Computers in Biology and Medicine 63 (2015) 251–260

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

Reducing sojourn points from recurrence plots to improve transition detection: Application to fetal heart rate transitions

Amira Zaylaa [a,b], Jamal Charara [b], Jean-Marc Girault [a,*]

[a] *Department of Medical Biophysics and Imaging, Signal-Imaging Group, Team-5 of UMR 930, François-Rabelais University of Tours, 7 Avenue Marcel Dassault, 37200 Tours Cedex, France*

[b] *Department of Physics and Electronics, Faculty of Sciences, Lebanese University, Beirut, Lebanon*

ARTICLE INFO

Article history:
Received 15 April 2014
Accepted 16 September 2014

Keywords:
Recurrence plots
Signal-based recurrence plots
Sojourn points
Dynamic transitions
Detection
Complexity analysis
Fetal heart rate

ABSTRACT

The analysis of biomedical signals demonstrating complexity through recurrence plots is challenging. Quantification of recurrences is often biased by sojourn points that hide dynamic transitions. To overcome this problem, time series have previously been embedded at high dimensions. However, no one has quantified the elimination of sojourn points and rate of detection, nor the enhancement of transition detection has been investigated. This paper reports our on-going efforts to improve the detection of dynamic transitions from logistic maps and fetal hearts by reducing sojourn points. Three signal-based recurrence plots were developed, i.e. embedded with specific settings, derivative-based and m-time pattern. Determinism, cross-determinism and percentage of reduced sojourn points were computed to detect transitions. For logistic maps, an increase of 50% and 34.3% in sensitivity of detection over alternatives was achieved by m-time pattern and embedded recurrence plots with specific settings, respectively, and with a 100% specificity. For fetal heart rates, embedded recurrence plots with specific settings provided the best performance, followed by derivative-based recurrence plot, then unembedded recurrence plot using the determinism parameter. The relative errors between healthy and distressed fetuses were 153%, 95% and 91%. More than 50% of sojourn points were eliminated, allowing better detection of heart transitions triggered by gaseous exchange factors. This could be significant in improving the diagnosis of fetal state.

1. Introduction

Complexity analysis of biomedical time series by means of various descriptors including, but not limited to, fractal dimension [1], multi-fractal spectra [2], and entropies [3–5] is quantitative and currently standard practice.

Large studies involving the analysis of biomedical systems and signals have recently used recurrence plots (RPs) that featured and located recurring states or patterns constituting the system's time series or variables in 2-dimensions [6–12]. Quantitative indicators named recurrence quantification analysis (RQA) have been computed in order to extract certain scalar indicators from RPs [13–15].

One of the significant uses of *RQA* was in the detection of the various dynamic transitions of logistic maps [13,12,16]. In addition, the Determinism (DET) parameter was employed to quantify chaotic-periodic and periodic-chaotic transitions [13,12]. Such transitions were detected in two different ways. The first focused on the computation of *RQA* promptly from a single unembedded time series [16]. This method was appealing due to its simple mathematical formulation. However, quantification was biased and a poor transition detection rate was obtained due to the presence of sojourn points [13–15,8].

The second method was based on embedding the time series [6,7,13,17]. Although this method required heavy computation, it reduced sojourn points empirically and promoted transition detection [13,12]. However, no one has yet quantified the improvement of the detection rate, nor identified whether it would be possible to enhance the transition detection rate. This leads us to the question regarding the best value of the embedding dimension that would allow the detection of all dynamic transitions.

This paper describes our on-going efforts to extract and cleanly quantify the dynamic information from nonlinear dynamic systems such as the logistic map and the fetal heart. The aim was to improve the detection rate of transitions by eliminating sojourn points present in recurrence plots. For the logistic map, the transitions to be detected were periodic-chaotic and chaotic-periodic transitions, while for the fetal heart the states to be detected were healthy-distressed and distressed-healthy fetal heart rates (FHRs). The solution adopted consisted of eliminating

* Corresponding author.
E-mail addresses: amira.zaylaa@inserm.fr (A. Zaylaa), jcharara@ul.edu.lb (J. Charara), jmgirault@univ-tours.fr (J.-M. Girault).

http://dx.doi.org/10.1016/j.compbiomed.2014.09.007
0010-4825/

sojourn points present in recurrence plots. Several RPs were employed to find an efficient solution to the above problems. The first empirical method comprised two plots with different embedding dimension values. As proposed in [16] the first plot required no embedding and was the unembedded RP. The second recurrence plot required an embedding dimension greater than 2, as suggested by Marwan et al. [13,12]. As the choice of the embedding dimension in the second method is often arbitrary, we developed a new method that comprised finding the optimal embedding dimension that minimized the number of sojourn points. We also developed two additional signal-based methods using the derivative concept and the m-time pattern concept, and compared them with the above plots.

To quantify the levels of performance of the proposed approaches, each technique was applied to the nonlinear logistic map and to the FHR, and both the sensitivity and the specificity were assessed in each case.

The remainder of this paper is organized as follows. In Section 2, we introduce the methods including the already existing RPs and the three signal-based recurrence plots developed. In Section 3, we set out the numerical results. Finally, in Section 4 we discuss the results, provide a general conclusion and suggest the future prospects of this work.

2. Methods

2.1. Complexity analysis prerequisites

2.1.1. Recurrence plots

An RP is a two-dimensional squared matrix, with black and white dots and two time-axes. Each black dot at the coordinates (i,j) represents a recurrence of the system state $\mathbf{X}_i$ with another $\mathbf{X}_j$, it is expressed as follows for tolerance r:

$$\mathbf{RP} = \Theta(r - \|\mathbf{X}_i - \mathbf{X}_j\|), \quad \mathbf{X}_i \in \mathcal{R}^d, \tag{1}$$

where $\mathbf{X}_i \in R^d$ stands for the points in the phase space at which the system is situated at time i, $\Theta(\cdot)$ the Heaviside function, $\|\cdot\|$ the L_∞ norm, $i,j = \{1,\dots,N-d+1\}$, N the total number of points and d the embedding dimension [7,13,12,18].

2.1.2. Determinism (DET)

After the computation of the qualitative RP, scalar quantitative parameters could be calculated. Of all the existing RQA, *DET* seemed to be the most sensitive scalar parameter to detect transitions [13,12]. The determinism (*DET*) [8] is calculated as follows:

$$DET = \frac{\sum_{l=l_{min}}^{N} lP(l)}{\sum_{i,j=1}^{N} RP}, \tag{2}$$

where $P(l)$ is the number of diagonal lines of length l and l_{min} the minimum length of a diagonal line [19–21,13,22,9], i.e. the number of points forming a diagonal line of at least length l_{min}.

2.1.3. Sojourn points

The removal of sojourn points is illustrated with sojourn points starting from a single time series. Fig. 1 is a diagram of how sojourn points appear in two dimensions and the mode of computing the RPs developed. Fig. 1 sets out (a) a sine wave $x(t)$ made up of 200 sample points, its time delayed version, $y(t) = x(t+\tau)$ and their elliptical phase space (i.e. $x(t)$ versus $y(t)$), (b) a sine wave, $x(t)$, its derivative, $\dot{x}(t)$ and their circular phase space (i.e. $x(t)$ versus $\dot{x}(t)$) and (c) a sine wave constituted of pairs of points. Note that the size of a single chosen slice is called tolerance r.

Fig. 1(a) shows the points denoted as 1 (red circles) and 3 (black cross) existing within the same slice of size r. In reality, only the points denoted as 1 truly recur with each other and not with points denoted as 3. According to the standard recurrence test (of an unembedded time series), all 1's and 3's were recurrences. This was very clear while comparing all the points existing on the same amplitude level of $x(t)$ to those of the delayed signal and confined within the same tolerance r. By introducing a second signal $y(t)$ (a delayed or a derivative version of $x(t)$), it was then possible to remove sojourn points by comparing points 2 and 4 of $y(t)$ to the corresponding points 1 and 3 of $x(t)$. Point 4 of $y(t)$ which corresponded to 3 in $x(t)$ did not exist at the same amplitude level, whereas all the red circles were within r. Consequently, point 3 was a sojourn point since it was not periodic[1] with 1's. However, in the two signal-based RPs Fig. 1(a) and (b) this was overcome. Tolerance r was fixed in Fig. 1 to ensure a fair comparison. This tolerance value r is usually 10% of the standard deviation of $x(t)$.

2.2. Existing methods

2.2.1. Unembedded recurrence plots

An unembedded recurrence plot is that produced from a single time series, there is thus no need for sub-time series. Eq. (1) becomes

$$\mathbf{RP_1} = \Theta(r - \|\mathbf{x}_i - \mathbf{x}_j\|), \tag{3}$$

where $\mathbf{x}_i$ stands for the time series points at time i. As reported by Iwanski et al. [16], when $d=1$, Eq. (1) is called an unembedded RP. This plot is denoted throughout this work as $\mathbf{RP}_1$ (see Table 1).

2.2.2. Embedded recurrence plots

Originally developed by Eckmann [7], embedded plots have been used to track recurrences of system states out of a reconstructed phase space of d-embedding dimension. This was fulfilled using the embedding theorem [17,6,13,23,24]. The reconstructed RP was obtained by calculating a time delay τ and embedding dimension d using the mutual information (M.I.) [25] and the false nearest neighbour (F.N.N.) [18] methods, and subsequently computing Eq. (1), given that $\boldsymbol{X_j} = \boldsymbol{X_{i+\tau}}$ and $d \geq 2$. Analogous to previous investigations [17,13,12,26], d was fixed at 3, i.e. three sub-time series produced from $x(t)$ were used to reconstruct the RP. The corresponding RP was denoted as $\mathbf{RP}_2$ (see Table 1). Note that such a plot has been recommended to eliminate sojourn points by using an embedding dimension $d \geq 2$ [8,26].

2.3. Developed methods

2.3.1. Embedded recurrence plot with specific settings

We provide here our first signal-based RP that is responsible for enhancing the detection of dynamic transitions. With this technique, instead of looking for the best embedding dimension and time delay that guarantee the independence of the sub-time series, as already demonstrated by Trulla et al. [17] and later by Marwan et al. [13,12], we looked for the best value of the embedding dimension and time delay that ensured the minimum presence of sojourn points in an RP. Both $d = d_{optimal}$ and $\tau = \tau_{optimal}$ were obtained by minimizing the cost function $(J(d_k, \tau_k) = CDET)$ characterizing sojourn points.

In contrast to *DET*, where $P(l)$ was the number of diagonal lines, the Cross-Determinism (CDET) was defined by Eq. (2) for $P(l)$,

[1] In 1-Dimension, sojourn points are non-periodic points existing within tolerance r.