EVALUATION OF THE COLLISION TECHNIQUE FOR ESTIMATING NERVE CONDUCTION VELOCITY DISTRIBUTION

Chad Gilbert, Jose Gonzalez-Cueto
Dptm Electrical & Computer Eng, Dalhousie University

ABSTRACT

The use of the collision technique for estimating nerve conduction velocity distribution (CVD) is assessed in this paper. Simulations were run in MATLAB and experiments were performed on six healthy human subjects. Since the estimator is intended for use in determining the severity of Carpal Tunnel Syndrome (CTS), the estimator must be able to distinguish between different unexpected CVDs and healthy ones. Simulations were run to determine the performance of the estimator for different CVDs. According to the literature, slowing of nerve conduction velocity (CV) can occur in the case of CTS, due to demyelination. A simulation was performed to evaluate the bias of the estimator in the case of slowing, and to compare these estimates with those of another CVD estimator (the 2-CNAP deconvolution method) for the same CVDs and slowing effects. The effect of random noise interfering with the recorded signals was tested in the simulation, and is compared to the amplitude of the noise that was seen in the experimental signals. Data and results from experiments are discussed in light of the simulation results.

INTRODUCTION

Carpal Tunnel Syndrome (CTS) is a nerve conduction syndrome caused by localized compression of the median nerve at the wrist. CTS is generally detected using electrophysiological testing such as the standard Nerve Conduction Studies (NCS). NCS are performed by placing stimulating electrodes at a distance from the recording electrodes. Sensory NCS are the most sensitive NCS in the diagnosis of CTS. The general measurements made are amplitude, area under the waveform, latency and CV. An average sensory CV of 45m/s or less suggests the presence of CTS [1][2]. NCS mainly evaluate the function of large myelinated nerve fibers, i.e. those with high CV. Selective evaluation of nerve fibers based on their diameter or CV is not feasible with these techniques. According to the literature [3], severity of CTS progresses from large nerve fibers to small nerve fibers. An early deficit in the activity of smaller nerve fibers will likely go unnoticed since the contribution of larger fibers to the compound nerve action potential (CNAP) recorded is significantly bigger than that coming from the smaller fibers [4]. Hence, a method to assess the diameter or CV of the active nerve fibers traversing the carpal tunnel (CT) will improve current CTS diagnostic techniques.

Characterizing a nerve in terms of the probability density function (pdf) that describes the distribution of active fibers across a velocity interval can be done by estimating its CVD. If a reliable CVD estimate for the median nerve fibers traversing the CT is obtained it will be a useful parameter to describe the nerve fibers being affected in a CTS patient. This paper compares the performances of two different CVD estimators.

COLLISION-BASED METHOD

The collision technique can be used to selectively activate nerve fibers of different diameters by varying the delay between two electric stimuli – one delivered at the wrist, and a delayed one delivered at the elbow [2]. The elbow CNAP is recorded using a bipolar channel consisting of two surface ring electrodes placed at the middle finger. The inter-stimulus interval (ISI) is the time interval between the delivery of the wrist stimulus pulse and the delivery of the elbow stimulus pulse. When the ISI is relatively large, the elbow CNAP does not collide with the wrist CNAP, hence a response from all the nerve fibers activated by the elbow stimulus pulse is recorded at the finger. When the ISI is gradually decreased, the contribution from small nerve fibers reduces as the slow traveling action potentials (APs) generated at both stimulation sites start colliding and only the faster traveling APs get through to the recording electrodes placed on the finger. Of these APs getting through, the one with the lowest CV is determined by the ISI value. This lowest velocity value can be calculated using [2]:

$$CV = \frac{D + 3.2}{ISI - 0.37} \qquad (1)$$

where CV is the conduction velocity in m/s

D is the distance between the two stimulating electrodes in mm, and

ISI is the inter-stimulus interval in ms.

By subtracting consecutive CNAPs obtained as the ISI is progressively reduced (CNAP difference), the CNAP contribution from fibers belonging to a certain velocity interval can be isolated. The nerve CVD can then be estimated by performing calculations on the CNAP difference, and a full (unblocked) CNAP [5].

2-CNAP DECONVOLUTION METHOD

The 2-CNAP deconvolution method described in [4] is performed using a similar lab setup, but only one stimulus channel is required. Two recording sites are selected on the arm, one at the wrist and one at the elbow, while the nerve response is elicited at the middle finger. A stimulus is applied at the stimulus site, and the CNAP is recorded at both the wrist and elbow. Calculations are then performed using the two recorded signals to estimate the nerve CVD.

EVALUATING THE ESTIMATORS

Since the CVD estimators are intended for use as a diagnostic tool in determining the severity of CTS, they must be able to accurately estimate the CVD of an unhealthy patient as well as that of a healthy patient, so that the two cases can be distinguished. The performances of both estimators were evaluated for five different cases. Simulations were run to test the accuracies of the two estimators for five different CVDs. These five cases are shown in figure 1. The first case represents the CVD of a healthy patient. Each case afterwards represents the CVD of an unhealthy patient, with an increasing severity of CTS.

As suggested by [6] it is possible that a case of CTS could cause excessive damage to the myelin sheath (demyelination) of a nerve fiber, without actually causing it to stop conducting APs. Since a demyelinated nerve fiber conducts APs at significantly different CVs, the presence of demyelinated fibers in the CT (due to the syndrome) would have an effect on the estimator. This scenario, where there is slowing of the nerve fibers in the CT segment of the median nerve, could potentially cause unexpected biases in the estimators since the estimators in question assume a constant CV along each nerve fiber.

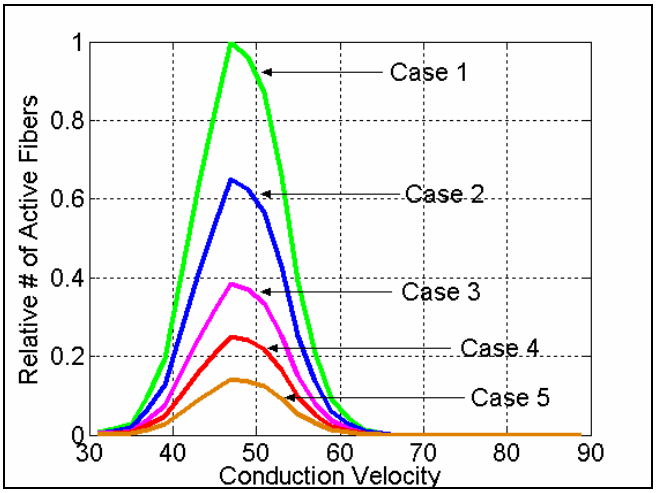

Figure 1: Five different hypothetical CVDs

PERFORMANCE OF THE ESTIMATORS

Both the Collision Technique and the Two CNAP Deconvolution method were tested in MATLAB. Their performances were assessed through the percent mean square difference between the test CVDs, used to generate the CNAP data fed to the estimators, and the estimated CVDs. The results of the simulations are shown in table 1. An example of a typical CVD estimate is shown in figure 2.

It can be seen from the table, that both estimators approximate the actual CVD within 1% mean square error. The 2-CNAP deconvolution estimator performed slightly better than the collision-based estimator.

Health Case	Estimator Error (PMSE)	
	Collision	***2 CNAP***
1	0.508 %	0.304 %
2	0.508 %	0.255 %
3	0.560 %	0.257 %
4	0.410 %	0.248 %
5	0.856 %	0.682 %

Table 1: Comparing the two techniques

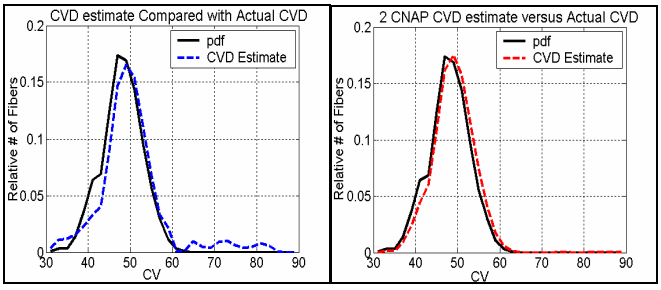

Figure 2: CVD Estimates for the same PDF (Collision-Based estimate is on the left)

SLOWING DUE TO DEMYELINATION

A MATLAB simulation was created to model the slowing of conduction velocity of nerve fibers. The simulation is based on the MATLAB simulations described in the previous section of this paper. Additionally, two parameters were incorporated, the length of the CT segment that the median nerve passes through and the number of fibers that will experience the effect of demyelination (slowing). It was assumed that as the severity of CTS increases, a larger number of nerve fibers will be slowed due to demyelination.

The simulation assumes that any fiber in the median nerve can conduct with two distinct velocities: the normal healthy velocity, or the slowed velocity in the case of demyelination. To determine the slow

velocity corresponding to any nerve fiber, the following relation was determined using information from [6]:

$$V_D = 2.3\left(\frac{V_M}{6.6}\right)^{\frac{1}{2}} \qquad (2)$$

where V_D is the CV of the demyelinated fiber, and
V_M is the CV of the myelinated healthy fiber.

A further assumption made in the slowing model is that the nerve fibers are only slowed for a portion of the CT, not the whole distance. It is unlikely that every single Schwann cell in the CT segment has failed. The length of demyelinated nerve fiber was assigned to each slowed nerve fiber as a random number, uniformly distributed between 0 mm and the length of the CT.

It was further assumed that the odds of a large nerve fiber experiencing slowing were larger than that of a smaller nerve fiber. To simulate this, a certain number of the smaller fibers were protected from the effects of slowing, in the model.

PERFORMANCE OF THE ESTIMATORS IN THE PRESENCE OF SLOWING

Both estimators are expected to exhibit a certain bias when estimating the CVD of a nerve in which there is conduction slowing. This is because the estimators assume that all nerve fibers are conducting at constant velocities uniformly throughout the entire nerve path. The methods mentioned above were simulated for different amounts of slowing, and the results can be seen in figures 3 and 4.

Represented in each figure is a plot of the CVD in a healthy part of the median nerve (PDF), the CVD representing the slowed nerve fibers (Slow), and the results from both techniques; collision-based method (CVD Collision) and the 2-CNAP deconvolution method (CVD 2 CNAP). Figure 3 shows the results for the simulation when it was run with 10% of fibers slowed, and Figure 4 shows the results for 30% slowing. It appears, by visual comparison of the results, that the collision-based estimator is more sensitive to the effects of slowing than the 2-CNAP deconvolution method.

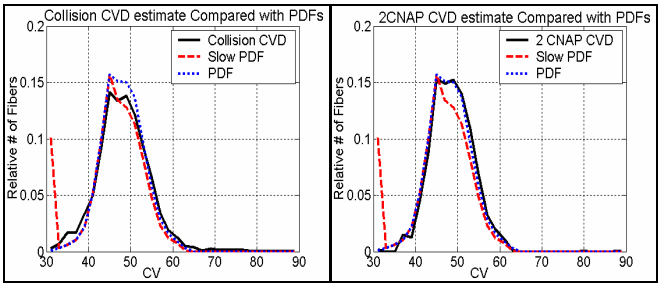

Figure 3: CVD estimates in the case of 10% slowing (The collision estimated CVD is on the left)

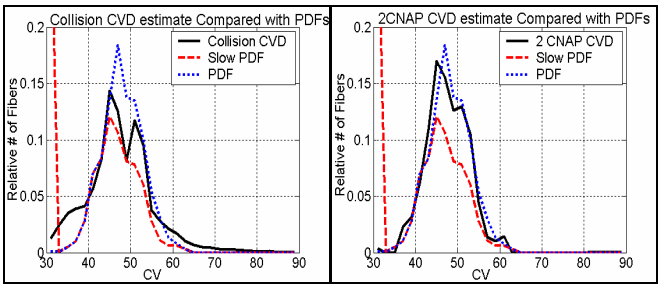

Figure 4: CVD estimates in the case of 30% slowing (The collision estimated CVD is on the left)

SNR EVALUATION

Simulations were run to evaluate the performance of the estimators when noise is added to the signals. For the collision technique simulation, the signal to noise ratio (SNR) was calculated by dividing the peak value of the unblocked elbow CNAP signal by the standard deviation of the noise. Similarly, for the 2-CNAP deconvolution method, the SNR was calculated as the peak value of the elbow-recorded signal, divided by the standard deviation of the noise in that channel. The performances of both CVD estimators were measured (in PMSE) for different noise powers. The simulations were each run 10 times for each SNR, holding all other variables constant and the results were averaged, so as to get a more reliable reading of the average performances. Table 2 compares the results for both techniques.

The results in the table show, that as more noise is added to the signals, the performance of the estimators becomes worse. In the lab, the SNR usually associated with the 2-CNAP deconvolution method was between 7 and 15 Volts/Volt and the SNR usually associated with the Collision technique were between 6 and 20 Volts/Volt. Comparing these values to the table above shows that a PMSE of 0.2-2.2% would be expected in the Collision technique estimated CVD, and between 0.25-0.82% for the 2-CNAP deconvolution method.

SNR	Estimator Error (PMSE)	
	Collision	***2 CNAP***
∞	0.218 %	0.250 %
50	0.300 %	0.386 %
20	0.537 %	0.733 %
10	0.945 %	0.846 %
5	2.235 %	0.821 %

Table 2: Comparing the estimators for different SNRs

EXPERIMENTAL RESULTS

To test the variability of the elbow signals from the collision experiment, eight recordings of the unblocked

elbow CNAP were taken from a subject. A CNAP difference was calculated, and used with a CNAP to estimate the CVD. This was done for all 8 elbow CNAPs. The percent mean square error between each CVD estimate and the average was below 0.01% for all 8 CVD estimates. This means that there was very little variability between each elbow CNAP recording.
It was noted with one subject in the collision experiments that some of the blocked signals had lower latency components than were expected. One of these signals is shown in figure 5.

Figure 5 shows a CNAP recording that was taken, with an ISI of 2.85ms, meaning the lowest CV signal that should reach the recording electrodes is 80m/s (the inter-stimulus distance was 220mm). However, the middle of the signal arrives at the recording electrodes with a delay of about 6.5ms. The proximal stimulus distance was 395mm (taken from the elbow to half way between the cathode and anode of the recording electrodes). This implies that the average CV of the non-blocked fibers is about 65m/s, which is impossible if all fibers with CV below 80m/s are being blocked. The result was that the signal contained information that was being assumed to have been blocked. This most likely caused error in the CVD estimates. The experimental trials for the 2-CNAP deconvolution method, as described in [4], did not have difficulties such as that described above.

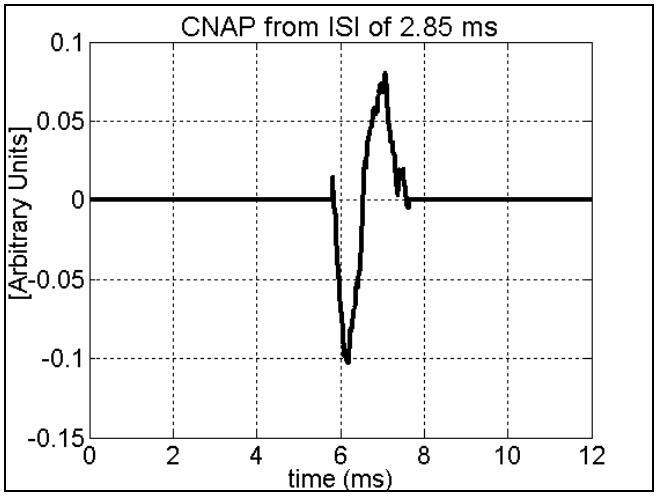

Figure 5: CNAP signal recorded when an ISI of 2.85ms is used

CONCLUSIONS

In simulations without slowing, both estimators performed similarly. A performance index below 1% would be accurate enough in a clinical setting. The case of slowing is more subjective than the other situations in which the collision-based estimator was compared to the 2-CNAP deconvolution method. The 2-CNAP deconvolution method estimates a CVD that looks similar to the PDF from figures 3 and 4. The collision-based estimator, on the other hand, shows a bias towards the lower velocities. It is possible that using an estimation technique that is sensitive to slowing, such as the collision technique, would help identify the early stages of CTS. More research should be performed to understand the effects of demyelination on the estimators.

Though it was shown in experiments that the same elbow stimulus could be applied consistently over a number of trials, it was also found that blocking can be unreliable. Obtaining an accurate CNAP difference is required for the collision-based estimator to be useful. The procedure that was used to perform the above mentioned experiments would need improvement for use in the diagnosis of CTS. The experimental procedure for the 2-CNAP deconvolution method is more reliable than that of the collision technique.

REFERENCES

[1] Akiyo Nishimura, *et al.*, “Objective evaluation of sensory function in patients with carpal tunnel syndrome using current perception threshold”, J of Orthopaedic Science, 8, 625-628 (2003).

[2] N. Dalkilic, B. Yuruten, and B. Ilhan, “Somatosensory conduction velocity distribution of median nerve middle palmar digital component”, Intern. J. Neuroscience, 114,153-165 (2004).

[3] A. Nishimura, *et al.*, “A correlative electrophysiologic study of nerve fiber involvement in carpal tunnel syndrome using current perception thresholds”, Clinical Neurophysiology, 115, 1921-1924 (2004).

[4] J.A. Gonzalez-Cueto and P.A. Parker, “Deconvolution estimation of nerve conduction velocity distribution”, IEEE Transactions on Biomedical Engineering, 49, No.2, 140-151 (2002).

[5] S. Sundar and J.A. Gonzalez-Cueto, “Conduction velocity distribution estimation using the collision technique for assessing carpal tunnel syndrome”, Proceedings of the 28th Conference of the IEEE-EMBS, pp. 2373-2376, New York, NY, USA, Sept 2006.

[6] J.M. Ritchie, “Physiology of axons”, in The Axon. Structure, Function and Pathophysiology, edited by S. G. Waxman, J. D. Kocsis, and P. K. Stys. New York: Oxford Univ. Press, 1995