PHYSA: 17440 Model 3Gsc pp. 1–16 (col. fig: NIL)

ARTICLE IN PRESS

Physica A xx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Physica A

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

Refined composite multivariate generalized multiscale fuzzy entropy: A tool for complexity analysis of multichannel signals

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HIGHLIGHTS

- We propose refined composite multivariate multiscale fuzzy entropy (RCmvMFE).
- The coarse-graining step of RCmvMFE uses variance (RCmvMFE$_\sigma^2$) or mean (RCmvMFE$_\mu$).
- The introduced fuzzy membership function significantly decreases the running time.
- Our simulations demonstrate that RCmvMFE$_\sigma^2$ and RCmvMFE$_\mu$ lead to more stable results.
- RCmvMFE$_\sigma^2$ and RCmvMFE$_\mu$ are less sensitive to the length of signals.

ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form 24 June 2016
Available online xxxx

Keywords:
Complexity
Multivariate generalized multiscale entropy
Statistical moments
Fuzzy entropy
Sample entropy
Biomedical signals

ABSTRACT

Multiscale entropy (MSE) is an appealing tool to characterize the complexity of time series over multiple temporal scales. Recent developments in the field have tried to extend the MSE technique in different ways. Building on these trends, we propose the so-called refined composite multivariate multiscale fuzzy entropy (RCmvMFE) whose coarse-graining step uses variance (RCmvMFE$_\sigma^2$) or mean (RCmvMFE$_\mu$). We investigate the behavior of these multivariate methods on multichannel white Gaussian and $1/f$ noise signals, and two publicly available biomedical recordings. Our simulations demonstrate that RCmvMFE$_\sigma^2$ and RCmvMFE$_\mu$ lead to more stable results and are less sensitive to the signals' length in comparison with the other existing multivariate multiscale entropy-based methods. The classification results also show that using both the variance and mean in the coarse-graining step offers complexity profiles with complementary information for biomedical signal analysis. We also made freely available all the Matlab codes used in this paper.

1. Introduction

Entropy is a prevalent method to quantify the regularity of physical systems and to compare time series. To quantify the degree of the irregularity, randomness, or unpredictability of signals, a number of entropy measures were introduced during the past few decades [1–5]. One of the most popular kinds of entropy methods is sample entropy (SampEn) that measures the degree of randomness or, inversely, the degree of orderliness of a signal [2]. Since SampEn is less sensitive to the signal length and noise than approximate entropy (ApEn), it has been broadly used in biomedical signal processing [2]. Despite its

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http://dx.doi.org/10.1016/j.physa.2016.07.077
0378-4371/© 2016 Published by Elsevier B.V.

popular use, SampEn is very sensitive to the threshold value. To tackle this problem, fuzzy entropy (FuzEn) was proposed [3]. These two entropy methods have attracted a great deal of attention over the recent years [6–11].

SampEn and FuzEn approaches, though powerful, are estimated only at a single temporal scale and therefore, may fail to account for the multiple time scales underlying nonlinear dynamics [12]. As an example, although the SampEn value of white Gaussian noise (WGN) signal is higher than that of $1/f$ noise, $1/f$ noise is theoretically more complex than WGN because of the long-range correlations of the former [13]. To overcome this shortcoming, multiscale entropy (MSE) [13,14] and multiscale FuzEn (MFE) [3,15] were proposed to take into account the various scales of a signal. It is worth noting that, in this context, the "complexity" concept stands for "meaningful structural richness", which may be in contrast with regularity measures defined from classical entropy approaches such as ApEn, SampEn, and FuzEn. For example, ApEn was proposed to quantify the degree of predictability of signals [16]. Thus, ApEn is primarily a "regularity" statistic, not a direct index of physiological complexity. SampEn and FuzEn are based on the ApEn, leading to regularity measures [2,3]. Thus, the entropy of $1/f$ noise is lower than that of WGN at scale factor 1 using MSE [13].

In fact, the least complexity illustrates either a completely ordered system with a small entropy value or a completely disordered system with maximum entropy value [13,14,16–18]. For instance, WGN is more irregular than $1/f$ noise although the latter is more complex, because $1/f$ noise contains long-range correlations and its $1/f$ decay produces a fractal structure in time. As another example, traditional entropy-based methods assign higher entropy values to certain pathologic cardiac rhythms that generate erratic outputs than to normal cardiac rhythms that are precisely regulated by multiple interacting control mechanisms [13,14]. In the physiological complexity literature, healthy systems or people correspond to high complexity due to their ability to adapt themselves in response to adverse conditions, exhibiting long range correlations and complex variability at multiple scales, while aged and diseased systems or individuals present complexity loss, that is, they lose the capability to adapt to such adverse conditions [13,16,19].

In the MSE and MFE approaches, the original signal is initially divided into non-overlapping segments of length β, termed the scale factor. Next, the average of each segment is estimated to obtain the coarse-grained signals. Finally, the SampEn or FuzEn measure is calculated for each segment [13]. Costa and Goldberger have very recently generalized the MSE method using the second moment (variance) rather than the first moment (mean), in the coarse graining step of MSE [20]. This was named MSE_{σ}^{2}. It should be added that to discriminate MSE_{σ}^{2} and the basic MSE, we will show the latter as MSE_{μ}.

MSE_{σ}^{2} quantifies the dynamical properties of volatility (variance) over multiple time scales. MSE_{σ}^{2} was applied to heartbeat signals from healthy young and older adults, and patients with congestive heart failure syndrome. The results showed that human heartbeat volatility signals depict complex bursting behaviors over a wide range of time scales. In addition, they found the multiscale complexity of both the volatility and mean degrades with aging [13,20].

Multivariate signals, like multichannel recordings, are becoming more and more common in neuroscience and biomedical and mechanical science [21–23]. The MSE-based approaches, though powerful and widespread, are not able to reveal the dynamics across the channels. For such time series, evaluation of cross-statistical properties between multiple channels is essential for a complete understanding of the underlying signal-generating system [21,24]. In this sense, Ahmed and Mandic proposed multivariate SampEn (mvSE_{μ}) [21], leading to an extension of MSE to multivariate signals (mvMSE_{μ}) [21]. The mvMSE analysis is interpreted based on (1) the multivariate signal **X** is more complex than the multivariate signal **Y**, if for the most time scales, the mvSE measures for time series **X** are larger than those for time series **Y**, (2) a monotonic fall in the multivariate entropy measures along the time scale factor demonstrates that the time series in hand only includes useful information at the smallest scales, and (3) a multivariate system illustrating long-range correlations and complex creating dynamics is characterized by either a constant mvSE or this declares a monotonic rise in mvSE with the time scale factor [21].

mvMSE has received much attention in the biomedical and mechanical fields [22,23]. Labate and company employed the mvMSE and multivariate multiscale permutation entropy (mvMPE) [25] to predict the conversion from mild cognitive impairment to Alzheimer's disease using EEG signals [22]. Gao et al. proposed a multiscale complex network and multiscale clustering coefficient entropy to analyze multivariate time series [26]. They also used the mvMSE method to characterize flow behavior underlying horizontal oil–water flows from experimental measurements [27].

Although mvSE is a powerful and popular algorithm, when applied to short time series, the results may be undefined or unreliable. To alleviate this limitation, we extend the refined composite MSE (RCMSE) [28], which was proposed for univariate signals, to multivariate time series. The mvMFE_{μ} method has been recently proposed to improve the stability of mvMSE_{μ} [15]. However, this approach, though powerful, is slow. In this paper, using another fuzzy membership function, the running time of mvMFE_{μ} is noticeably improved. Finally, we extend and investigate the new moment for coarse-graining process, variance, proposed for univariate signals, to multivariate signals. These methods are named as RCmvMFE_{μ} and $\text{RCmvMFE}_{\sigma}^{2}$.

This paper is organized as follows. In the next section, $\text{RCmvMFE}_{\sigma}^{2}$ and RCmvMFE_{μ} are presented in detail. In Section 3, the synthetic and real biomedical signals, employed in this piece of research, are described. The results and discussion are provided in Section 4. Finally, a conclusion is presented in Section 5.

2. Refined composite multivariate multiscale fuzzy entropy

All multivariate multiscale sample/fuzzy entropy-based algorithms include two main steps as follows:

Please cite this article in press as: H. Azami, J. Escudero, Refined composite multivariate generalized multiscale fuzzy entropy: A tool for complexity analysis of multichannel signals, Physica A (2016), http://dx.doi.org/10.1016/j.physa.2016.07.077