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Poincaré Plots in Analysis of Selected Biomedical Signals

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Abstract. Poincaré plot is a return map which can help perform graphical analysis of data. We can also fit an ellipse to the plot shape by determining descriptors $SD1$, $SD2$ and $SD1/SD2$ ratio to study the data quantitatively. In this paper we show examples of application of Poincaré plots in analysis of various kinds of biomedical signals: RR intervals, EMG, gait data and EHG.

Introduction

In the study of biomedical signals we are always searching for new methods of analysis. The most popular are linear methods, like Fourier transform, but in recent years we have observed increased interest in new, nonlinear methods, like eg. methods originating from chaos theory. In this paper we share the results of the application of an interesting and simple nonlinear method – Poincaré plot.

This method can be used in analysis of non-filtered and also non-stationary data. Some authors (Brennan et al., 2001; Karmakar et al. 2009; Tulppo et al., 1996) claim that it is a valuable method due to its ability to display nonlinear features of the time series.

Our aim is to show how this method works on biomedical signals and what new information can be obtained in this way.

The most common application of Poincaré plot is to ECG data (R-R intervals). In this paper we focus on EMG, gait data, and EHG and only mention R-R intervals because they are extensively studied.

Poincaré Plots – Basics, Descriptors $SD1$ and $SD2$ and Selected Examples

Poincaré plots are return maps in which each result of measurement is plotted as a function of a previous one. It is a simple and effective concept.

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The idea is as follows:

Let us denote the data by: $x_0, x_1, x_2, x_3, x_4, \ldots$. The return map will be a plot of the points (x_0, x_1), (x_1, x_2), (x_2, x_3), (x_3, x_4), …...

A shape of the plot describes the evolution of the system and allows usto visualize the variability of time series x_n (Hoshi et al., 2013; Karmakar et al., 2009).

There are standard descriptors used in quantifying Poincaré plot geometry, namely $SD1$ and $SD2$ (Brennan et al., 2001; Piskorski et al., 2007; Tulppo et al., 1996). We can obtain them by fitting an ellipse to the plot shape (Figure 1). Descriptors $SD1$ and $SD2$ represent the minor and the major semi-axes of this fitted ellipse. Brennan et al. (2001) gave a description of $SD1$ and $SD2$ in terms of linear statistics. $SD1$ is the standard deviation of the distances of points from axis 1 and determines the width of the ellipse (short-term variability), $SD2$ equals the standard deviations from axis 2 and length of the ellipse (long-term variability).

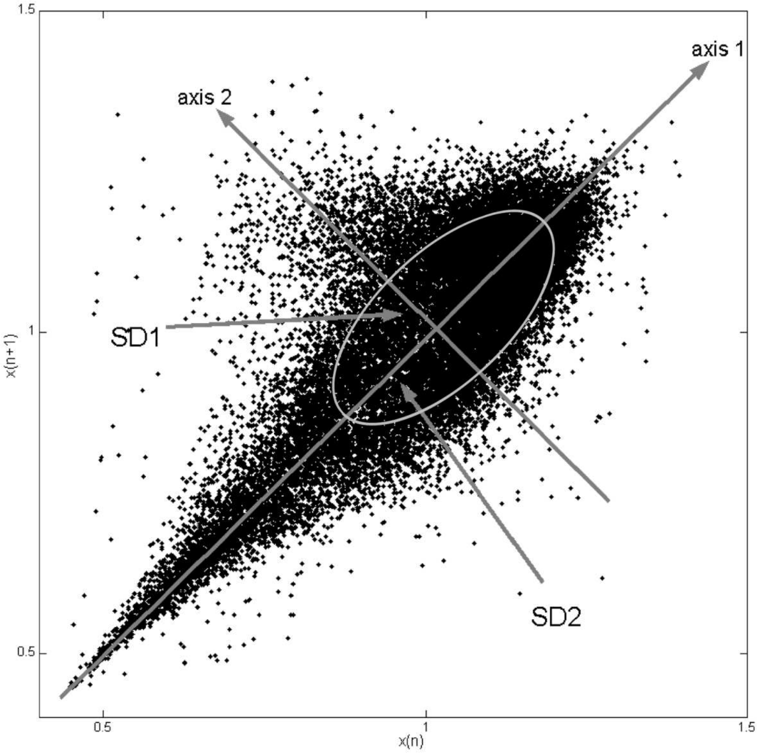

Figure 1. The idea of an ellipse fitted to the Poincaré plot and descriptors $SD1$ and $SD2$

Descriptors $SD1$ and $SD2$ can be defined as:

$$SD1 = \tfrac{\sqrt{2}}{2} SD(x_n - x_{n+1}) \tag{1}$$

$$SD2 = \sqrt{2SD(x_n)^2 - \tfrac{1}{2} SD(x_n - x_{n+1})^2} \tag{2}$$

where SD is a standard deviation of the time series.

Uncorrelated noise and its Poincaré plot are shown in Figure 2. Here we have no structures on the Poincaré plot.

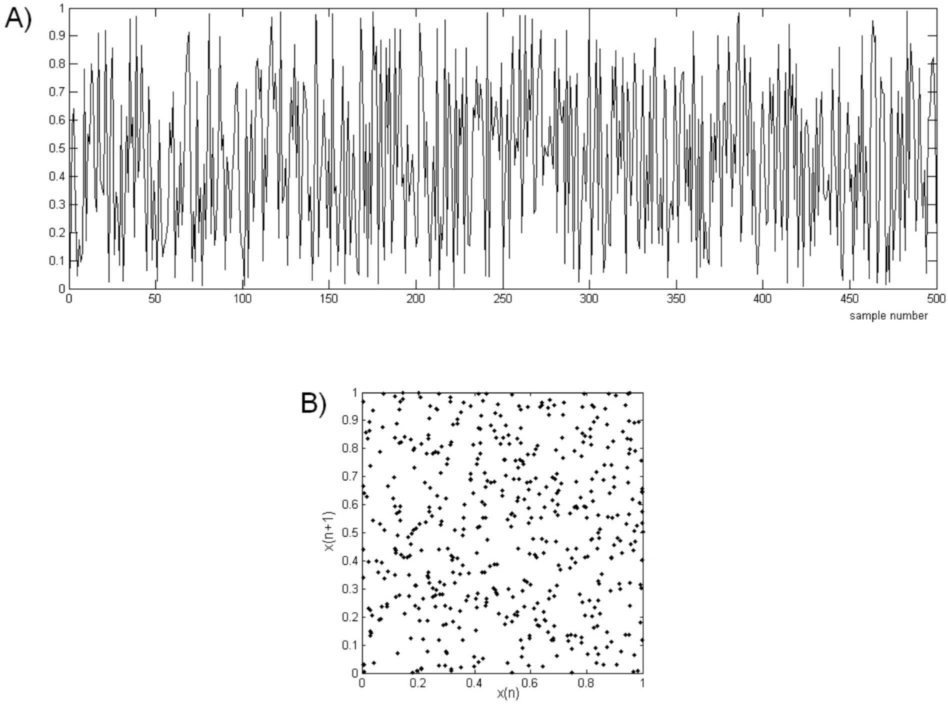

Figure 2. A) Uncorrelated noise and B) its Poincaré plot

Periodic function (here function *cos*) and its Poincaré plot are shown in Figure 3. Here we obtain an ellipse on the Poincaré plot.

As we can see above one can observe various kinds of shapes of Poincaré plots. In the literature, we can find mainly comet-shaped plots, torpedo-shaped plots and ellipse-shaped plots (Brennan et al., 2001; Kitlas et al., 2004; Tulppo et al., 1996). In ECG record studies,the shape of the Poincaré plot can be categorized into functional classes associated with degrees of heart failure (Woo et al., 1992).

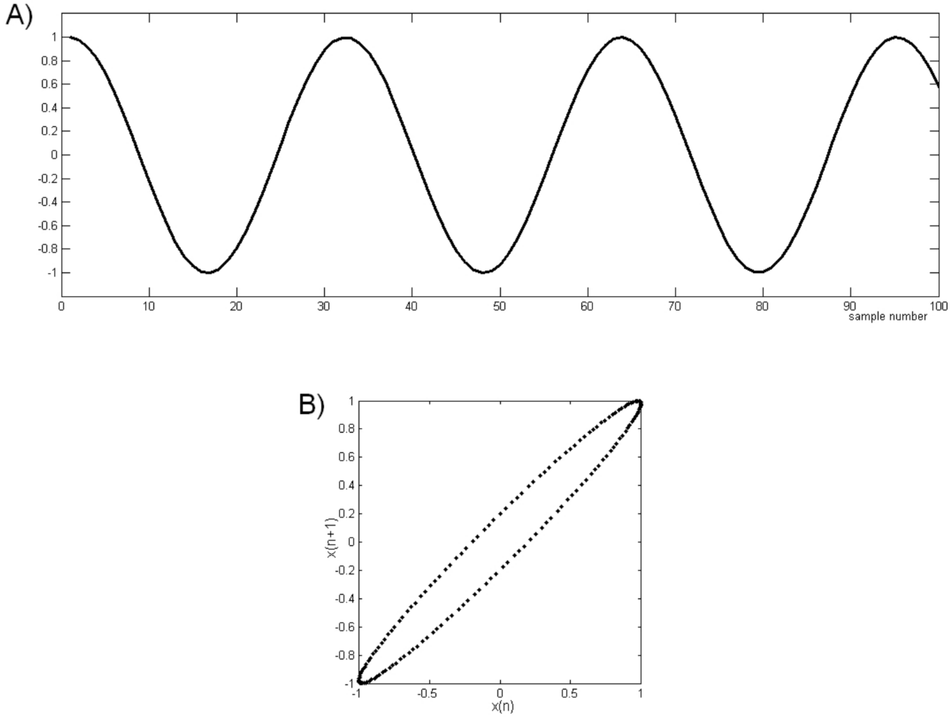

Figure 3. A) Periodic function *cos* and B) its Poincaré plot

Analyzed Signals (R-R Intervals, EMG Signals, Gait Data and EHG Records) and their Poincaré Plots

We analyzed various kinds of signals: RR intervals, EMG, gait data and EHG. All these signals were obtained from Physionet (Goldberger et al., 2000).

As mentioned above, R-R intervals were extensively studied by means of Poincaré plot, so we present only basic information about it. R-R intervals are the series of time intervals between the beats of heart (Brennan et al., 2001).

There are interpretations of $SD1$ and $SD2$ in these kindsof studies. $SD1$ is an instantaneous beat-to-beat variability and $SD2$ acontinuous beat-to-beat variability (Brennan et al., 2001; Kitlas et al., 2004; Piskorski et al, 2007). The $SD1/SD2$ ratio represents the randomness in the heart rate variability time series (Biala et al., 2010).

RR-intervals and Poincaré plot are shown in Figure 4. Values of $SD1$, $SD2$ and their ratio for R-R intervals (normal sinus rhythm) are presented in Table 1.

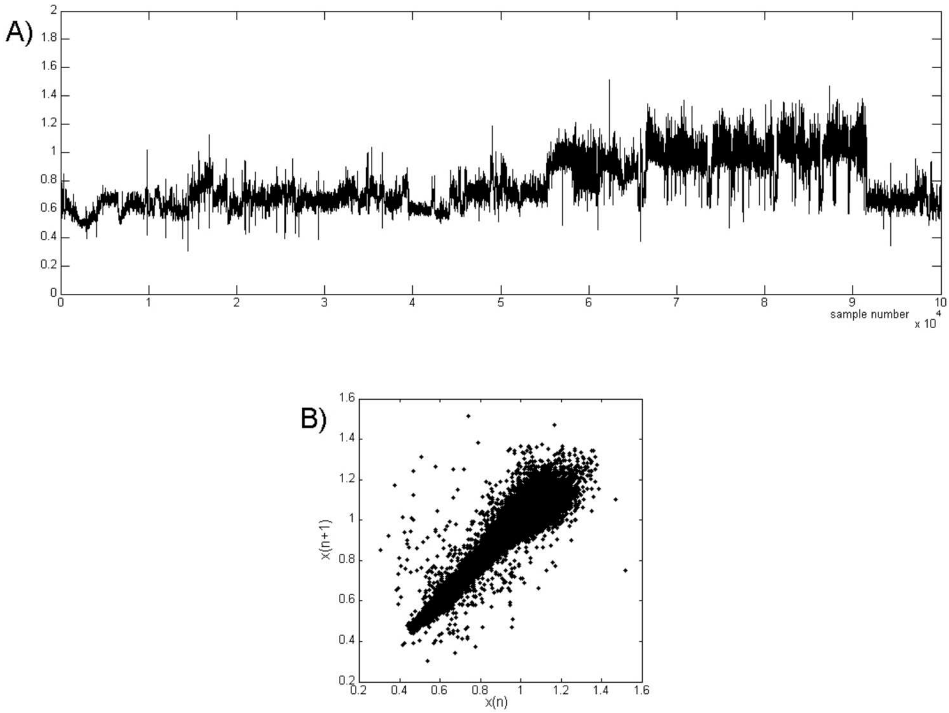

Figure 4. A) R-R intervals from a healthy subject (normal sinus rhythm) and B) Poincaré plot

Table 1. Values of descriptors $SD1$, $SD2$ and $SD1/SD2$ ratio for selected R-R intervals

R-R intervals	$SD1$	$SD2$	$SD1/SD2$ ratio
subject with normal sinus rhythm	0.019	0.189	0.103

Electromyography (EMG) is an important technique for evaluating activity and properties of muscles. Selected EMG signals and their Poincaré plots are presented in Figure 5. These are short EMG recordings from three subjects: one healthy, one with myopathy and one with neuropathy. EMG records were obtained using a 25 mm concentric needle electrode placed in the tibialis anterior muscle. Subjects dorsiflexed the foot gently against resistance and then relaxed (Goldberger et al., 2000). Values of $SD1$, $SD2$ and their ratios are presented in Table 2. One can observe that the lowest $SD1/SD2$ ratio value is for the healthy subject.

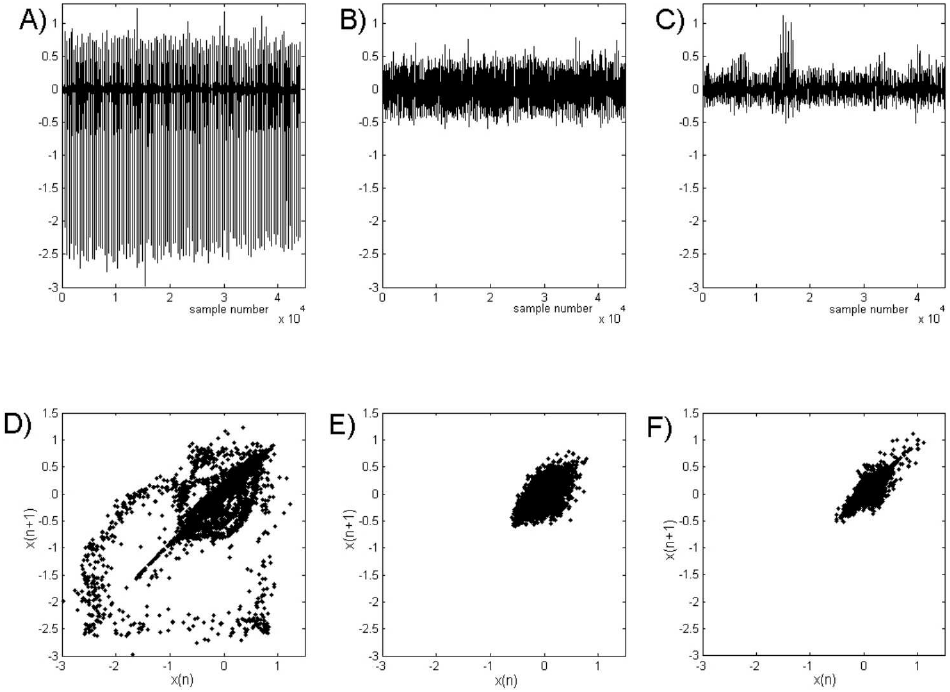

Figure 5. EMG signals from three subjects: A) one with neuropathy, B) one with myopathy and C) one healthy and their respective Poincaré plots D) E) F)

Table 2. Values of descriptors *SD*1, *SD*2 and *SD*1/*SD*2 ratio for selected EMG signals

EMG signal	*SD*1	*SD*2	*SD*1/*SD*2 ratio
subject with neuropathy	0.029	0.128	0.230
subject with myopathy	0.037	0.087	0.427
healthy subject	0.016	0.097	0.164

Gait data is the data of human motion. Selected gait data signals and their Poincaré plots are presented in Figure 6. These are short gait data, illustrating the right stride interval from three subjects: one healthy subject, one with Huntington's disease and one with Parkinson's disease. The signals were obtained using force-sensitive resistors, with the output roughly proportional to the force under the foot (Goldberger et al., 2000). Values of $SD1$, $SD2$ and their ratios are presented in Table 3. One can observe that the lowest $SD1/SD2$ ratio value is for the healthy subject.

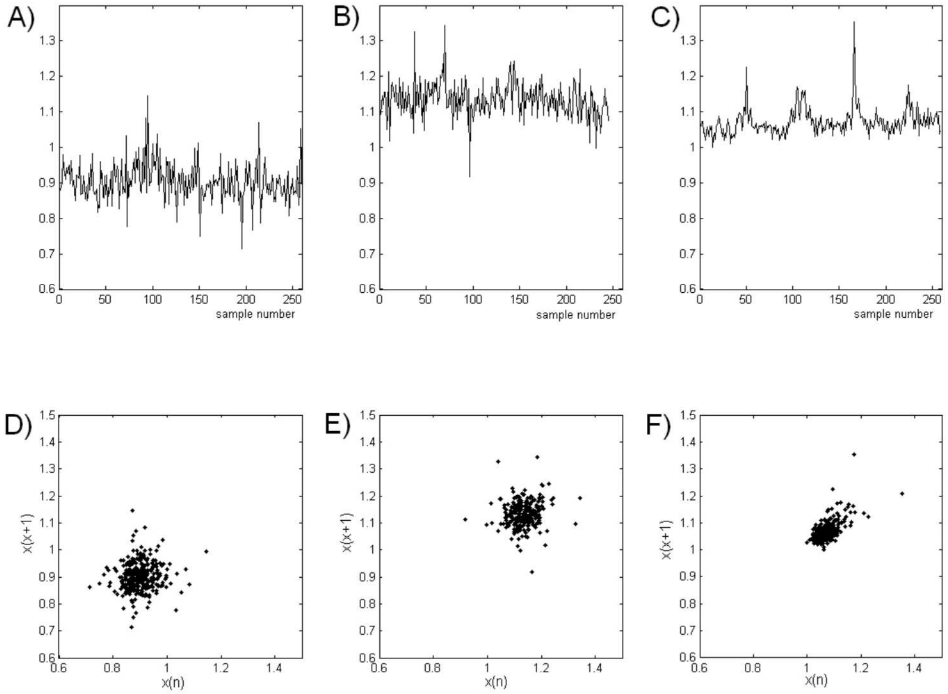

Figure 6. Gait data signals from three subjects: A) one with Huntington's disease, B) one with Parkinson's disease and C) one healthy subject, along with their respective Poincaré plots D) E) F)

Table 3. Values of descriptors $SD1$, $SD2$ and $SD1/SD2$ ratio for selected gait data

Gait data (right stride interval)	$SD1$	$SD2$	$SD1/SD2$ ratio
subject with Huntington's disease	0.045	0.041	1.094
subject with Parkinson's disease	0.037	0.045	0.834
healthy subject	0.017	0.036	0.466

Electrohysterography (EHG) is a technique used for recording changes in electric potential associated with uterine contractions. Selected EHG records and their Poincaré plots are presented in Figure 7. Signals were obtained during pregnancy from two subjects: one with delivery on term and one with preterm delivery (Goldberger et al., 2000). Values of $SD1$, $SD2$ and their ratios are presented in Table 4. One can observe that the lowest $SD1/SD2$ ratio value is for the subject with term delivery.

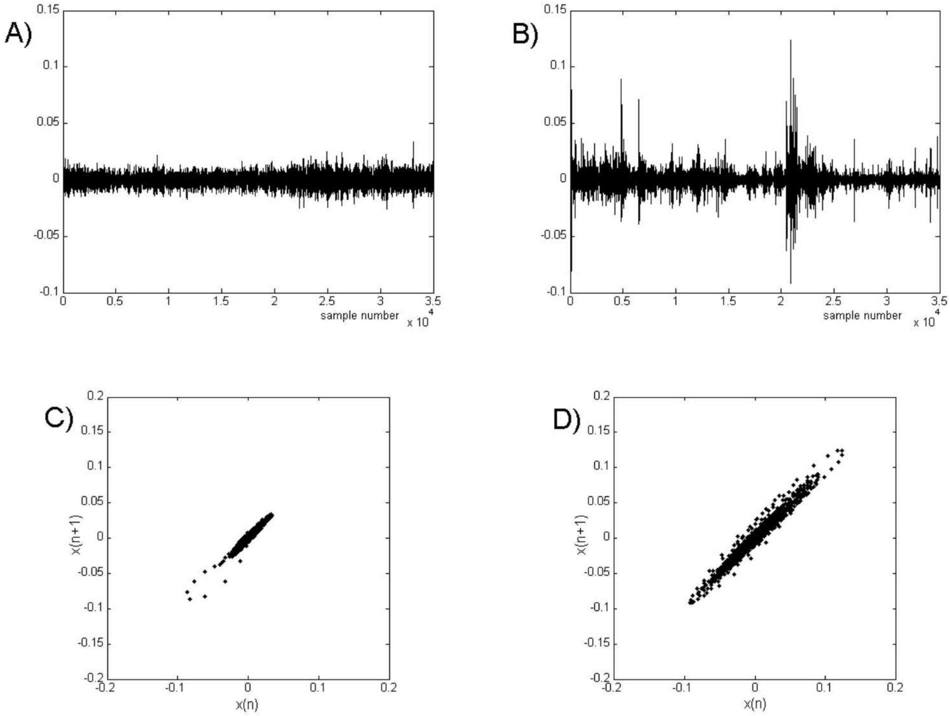

Figure 7. EHG signals (obtained during pregnancy) from two subjects: A) one with preterm delivery, B) one with term delivery and their respective Poincaré plots C) D)

Table 4. Values of descriptors SD1, SD2 and SD1/SD2 ratio for selected EHG signals

EHG signals	$SD1$	$SD2$	$SD1/SD2$ ratio
subject with preterm delivery	0.001	0.008	0.134
subject with term delivery	0.001	0.013	0.081

A Short Literature Overview

There are many papers on the application of Poincaré plots in heart variability studies (mainly R-R intervals), but not in other studies. We mention only afew of them with recent interesting results.

Hoshi et al. (2013) performed the studies to verify whether there is a correlation between $SD1$, $SD2$, and $SD1/SD2$ ratios and nonlinear indexes (e.g. Lyapunov Exponent, Correlation Dimension, DFA method...) of heart rate variability either in cases of disease or inhealthy conditions. They claim that a high relationship with nonlinear indexes and low relationship with linear indexes suggests nonlinear fractal features.

Biala et al. (2010) studied the effect of maternal smoking habits during pregnancy on healthy and intrauterine growth restricted children (some with asthma). They analyzed ECG records during sleep and suggest that smoking can have adverse implications for the development of the autonomic nervous system of intrauterine growth restricted children, especially those with asthma, who showed a decrease in short-term variability amongst this group.

Karmakar et al. (2009) pointed out that Poincaré plot and descriptors SD1 SD2 have some limitations, so they provided a new descriptor – Complex Correlation Measure – to study the temporal variation of Poincaré plot.

Piskorski et al. (2007) studied the geometry of Poincaré plot of RR intervals and redefined $SD1$, which allowed them to define two new useful descriptors. They have shown that there is an asymmetry in the Poincaré plot and called it heart rate asymmetry. This paper is very interesting from a theoretical point of view.

In our previous studies, we have analyzed heart rate variability using Poincaré plots in cases of children with diabetes type 1 and late vascular complications (Kitlas et al., 2004). There were two groups of children: atest group of 35 children and acontrol group of 50 healthy children. For each subject, a 24-hour Holter ECG was recorded and then divided into two segments: day activity and night activity. $SD1/SD2$ ratios were lower for unhealthy children, which indicates a more regular heart rate. Similar results were obtained by Faust et al. (2012). They studied ECG records from 15 patients with diabetes and from 15 healthy volunteers by means of different methods, including Poincaré plots. They computed descriptor $SD2$ and compared the results – diabetic subjects had lower values of this descriptor than healthy subjects.

Conclusion

Poincaré plot is a nonlinear method that can help us to analyze signals qualitatively and quantitatively. It reflects the variability of data. It seems that too low or too high $SD1/SD2$ ratio values are connected with illness, with respect to the biomedical signal. This requires further study. We hope that other signals, not only R-R intervals, will be investigated by means of Poincaré plot. Through such investigation, a new interpretation of this method can emerge in biomedical signal studies.

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