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Analysis of evoked EMG responses for automated test of Cervical Spondylosis

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Abstract : *Cervical Spondylosis (CS), a common neurological disorder can be identified by a new technique. The technique involves recording of an evoked EMG M-responses from the thenar muscle, by electrical stimulation of the 'Median nerve'. The new findings says that for normal healthy subjects the M-responses from the thenar muscle has a typical characteristic shape which has a smooth variation with time. On the other hand for patients with CS the waveshape is characterised by one or more small kinks at different points of the response. The present work was taken up to develop an automated method for the identification of neurological disorders from the relevant waveshapes with kinks. Since the kinks are likely to increase the high frequency contents of the waveshape the method of choice went for an analysis of the signal in the frequency domain. MATLAB was used to obtain Fourier Transform of M-responses data obtained from normal healthy subjects and from subjects with CS. More than 30 features of the responses in the frequency domain were chosen to perform a comparison between the two groups, which included some basic parameters like peak frequency, frequency bandwidth at 90%, 50% and 10% of the peak amplitude, area in a low frequency segment and in a high frequency segment. The derived parameters constituted of the ratios between some of the above basic parameters. These analyses were performed for the two sets of data corresponding to two conduction distance in the relevant nerve. Statistical tests (Mann-Whitney distribution free technique) were performed to identify which of the above parameters would be useful in identifying CS from normal healthy subjects. Parameters that came out as 'highly significant', 'significant' and 'tending to be significant' were identified for this purpose. This simple electrophysiological technique may replace the sophisticated and expensive MRI and X-ray CT techniques for the diagnosis of CS and contribute significantly in neurological medicine.*

Keywords : *DCV, CMAP, FFT, Nerve Conduction, M-response, EMG*

Introduction:

In the EMG measurement the electrical signals of the muscle are taken from the body either by placing needle electrodes in the muscle or by attaching surface electrodes over the muscle. Nerves and muscles produce electrical activity when they are working voluntarily, but it is also possible to use an artificial electrical stimulator to cause a muscle to contract and the electrical signal then produced is called an evoked EMG potential. This is the basis for nerve conduction measurements where a motor nerve supplying a group of muscles is electrically stimulated while the resulting muscle action potential is recorded using surface electrodes on the muscle.

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Traditionally a value of Motor Nerve Conduction Velocity (MNCV) is obtained from the onset latencies of direct evoked EMG (or M-responses) by stimulating the nerve at two distant points. There should be more diagnostic information hidden in the evoked EMG signal itself, however, so far our knowledge goes, no attempts in this direction have been taken by any one except our group in Dhaka University [1][2][3][4][5]. Much has been done in the analysis of voluntary EMG [6][7][8][9] for extracting diagnostic information, on analyses of evoked Nerve action potential in order to obtain estimates of Distribution of Conduction Velocity (DCV) of nerve fibres [10][11][12], and on correlation of diseases or disorders with latency values or amplitudes of evoked EMG responses [13][14][15], but no one else attempted analyses on evoked EMG waveforms. Evoked EMG involves some uncertainties due to delays at the neuromuscular junctions [16], and possibly it is due to this reason that no one has attempted analysing these outputs from the human body.

The Biomedical Physics Group at Dhaka University has a long clinical experience of using evoked EMG signals for nerve conduction studies. Observing systematic patterns of these waveforms this group felt that evoked EMG may be useful in extracting useful diagnostic information. Since the delays involved in the neuromuscular junctions would remain unchanged for a particular neuromuscular junction group of a particular subject, they argued, differences in the evoked EMG waveforms obtained from the same recording electrodes for two or more points of stimulation on the supplying nerve would be related only to the DCV of the nerve trunk. Therefore there could be a possibility of extracting DCV information, at least grossly, from the evoked EMG waveforms obtained from several points of stimulation on the same nerve. Again, observing similar patterns of evoked EMG waveforms for different healthy normal subjects, they assumed that the statistical nature of the neuromuscular delays would be the same for all subjects, though varying in actual range of values from person to person, and that for neural disorders not involving neuromuscular junctions or muscle fibres, it may be possible to extract diagnostic information from evoked EMG responses. Initially this group performed synthesis of evoked CMAP through numerical simulation based on DCV and assumed gross disorders like fast fibre loss, slow fibre loss, middle fibre loss, etc. as a forward problem. Then they used these information to extract qualitative information on DCV from evoked CMAP. This work had an important finding, the DCV of the median nerves demonstrated a double peak for patients having diagnosed Cervical Spondylosis (CS) which was clearly distinct from that of normal subjects whose DCV's showed only a single peak. CS is a disorder which is very common in the aged population and which occurs because of local pressure on the spinal cord or to nerve coming out of the spinal cord. Through these attempts the group developed some insight into the underlying phenomena and these are the subjects of the above mentioned five references [1][2][3][4][5].

For a normal healthy subject the evoked CMAP from abductor policis brevis muscle of the palm, supplied by the median nerve, has a smooth bipolar shape[16]. Based on the above mentioned simulation work the group has shown that kinks in this CMAP is a signature of neurological disorder, particularly related to loss of fibres in the mid-velocity range. This information may be useful for an objective analysis of neurological health. The group has also found evidence to relate these kinks to Cervical Spondylosis (CS) though further work is necessary to confirm and specify this claim [19][20][22].

The present work was taken up to develop an objective method to identify such kinks in the CMAP using pattern recognition techniques, so that an automated diagnosis may be obtained. Since kinks in a smooth waveshape is expected to come from higher frequency components, the first method of choice in identifying such kinks is the Fourier transform which would give a description of the M-response in frequency domain. In order to identify parameters in the frequency domain that can provide the desired objective tests, real life CMAP's were collected that represent both normal subjects (having smooth bipolar shape) and patients (having kinks). Sometimes a single parameter may not give reliable pattern recognition. So, in the present work several parameters in the frequency domain were tried. If a number of parameters can be found which are individually identifiers of the above neurological disorder, then a combination of these could increase the confidence in the diagnosis. In order to perform the above tasks, Digital Signal Processing (DSP) techniques were used and was implemented using MATLAB, a well-known mathematical software package [21]. Statistical tests were performed in order to ascertain the parameters that could distinguish the two groups significantly.

In statistical inferential analysis most of the methods are based on the assumption that the underlying population is approximately normal, or they depend on the central limit theorem. So, for large sample size the corresponding population distribution is considered to be normal, but in real life situation it does not always happened that data are generating from a normal population. For this reason we cannot resort parametric approaches to take the decision. In that situation a more appealing method is non-parametric or distribution free techniques. In the present study the sample size is small so it is more appropriate to consider distribution free techniques.

A good number of parameters eventually came out significantly different between the two groups normal subjects and patients with CS. Further work may be necessary in order to determine the weightage of each these parameters in this identification. Eventually a combination of all these parameters together with their weightage, may be using *Neural Network* Algorithms, will provide a single deterministic number which will give the diagnosis objectively.

Methods :

In the present research the CMAP or M-response signals were obtained from the computerised EMG equipment designed and fabricated by the Bio-Medical Physics Group, University of Dhaka in collaboration with Bangladesh Institute of Biomedical Engineering & Appropriate Technology (BIBEAT), which has been providing routine clinical services for nerve conduction investigation in Bangladesh since 1988.

The CMAP signals used for this study were obtained from the Median nerves of many subjects. The subjects were chosen irrespective of neurological history. From the evoked CMAP signals of different subjects obtained by stimulating the Median nerve it was observed that for some cases, there are deviations in the waveshapes from the standard shape. The variations of the signals from the standard shape of CMAP can be classified as- i) waveshapes having kinks and ii) waveshapes deshaped or changed without kinks. The present work attempts to introduce an unprejudiced approximation of disorders by identifying those cases with kinked waveshapes. To do this we categorize the collected signals into three groups-

Group A: having standard shape, which relates to normal healthy nerve.

Group B: having kinks in the CMAP response, which have been assumed to be related to Cervical Spondylosis.

Group C: having changed shape without kinks, related to other neurological disorders.

Typical shapes of CMAP's, identified to the above three groups are shown in Figure 1.

The CMAP's belonging to Group C have not been identified with any known neural disorders so far. So we have not used such CMAP's in our present work. Only CMAP's belonging to Group A and Group B will be considered for the present pattern recognition work. The aim would be to identify some parameters that can be obtained as numerical value from an analysis of the original CMAP, and which can distinguish Group B from Group A significantly.

The object of frequency domain analysis is to break down a complex signal into its components at various frequencies. The mathematical basis of frequency analysis is the Fourier Transform (FT), which takes different forms depending on the shape and size of the signal in time domain.

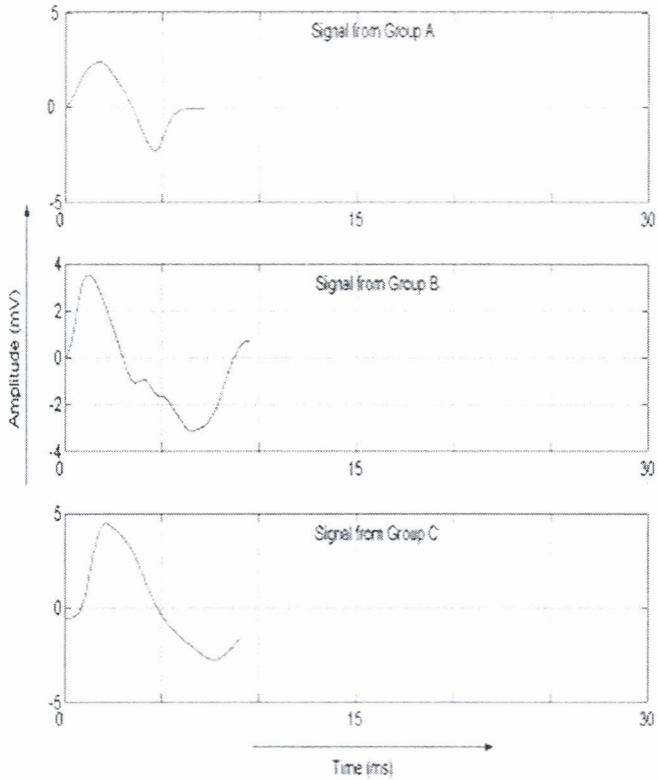

Figure 1: Typical M-responses from Median nerve from Group A, Group B and Group C

Fast Fourier Transform (FFT) is a specially designed algorithm for computation of Fourier Transform. FFT now becomes a popular method of obtaining the frequency components in a waveform. The clinical CMAP signal can also be broken down into its constituent sinusoids of different frequencies using FFT. In the present work an attempt has been made to indicate CS (which recognized by kinks) by extensively using the FFT of the CMAP signals.

Since the M-response signals are in the discrete-time sequence form the Fourier analyses was carried out directly. If the N is the length (number of sample points) of the discrete-time sequence $x[n]$, and $\triangle$t is the sampling interval; the corresponding frequency f_k (Hz) of the transformed signal is given by,

$$f_k = \frac{kF_s}{N}, \qquad (1)$$

Where, Fs = $1/\triangle t$ is the sampling frequency and k = 0, 1, 2,...., N-1 is the index number in the frequency domain. In the present study the sampling interval for some of the data sets was $\triangle t$ = 25 μs and for other data sets $\triangle t$ = 40 μs and N depends on the spread of the signal. The numbers of sample points were 512 for all the samples.

Basically from a Fourier transformed signal we can obtain the following:

-Amplitude spectrum with Real & Imaginary part of the amplitude separately

-Amplitude spectrum with Absolute value of the amplitude

-Phase spectrum

In the present study only the Absolute value spectrum (Magnitude of Amplitude vs. Frequency graph) has been selected for frequency domain analyses, because of time limitation.

The parameters of the transformed signal in the frequency domain which have been picked up initially for analyses are as follows-

- Peak Amplitude (A_P)
- Peak Frequency (f_P)
- Frequency Width at 10% of A_P ($\triangle f_{10\%}$)
- Frequency Width at 50% of A_P ($\triangle f_{50\%}$)
- Frequency Width at 90% of A_P ($\triangle f_{90\%}$)
- Area under the curve from 0 to 2 kHz ($a_{0\text{-}2}$)
- Area under the curve from 2 to 5 kHz ($a_{2\text{-}5}$)

Based on the above parameters the following ratio parameters were evaluated-

- $R_{10/90} = \dfrac{\triangle f_{10\%}}{\triangle f_{90\%}}$
- $R_{10/50} = \dfrac{\triangle f_{10\%}}{\triangle f_{50\%}}$
- $R_{10/P} = \dfrac{\triangle f_{10\%}}{\triangle f_P}$
- $R_{50/P} = \dfrac{\triangle f_{50\%}}{\triangle f_P}$
- $R_{90/P} = \dfrac{\triangle f_{90\%}}{\triangle f_P}$
- $R_a = \dfrac{a_{0\text{-}2}}{a_{2\text{-}5}}$

It can be expected that frequency domain variations between distal stimulation (giving short conduction distance) and for proximal stimulation (giving a long conduction distance) would identify certain features that may have a bearing on CS. Therefore the following deviation parameters between corresponding distal and proximal parameters were also evaluated and analysed.

- $\delta A_p = |A_{p,distal} - A_{p,proximal}|$
- $\delta f_p = |f_{p,distal} - f_{p,proximal}|$
- $\delta f_{10\%} = |\triangle f_{10\%,distal} - \triangle f_{10\%,proximal}|$
- $\delta f_{50\%} = |\triangle f_{50\%,distal} - \triangle f_{50\%,proximal}|$
- $\delta f_{90\%} = |\triangle f_{90\%,distal} - \triangle f_{90\%,proximal}|$
- $\delta a_{0,2} = |a_{0,2distal} - a_{0,2proximal}|$
- $\delta a_{2,5} = |a_{2,5distal} - a_{2,5proximal}|$
- $\delta R_{10\text{-}90} = |R_{10/90,distal} - f_{10/90,proximal}|$
- $\delta R_{10\text{-}50} = |R_{10/50,distal} - f_{10/50,proximal}|$
- $\delta R_{10/p} = |R_{10/p,distal} - f_{10/p,proximal}|$
- $\delta R_{50/p} = |R_{50/p,distal} - R_{50/p,proximal}|$
- $\delta R_{90/p} = |R_{90/p,distal} - R_{90/p,proximal}|$
- $\delta R_a = |R_{a,distal} - R_{a,proximal}|$

In order to identify the parameters that may distinguish Group B from Group A, Mann-Whitney U-statistic is used in two group situations, in which the groups are independent i.e., the observations are not matched in any way nor or before after measures involve. Mann-Whitney test statistic-U is defined as,

$$U = N_1 N_2 + \frac{N_1(N_1+1)}{2} - R_1 \quad (2)$$

or,

$$U' = N_1 N_2 + \frac{N_1(N_2+1)}{2} - R_2 \quad (3)$$

where, N_1, N_2 are number of samples

R_1 = the sum of ranks assigned to the group with a sample size of N_1

R_2 = the sum of ranks assigned to the group with a sample size of N_2

Tests are performed at 5% level of significance in general situation. In our context we will consider a test to be highly significant (H) if P<0.02, significant (S) if P<0.1, tending to be significant if P<0.2 and for greater values tests will be termed as insignificant (I).

Results and Observations:

The absolute value spectrum of M-responses for both distal and proximal stimulation, obtained using FFT, typical samples each from Group A/Group B and are shown in Figure 2. It can be seen that those from Group B, having kinks in their M-responses, have higher frequency components as expected, and this would have an important bearing on the results to be discussed below.

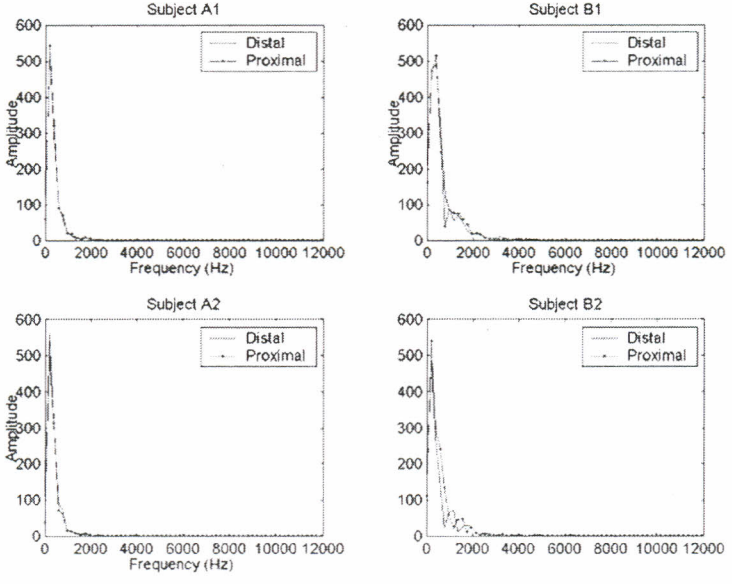

Figure 2: Typical Fourier transform of M-response for both distal and proximal stimulation (subjects A1, A2: without kink, and B1, B2: with kink)

Table 1 presents values of some of the chosen parameters in the frequency domain and the results of the tests of significance in order to distinguish Group B from Group A. This table uses the data for distal stimulation with 14 subjects in Group A (N_1 = 14) and 22 subjects in Group B (N_2 = 22). Table 2 presents the same for proximal stimulation for the same subjects. More parameters in the proximal case appear to be significant compared to that for the distal case. This is somehow expected since in the proximal case, the action potentials conduct over a longer distance along the nerve allowing individual components in each fibre to become more dispersed in time. The highly significant parameter common in both the cases are $\Delta f_{10\%}$ while in the proximal case $a_{2\text{-}5}$, $R_{10/90}$, $R_{10/50}$ and R_a are also highly significant. The frequency width at 10% of the peak amplitude, $\Delta f_{10\%}$, which is expected to be large if high frequency components are present, and therefore, is one of the major parameters in identifying the kink. At the same token the insignificance of $\Delta f_{10\%}$, is expected as it only contains mostly the low frequency components, which would almost be the same in both the groups. Again, area under the curve within a high frequency band as for $a_{2\text{-}5}$ is expected to show up the difference, which it has done, by being highly significant in the proximal case, and significant in the distal case. As a first consideration, the peak frequency f_p would be a good candidate in distinguishing the two groups. However, since its value depends on the combination of all the frequency components, this would soften the distinction, and it has been truly demonstrated through this parameter being significant, but not highly significant in both the cases. The amplitude of the peak, A_p, has diminished in Group B, which is again expected since the peak appears at a relatively low frequency zone while a kink in the original time domain response would shift some of the components to higher frequencies. Besides, the number of nerve fibres contributing to the response cannot be greater in disease than in normal health.

Table 3 presents the deviation parameters obtained from responses due to proximal and distal stimulations. Again Group A has 14 subjects while Group B has 22 subjects. There are two highly significant parameters and four significant parameters. The causes behind these parameters depend on several factors and explanations are not so straightforward. The significance for $f_{10\%}$ and $f_{50\%}$, with a high significance for the latter, but insignificance of $f_{90\%}$ indicates that the contribution of kinks in the dispersion due to distance is around the middle region in the frequency domain, not so much at the high end.

Table I: Test of significance for Distal Parameters

Parameter	Mann-Whitney U-statistics	P	Remarks
A_p	107	0.127	T
f_p	97	0.064	S
$\triangle f_{10\%}$	57	0.002	H
$\triangle f_{50\%}$	95	0.056	S
$\triangle f_{90\%}$	116	0.18	T
$A_{0\text{-}2}$	122	0.299	I
$A_{2\text{-}5}$	118	0.243	I
$R_{10/90}$	90	0.038	S
$R_{10/50}$	93.5	0.05	S
$R_{10/p}$	102	0.092	S
$R_{50/p}$	144	0.746	I
$R_{90/p}$	143	0.721	I
R_a	80.5	0.017	S

Note **H:** Highly Significant; S: Significant; T: Tending to be Significant; I: Insignificant

Table II: Test of significance for Proximal Parameters

Parameter	Mann-Whitney U-statistics	P	Remarks
A_p	119	0.256	T
f_p	98	0.069	T
$\triangle f_{10\%}$	55	0.001	H
$\triangle f_{50\%}$	152	0.961	I
$\triangle f_{90\%}$	123	0.314	I
$a_{0\text{-}2}$	102	0.091	S
$a_{2\text{-}5}$	84.5	0.024	H
$R_{10/90}$	58	0.002	H
$R_{10/50}$	58	0.002	H
$R_{10/p}$	105.5	0.11	T
$R_{50/p}$	104	0.108	T
$R_{90/p}$	102.5	0.095	S
R_a	35	0.000	H

Note H: Highly Significant; S: Significant; T: Tending to be Significant; I: Insignificant

Table III: Test of significance for Deviation Parameters

Parameter	Mann-Whitney U-statistics	P	Remarks
δA_p	132	0.475	I
δf_p	148	0.846	I
$\delta f_{10\%}$	94	0.052	S
$\delta f_{50\%}$	62.5	0.003	H
$\delta f_{90\%}$	123	0.314	I
$\delta a_{0\text{-}2}$	92	0.044	S
$\delta a_{2\text{-}5}$	153	0.974	I
$\delta R_{10/90}$	117	0.23	I
$\delta R_{10/50}$	133	0.506	I
$\delta R_{10/p}$	131	0.465	I
$\delta R_{50/p}$	97	0.064	S
$\delta R_{90/p}$	96	0.06	S
δR_a	55	0.001	H

Note H: Highly Significant; S: Significant; T: Tending to be Significant; I: Insignificant

Discussion:

Basic motivation of the present work is to provide an objective diagnosis of Cervical Spondylosis (CS) using evoked EMG responses directly, which can be easily recorded. M-responses from Thenar muscles in the palm, served by median nerve, were used since their normal shapes are well known, which usually is a smooth bipolar one. M-responses having kinks were found to be associated with Cervical Spondylosis, a very common disorder. Kinks are associated with high frequency components, so, 13 frequency-domain parameters were chosen for this study, with an expectation that some of these may bring forth a pattern, which may be useful in identifying the M-responses with kinks. These included some basic parameters like peak amplitude, peak frequency, and frequency bandwidth at 90%, 50% and 10% of the peak amplitude, area under the curve in a low frequency segment and in a high frequency segment. The derived parameters constituted of the ratios between some of the above basic parameters. Again the above parameters were evaluated for M-responses obtained for two conduction distances, here for a distal stimulation site at wrist, and a proximal stimulation site at elbow. As the indi-

vidual fibre components of the total nerve action potentials get more time for dispersion in the proximal case, so this offered additional 13 parameters for a different conduction distance and further 13 deviation parameters between pairs of corresponding values for study. Some of the parameters showed significant differences that can be a basis of an objective test.

Rather than relying on a single parameter, this work targets many, so that a weighted combination of these parameters would increase the confidence in the diagnosis. Use of Digital Signal Processing (DSP) techniques and MATLAB, a well known mathematical software package, has made the analyses simpler.

Segregation of the data into different groups was tricky. Particularly, choosing healthy normal data under Group A had to be done under some constraints. Not many data sets were available which matched the perfect assumed shape and values of latency and NCV that were assumed to represent a normal data set. Therefore some data sets demonstrating smooth wave shape but deviating slightly from the expected behavior were also included in this graph. The data sets from Group B were rather easier to choose, since they had to have kinks somewhere in the response. The rest that had abnormal wave shape or abnormal distal latency and NCV were classified under Group C, and these data were not used in the work. There may be different pathological causes behind the abnormalities demonstrated in Group C for which further work is necessary. However if the causes and features are identified in future, these data may be used for further automated analysis as well.

Altogether 39 parameters were studied with statistical tests in this study. Out of these parameters 8 came out highly significant, 13 came out significant, 4 came out tending to be significant and the rest were insignificant. A weighted combination of the significant and highly significant parameters may possibly increase the chances of identifying the neurological complaint manifold. A possible technique would be to use *Neural Network* with appropriate weights. Furthermore the position of the kinks in the M-response in time domain may provide further information regarding the type of neural pathology. Application of other numerical techniques like *'Wavelet Transform'* may be attractive in this regard.

The present work is very significant in that it has targeted development of an objective method to identify kinks in the M-responses using computational techniques, so that an automated diagnosis may be obtained on such neurological disorders. Although further work is necessary to establish the specific disorders that the kinks represent, the present work may be useful in an automated system to isolate such cases. As mentioned before, there is a possibility of relating these kinks to Cervical Spondylosis (CS), a disorder leading to disability of a great number of people globally. If that happens then the present work would make a very attractive alternative for its diagnosis.

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