Original Article: Properties of the surface electromyogram following traumatic spinal cord injury: a systematic review

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ABSTRACT

Introduction: Surface electromyography (sEMG) changes as a result of traumatic spinal cord injury (SCI), which disrupts spinal and supraspinal pathways. The sEMG is a useful addition to current clinical testing and can capture the residual motor command in great detail, even in muscles below the level of injury with seemingly absent motor activities. We aimed to explain how the sEMG properties are altered after SCI in this in-depth review. **Material and Methods:** Following a thorough review of the literature, we focused on sEMG analysis methods and signal characteristics post-SCI. Early reports, according to what we discovered, tended to be primarily concerned with the qualitative analysis of sEMG patterns before moving on to semi-quantitative scores and a more thorough amplitude-based quantification. **Results:** On the other hand, recent studies are still limited to an amplitude-based analysis of the sEMG, and there are opportunities to more thoroughly characterize the time- and frequency-domain properties of the signal as well as to fully utilize high-density EMG techniques. We advise incorporating a wider variety of signal properties into the neurophysiological evaluation following SCI and gaining a better understanding of the relationship between these sEMG properties and underlying physiology. **Conclusion:** Improved sEMG analysis may help in understanding the mechanisms of change after neuromodulation or exercise therapy, as well as provide a more thorough description of how SCI affects upper and lower motor neuron function and their interactions.

Introduction

The Depending on the level and severity of the injury, traumatic spinal cord injury (SCI) can cause severe sensorimotor dysfunction. Muscle atrophy, altered muscle fiber types, and increased passive stiffness in muscles and tendons are changes in motor properties that significantly reduce muscle strength, coordination, and functionality [1].

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Clinical evaluation of the residual strength, sensibility, and/or muscle activation of specific muscle groups affected by the lesion, such as manual muscle testing (MMT), is one method for identifying motor impairment symptoms. Clinical motor tests, such as the Graded Redefined Assessment of Strength, Sensibility, and Prehension (GRASSP) and the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI), offer important insights into strength and function. Electrophysiological methods can be used to supplement this data further [2-4].

One such method has a number of benefits over invasive methods: the surface electromyogram (sEMG). It has been proposed that sEMG is a reliable indicator of the health and performance of muscles. Importantly, sEMG amplitude can detect muscle activity in patients who have no visible movement below the level of spinal injury and is highly correlated with strength and recovery (Fig 1).

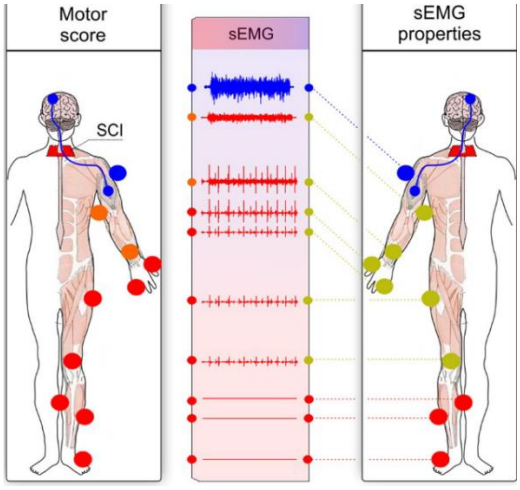

Figure 1: The surface electromyography (sEMG) is sensitive to detect residual motor commands from muscles with motor scores of zero. Spinal cord injury (SCI, red) disrupts motor commands from the brain (blue), hampering the motor output.

The figure shows a hypothetical example using the main muscles assessed in the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI). The motor output is commonly measured using motor scores (blue, orange or red dots in the left figure for intact, impaired or absent output, respectively). The sEMG assessment is able to capture the residual motor output in greater detail compared to motor scores because muscles with no motor scores can still display sEMG activity (blue, yellow or red dots in the right-side figure for normal, altered or absent sEMG, respectively). Symmetrical impairment has been assumed for ease of visualization [5]

Ceiling effects do not limit sEMG assessments; for instance, high variability of sEMG amplitude has been observed in people whose muscles were at a given "ceiling" motor score of 5/5 (using MMT). Additionally, sEMG can be helpful in examining muscles whose strength is challenging to gauge, like those at the thoracic levels. sEMG enables us to evaluate the simultaneous activity of multiple muscles during complex motor tasks, such as activities of daily living, gait, or reaching and grasping movements, in high resolution.

Additionally, it enables the investigation of the intrinsic spinal cord reflex and spontaneous activity as well as neuromuscular properties at rest or during passive movements and residual motor cortex control of voluntary activity. Given the breadth and depth of information that can be gleaned from sEMG, a precise interpretation of the signal properties following SCI is required. Characterizing how the SCI itself affects sEMG is relevant in this situation for a number of reasons [6-8].

To isolate the effect of interventions, one must first comprehend injury-related changes and spontaneous recovery in the sEMG.

The expected signal properties must be well understood for neural interfaces that rely on sEMG. Third, advancing the adoption of electrophysiological techniques into common clinical practice requires a thorough understanding of the information that can and

cannot be gathered using non-invasive techniques.

The question of how the sEMG properties change after SCI is not simple, especially because the sEMG signal represents the net result of complex interactions between intrinsic spinal cord circuits, motor axon properties, and muscular mechanisms [9-11].

In order to examine muscle activity after SCI, sEMG is a well-established methodology; however, there is no agreement on data analysis and reporting techniques. The signal amplitude, which typically represents the average or maximal value recorded at a given time or window after some smoothing and normalization steps, is used as the most popular reporting methodology. However, using temporal, spectral, and spatial methods, the raw sEMG signal has the potential to be examined and expressed in a variety of ways. To fully realize this measurement modality's potential to describe neurorecovery and support the creation of neurorehabilitation technologies, a thorough understanding of sEMG changes after SCI is of utmost importance [12].

The goal of this scoping review is to compile and evaluate the body of knowledge on how SCI can change sEMG properties. We summarized the extensive SCI literature describing sEMG characteristics during persistent voluntary movements or abnormal spontaneous activity. Given that neurorehabilitative interventions following SCI are believed to increase volitional control and decrease spontaneous activity, these two domains have clinical importance.

As a result, the various sEMG properties that can be anticipated to change as a result of SCI are the foundation of our findings. A fresh, evidence-based viewpoint on the application of sEMG following SCI is presented along with insights into the neurophysiological underpinnings of these phenomena [13].

Material and Methods

Information resources

To prevent a biased literature sample, seven electronic databases were searched: Medline (Ovid; 1510 entries), Cochrane Central Register of Controlled Trials (116 entries), Cochrane Database of Systematic Reviews (17 entries), Embase (1680 entries), Emcare (555 entries), Cumulative Index to Nursing and Allied Health Literature (CINAHL; 295 entries), and PubMed (non-Medline; 157 entries). The initial searches were conducted without time restrictions on December 23, 2019, and they were repeated on September 22, 2020. To prevent excluding references not assigned to a language, no language restrictions were put in place. By looking over the reference lists of the studies that were included, references were also manually searched. The Medline search method is detailed in Additional file 1: Table S1; similar methods were employed for the other six databases.

Eligibility requirements

Studies had to meet the following criteria in order to be considered: (1) report sEMG properties in SCI participants (4 SCI participants); (2) include participants with traumatic SCI (> 50% of the total SCI sample); and (3) be written in English.

Regarding (1), we predetermined the sample size threshold to account for the low prevalence trait of SCI while balancing the requirement to pick studies that have information that can be generalized. In (2), despite the clear distinctions between the timing of disease onset in traumatic and non-traumatic cases (e.

g. SCI, it is believed that both conditions cause a similar level of white matter degeneration (degenerative cervical myelopathy). Understanding the existence of subtle white matter degeneration between these conditions

requires additional research. To the best of our knowledge, there is no proof that the sEMG properties differ between these conditions.

But because we wanted to be cautious, we excluded one article where the majority of participants had non-traumatic SCIs and were therefore impaired. Due to incomplete methods and incomplete data sets, conference abstracts were disregarded. The peer-review status of theses and dissertations was also unknown, so they were excluded. A low sample size and statistical heterogeneity led to the exclusion of case studies and case reports with fewer than four participants.

studies on the breathing muscles (e.g. g. , diaphragm), sphincter, pelvic floor, or smooth muscles were not included as some of these muscles are deep (better assessed using intramuscular EMG), display distinct physiological properties (e.g. or heavily rely on rhythmic movement as opposed to voluntary movement (e.g., smooth muscles).

Research on intramuscular EMG was not included. Finally, because our focus was on determining how the SCI itself affected the sEMG, studies examining the effects of interventions or treatments like pharmacotherapy and neurostimulation were also excluded.

Eearch tactics

Search criteria for the electronic databases were created using the PICO model (Problem/Patient/Population, Intervention/Indicator, Comparison, and Outcome). The population, intervention, and outcome (PICO) were "Spinal Cord Injury," "sEMG," and "Muscle/Motor Response," respectively. The search strategies made use of free-text terms pertinent to each topical concept as well as valid subject headings as appropriate for each database.

Selection of the studies

In addition to using the Covidence and Mendeley software, duplicate references were eliminated manually and by hand. For the purpose of determining initial eligibility, two authors independently reviewed titles and abstracts. For full-text screening, appropriate references were included. A third reviewer (MJW) was used to settle disputes.

Extraction of data

The first author extracted data from each full-text article using a customized spreadsheet, which was then tested and improved on using 5% of the references that passed full-text screening. Extracted information included the following: (1) study identification information (author and year); (2) study design; (3) participant demographics: level of injury, American Spinal Injury Association Impairment Scale (AIS), time post-injury, sex, and age; (4) sample size; (5) the reasons for using sEMG; (6) muscles evaluated; (7) sEMG equipment and electrodes; (8) electrodes placement and reliability information; (9) sEMG data analysis and reporting strategy; (10) main . The authors were emailed if there weren't enough data reported.

Scores on the SEMG

After conducting a literature search and selecting relevant articles, the first author (GB) assigned a data score based on the following criteria to determine whether or not sEMG methodology descriptions were present: sEMG equipment/electrode and amplification/filtering descriptions were rated as present (yes) if the type and settings of equipment were sufficiently described (e.g.either "surface electrodes" or "surface Ag/AgCl electrodes with a diameter of 2cm).

Similar to the electrode placement, it was regarded as present if sufficiently specific

descriptions of it (e.g., an indication that "placed on the muscle belly" is not the same as "electrodes were placed at the T-10 vertebral level, 2 cm lateral from midline") or based on reliable sources (e.g. yes: SENIAM guidelines for EMG recording techniques). We also assigned a 3-point rating to the sEMG findings used in the studies: a qualitative score of 0 (based on sEMG visuals/graphs), a semi-quantitative score of 1 (e.g., quantitative (2), scale from 0 to 5.

Results

175 references were chosen and included in the scoping review out of the 4522 that were originally found in the primary search. The characteristics of the sEMG after SCI are discussed in terms of voluntary effort reflecting movement control by the spinal cord, or rest/spontaneous activity reflecting pathologic activation of the spinal cord.

These two domains are intertwined and reliant on UMN and LMN dysfunctional patterns. As a result, integrative factors are covered in every section. When measuring sEMG properties at rest (32 studies) or during volitional effort (76 studies), the majority of the references found used the ASIA Impairment Scale (AIS) component of the ISNCSCI.

More AIS A and B participants participated in studies that measured sEMG at rest (71%) than AIS C and D participants did in studies that measured volitional control (62%). Most research (about 67%) was done on cervical lesions, which showed sensorimotor impairments in the upper and lower limbs.

Studies conducted before 1995 did not include AIS information for historical reasons. However, some recent work also describes participant injury state only with complete or incomplete or as a mix of gradings, without explicit descriptions of impairments.

Tibialis anterior and gastrocnemius were the most studied among lower limb muscles, triceps and biceps brachii were the most studied among upper limb muscles, and abdominal muscles were the most studied for the trunk/head . Sixty-one percent of the extracted data came from male participants with SCI, and 29 percent from able-bodied (AB) control participants.

Historical perspectives can explain the interest in lower limb muscles, the dominance of men, and the absence of AB control groups, but some recent studies still fail to report sex or gender. The evidence that is currently available regarding changes in the sEMG signal's properties after SCI is compiled in the sections that follow.

Fig. 2 summarizes the area of these investigations' focus.

Left: Changes in sEMG properties may be related to weak cortical control (hashed blue lines) but also to aberrant plasticity within the intrinsic spinal cord circuitry (green lines). For example, the lack of UMN control may be reflected in reduced muscle strength and coordination to control volitional muscle activity, reflected in amplitude- and frequency-based sEMG properties [e.g., amplitude: root mean square (RMS), peak; frequency: median frequency (MDF), power spectrum density (PSD), intra- or intermuscular coherence at the β-band]. Right: The lack of UMN efferents to the spinal cord induces sprouting within the spinal cord circuitry. Given the intact afferents arriving from the periphery and/or pathways within the spinal cord, the intrinsic spinal cord circuitry is prone to hyperexcitability. This is reflected in the amplitude-based sEMG properties as an involuntary activation, many times propagating to several muscle groups in the form of tonic, clonic, or unit spams. These forms of spontaneous activity, thought to involve intrinsic spinal cord circuitry, are detected at rest and present unique frequency-based sEMG features such as low-frequency muscular coherence. SCI spinal cord injury, sEMG superficial electromyography, UMN upper

motor neuron, F flexors, E extensors, Hz hertz, LMN lower motor neuron.

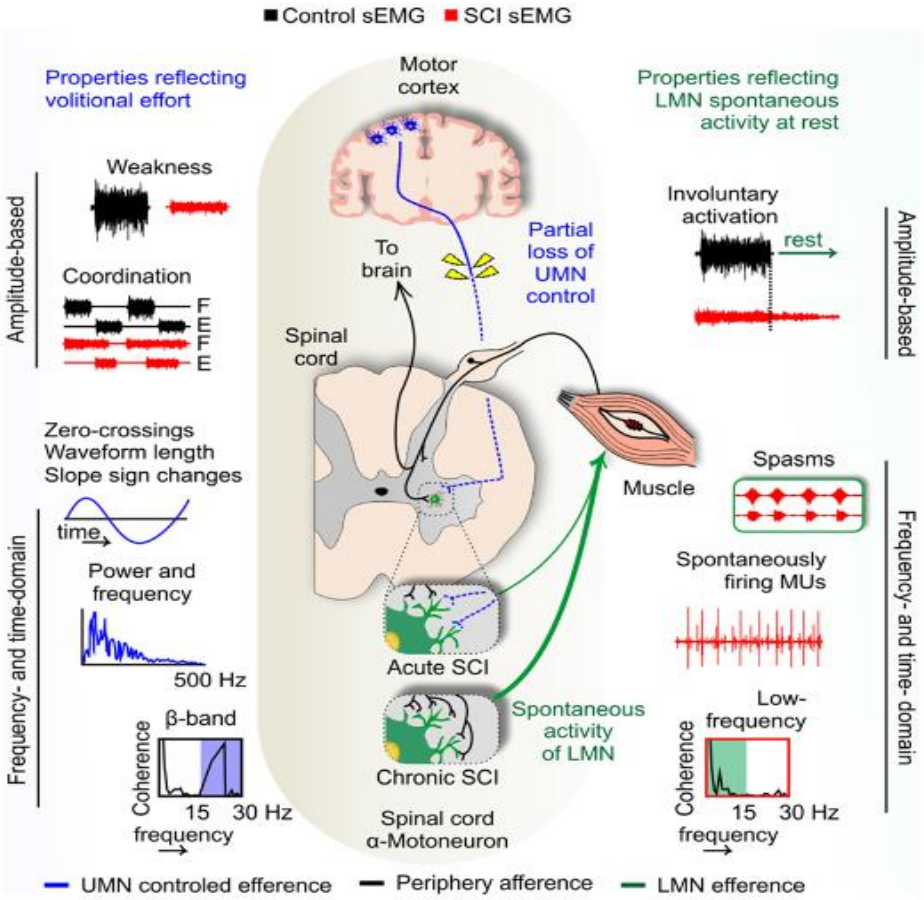

Figure 2: Surface electromyography (sEMG) properties following spinal cord injury (SCI).

Amplitude-based sEMG.

Early studies used qualitative sEMG graph analysis to investigate the use of voluntary muscle activation during postural movements. These studies described postural patterns, the propensity for hip flexor/extensor clonus during the act of rising, and the emergence of abnormal movement synergies after SCI. With the advancement of sEMG technology, scientists were able to evaluate multiple muscle groups simultaneously and with greater resolution.

It was clear to these pioneers that sEMG during volitional effort had the capacity to detect motor control alterations and was applicable to assistive technology as different sites for myoelectric control in people with high-level quadriplegia were tested using integrated sEMG amplitude to measure the degree of volitional control over trunk/head muscles dot.

However, some of these early studies (e.g. g. , the sEMG signal's amplitude and shape) to draw conclusions about the neurophysiological and functional state of people with SCI.

Muscle weakness and spontaneous recovery in acute and subacute SCI

Only 18 of the 178 studies were carried out during the acute and subacute stages of SCI. Following SCI, reports of muscle atrophy, weakness, and paralysis have been made. Although people with SCI typically produce lower MVC forces, an orderly recruitment of the few units that are still under voluntary control could be seen. Individuals with SCI typically

produce lower MVC forces. The mean integrated sEMG generated by individuals with SCI during maximum voluntary contractions (MVCs) were significantly lower than those produced by controls.

Muscle-specific weakness is caused by the disruption of UMN and LMN activity at particular spinal cord segments, which is related to the severity of the spinal cord lesion and affects muscle activity after SCI. Using sEMG, detailed descriptions of mixed weakness and its dependence on the level of injury, including amplitude-based properties during voluntary movements and the use of transcranial magnetic stimulation (TMS), were made. These studies used voluntary sEMG measurements along with artificial electric or magnetic stimulation to test the integrity of the central nervous system.

It is believed that all motor units, regardless of size or number, are activated when the peripheral nerve is stimulated, resulting in the generation of an M-wave on the muscle. The M/RMS ratio, which can be calculated by dividing the M-wave by the sEMG RMS recorded during MVC, indicates the degree of voluntary activation of motor units relative to the maximum. The M/RMS ratio would be 0 in the absence of an M-wave, indicating a lesion in the LMN, but weak muscles with M-wave amplitudes within the normal range showed additional sEMG characteristics that suggested UMN dysfunction.

For instance, muscles with large M/RMS ratios and slow maximum motor unit firing rates (measured using intramuscular EMG) denoted predominant UMN weakness, and muscles with both very small M-responses and large M/RMS ratios were thought to represent mixed UMN and LMN impairment. A similar approach using TMS over the motor cortex produced similar results. There is a correlation between volitional sEMG and residual UMN control in muscles that exhibit high semi-quantitative sEMG scores at volitional effort and greater evoked responses.

The strong correlation between muscle strength and sEMG resulted from the groundbreaking work of Calancie and colleagues, and it opened up new possibilities for using sEMG to understand neural plasticity and movement recovery after SCI.

These studies demonstrated a reliable correlation between sEMG and muscle force following SCI and the capability to evaluate the recovery of voluntary movement after acute SCI. Spontaneous recovery of muscle force could be detected in the sEMG signal in great detail and scored using a straightforward 6-point scale to mimic the ISNCSCI muscle function grading (also from 0 to 5).

It became easier to apply the sEMG in clinical settings and gain a better understanding of motor recovery after SCI by using comparable sEMG scores between clinical and sEMG assessments.

The abnormal interlimb responses, the use of the sEMG interference pattern as a biomarker for observing lower limb recovery, and insights into the distribution and latency of muscle responses to TMS were all covered in this. The majority of these research projects involved sizable participant cohorts and offered insightful information about the mechanisms underlying the recovery of axonal conduction in central motor pathways after SCI.

The spontaneous recovery of locomotor muscles over a period of 26 weeks following injury was described by Dietz and colleagues using electrophysiological evaluations. Up to 14 weeks after SCI, sEMG amplitude and reflex activity were absent; after the spinal shock resolved, tendon tap response returned, and the sEMG amplitude gradually increased over the following 4 weeks peaking at about 22 weeks after SCI.

Additional research has confirmed the gradual improvement of muscle strength, gait, and motor evoked potential amplitudes during the first 24 weeks after SCI. Although the

corticospinal tract experienced a persistent conduction delay during this time, the motor evoked potential's amplitude increased at a stable background sEMG activity level of 20 percent MVC (unchanged during the first 24 weeks after SCI). This increase in activation at a stable background sEMG activity level may indicate improved synchronization of the descending volley and/or responsiveness of motoneurons to supraspinal input with spontaneous recovery.

Therefore, it is likely that intrinsic spinal cord plasticity mechanisms play a significant role in this process of spontaneous recovery since the corticospinal function did not significantly improve in conduction during motor recovery from acute SCI. In subsequent research, the heterogeneity of the sEMG response after SCI was highlighted, and it was discovered that the spontaneous recovery was highly individualized in terms of sEMG patterns and rate of change over time.

By developing the Brain Motor Control Assessment protocol, Sherwood and colleagues added to our understanding of muscle weakness and recovery after SCI. The assessment consisted of a battery of tests initially using semi-quantitative features of the sEMG amplitude properties during relaxation (spontaneous firing), reinforcement (amplitude), voluntary movement (amplitude), tonic stretch response, phasic stretch response, presence of clonus, and response to vibration or p.

This protocol was later supplemented with quantitative amplitude measurements of the RMS sEMG, which showed a strong between-day reliability and relationship to the Ashworth scale. By comparing the sEMG patterns of the muscles from AB control and SCI participants, similarity indices were used to further develop the Brain Motor Control Assessment protocol.

The ability to activate motor units on command, the rate at which those motor units were recruited, and the ability to appropriately organize the motor unit activation across the prime mover, antagonist, and distant muscles were all significantly increased during spontaneous recovery. These findings were based on serial recordings made up to 33 weeks after SCI and showed charac-

Initially, only a small number of motor units fired in some muscles; however, as the muscles recovered, an increase in amplitude was visible along with a progressive shortening of the period between the start of activity and the peak of activation.

The research by Mckay et al. also employed similarity indices examined the use of sEMG to evaluate various muscle groups. This demonstrated how increased agonist activation is associated with decreased co-activation of antagonist or distant muscles during spontaneous recovery. A second study evaluated mixed cohorts of participants with acute and chronic conditions and demonstrated the spontaneous recovery process from chosen participants.

Utilizing amplitude-based RMS sEMG properties from 3 to 5 months after subacute SCI, co-activation was also investigated longitudinally. The findings indicated an uneven recovery of UMN control over muscles (co-activation), and the recovery process was slowed down by the presence of lower limb hypertonia and involuntary muscle activity. Muscle coordination and sEMG properties at rest will be covered in more detail in the sections that follow.

Early research on voluntary muscle activation during the chronic stage of SCI was done to identify the best myoelectric control sites and later, the neurophysiological traits of UMN and LMN lesions. The viability of using muscles with innervations below the injury level as control sources for a neuroprosthesis was also investigated using sEMG. The findings showed that although the preservation of a small

number of axons might not be enough to produce functional movement on its own, these signals are probably enough to control a motor neuroprosthesis. Additionally, well-recovered individuals with incomplete SCI were also able to detect subtle differences during the chronic phase of their recovery.

After SCI, the ability of sEMG to record residual impairments or muscle activity has been used to classify muscles according to the presence or absence of detectable movement and assess the degree of preserved muscle activity, including in the abdominal muscles. In contrast to SCI muscles with volitional sEMG and AB controls, it should be noted that in muscles lacking volitional sEMG, an event-related desynchronization was visible when trying to move.

According to the pattern of plantar flexor central motor drive, people with SCI activated their plantar flexors more during eccentric MVCs than isometric or concentric MVCs. This finding is probably due to the increased efficacy of muscle spindles Ia- motoneuron transmission during lengthening contractions. The study of sustained contractions of weak hand intrinsic muscles revealed that impaired activation due to SCI was more significant for explaining weakness than muscle atrophy, and that greater central fatigue was probably balanced by less peripheral fatigue as a result of lower muscle activation.

High-density sEMG and wearable electrodes are used in novel technologies. High-density sEMG can provide more precise details on patterns of muscle activation, which can also be summarized, for example, using the center of gravity .. Wearable technology will soon make it possible to characterize muscular activity under a wider range of sedentary and active conditions in the home environment.

sEMG has been widely used to gain understanding of changes in motor control following SCI. Studies have frequently concentrated on these issues in the context of locomotion, while fewer studies have focused on reach-to-grasp, posture, and balance. Lines of inquiry have included abnormal synergies, completion time and accuracy of movements, and patterns of co-activation.

While many of these studies use the same approaches to quantify the sEMG signal, they have nevertheless produced significant insights into neural control after SCI. A number of studies built on these representations to apply synergy extraction methods that can characterize changes in muscle coordination patterns. Frequency-based descriptions of the sEMG have also been used in the context of motor control and coordination, and are summarized in the following section. Timing information has been focused on to describe patterns of activation, and normalized envelope amplitudes have been used to describe these patterns.

Discussion

Examining the characteristics of the sEMG after SCI was the goal of this scoping review. This review aims to support the interpretation of sEMG signals after SCI, facilitate the choice of sEMG methodology for planning and conducting research in SCI, support the development of assistive technologies, and highlight knowledge gaps in light of the growing role of technology and the potential to assess neurorecovery in more detail [14-16].

The minority of studies that were included in the identified body of evidence used sEMG measurements rather than just amplitude-based analysis. RMS, normalized sEMG, and qualitative or semi-quantitative scores of the sEMG pattern were used in the majority of studies (16 studies) that used amplitude-based analysis. Only 19 studies, in contrast, employed time-domain or frequency-domain analysis [17-19]. The findings of this review, as summarized, suggest that amplitude-based analysis is useful in

predicting muscle strength and recovery after SCI, including significant aspects of multi-muscle coordination [20-22].

Despite these encouraging results, time- and frequency-domain analysis may be able to describe the sEMG properties in ways that amplitude-based analysis alone cannot, giving a more thorough description of the neurophysiological changes following SCI.

The motor unit firing patterns, whether spontaneous or cortically driven, are thought to reflect time- and frequency-domain sEMG properties, but further research is required to confirm this. In the end, sEMG signals might be better described if more factors are taken into account. The susceptibility of amplitude-based sEMG properties to intra- and inter-day variability due to variations in factors like electrode locations and skin impedance is a crucial methodological consideration when working with these properties [23-25].

The lack of reported electrode placement and between-days reliability of the sEMG measurements were limitations of most sEMG studies in SCI, despite the widespread use of normalization to try and correct for these problems. Only 51 out of 178 references provided information on electrode placement in detail, but the majority provided information on the sEMG apparatus or filtering/amplifying techniques [26-28].

Additionally, 57 percent of studies used an AB control group. The use of an uninjured control group depends on the research question, but appropriate experimental controls are crucial to deal with the stochastic and variable nature of the sEMG signal after SCI. The notable well-powered studies from Calancie and Sherwood from the 1990s and 2000s mostly used semi-quantitative sEMG analysis [29].

The fact that there aren't many studies combining sEMG and intramuscular EMG methodologies is another thing to take into account. We could gain more insight into how motor unit firing patterns are reflected in the sEMG by making simultaneous recordings using the two methods.

A recent systematic review of the electrophysiological outcome measures in SCI clinical trials, which found that only 1/64 of clinical trials used intramuscular EMG and that 27/64 of clinical trials used sEMG analysis, supports the significance of this scoping review. Given its non-invasiveness and simplicity of use, it is reasonable to consider sEMG as the top option for neurophysiological testing in clinical trials for SCI.

A thrilling opportunity to directly measure motor unit firing rates and gain deeper neurophysiological insights without the need for invasive measurements is presented by recent advancements in motor unit decomposition from sEMG. These techniques need specialized equipment, so their use in SCI research has been constrained thus far [30-32].

A more comprehensive understanding of the sEMG signal properties has the potential to produce new outcome measures for use in clinical trials and to advance the field by illuminating the connections between these properties and physiology. The majority of studies examining time- and frequency-domain sEMG properties in depth are carried out in non-injured subjects, other populations, or with too few SCI participants (less than 4 SCI) to be included in this scoping review. On the other hand, SCI research with larger sample sizes mainly uses amplitude-based analysis. The sample size and the range of reported sEMG properties are now inversely proportional [33].

A potential use for the characterization of the volitional sEMG activity below the lesion in clinical settings in the new era of machine learning is as a screening tool. The creation of novel devices with improved portability and usability may be encouraged by technological advancement.

These sEMG tools may be used by clinicians during neurorehabilitation, which could have an impact on diagnosis and the efficient use of treatment time. The development of assistive technologies like myoelectric control interfaces may also be aided by further sEMG characterization following SCI [34-36].

The usefulness of sEMG is widely acknowledged because it is thought to offer quick, straightforward evaluations of motor impairments and post-SCI rehabilitation. But on the other hand, as recently explained by Pilkar et al. also Merletti et al. When using sEMG assessments in clinical practice, there are many things to take into account. For instance, sEMG needs specialized infrastructure and resources for tools, maintenance, and training. In this context, this scoping review has identified a body of consistent evidence indicating that sEMG is an informative complement to current clinical testing, but probably not being fully utilized in terms of the information that it can provide [37-39].

Health professionals will need specialized training, ongoing support, and user-friendly sEMG interfaces. In the future, engineers and software developers must create sEMG systems that allow a wider variety of metrics to be available at the point of care, not just those based on amplitude calculations. When attempting surgical nerve transfer to restore upper limb function in SCI, for instance, it may be possible to avoid common mistakes if simple-to-use sEMG data is available beforehand [40]. More generally, a thorough understanding of the spontaneous recovery profile in sEMG may offer helpful guidance for the choice and progression of therapy.

Conclusion

There is a wealth of evidence regarding changes in the sEMG properties following the injury thanks to the seven decades of research on sEMG in SCI. The majority of studies use sEMG amplitude properties to describe muscle weakness, coordination, and spontaneous activity. It is well known that sEMG can capture the residual motor command in great detail, including in muscles below the level of injury with seemingly absent motor activities. The goal of treatments promoting sensorimotor recovery is to use these remaining supraspinal inputs to improve muscle strength and coordination while lowering spontaneous activity. Therefore, including sEMG evaluations in clinical settings provides crucial information on how cutting-edge therapies may activate and maximize the residual motor command. However, there are still current gaps, such as the absence of studies documenting modifications in sEMG properties outside of the amplitude measurement. We recommend incorporating a wider variety of signal properties into the neurophysiological assessment post-SCI and developing a better understanding of the relationship between these sEMG properties and underlying physiology in order to advance the field.

References

[1] L.H Anvar, et al., The study of rs324420 (C385A) polymorphism of the FAAH gene of the endocannabinoid system in patients with epilepsy and ADHD. Epilepsy Research, **2023**. 192: p. 107100. [Crossref], [Google Scholar], [Publisher]

[2] A. Mobed, et al., Biosensors technology for anti-epileptic drugs. Clinica Chimica Acta, **2022**. 533: p. 175-182. [Crossref], [Google Scholar], [Publisher]

[3] S. Charsouei, S., et al., Evaluation of Three- and Five-Year Disease-Free Survival in Patients With Cervical Cancer With Spinal Cord Metastasis Under Treatment With External Radiotherapy+ Brachytherapy. International Journal of Women's Health & Reproduction Sciences, **2022**. 10(2). [Google Scholar], [Publisher]

[4] M. Zamani Esfahlani, et al., Oral Levothyroxine Prophylactic Administration on Bleeding and Hemoglobin Changes During and after Total Hip Arthroplasty in Patients with a History of Ischemic Heart Disease: A Randomized Clinical Trial. Trauma Monthly, **2023**. 28(3): p. 805-814. [Google Scholar], [Publisher]

[5] K. Komlakh, et al., Designing a Guideline for Elective and Emergency Spinal Cord Surgeries During the COVID-19 Pandemic. Trauma Monthly, **2022**. 27(Especial Issue (COVID-19 and Emergency Medicine)): p. 1-7. [Crossref], [Google Scholar], [Publisher]

[6] S. Charsouei, et al., Effects of COVID-19 pandemic on perceived stress, quality of life, and coping strategies of women with breast cancer with spinal metastasis under chemotherapy. Int. J. Women's Health Reprod. Sci, **2021**: p. 55-60. [Crossref], [Google Scholar], [Publisher]

[7] S.M. Haghdoost, and M.K. Gol, The necessity of paying more attention to the neurological and psychological problems caused by the COVID-19 pandemic during pregnancy. Health, **2020**. 3(4). [Crossref], [Google Scholar], [Publisher]

[8] M.K. Gol, and D. Aghamohamadi, Effect of massage therapy with and without elastic bandaging on pain, edema, and shoulder dysfunction after modified radical mastectomy: a clinical trial. International Journal of Women's Health and Reproduction Sciences, **2020**. 8(1): p. 73-8. [Crossref], [Google Scholar], [Publisher]

[9] M.K. Gol, A. Dorosti, and M. Montazer, Design and psychometrics cultural competence questionnaire for health promotion of Iranian nurses. Journal of education and health promotion, **2019**. 8. [Crossref], [Google Scholar], [Publisher]

[10] K. Hashemzadeh, M. Dehdilani, and M.K. Gol, Effects of Foot Reflexology on Post-sternotomy Hemodynamic Status and Pain in Patients Undergoing Coronary Artery Bypass Graft: A Randomized Clinical Trial. Crescent Journal of Medical & Biological Sciences, **2019**. 6(4). [Google Scholar], [Publisher]

[11] M. Khanbabayi Gol, M. Eidy, and M. Zamani Esfahlani, Frequency ratio of carpal tunnel syndrome in women with breast cancer treated with lymphedema in Tabriz medical education centers; 2018-2019. The Iranian Journal of Obstetrics, Gynecology and Infertility, **2020**. 22(12): p. 62-68. [Crossref], [Google Scholar], [Publisher]

[12] N. Shahidi, F. Mahdavi, and M.K. Gol, Comparison of emotional intelligence, body image, and quality of life between rhinoplasty candidates and control group. Journal of Education and Health Promotion, **2020**. 9. [Crossref], [Google Scholar], [Publisher]

[13] S. Jiang, et al., A meta-analysis review of the effect of Zn-doped synthetic polymer materials on bone regeneration. Journal of Drug Delivery Science and Technology, **2022**: p. 103792. [Crossref], [Google Scholar], [Publisher]

[14] L.H. Anvar LH, et al. The study of rs324420 (C385A) polymorphism of the FAAH gene of the endocannabinoid system in patients with epilepsy and ADHD. Epilepsy Research. **2023**;192:107100. [Crossref], [Google Scholar], [Publisher]

[15] A. Mobed et al., Biosensors technology for anti-epileptic drugs. Clinica Chimica Acta. **2022**;533:175-82. [Crossref], [Google Scholar], [Publisher]

[16] S. Charsouei, et al., Evaluation of Three- and Five-Year Disease-Free Survival in Patients With Cervical Cancer With Spinal Cord Metastasis Under Treatment With External Radiotherapy+ Brachytherapy. International Journal of Women's Health & Reproduction Sciences. **2022**;10(2). [Crossref], [Google Scholar], [Publisher]

[17] M. Zamani Esfahlani, et al., Oral Levothyroxine Prophylactic Administration on Bleeding and Hemoglobin Changes During and

after Total Hip Arthroplasty in Patients with a History of Ischemic Heart Disease: A Randomized Clinical Trial. Trauma Monthly. **2023**; 28(3): 805-14. [Crossref], [Google Scholar], [Publisher]

[18] K. Komlakh et al., Designing a Guideline for Elective and Emergency Spinal Cord Surgeries During the COVID-19 Pandemic. Trauma Monthly. **2022**; 27(Especial Issue (COVID-19 and Emergency Medicine)):1-7. [Crossref], [Google Scholar], [Publisher]

[19] S. Charsouei, et al., Effects of COVID-19 pandemic on perceived stress, quality of life, and coping strategies of women with breast cancer with spinal metastasis under chemotherapy. Int J Women's Health Reprod Sci. **2021**: 55-60. [Crossref], [Google Scholar], [Publisher]

[20] M.K. Gol, et al., Design and psychometrics cultural competence questionnaire for health promotion of Iranian nurses. Journal of education and health promotion. **2019**; 8. [Crossref], [Google Scholar], [Publisher]

[21] K. Hashemzadeh, M. Dehdilani, M.K.Gol Effects of Foot Reflexology on Post-sternotomy Hemodynamic Status and Pain in Patients Undergoing Coronary Artery Bypass Graft: A Randomized Clinical Trial. Crescent Journal of Medical & Biological Sciences. **2019**; 6(4). [Google Scholar], [Publisher]

[22] M. Khanbabayi Gol, et al., Frequency ratio of carpal tunnel syndrome in women with breast cancer treated with lymphedema in Tabriz medical education centers; 2018-2019. The Iranian Journal of Obstetrics, Gynecology and Infertility. **2020**; 22(12):62-8. [Crossref], [Google Scholar], [Publisher]

[23] N. Shahidi, et al., Comparison of emotional intelligence, body image, and quality of life between rhinoplasty candidates and control group. Journal of Education and Health Promotion. **2020**;9. [Crossref], [Google Scholar], [Publisher]

[24] S. Jiang, Y. Zhang, F. Alsaikhan, AT. Jalil, M.K. Gol, A. Tarighatnia, A meta-analysis review of the effect of Zn-doped synthetic polymer materials on bone regeneration. Journal of Drug Delivery Science and Technology. **2022**:103792. [Crossref], [Google Scholar], [Publisher]

[25] A Fathi, Ebadian, S Nasrollahi Dezaki, N Mardasi, R Mosharraf, S Isler, S Sadat Tabatabaei, " International Journal of Dentistry, vol. 2022, Article ID 4748291, **2022**. [Crossref], [Google Scholar], [Publisher]

[26] D Nakuci, E Kola, E Horjeti, I Kola, B Shaipi, J Musa, A Guy, M Alimehmeti, Archives of Clinical and Medical Case Reports, **2020** 4 (5), 760-765 [Google Scholar], [Publisher]

[27] E Ghasemi, AH Fathi, S Parvizinia., J Iran Dent Assoc **2019**; 31 (3):169-176 [Crossref], [Google Scholar], [Publisher]

[28] E Kola, A Gjata, I Kola, A Guy, J Musa, et al., Radiology Case Reports, **2021** 16 (11), 3191-3195 [Crossref], [Google Scholar], [Publisher]

[29] E Kola, A Gjata, I Kola, et al., Radiology Case Reports, **2022** 17 (3), 1032 [Crossref], [Google Scholar], [Publisher]

[30] E Kola, I Kola, M Brati-Dervishi, et al., Journal of Surgery and Research, **2020** 3 (2), 140-146 [Crossref], [Google Scholar], [Publisher]

[31] E Kola, J Musa, A Guy, I Kola, E Horjeti, V Filaj, M Alimehmeti, Medical Archives, **2021** 75 (2), 154 [Crossref], [Google Scholar], [Publisher]

[32] E Kola, J Musa, A Guy, I Kola, E Horjeti, V Filaj, M Alimehmeti, Journal of Medical Archives. **2021** 75(2) 154 [Crossref], [Google Scholar], [Publisher]

[33] E Kola, L Berdica, et al., ASMS, **2020** 4 (5), 45-48 [Crossref], [Google Scholar], [Publisher]

[34] E Kola;et al, J Clin Rev Case Rep. 2019; 4(6):1-4 [Crossref], [Google Scholar], [Publisher]

[35] E Harizi; et al, Radiology Case Reports **2022** 17 (11) 4152-4155 [Crossref], [Google Scholar], [Publisher]

[36] E. Ghaibi, et al., Eurasian Journal of Chemical, Medicinal and Petroleum Research, **2022**, 1, 33-39. [Google Scholar], [Publisher],
[37] F Beiranvandi, Z Kuchaki, A Zare, E Khoshdel, A Jalali, Journal of Pharmaceutical Negative Results, **2022**, 4417-4425 [Crossref], [Google Scholar], [Publisher]
[38] F HYSENI; et al, The Importance of Magnetic Resonance in Detection of Cortical Dysplasia, Curr Health Sci Journal. **2021**; 47(4): 585–589 [Crossref], [Google Scholar], [Publisher]
[39] F Rokhtabnak, S Sayad, M Izadi, SD Motlagh, P Rahimzadeh, Anesthesiology and Pain Medicinem **2021** 11 (5) [Crossref], [Google Scholar], [Publisher]
[40] F Safari, H Safari, Eurasian Journal of Chemical, Medicinal and Petroleum Research, **2022** 1 (2), 150-154 [Google Scholar], [Publisher]