Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Conduction Velocity Distribution Estimation using the Collision Technique for Assessing Carpal Tunnel Syndrome

Swarna Sundar, Jose A. Gonzalez-Cueto
Dptm of Electrical & Computer Eng
Dalhousie University, Halifax, NS, Canada

Abstract- **A technique for selectively activating nerve fibers based on their diameter using the collision technique and evaluating nerve integrity using a conduction velocity distribution (CVD) estimator is discussed in this paper. This study is aimed at improving current diagnostic techniques used for assessing carpal tunnel syndrome (CTS). Current nerve conduction studies are influenced by the activity of the largest fibers active at the moment of recording and it is not possible to selectively analyze the functioning of smaller nerve fibers. According to the literature, the severity of CTS progresses from large nerve fibers to small nerve fibers. Therefore, the current study is an attempt to selectively evaluate nerve fibers based on their diameter and hence detect the severity of CTS in a patient more effectively.**

I. Introduction

A. Carpal Tunnel Syndrome

Carpal Tunnel Syndrome (CTS) is a nerve conduction syndrome caused by compression of median nerve, traversing through the carpal tunnel, at the wrist. Clinically, it is diagnosed using Nerve Conduction Study (NCS) [1]. NCS generally evaluates the functioning of the large nerve fibers as a whole. It does not selectively evaluate the performance of different diameter ranges of nerve fibers. Therefore, an early deficit in the functioning of the smaller nerve fibers may get unnoticed. Moreover, the CTS progresses from large nerve fibers to small nerve fibers [2]. Therefore, a method to selectively evaluate nerve fibers based on their diameter would improve current diagnostic techniques used for assessing CTS that are only capable of accounting for the largest fibers active or healthy at the time the test is performed. It would also provide insight in the progress of CTS and test if it actually progresses from large to small fibers in all cases.

B. Collision Technique

Selective activation of nerve fibers is achieved by varying the time of application between two stimuli, one applied at the wrist and another at the elbow, using bipolar surface stimulation electrodes [3]. Bipolar ring electrodes placed on the middle finger are used for recording. The delay between the two stimulus applications is called inter-stimulus interval (ISI). When the ISI is relatively large, response from all the nerve fibers is recorded. In this case, the proximal compound nerve action potential (CNAP), elicited at the elbow, and the distal CNAP, evoked at the wrist, do not collide with each other. When the ISI is decreased gradually the response from small nerve fibers decreases because some of the slow-traveling AP's from both stimulus sites collide with each other, therefore only the rest of the AP's getting through to the recording electrodes are recorded. The lowest conduction velocity (CV) getting through to the recording electrode, which is also interpreted as the highest CV being blocked, is obtained from the ISI used through the expression given in [3].

C. CNAP Difference

By reducing the ISI sequentially, the CNAPs obtained for each ISI are recorded. Subtracting two subsequent CNAPs gives the CNAP contribution from nerve fibers of a CV range [4]. This difference will be referred to as CNAP difference in the rest of the paper. By analyzing each of these differences, the velocity/size of the nerve fiber affected can be found. The relative number of active fibers in these velocity ranges can then be used to find the severity of CTS. This can be determined using a conduction velocity distribution (CVD) estimate.

D. Conduction Velocity Distribution

Characterizing a nerve or muscle in terms of the probability density function (PDF) that describes the distribution of active fibers across a velocity interval involves estimating its CVD. An estimate of the velocity distribution can be obtained by dividing the CV interval into bins [5]. The objective of this study is to build a CVD estimator and test it in MATLAB using simulated data.

II. Method

A. CNAP Difference

For the modeling of the CVD estimator, a description of the electrical source used to build this estimator is essential. To find the electrical source pertaining to the subject under study, CNAP differences obtained from the individual using the collision technique are used. The CNAP model and the surface single fiber action potential (SSFAP) model were adopted from the literature [5] [6].

The CNAP contribution of fibers sharing a small velocity/delay range, let us call it bin *i*, can be obtained by taking the difference between two CNAPs recorded using ISI values determined by the velocities delimiting this velocity interval or bin *i*.

1-4244-0033-3/06/$20.00 ©2006 IEEE.

This CNAP difference can be expressed as [4]:

$$CNAP_{\Delta}(t) \cong K1 \cdot m_i \left[s(t) * h_i\left(t - \frac{d}{v_i}\right)\right] \quad \text{(Eq.1)}$$

where

$CNAP_{\Delta}$ represents the CNAP contribution from active fibers in bin *i*,

$s(t)$ is the electrical source to be estimated,

$h_i(t)$ is the tissue filter function for bin *i*,

t is the time variable,

d is the distance between stimulation and recording site,

v_i is the mean CV representative of bin *i*,

m_i is the number of active fibers in bin *i*, and

K1 is a constant accounting for the electrical conductivities of the media.

B. Estimation of the Source

Using the Fourier transform, the CNAP difference obtained was transformed into its corresponding frequency domain spectrum $CNAP_{\Delta}(j\omega)$ and the tissue filter function used to describe the CNAP difference is also converted to its frequency domain representation $H_i(j\omega)$ [4]. By taking Fourrier transform on both sides of Eq.1 and using the convolution and time shifting properties of the Fourier transform we obtain:

$$CNAP_{\Delta}(j\omega) \cong K1 \cdot m_i [S(j\omega) \cdot H_i(j\omega) \cdot e^{-j\omega d/v_i}] \quad \text{(Eq.2)}$$

In Eq.1, K1 & m_i are constants that can be replaced by a scaling factor. Therefore, the spectrum of the estimated source is given by:

$$\hat{S}(j\omega) = \frac{CNAP_{\Delta}(j\omega)}{H_i(j\omega) \cdot e^{-j\omega d/v_i}} \quad \text{(Eq.3)}$$

This source spectrum estimate can be converted to the time domain by taking its inverse Fourier transform, thus the source is estimated as:

$$\hat{s}(t) = \Im^{-1}\left\{\hat{S}(j\omega)\right\} \quad \text{(Eq.4)}$$

By using this estimated source $\hat{s}(t)$ with the SSFAP model [6], SSFAPs can be generated for a full range of velocities, *i.e.* 20m/s to100m/s. A collision-free CNAP recorded by just stimulating the elbow will contain contributions from fibers over this full range of velocities.

C. CVD Estimator

Using this collision-free CNAP and the SSFAPs generated, the relative number of active fibers *m* (the CVD) can be estimated. The CNAP model can be written in matrix notation as:

$$cnap = SFAP \cdot m \quad \text{(Eq.5)}$$

where

$cnap$ is a $K \times 1$ column vector composed of K time samples of *CNAP(t), i.e.* $CNAP = [C(t_1), C(t_2), ..., C(t_k)]^T$,

$SFAP$ is a $K \times M$ matrix whose i^{th} column is time-sampled signal $SSFAP(t - \tau_i, v_i)$, and

m is an $M \times 1$ column vector containing the relative number of active fibers corresponding to each of the M bins, *i.e.* $m = [m_1, m_2, ..., m_M]^T$.

The objective of the CVD estimation is to find the relative number of active fibers m_i. Eq.5 can be viewed as a set of *K* equations and *M* unknowns (the vector *m*). A non-negative least square estimator was used for this purpose. The resulting vector, represented as $\hat{m}$, is in the delay domain. Thus, it is transformed to the velocity domain and denoted by $\hat{w}$ [4].

D. Performance Index

To measure the performance of the estimator, the estimation error was found using the percent mean square error (PMSE) given by [4]:

$$PMSE = \frac{\sum(\hat{w} - v\_pdf)^2}{\sum(v\_pdf)^2} \text{ x } 100\% \quad \text{(Eq.6)}$$

where $\hat{w}$ is the column vector of the CVD estimates,

v_pdf is the column vector of the velocity PDF used for generating the CNAPs.

III. RESULTS

For simulation, the distance between the two stimulating electrodes was assumed to be 180 mm. The distance from proximal stimulation site to anode and cathode of the recording sites were 360mm and 380mm respectively. In order to assess different stages of CTS in a patient, the different velocity distributions shown in Fig.1 were generated in MATLAB. Case 1, a normally distributed curve, represents the velocity distribution of a healthy subject without CTS. The number of active fibers in the higher velocity range was decreased to account for different degrees of CTS. Case 5 represents the most severe case of CTS with the least number of active fibers.

The ISI was decreased constantly from 9ms to 2.5ms with a 0.7ms step and CNAP's were recorded each time. Fig.1 and Fig.2 show CNAP's from fibers with CV≥50m/s (50m/s to 80m/s) and CV≥55m/s (55m/s to 80 m/s), respectively. The ISI values used were 4.03ms and 3.7ms, respectively. The velocity distribution used to plot Fig.2 and Fig. 3 is given by the healthy case shown in Fig.1 truncated at the CVs mentioned. The CNAP difference was obtained by subtracting the CNAP with

CV≥50m/s and CNAP with CV≥55m/s. This difference representing the CNAP contribution of fibers with CV in [50,55]m/s is shown in Fig.4.

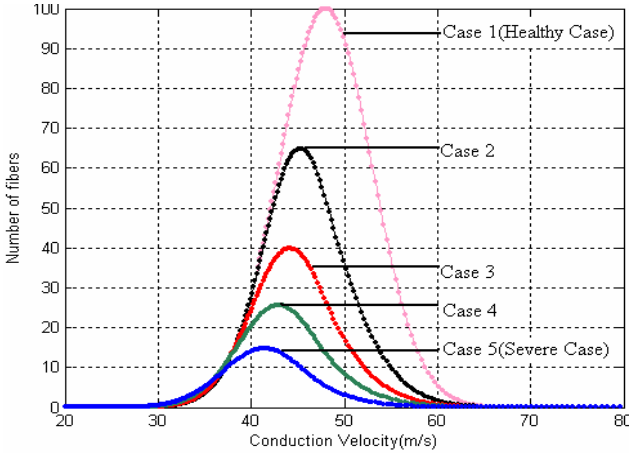

Fig. 1. Test velocity distributions

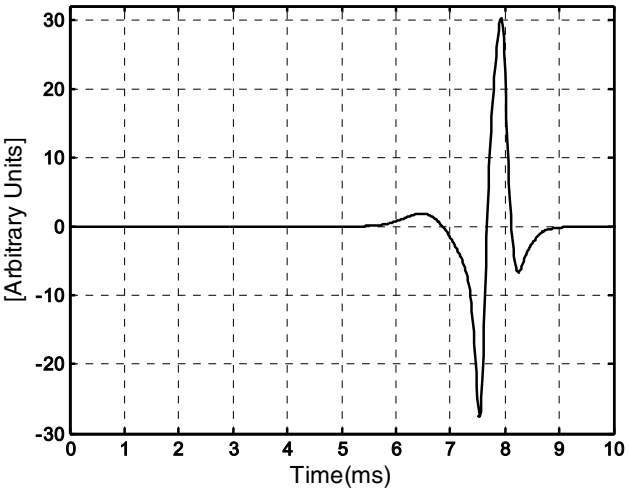

Fig. 2. CNAP for nerve fibers having CV down to 50m/s

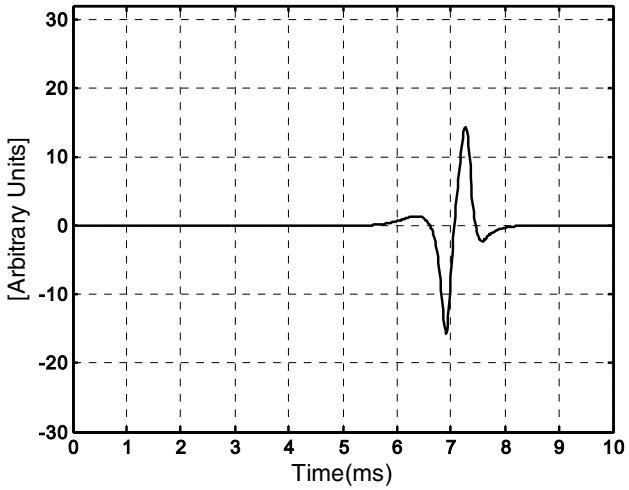

Fig. 3. CNAP for nerve fibers having CV down to 55m/s

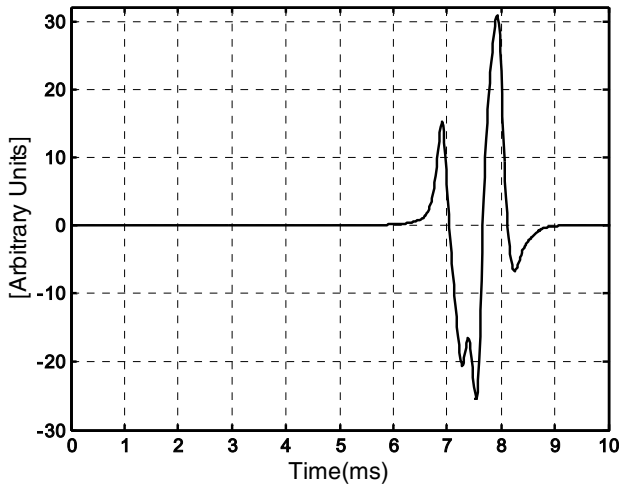

Fig. 4. CNAP contribution of fibers in CV range 50-55m/s

Likewise, the CNAP contribution of nerve fibers representing other CV ranges could be obtained using the same procedure. This CNAP difference (50m/s to 55 m/s) was used to estimate the source. Fig.5 shows the original source, it follows the mathematical function described by Plonsey [14] and was time scaled as described in [5]. The source estimate shown in Fig. 5 was obtained using the procedure described in Section II-B.

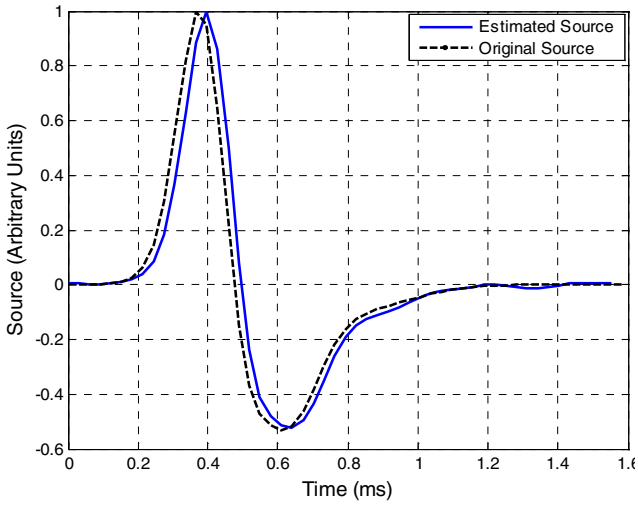

Fig. 5. Original source and estimated source

The source estimated is used for generating the *SFAP* matrix involved in the CVD estimation. The number of delay bins used in Eq.5 was $M = 30$. Fig.6 shows a CVD estimate, obtained using the non-negative least square estimator, together with the original velocity PDF used to generate the CNAP fed to the estimator.

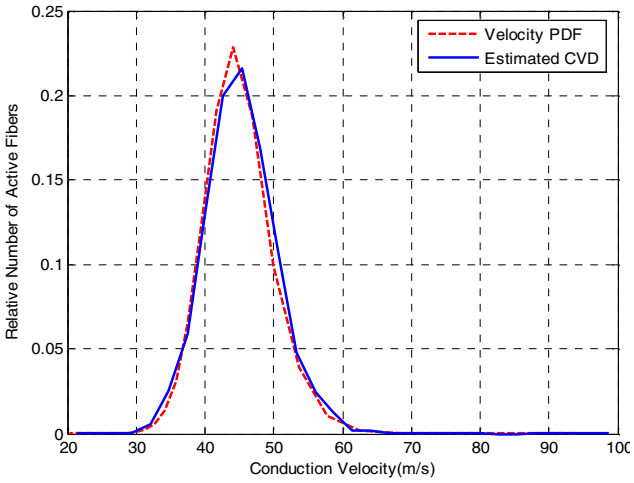

Fig. 6. CVD estimate & original velocity PDF of Case 3

IV. Discussion and Conclusion

The performance index PMSE was calculated for each of the CVD estimated against the original velocity distributions shown in Fig.1. These values are given in Table 1. The performance index was observed to fall below 10%. This indicates a good estimator performance since the estimated CVD's do not deviate much from the distributions used to generate the CNAP data. This would help in more accurately determining the size/velocity of the fibers affected in a CTS patient.

Curves shown in Fig.1	PMSE (%)
Case 1	7.3112
Case 2	0.6990
Case 3	0.1934
Case 4	2.9489
Case 5	9.6825

Table 1. Percent Mean Square Error

CVD estimates can be used to detect the stage of CTS in a patient. As already stated, large fibers are affected during early stages of CTS. When the severity increases smaller nerve fibers start getting affected. Since the CVD estimate shows the relative number of active fibers across the whole velocity interval, by looking which intervals have a reduced active fiber population when compared to normal values, severity of CTS could be established more precisely than with current NCS methods.

V. References

[1] J. Daube, "Nerve conduction studies", In MJ Aminoff (Ed.), Electrodiagnosis in Clinical Neurology, Churchill Livingston, New York, 265-306 (1986).

[2] Akiyo Nishimura, Taku Ogura, Hitoshi Hase,Atushi Makinodam, Tatsuya Hojo, Yasukazu Katsumi, Katsumi Yagi, Yasuo Mikami, Toshikazu Kubo, "A correlative electrophysiologic study of nerve fiber involvement in carpal tunnel syndrome using current perception thresholds", Clinical Neurophysiology, 115, 1921-1924 (2004).

[3] Nizamettin Dalkilic, Betigul Yuruten, BarKin Ilhan, "Somatosensory conduction velocity distribution of median nerve middle palmar digital component", Intern. J. Neuroscience, 114,153-165 (2004).

[4] Swarna Sundar, "Selective stimulation of nerve fibers for detecting the severity of Carpal Tunnel Syndrome", M.A.Sc. Thesis, Dept. Elect. Comput. Eng., Dalhousie University, Canada, (2005).

[5] J.A. Gonzalez-Cueto, "An investigation of non-invasive techniques for the estimation of conduction velocity distributions in skeletal muscles and nerve bundles", PhD dissertation, Dept. Elect. Comput. Eng., Univ. New Brunswick, Fredericton, Canada (2001).

[6] J.A. Gonzalez-Cueto and Phillip A. Parker, "Deconvolution Estimation of Nerve conduction velocity distribution", IEEE Transaction on Biomedical Engineering, 49, No.2, 140-151 (2002).

[7] R. Plonsey, "The active fiber in a volume conductor", IEEE Transaction on Biomedical Engineering, 21, 371-381 (1974).