPs can assist in evaluating the potential for sensory recovery after spinal cord injury. By measuring the conduction of sensory signals along the spinal cord, SSEPs can indicate the presence or absence of sensory transmission from the level of the injury and below. If SSEPs show intact or improved sensory responses, this indicates a better prognosis for sensory recovery (Zeiler and Koenig 2013).

Determining the level of injury, which can be identified through neurological examination and imaging methods, can be confirmed using SSEPs, providing more detailed data on the damage that the spinal cord suffered. By stimulating specific nerves or dermatomes and recording the resulting responses, SSEPs can determine the segmental level of sensory dysfunction and correlate it with the corresponding level of spinal cord injury (Nardone et al. 2015). Additionally, assessing the severity of the injury is of utmost importance to be performed as early as possible, to make decisions about limiting secondary damage in the affected area. A particular feature of SSEPs is that they can provide necessary information even if the patient is in a comatose state. Decreased or absent SSEP responses indicate significant damage to the sensory pathways and may indicate a more severe injury.

Nevertheless, it is worth noting that SSEPs are a part of a comprehensive evaluation process, and prognosis is determined based on multiple factors, including clinical examination, imaging, and other neurophysiological tests.

3.4. Somatosensory Evoked Potentials as Therapy for Spinal Cord Injuries

SSEPs are not typically used as a direct therapy for SCI. SSEPs are primarily used as diagnostic tools to assess the integrity of sensory pathways and provide information about the level and severity of the injury. They are used during the diagnostic phase to help healthcare professionals understand the extent of the injury and guide the development of an appropriate treatment plan. SSEPs, along with other diagnostic tests and clinical evaluations, provide valuable information for determining the course of treatment, such as surgical intervention, rehabilitation interventions, or medical management (Schwab and Bartholdi 2006; Fehlings and Vaccaro 2019).

However, ongoing research efforts are exploring potential therapeutic interventions for SCI, including regenerative medicine, electrical stimulation, and other emerging approaches. While SSEPs can be used as part of the assessment process for these experimental therapies, they are not the therapy itself (Ahuja and Fehlings 2016).

3.5. Machine Learning in the Diagnosis of Spinal Cord Injuries

Personalized medicine is a model of a much better medical approach where interventions are based on individual patient characteristics rather than guidelines. As epidemiological datasets continue to grow in size and complexity, robust methods such as statistical machine learning and Artificial Intelligence (AI) become necessary for the interpretation and development of prognostic models from underlying data. Through such analysis, machine learning can facilitate personalized medicine through its accurate predictions (Khan et al. 2020). Additionally, other AI tools, such as natural language processing and computer vision, can play a crucial role in customizing care for patients with SCIs.

Traumatic SCI and degenerative changes in the spine that cause compression of the spinal cord or nerve roots are the two main categories of diseases treated by spine surgeons. SCI results in catastrophic physical, vocational, and psychosocial consequences for almost 180,000 patients worldwide each year. The damage suffered by the spinal cord in the context of the injury, combined with the limited ability of nervous tissue to regenerate, can occasionally lead to irreversible neurological consequences (Khan et al. 2020). Based on the data accumulated so far, the use of predictive algorithms such as machine learning could provide significant preoperative information to both doctors and patients regarding the outcome and the likelihood of adverse events of surgical treatment. As a result, instead of being the outcome of a general analysis, treatments can be personalized, taking into account individual characteristics, relevant factors affecting outcomes, and comorbidities.

It is now a fact that the field of AI has profoundly influenced many industries, including healthcare (Dietz et al. 2022). Its ability to recognize patterns and self-correct to improve over time mimics human cognitive function but on a much larger scale. Machine learning (ML), a subset of AI, ranges in complexity from classical ML to unsupervised ML to deep learning, where Natural Language Processing and Computer Vision are possible. AI-based tools have been developed for segmenting spinal structures, obtaining basic measurements of the spine, and even detecting pathologies such as tumors or degeneration. AI algorithms could be used to guide clinical management by aiding treatment selection, predicting outcomes for individual patients, and even powering neuroprosthetic devices after SCI. While the use of AI has its pitfalls and must be adopted with caution, its future use is promising in the field of spine surgery and medicine as a whole (Katsuura et al. 2021; Katsos et al. 2023). A diagram of knowledge discovery by data collectors in new guidelines is following (figure 2).

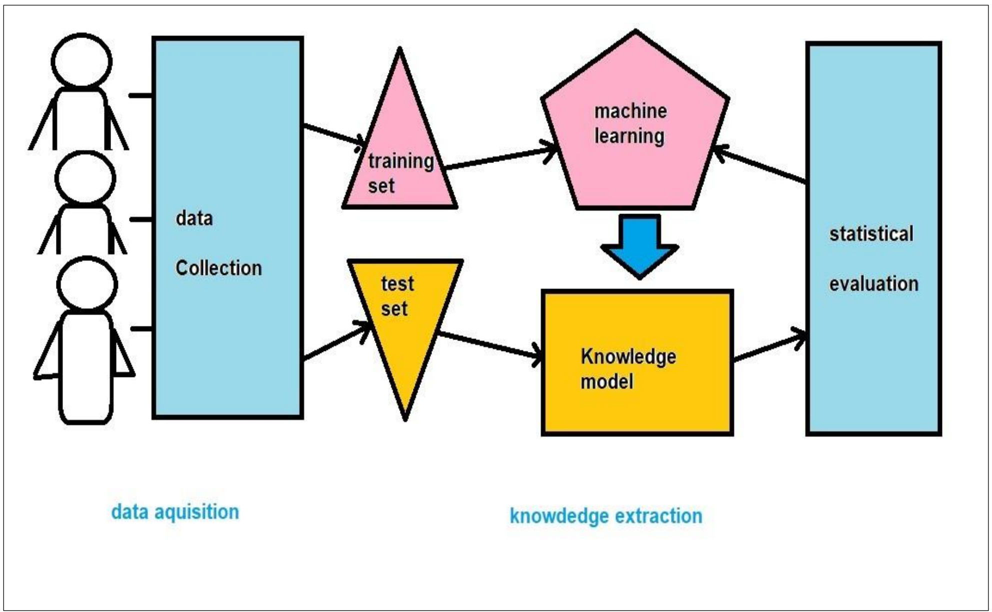

Figure 2 Knowledge Discovery from Data collectors to new Guidelines

4. Discussion and Conclusion

Studies using SSEPs have made steady progress since Dawson's initial description. The introduction of information technology has allowed digital analysis, leading to the rapid scaling of SSEP and other Neural Conduction Studies in the clinical field (Athanasiou et al. 2018).

The bidirectional communication between the central and peripheral nervous systems is at stake during SCI due to neurological trauma of the anterior and posterior spinal tracts. Changes in brain organization after SCI have been correlated with prognosis. Changes in functional connectivity can serve as injury biomarkers (Yoon et al. 2020). Most studies related to functional connectivity have focused on chronic complete injury or resting state conditions. A chronic interruption of bidirectional communication in incomplete injury could lead to a permanent significant reduction of connectivity in a subset of the sensorimotor network, regardless of the positive or negative neurological outcome. It has been found that patients with SCI show signs of increased local processing as an adaptive mechanism.

The literature includes numerous recent studies regarding the rehabilitation of individuals with SCI, as it affects a substantial part of the population. Various protocols with different approaches are being tested and recommended. However, the majority treat these patients with a basic estimation of their outcome, making rehabilitation programs imprecise. A more detailed evaluation using electrophysiology with SSEPs, and AI could offer a more accurate prognosis and provide maximum assistance in rehabilitation program recommendations, leading to improved functional and walking ability for patients (Khan et al. 2020).

Using SSEPs and electrophysiological responses, along with data from assessment scales, imaging tools, and managing all this information through AI systems, the gathering of more objective and specialized prognosis data for the functional outcome of individuals with SCI is expected (Schading et al. 2021). According to studies, the existing basic examinations alone do not have significant predictive value concerning the functionality and autonomy of patients. SSEPs are suitable for pointing out the severity of SCI and now with ML assisting there will be much more understandable information from SSEP data analysis which should lead to a precise estimation of the patient's outcome. The more the spinal cord is compressed, the more significant the changes in SSEPs. Changes in the amplitude of SSEPs after SCI are more sensitive than changes in the latent state for early diagnosis and evaluation of SCI (Bazley et al. 2014). With ML, SSEPs are of a better, easier, and increased importance use.

Based on reliable data from international search databases, this research concludes that with the assistance of AI in the analysis of electrophysiological measures and SSEPs, Biomarkers, and Biosignals from neurophysiological indicators, it will eventually lead to the use of a unified tool model that will provide a personalized prediction of the restoration outcome of individuals with SCI, combined with imaging methods such as Magnetic Resonance Imaging. Therefore, it is of great importance to widely accept an intelligent tool that will predict the walking ability and autonomy of a patient with SCI, i.e., a model predicting the progress of rehabilitation based on AI for analyzing, SSEPs and biomarkers due to the valuable information they can offer in established clinical and imaging examinations. In that way, the diagnosis and prognosis of each patient will not be based on linear models that may not fully estimate data and do not consider the complex behavior of variables that often exist in biological conditions, especially in the case of SCIs where the variety of injuries is limitless and unique.

ML algorithms are already being used to analyze and combine vast amounts of data related to spinal cord tumors, allowing the identification of patterns and the establishment of clinical associations. Some specific techniques mentioned, include deep learning and artificial intelligence-based systems that can assist with preoperative planning and surgical resection (Katsos et al. 2023). Additionally, ML models are being used to predict genetic, molecular, and histopathological profiles, which can improve diagnostic precision. The use of ML in the context of spinal cord tumors has the potential to improve diagnostic accuracy and patient outcomes in several ways. As established before, ML algorithms can analyze large amounts of data and identify patterns that may not be apparent to human clinicians, which can lead to more accurate diagnoses and treatment plans (Dietz et al. 2022; Katsos et al. 2023; Yoon et al. 2020). Also, ML models can be used to predict treatment response, survival, and postoperative complications, which can help clinicians make more informed decisions about patient care. Overall, ML has the potential to promote personalized medicine and improve patient outcomes including the field of SCIs, as well.

Nevertheless, limitations and challenges associated with using ML models are that require extensive validation processes and quality assessments to ensure safe and effective translation to clinical practice. Additionally, the use of ML in clinical decision-making must be balanced with clinical expertise and patient preferences. Furthermore, the availability and quality of data can be a challenge, as ML algorithms require large amounts of high-quality data to be effective. Finally, the interpretation of ML results can be complex and may require also specialized expertise.

Future Work

It is important to set correct parameters, as creating such a valuable Al tool which can maximize the importance of electrophysiology and SSEPs data in collaboration with other useful tests and tools already existing. To give this tool a greater extent, it is crucial to build it with information not only from the existing damage of the SCI or information from just hospitalization and recovery periods but also insert data from the progression of the condition. The follow-up should last forever after a spinal cord trauma, and the data should be collected annually to strengthen its importance.

Compliance with ethical standards

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No conflict of interest to be disclosed.

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