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Detection and Assessment of Spinal Cord Injury Using Spectral Coherence

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Abstract—**Graded spinal cord injury was induced in rats using the NY-Impactor. Somatosensory evoked potentials (SEPs), in response to stimuli to the nerves in the limbs, were recorded from the cranium. These signals were analyzed using spectral coherence analysis. Results obtained from 15 rats show information that was missed when other techniques are used.**

I. Introduction

THERE are approximately 14,000 spinal cord injury (SCI) incidences per year in the United States. Millions of patients worldwide are living with the devastating effects of spinal cord injuries [1]. This number is rising because of the steady improvements in life expectancy without the analogous improvement in the quality of life.

Research in the area of spine injury is becoming even more important as the number of accidents and misfortunate incidents is increasing.

The conventional method to assess SCI involves observation of the rats for four minutes in an open field by a trained examiner. This method is called the Basso, Breathe and Breshnahan (BBB) technique [2]. The examiner gives a score between 0-21, where 0 and 21 stand for the lowest and highest possible scores respectively. BBB is well-accepted and easy to execute. Nevertheless, it does not show distinguished recovery for mild injuries [3]. Moreover, BBB results are not concurrent between two examiners. It also does not account for the non-willingness of the rodent to move. Another disadvantage of BBB is that the examiner needs to have a trained eye.

In this research work, rodents were used to verify a potential method to provide a quantitative measure of SCI. An Evoked Potential (EP) can be defined as an electrophysiological response of a neural system to an external stimulus. Somatosensory evoked potentials (SEPs) are generally obtained by electrical stimulation of the median nerve at the wrist or the posterior tibial nerve at the ankle [4]. This mechanism was applied as a means of evaluating ongoing neuropsychological changes throughout the recovery period after SCI. Previous studies using SEP data for SCI detection have used changes in latency and peak amplitude of SEP signals as seen in Fig. 1. The inherent disadvantage of time analysis is that spectral changes can not be detected. Moreover, some SEP signals, like in Fig. 2, do not have a detectable latency or peak amplitude. Other methods that have been used to analyze SEP signals include autoregressive algorithms, adaptive latency measurement, kinematic measures, etc. [5-7].

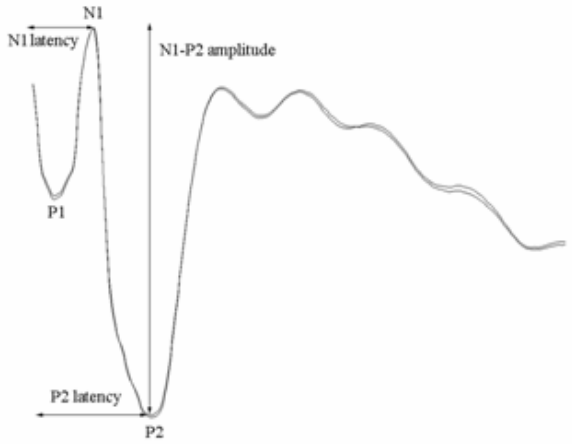

Fig. 1. Latency and peak amplitude measurement in an SEP signal.

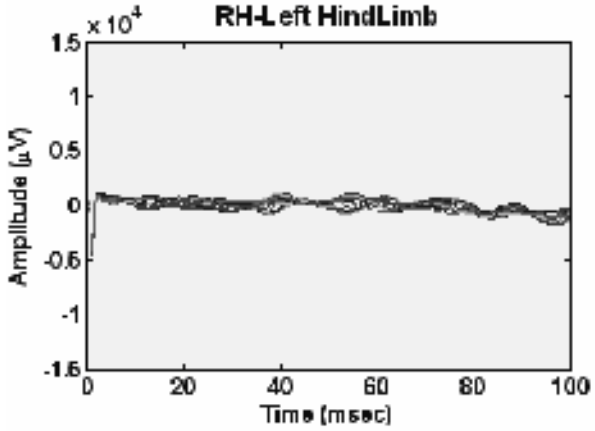

Fig. 2. A SEP signal that has been taken from one of the experimental rats. The signal has no detectable latency and peak amplitude.

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Coherence analysis is being introduced to obtain a quantitative measure for the detection and monitoring of SCI. Recent work also shows that there is a very sharp drop in the magnitude coherence estimation during hypoxic brain injury [8].

A quantitative assessment method was developed via signal processing and event-related neurological monitoring. This is done in order to enable researchers, in the area of SCI recovery and rehabilitation, to evaluate more accurately and objectively any possible therapeutic mechanisms to reverse or prevent the devastating effects of SCI.

The paper is organized as follows. In section II, the injury protocol and spectral coherence are introduced. In section III, we present some results of the spectral coherence assessment method. Finally, conclusions and suggestions for future work are included in section IV.

II. Methodology

A. Injury Protocol

Female adult Fischer rats were used as samples. Five burr holes were drilled into the cranium at the forelimb and hindlimb somatosensory cortex area on the right and left hemispheres. The four screw electrodes made very light contact with the duramater, but did not compress the dura or brain structures. The fifth screw electrode, on the anterior of the cranium, was used as a reference electrode. The SEP signals were monitored using these skull electrodes.

After implanting skull SEP electrodes, a 30-60 minute *baseline* SEP was recorded. This was followed by laminectomy which takes around 20 minutes. Right after that, *post-lamin baseline* SEP was recorded for 30-60 minutes. The rat was then removed from SEP set-up and put under NY-impactor to induce an injury in the T-8 region. The graded levels of SCI were produced by dropping a 10 g rod with a flat circular impact surface from heights of 6.25, 12.5, 25 or 50 mm for the mild, moderate, severe and very severe injury groups respectively. This process takes around 10 minutes. The rat was returned for *post-injury* SEP recording for 60 minutes.

To generate stimulation for SEP, subcutaneous needle electrodes are used for left and right median and tibial nerves (1 Hz frequency, 3.5 mA amplitude, 200 ms duration, 50 % duty cycle) without direct contact with the nerve bundle.

Contralateral SEP recordings were used for the left and right forelimbs, as well as the hindlimbs. Averaging of the recorded evoked potentials was performed to enhance the signal-to-noise ratio.

Biologically, the left hemisphere controls the right side of our bodies and vice versa. Therefore, it is reasonable to use signals from the left hemisphere to analyze right forelimbs and hindlimbs. In this report, all the analysis is done baring this in mind and focus is given to the right limbs.

B. Spectral Coherence Analysis

The coherence function gives a measure of similarity between signals and is related to cross correlation function. The magnitude-squared spectral coherence function Γ_{xy}^2 of two signals x and y is a normalized version of the cross power spectral density between x and y and is defined as:

$$\Gamma_{xy}^2(\omega) = \frac{\left|P_{xy}(\omega)\right|^2}{P_{xx}(\omega)P_{yy}(\omega)} \tag{1}$$

where $P_{xy}(\omega)$ is the cross power spectrum between x and y signals, $P_{xx}(\omega)$ and $P_{yy}(\omega)$ are the power spectrums of the x and y signals respectively.

Assume that the 1 Hz input stimulus signal S is the same for all limbs. x, in Fig. 3, is the SEP signal recorded at the cortex which results from stimulating the Left Forelimb, Right Forelimb, Left Hindlimb or Right Hindlimb. Similarly, y is the SEP signal recorded at the cortex which results from stimulating the Left Forelimb, Right Forelimb, Left Hindlimb or Right Hindlimb. Assume that x and y are related to S through linear systems H_1 or H_2 but they also contain additive independent noise n_1 and n_2. H_1 or H_2 is used to model the transfer function of the biological system or network from the stimulation site to the recording site at the cortex.

For a normal healthy spinal cord transmission system, H_1

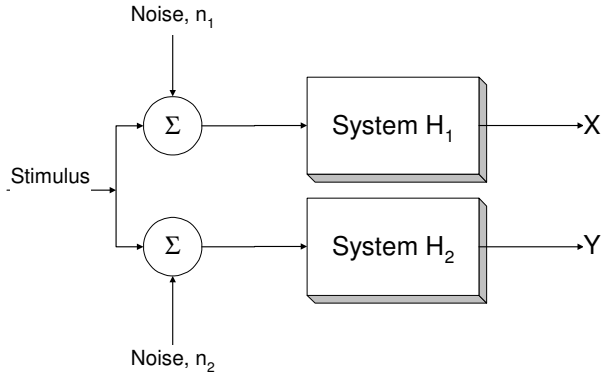

Fig. 3. Stimulus source signal passing through two networks H_1 and H_2, which represent the biological system from the simulation site to the recording site.

and H_2 are expected to have a relatively fixed frequency transfer characteristics. However, following SCI, H_1 or H_2 or both will be modified and hence their frequency transfer characteristics will also be modified. Therefore, the spectral coherence function will also be modified.

To model the effect of variations of H_1 and H_2 on Γ_{xy}^2, assume that n_1 and n_2 are independent of x and y, and

$$H(\omega) = \frac{H_2(\omega)}{H_1(\omega)} \tag{2}$$

$$N(\omega) = N_2(\omega) - N_1(\omega) \tag{3}$$

then, it can be shown that

$$\Gamma^2(\omega) = \frac{\left|H(\omega)P_{xx}(\omega)\right|^2}{P_{xx}(\omega)\left|H(\omega)\right|^2\left[P_{xx}(\omega) + N(\omega)\right]} \tag{4}$$

Under normal conditions, with finite $H(\omega)$ and low noise power density, we expect Γ_{xy}^2 to approach 1. However, Γ_{xy}^2 may decrease down to zero under SCI conditions, where $H(\omega)$ may approach zero. In this work, Γ_{xy}^2 is computed for N epochs averaged, with a spectral coherence given by:

$$\overline{\Gamma}^2(\omega) = \frac{1}{N}\sum_{i=1}^{N}\Gamma_i^2(\omega) \tag{5}$$

The SEP data size controls the selection of N. The available data enabled us to select N between 20 and 50. N was selected to be around 20 for all average spectral coherence values. Average coherence was performed for a band that concentrated on the region with the highest baseline spectral coherence. This is called the *global coherence*.

III. Results

The following results are obtained for a cohort of 15 rats. Each of the four groups mentioned in the previous section had three rats.

A. Baseline Right Forelimb as Control for Other Right Forelimb Signals

Looking at the change in the spectral coherence over time before and after injury helps us understand the effect of injury on the forelimbs. We expect that injury affects mostly the hindlimbs and not the forelimbs. Therefore, the coherence should be high between forelimbs signals.

The results shown in Fig. 4 support this assumption. Fig. 4 is a plot of the averaged global spectral coherence for all the rats from the control group and the very severe injury level group.

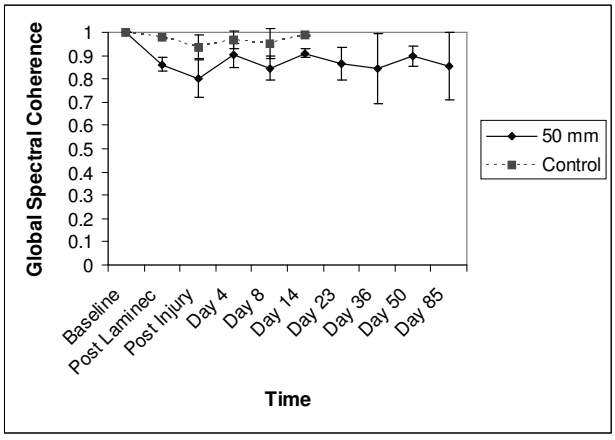

Fig. 4. Plot of the averaged global spectral coherence for all the rats from the control group and the 50 mm injury level group.

Although the global spectral coherence is affected slightly by injury, the global coherence is always relatively high. It can be assumed that the effect of injury on the forelimb is insignificant. Hence, any right forelimb signal can be used instead of its baseline for analysis of rats injured by the NY-impactor.

B. Baseline Right Forelimb as Control for Right Hindlimb Signals

Baseline hindlimb information is not available to us after an accident or injury to the spine. In real life, such information is not obtainable and therefore, using the baseline hindlimb as a control signal is of no practical importance. Maintaining the results from the previous simulations, forelimb signals, even after injury, have a very high spectral coherence with the baseline forelimb. This means that the forelimb signals are spectrally alike the baseline forelimb signal. Therefore, after injury, forelimb signals can be used as a control signal for the hindlimb.

Choosing the right frequency band of interest is very important. The frequency band of interest is chosen to maximize spectral coherence before injury. The high coherence occurs at low frequencies as expected. Closer observation of the average of the spectral coherence for the right hindlimb baseline with the right forelimb baseline for all rats (Fig. 5) helps us choose the band of 125-175 Hz.

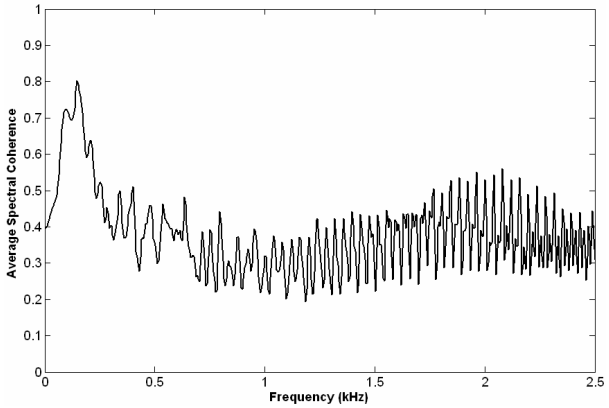

Fig. 5. The average of the spectral coherence for the right hindlimb baseline with the right forelimb baseline for all rats.

The results of three rats can be seen in Fig. 6. The control rat, Rat 1, has relatively no change in the global spectral coherence between the right baseline forelimb and right hindlimb over time. The relatively high coherence is analogous to no injury which is expected. The global spectral coherence of the rat from the 6.25 mm injury group, Rat 14, shows a dip when injury occurs and a rise over time. This result is analogous to recovery; whereas the results for Rat 1, from the very severe injury group, do not show a lot of recovery.

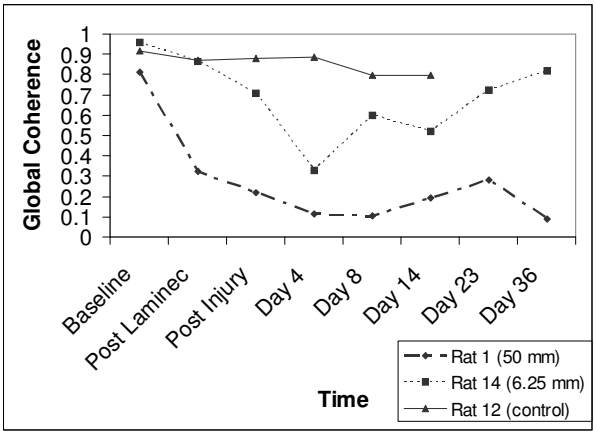

Fig. 6. Global spectral coherence between baseline right forelimb and right hindlimb for Rat 1, 14 and 12 from the 50 mm, 6.25 mm and control groups respectively.

Some of the results can be correlated to the results from BBB (Fig. 7). For smaller injury levels, the correlation between the results is relatively higher than for higher injury levels. Moreover, the differences in results occur because BBB assesses motor function whereas SEP analysis assesses sensory function.

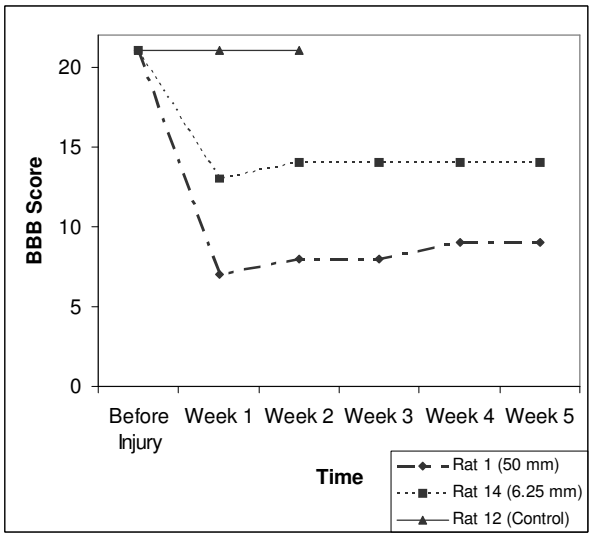

Fig. 7. The average of the spectral coherence for the right hindlimb baseline with the right forelimb baseline for all rats.

Similar results were obtained from the rest of the rats. The coherence after 36 days of SCI varied between 0.03 to 0.86. The results of global spectral coherence over the recovery period may differ amongst the rats from the same injury group. This could be due to several reasons such as the differences in every individual's recovery or the exact location of injury.

IV. Conclusion

A series of experiments were performed on rats and the strength of spectral coherence analysis was tested. The method has many advantages such as it: a) is a normalized quantitative measure; b) does not require a trained examiner; c) does not necessarily require the baseline signals; and d) is an objective method. This method can show improvements in a particular hindlimb. Such information is missed when other techniques are used. The main disadvantage of the proposed method is that it is noise sensitive.

Every rat has a different frequency band of interest. In this research, we have assumed that averaged peak coherence before injury coincides for all rats.

As the time domain SEP signal is non-stationary, our future work will focus on the development and testing of a method that incorporates time with spectral coherence.

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