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Nonlinear Processing of Wrist Pulse Signals to Distinguish Diabetic and Non-Diabetic Subjects

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Abstract: In pulse diagnosis, the pulse signals obtained at wrist have been used for analysis of certain diseases in ancient systems of medicine in which the practitioner feels the pulse of the subject by placing his three fingers on the subject's wrist at three distinct radial pulse point locations. The preliminary studies show that there are many conventional linear techniques applied to analyze the wrist pulse signals and less focus on non-linear techniques. Hence, the main aim of this research is to apply Recurrence Plot and Recurrence Quantification Analysis (RQA), a nonlinear technique to analyze the wrist pulse signals for distinguishing between diabetic and non-diabetic subjects. Wrist pulse signals from 32 subjects were recorded during the morning hours and were analyzed using RQA techniques. The results show significant differences in the RQA parameters of the wrist pulse signals as they are obtained from the recurrences occurring in the phase space plots of the wrist pulse signals. It was found that parameters like entropy, divergence and average diagonal line length showed significant variations for diabetic and non-diabetic subjects. Therefore, it can be concluded that RQA parameters can be used effectively to identify diabetic and non-diabetic subjects and thus may be applied on the wrist pulse signals for early detection of various diseases.

Keywords:
Non-linear technique, Pulse diagnosis, Recurrence plots, RQA, Wrist pulse signals

I. INTRODUCTION

Pulse based diagnosis has an important role in ancient literatures be it Ayurveda, Unani, Chinese or Greek from thousands of years. The pulses are felt by placing the practitioners hand in a certain orientation at proper positions on the patient's wrist. The pressure applied on the wirst is varied to obtain the maximal pulse and also the different phases of the pulse. [1]. Just like most of the other physiological signals, wrist pulse also contained some singularities which vary rapidly for a very small change in time [2].

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Usually the radial pulse is chosen as the site to read the pulse as it is the most convenient position to read and also more easily available than any other pulse sites. The blood flow through the artery and change in vessel diameter along with the cardiac activities results in obtaining the pulse signals on the radial artery at three distinct positions. This makes pulse diagnosis effective for analyzing both cardiac and non-cardiac diseases [3]. The heart generates a forward traveling wave-front in complex patterns of blood flow. There will be pressure changes at different points in the arterial circulation. Physiological signals such as heart sound, electrocardiogram, and wrist pulse waveform are recorded at these locations non-invasively for the assessment of the physiological condition of the human body [4].

The palpation is used as an important diagnostic method in traditional medicine to know the nature of illness and identify effective treatments. The connection of pulse signals with several diseases is verified by the preliminary studies [5],[3],[6]. Literature also shows that when certain external pressure is applied it is possible to analyze certain semi-solid and hollow organs by feeling the pulse at different layers and depths of the radial. The evidence is discovered that the harmonic parameters of the pressure pulse waveform is affected by the pathological changes in different organs, which has lead to the pulse wave analysis as an effective tool for diagnosis [7].

Fig. 1. Diagram of the three axial directions and position of fingers on the wrist to feel the palpation [7]

The radial artery can be compared to a cylinder having three dimensions. Three axes are required for the location of measuring points and they are considered as shown in the Fig. 1. Considering Y axis to be parallel to the radial artery, perpendicular to the radial artery (i.e., vertical) is Z axis and X axis is considered to be perpendicular to the forearm (i.e., horizontal). The exerted pressure by the sensor on the artery is actually at the location on th Z axis which can be viewed as the transmural pressure. It is reported that the raidal pulse amplitude increases when greater pressure is exerted on the skin [8]-[10].

But when the exerted pressure exceeds a certain level, the wave velocity and the pulse amplitudes decreases.
The variance in transmural pressure of blood vessel is acquired by pressure sensor [3]. Based on the pressure sensors, the pulse signal is acquired by exerting pressure on the radial artery of the patient's wrist and the pressure variation at that position is measured. Actually, pulse waves are generated when the heart contracts as there is an expulsion of blood into the aorta which causes dilation of that blood vessel. Any generated pressure will affect the complete physiological system and hence, any changes in the pressure of the radial artery can be measured on the wrist non-invasively.
The physiological status of the entire human body is obtained by these pulsations as their changes are sensed by the three fingers (index, middle and ring) of a pulse examiner [11]-[12]. The change in frequency, size, shape, width, strength and power of the pulse can be determined by palapting the radial artery on the patient's wrist using the three fingers. This approach is subjective in nature and takes years of practice to master [13]. This is a tedious and inconvenient process. Pulse is classified based on its characterisitcs like rate, rhythm, volume, regulatiry, force and contact pressure required to feel the pulse. Further, the pulse can be classified as tender or tense, sinking or floating, large or small, fast or slow, emplty or full etc., where each of these parameter reflect the personal condition of the body. To obtain the pulse conditions of the patients various pulse diagnosis instruments have been proposed [14]-[16]. Several pulse taking platforms are invented but will restrict its applications due to its complexity and insufficiency. Usually the pulse is transmitted from the heart by blood flow through arteries and this is affected by several conditions of organs, muscles, nerves and so on [17]. More body information is obtained from wrist pulse based on this principle to get broader applications in health status analysis [18]. One of the major disorders is Diabetes Mellitus (DM) which is a group of metabolic diseases. The prevalence of diabetes is globally increasing. There has been a growing research interest in finding alternate indicators for early identification of diabetes [19]. In the recent past wrist pulse signal analysis has obtained much importance in research and is said to be a good predictor of diabetes. Various pulse acquisition systems had been reported with single sensor which are larger in size and not user friendly. By using a single sensor it is inconvenient to locate the position. Moreover, for the pulse diagnosis, the signals from the three positions of the wrist is required. Hence, having a single sensor makes the sampling procedure very time consuming as one need to sample the three signals Individually.
Hence a multichannel wrist pulse system with different sensor arrays can be used to reduce information loss. In multichannel wrist pulse acquisition, three independent channels are used in the pulse probe. The center of the radial artery and pulse width information is detected using photoelectric sensor array. The fluctuations of the blood vessel is reflected in the signals collected using pressure sensors and the changes in blood volume is reflected in the signals collected using photoelectric sensors. Both these sensors are combined to get detailed pulse information. Since the pressure applied on the wrist to acquired these signals differs in the three positions, there is a need to gain primary knowledge to ensure correct position for acquiring the pulse signal.

The pulse signals are processed using time domain and frequency domain analysis. The main pulse features in time domain analysis are the tidal wave, the prominent peak amplitude etc. In the frequency domain analysis, the spectrum features such as energy ratio and power spectrum are extracted from the pulse signals. The biomedical signals are generally analyzed as stochastic process output. There are several approaches towards linear model. There limitation is that these models do not consider nonlinear process from which the biomedical signals are generated. Hence, linear models cannot give a peculiar represenation of the biological system considered. Therefore, a different approach is required to analyse biomedical signals and one such approach can be to use a nonlinear technique for analysis rather than using conventional linear techniques. The maximal Lyapunov exponent and correlation dimension are among few signal processing techniques which has the properties of nonlinear system and can be used for the dynamic analysis of biological signals [20]. Phase space is used by both these techniques to demonstrate the changes in the nonlinear system. The complexity of time series is estimated using correlation dimension and the amount of chaos in the system is estimated using maximal Lyapunov exponent. The correlation dimension also calculates the embedding dimension while reconstructing the phase space.
The method used in this work utilizes one of the fundamental property of recurrences. At first, it was Poincar´e who proved that in a phase space the trajectory of a chaotic system will return arbitrarily close to any former point of its route with probability one after a sufficiently long time. Then, Lorenz discovered three ordinary differential equations that can exhibit chaotic behavior [21]. Later, the method of recurence plots (RPs) was intoduced to visualize the recurrences of a dynamical system [22]. Hence this method gained importance for its applicability to short and non-stationary time series data. In addition, researchers have studied the relationship between RPs and the properties of dynamical systems [23]. In this work, our main concern is the application of a nonlinear technique for distinguishing the diabetic and non-diabetic subjects.

II. MATERIAL AND METHODS

The main objective of this study is to apply the nonlinear signal processing technique to infer about the variations in the wrist pulse signals obtain from diabetic and non-diabetic subjects at different positions.

A. Acquisition of Wrist Pulse Signals

An experimental set up was designed to record the wrist pulse signals at two positions. A differential pressure sensor is used to acquire the wrist pulse signal which is then passed through the instrumentation amplifier. The amplified signal is further filtered using high pass filter to remove the motion artifacts and other noise components. The signal is further passed through the low pass filter to remove the ripples. This signal is given as input to microcontroller for converting analog to digital form and then transmitted to PLX-DAQ software to store the data in an excel format. Further the data stored in excel format is read in MATLAB (Mathworks Inc.) for further processing and analysis.

B. Subjects

Thirty two subjects were recruited for the current study. All the subjects identified are above 35 years of age including men and women. The wrist pulse signals were recorded in the morning on the left hand of the subjects.

C. Signal Processing

The use of nonlinear methods to analyze wrist pulse signals is becoming popular as they are sensitive enough to detect the early phases of health damages. With the application of this method there can be improvement in healthcare as it helps in understanding the process occurring in human body.

One such method that can describe the basic dynamics of a system with chaotic behavior which is found to be in every biological system is the recurrence analysis. The signal obtained from the natural system is used to construct the phase space trajectory. The procedure followed to map a discrete signal *x* into phase space is as follows. Given a signal assumed to have N_s terms, $x_1, x_2, x_3, \cdots\cdots x_i, \cdots x_{N_s}$, vectors $\mathbf{y}_i$ of dimension *D* with a lag (delay) *d* are defined as

$$\boldsymbol{y}_i = \begin{bmatrix} x_k \\ x_{k+d} \\ x_{k+2d} \\ \vdots \\ x_{k+(D-1)d} \end{bmatrix} \quad (1)$$

$d \geq 1$, $D \geq 1$, i=1 to N_s, $k = i \bmod N_s - (D-1)\,d$

This is referred to as embedding the signal, *x*, into a phase space of dimension *D* along with lag *d* and the variable ***y*** gives the trajectory of *x* in phase space of dimension *D*. Consider a signal of duration N_s there are N_s number of vectors.

The original state space of phase space is topologically represented by preserving all its properties as stated by Takens' theorem. The phase space preserves the recurrences as they are the topological property of state space [24].

The recurrence of states in phase space is visualized using a tool called recurrence plot (RP). The D-dimensional phase space trajectory can be investigated through a two-dimensional representation of its recurrences by using a NxN matrix whose elements take values 1 or 0. The recurrence plot graphically shows a recurrence of a state at time *i* and at time *j* by a square of size N×N pixels. A unit black or white pixel is mapped to each element of the matrix at the corresponding location [22].

The higher dimensional trajectory in a two-dimensional space is mathematically expressed as an N×N matrix and is calculated as:

$$R_{i,j} = \Theta\left(\varepsilon - \|\boldsymbol{y_i} - \boldsymbol{y_j}\|\right) \quad (2)$$

Where a norm is represented as $\|.\|$,ε is used to represent the recurrence threshold and Θ( ) shows the Heaviside step function forcing $R_{i,j}$ to be either 0 or 1.

D. Recurrence Quantification Analysis

Even though graphical appeal is the main advantage of RP, it often contains subtle patterns. A visual inspection or qualitative analysis is not sufficient to detect these patterns in practical applications. Henceforth, the concept of Recurrence Quantification Analysis (RQA) was introduced to solve this problem by quantifying RPs [25]. RQA measures are defined for signals of finite duration. The various RQA parameters considered in this paper are recurrence rate, determinism, diagonal length, laminarity, divergence and entropy.

III. RESULTS AND DISCUSSION

The main focus of this study was to identify how the the wrist pulse signals of the subjects vary between the diabetic and non-diabetic subjects. An experimental set up is used for acquisition of wrist pulse signals from different subjects. The Recurrence Quantification Analysis (RQA) which is a nonlinear technique were applied on the wrist pulse signals to determine the parameters that show the differences between the diabetic and non-diabetic subjects. Also, the previous studies have shown that processing of wrist pulse signals will help in identification and diagnosis of various diseases. Because of these reasons, wrist pulse signals acquired at different positions were considered for the identification of diabetic subjects. Nonlinear techniques such as recurrence plot and various RQA parameters such as laminarity, divergence, diagonal line length, entropy, recurrence rate, and determinism were extracted from the signals. The results obtained showed significant differences in recurrence plots and RQA parameters extracted from the wrist pulse signal for diabetic and non-diabetic subjects.

The wrist pulse signals are recorded simultaneously at two positions (position 1 is index finger and position 2 is middle finger) on the radial artery located at the wrist of the subject. Fig.2 shows the signals obtained for non-diabetic subjects.

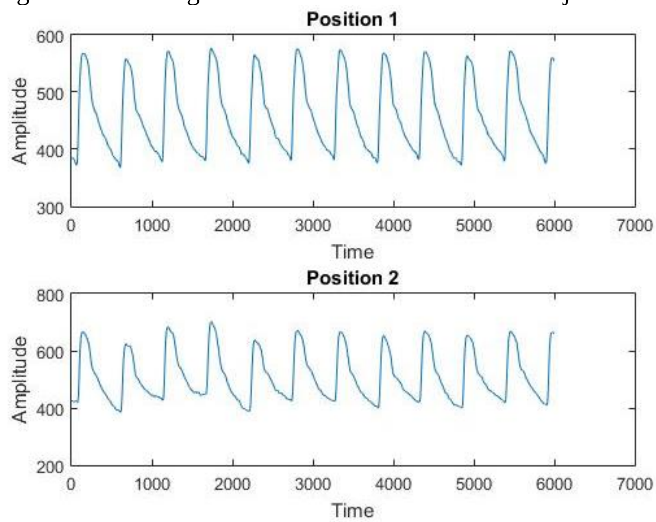


Fig. 2: Wrist pulse signal of non-diabetic subject

Similarly, Fig. 3 shows the wrist pulse signal obtained for two positions on the radial artery located at the wrist. The wrist pulse signal obtained from diabetic subjects shows drastic variations compared to non-diabetic subjects.

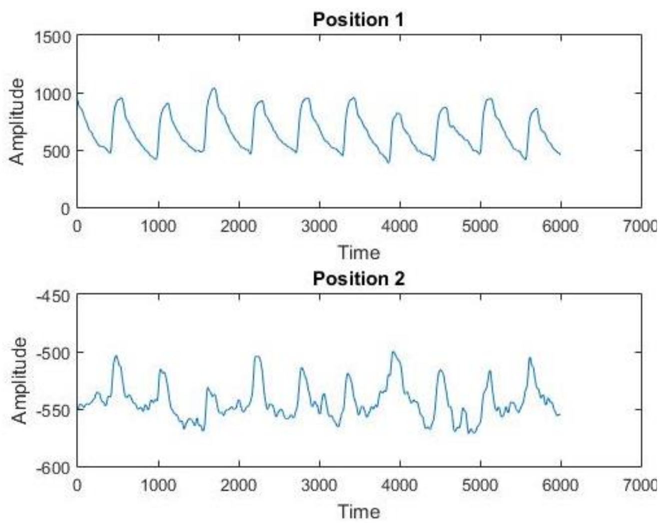
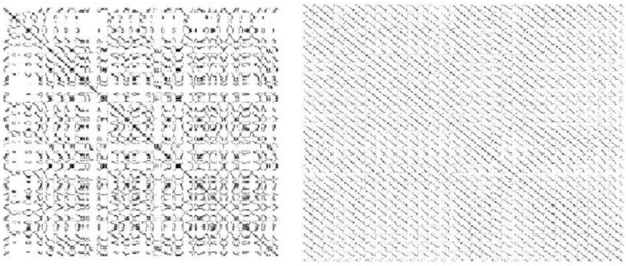


Fig. 3: Wrist pulse signal of diabetic subject

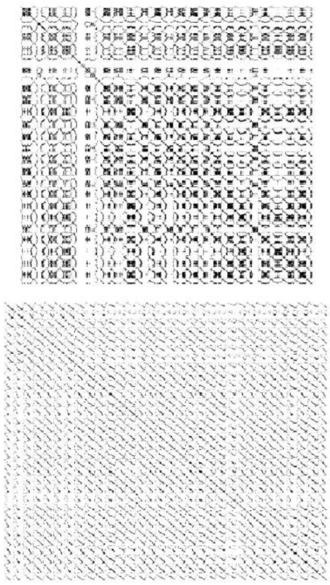
Fig. 4 shows the variation in the recurrence plot of wrist pulse signals acquired on the left hand for position 1 (index finger) on the radial artery of the wrist of the subjects.



Diabetic Non-diabetic

Fig. 4: Recurrence plot for diabetic and non-diabetic subject for position 1

Fig. 5 shows the variation in the recurrence plot of wrist pulse signals acquired on the left hand for position 2 (middle finger) on the radial artery of the wrist of the subjects.



Diabetic Non-diabetic

Fig. 5: Recurrence plot for diabetic and non-diabetic subject for position 2

Fig. 6 and Fig.7 show the variations in RQA parameters i.e., entropy, laminarity and divergence for both position 1 (index finger) and position 2 (middle finger). We can see that Average Entropy (Avg Entr) decreases for diabetic subjects. The average diagonal line length (Avg Lmax) is less for diabetic compared to non-diabetic subjects. The Average Divergence (Avg DIV) increases for diabetic subject.

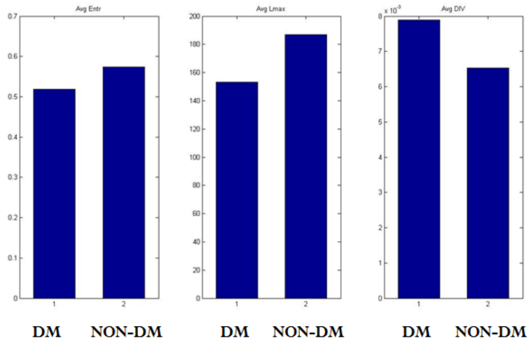


Fig. 6: Recurrence Quantification Analysis parameter for position 1. DM - Diabetic, NON-DM –Non-Diabetic

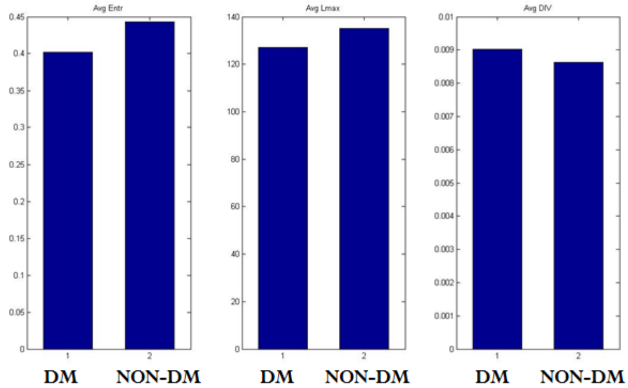


Fig. 7: Recurrence Quantification Analysis parameter for position 2. DM - Diabetic, NON-DM –Non-Diabetic

We can see that several parameters show changes for diabetic subjects. We can conclude that the recurrence quantification analysis technique applied on wrist pulse signals is suitable for identifying the diabetic and non-diabetic subjects.

IV. CONCLUSION

This paper is concerned with distinguishing between diabetic and non-diabetic subjects by using the wrist pulse signals. Biomedical signals are inherently non-linear in nature. It is much suitable to use a non-linear approach to study wrist pulse signals and hence the systems from which they arise. The use of linear techniques leads to the loss of some information which could be of potential use. In general, non-linear techniques are computationally intensive and require a large number of data points for analysis. Some of the non-linear techniques in use are correlation dimensions and Lyapunov exponents. Due to the computational difficulties faced in using these techniques we have used here the concepts of recurrence plots and recurrence quantification analysis to wrist pulse signals. RQA is found to be computationally less intensive and requires only a small number of data points for analysis.

The advantage of recurrence plots is that the pictorial representation of the signal gives us a better insight into the changes happening in its trend and thereby simplifies understanding complex non-linear systems.

In this paper, we have used recurrence plots and RQA for identification of diabetic and non-diabetic subjects. The study has shown that RQA is effective in distinguishing diabetic from non-diabetic subjects. In addition to this, the RQA parameter values show effective variations in distinguishing diabetic and non-diabetic subjects. It is found that the wrist pulse signal obtained from position 1 show variations for average entropy, average diagonal line length and average divergence. The average entropy and average diagonal line length for diabetic subjects was less compared to non-diabetic subjects. Similarly, the average divergence for diabetic subjects was more compared to non-diabetic subjects. The results obtained for position 2 also shows the similar variations for diabetic and non-diabetic subjects. Hence, both the positions show variations for the same parameters. Therefore, nonlinear technique can be used effectively for analysis of wrist pulse signals. In future, it may be useful to extend the study of wrist pulse signals for the third position for better identification of the abnormalities at the early stages.

CONFLICT OF INTEREST

None

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