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Local Noise Sensitivity in Human Photoplethysmogram

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Abstract– Photoplethysmography is one of the widely used techniques to measure biological signals produced by the cardiovascular system. The photoplethysmogram can provide valuable information about cardiovascular system performance. Methods of nonlinear dynamics are recognized to be useful for analyzing the photoplethysmogram; however, their application is often limited by the presence of noise in experimental data. This study sought to investigate the effects of noise on photoplethysmogram dynamics in terms of local noise sensitivity. Wayland test local translation errors were calculated for a photoplethysmogram data set. The results demonstrated that the photoplethysmogram time-delay-reconstructed attractor has a region that is highly affected by noise induction, while the effect of noise on other parts is minor. This finding provides important information for achieving a better understanding of the interaction between noise and photoplethysmogram dynamics, and it may contribute to applied studies utilizing the photoplethysmogram.

1. Introduction

The photoplethysmogram (PPG) is a biological signal produced by the cardiovascular system that is widely used in medical and sports equipment. The PPG signal can be recorded by detecting the near infrared light reflected by vascular tissue following illumination with a LED. The PPG measurement technique is simple and noninvasive, and the PPG is recognized to contain valuable information about cardiovascular system performance [1, 2]. Various studies have demonstrated the usefulness of the PPG analyzed by methods of nonlinear time series analysis, to a wide-range of applications in physical and mental health monitoring [3-6]. However, results obtained from noise-contaminated biological signals, such as the PPG, are often not straightforward to understand or may even be misleading. For example, the Lyapunov exponent calculated numerically from experimental data is not always reliable and might appear positive for non-chaotic data due to the presence of noise in the original signal [7, 8].

Various aspects of noise interaction with complex dynamics signals have been intensively studied [9]. Noise contamination effects, noise filtering, as well as the role of noise as a stochastic force, which allows the creation of realistic models describing natural phenomena and even the possibility of noise-induced chaos, have been investigated in many studies over the last few decades [10-12].

Developing efficient noise filtration techniques or nonlinear time series methods that can perform well for noisy chaotic data may ameliorate noise issues in experimental data. However, conventional noise filtering techniques cannot be efficiently applied to the PPG's complex dynamics while preserving its unique chaotic characteristics, and modifying existing analysis methods or developing noise-stable analysis methods requires a deep understanding of noise and PPG chaotic dynamics interactions. However, the interaction between noise and complex PPG dynamics and the effect of noise on the PPG are not yet well studied.

In our recent study on noise-induced chaotic models, it was found that noise produces certain effects on chaotic dynamical systems, and a phenomenon that was defined as "local noise sensitivity" was observed. PPG dynamics is recognized to be consistent with chaotic motion [13]. Here we assumed that experimentally obtained PPG signal has a certain amount of noise contamination. It is expected that the PPG dynamics may also demonstrate the presence of a local response to noise induction, which may provide one of the keys necessary for understanding noise-dynamics interactions in the PPG signal.

Understanding the effect of noise on PPG dynamics could significantly contribute to applied studies using the PPG, especially in the area of human health monitoring, as well as to theoretical studies, as it would provide an example of noise produced changes in chaotic motion and may provide the basis for developing noise filtration techniques for chaotic biological data. Therefore, this study sought to investigate the effects produced by noise on the PPG in terms of its local noise sensitivity.

2. Methods and Materials

2.1. Photoplethysmogram data collection

The PPG data were collected by a finger PPG recorder from healthy 19- to 27-year old volunteers among Tokyo University of Agriculture and Technology (TUAT) students. Experimental data collection was approved by TUAT authorities. Written informed consent was given to participants prior to the experiment. At the time of the study all subjects were healthy non-smokers, physically active to similar levels, were not taking any medication, and all of them declare no history of heart disease.

For each participant the measured period was 5 min with 5 msec sampling steps. For all data collection sessions, a BACS (Computer Convenience, Inc.) PPG sensor was located on the right forefinger. According to the recommended settings for data collection and significant factors that may affect PPG measurements described previously [14], all measurements were done with the subject in a relaxed sitting position in a room with temperature, noise and vibration control. Prior to the test, each test subject was asked to rest for 5 min under quiet conditions in the laboratory room with the test site uncovered.

2.2. Local Noise Sensitivity

In our previous works [6, 13] the Wayland test translation error [15] was successfully utilized for detecting determinism in the PPG signal obtained in a reference environment and under noise exposure. The translation error appeared to be quite a useful index for characterizing the chaotic properties of the PPG signal, and it provided us with quantitative information regarding the determinism of the investigated PPG signal and the smoothness of its reconstructed attractor. Previously only the translation error averaged over the reconstructed trajectory was applied to the PPG. In this study we calculated the Wayland test local translation error (LTE) in every point of the data set using the following formula [15]:

$$e_{loc} = \frac{1}{k+1}\sum_{j=0}^{k} \frac{\left\|v_j - \langle v\rangle\right\|^2}{\|\langle v\rangle\|^2},$$

where $v_j=y_j\text{-}x_j$ are translation vectors, $\langle v\rangle$ is the average of v_j, x_j ($j=1,2,\ldots,k$) are k nearest neighbors to the fixed and arbitrary chosen point x_0 on the reconstructed trajectory and y_j are projections of x_j.

Previously, a local noise sensitivity phenomenon was detected in chaotic dynamical systems by utilizing LTE on examples of the Lorenz and the Rössler systems in the chaotic regime. As the concept of local noise sensitivity is new, it will be briefly described below in an example of the chaotic Lorenz model.

3. Results

Experimentally obtained biological data, such as the PPG, are inevitably noise contaminated, which may complicate drawing conclusions from the analysis results. Therefore, to analyze the effects of noise on the PPG dynamics, the well-known Lorenz model in the chaotic regime and its local noise sensitivity were utilized for comparative investigation.

3.1. The chaotic Lorenz model

The Lorenz model, which is one of the typical examples of models generating chaos, is described by the following system of equations [16]:

$$\begin{cases} \dot{x} = -\sigma(x-y), \\ \dot{y} = \rho x - y - xz, \\ \dot{z} = xy - \beta z, \end{cases}$$

where system parameters σ=10, ρ=28, β=8/3 correspond to the chaotic regime [16]. This system was solved numerically with the 4th order Runge-Kutta method.

The LTE was calculated in each data point for the data obtained as numerical solutions of the chaotic Lorenz system above, and for noise-induced Lorenz data. Results were plotted along a reconstructed attractor as shown in Fig. 1. Noise, whose components are uniformly distributed random numbers, with 7% of its amplitude, was induced on the Lorenz data. For clarity in the graph the threshold for LTE was chosen as *0.5* since this or any higher LTE value would correspond to non-deterministic flow. Fig. 1 (a) corresponds to the noise-free case, i.e., to the data calculated from the above described model. Fig. 1 (b) shows the case of 7% noise induced on the Lorentz data.

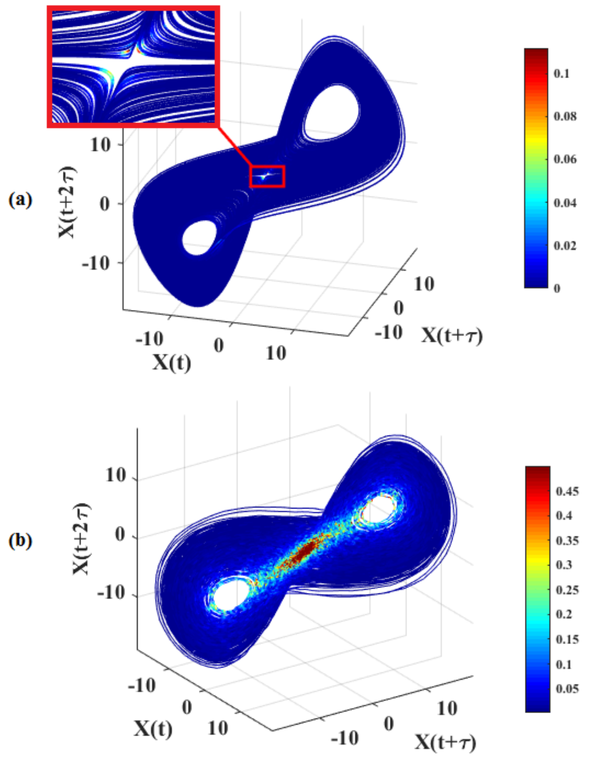

FIG. 1 The distribution of local translation error along the time-delay-reconstructed chaotic Lorenz attractor: (a) noise-free and (b) 7% noise induction case.

As seen from Fig. 1 (a) and (b) with noise induction, the number of high values for the LTE increased; moreover, high values were not distributed evenly along the trajectory but were concentrated in certain regions of the reconstructed attractor. This phenomenon can be observed in chaotic models and it is called local noise sensitivity.

3.2. Photoplethysmogram

The LTE was calculated for the PPG at each data point. LTE distribution along the PPG trajectory is shown in Fig. 2 (a). As seen in Fig. 2, only several areas have a clearly observable concentration of high LTEs, while other parts of the trajectory have LTEs close to zero. However, although we assumed noise contamination of the PPG data, the actual amount of noise as well as the types of noise induced during data collection are unknown. This makes it difficult to draw unambiguous conclusions from results shown in Fig. 2 (a). As shown in Fig. 1 for the Lorenz model, with subsequent noise increase, the high LTE values area expanded. To test whether the PPG's LTE distribution would significantly change in response to further noise increases, additive noise, as in the Lorenz case, was induced on the PPG time series. The LTE distribution for noise induced PPG is shown in Fig. 2 (b) and (c) for noise with the original amplitude and with a two-fold increase in the amplitude value, respectively.

The global Wayland test translation errors were 0.0561, 0.0936, and 0.1841 for the original, noise-induced and double amplitude noise-induced PPG data.

As seen in Fig. 2, similar to the chaotic Lorenz case, high LTE values tended to concentrate in certain regions of the PPG reconstructed attractor; however, the character of the distribution, the number of high LTE concentration areas, as well as distribution changes under further noise induction, differed from the Lorenz case.

It is important to notice that the noise amplitude values were chosen in consideration with the Lorenz and PPG data scales, as well as the PPG time series finiteness and resolution.

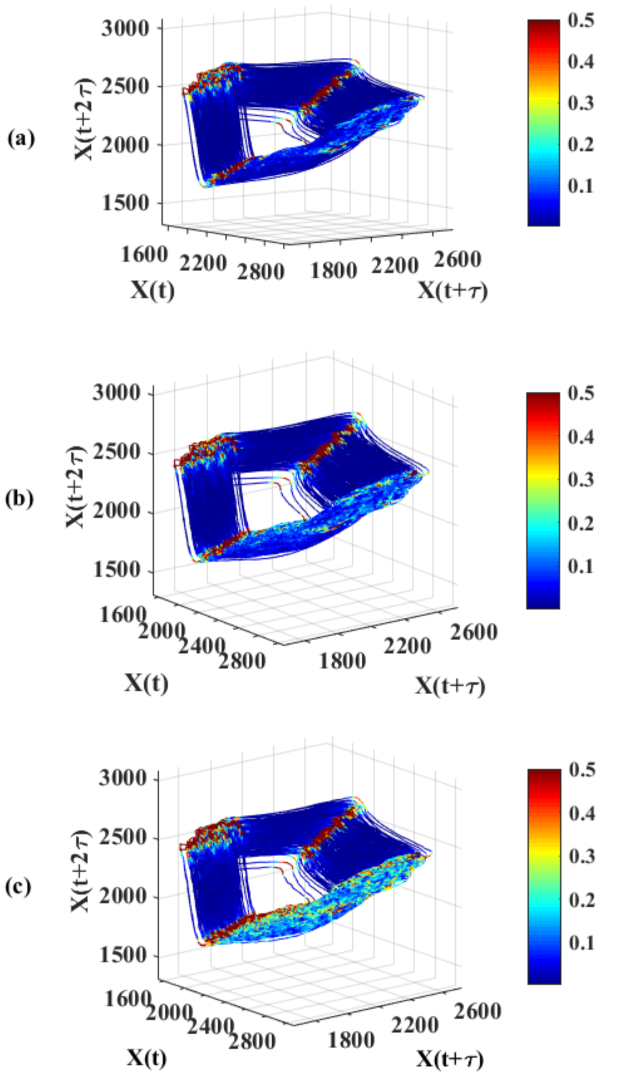

FIG. 2 Distribution of local translation error along the reconstructed PPG trajectory: (a) original, (b) additive noise, and (c) additive noise with doubled amplitude induced on the PPG data.

4. Discussion

The main objective of this study was to investigate the effects produced by noise on the PPG dynamics in terms of local noise sensitivity.

Even though the actual noise level in the PPG is unknown, it was assumed that experimentally obtained PPG data must contain a certain amount of noise. Under this assumption and taking into account that the PPG dynamics is consistent with the definition of chaotic motion, the presence of local noise sensitivity, which was previously demonstrated for the chaotic Lorenz model, was investigated.

Similar to the Lorenz case, the distribution of the LTE along the PPG trajectory demonstrated the presence of local regions on the PPG attractor with high value LTEs concentrated areas (Fig. 2 (a)). However, local noise sensitivity is not an exclusive reason for high LTE values, and therefore it was important to observe the changes in the distribution in response to further noise induction. As demonstrated for the chaotic Lorenz system (Fig. 1), in noise sensitive regions, the area with high LTE values appeared to be spreading as the noise increased. For the original PPG time series four regions on the attractor demonstrated concentrations of high value LTEs: three rapidly bending parts and the spiral part of the trajectory. However, subsequent noise induction on the PPG time series (Fig. 2 (b-c)) only resulted in increased LTE values over the spiral region of the attractor, while the distribution at three other regions remained essentially unchanged. The concentration of high value LTEs in the spiral region of the attractor and its distribution dynamics in response to increased induced noise indicates the presence of a local noise sensitivity phenomenon in the spiral region of the PPG time-delay-reconstructed attractor. However, conclusions regarding the presence of local noise sensitivity for the other three regions with high value LTEs cannot be drawn unambiguously and further investigation of the response of these regions to noise induction is required. It is important to notice that in this study only the simplest case of additive noise with uniform random distribution was analyzed, and therefore, future study of the effects of various types of noise may provide the key for understanding the noise-dynamics interaction of the other three regions.

Local reaction of the spiral part of the trajectory expressed by the increase of LTE values can be partially explained by taking into consideration the fact that in spiral and bending areas of an attractor reconstructed from a discreet time series, data point density is higher compared with other parts of the trajectory. Therefore, the presence of noise, whose scale is comparable with the original data, can create a significant disturbance in the trajectory. In this case due to the high data points concentration, relatively remote noise-contaminated data points may replace closer ones and act as nearest neighbors. Due to these false neighbors, not only the LTE may have high values even in apparently deterministic data, but it may also affect various nonlinear time series analysis methods that rely on nearest neighbor searches or the smoothness of the reconstructed trajectory.

Additionally, apparent differences in the type of LTE distribution and the number of regions with high LTE between the chaotic Lorenz case and the PPG may be partially explained by topological differences between the Lorenz layering type attractor and the PPG attractor, which can be recognized as a folded band.

The presence of a noise sensitive region on the time-delay reconstructed PPG attractor discovered in this study can improve our understanding of the effect of noise on PPG dynamics, and it is expected to contribute to further applied studies of the PPG signal.

5. Conclusions

In this study the local Wayland test translation error was utilized for investigation of the effect of noise on the PPG chaotic dynamics. Results demonstrated that the PPG display local noise sensitivity, which indicates that noise present in the experimental PPG data does not affect it evenly, and while noise may cause considerable effects, they only occur in specific regions. The noise-sensitive portion of the PPG attractor, where the LTE reached high values and its area increased with subsequent noise induction, was represented by the spiral part of the reconstructed trajectory.

Discovery of local noise sensitivity in the human PPG can significantly contribute to various applications in the field of human health monitoring. Additionally, it is expected that further comparative investigation of the PPG noise sensitivity may lead to the development of methods for estimating noise levels in experimental PPG data.

Acknowledgments

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