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A pattern recognition framework for detecting dynamic changes on cyclic time series

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ABSTRACT

This paper proposes a framework for binary classification of the time series with cyclic characteristics. The framework presents an iterative algorithm for learning the cyclic characteristics by introducing the discriminative frequency bands (DFBs) using the discriminant analysis along with k-means clustering method. The DFBs are employed by a hybrid model for learning dynamic characteristics of the time series within the cycles, using statistical and structural machine learning techniques. The framework offers a systematic procedure for finding the optimal design parameters associated with the hybrid model. The proposed model is optimized to detect the changes of the heart sound recordings (HSRs) related to aortic stenosis. Experimental results show that the proposed framework provides efficient tools for the classification of the HSRs based on the heart murmurs. It is also evidenced that the hybrid model, proposed by the framework, substantially improves the classification performance when it comes to detection of the heart disease.

1. Introduction

Time series classification has become a topic of great interests over decades. Many supervised methods have been proposed for the classification purposes based on the dynamic characteristics of time series. Dynamic time warping and Hidden Markov Model (HMM) are the two well-known statistical methods, extensively used in the context of the automatic speech recognition [1,2]. However, a solid method for the classification of the cyclic time series is still questionable, even though a number of the applied-studies subjectively suggested methodologies in which the case studies consisted of the time series with cyclic properties [3–5]. In this study, a cyclic time series is described as a non-stationary time series which resembles repetitive contents, while the duration of the cycles could be inconsistent. In a cyclic time series, some specific patterns with non-stationary properties are repetitively seen with an ordered rhythm that associates indicative characteristics with the time series. These characteristics attribute new traits to the context of time series classification, which could be employed by a dynamic method to enhance the classification performance. This perspective can be expanded from the theory to the applied-studies to provide a base for similar purposes in different fields.

Several biological activities of a human body could be recognized as the cyclic time series. Recordings of the cardiac signals, electrocardiogram (ECG) and phonocardiogram (PCG), are the two important examples of the cyclic time series where the cardiac cycle varies due to the physiological activities of the body. The PCG is a recording of the heart sounds, emanating from mechanical activity of the heart [6]. Importance of the PCG becomes clearer, when one considers the fact that the cardiovascular diseases are still the main factor of the human mortality [7], while studies show that accuracy of the heart disease diagnoses could be substantially improved by using a computer-assisted phonocardiogram [8]. Nevertheless, interpretation of the PCG is a complicated task that needs expertise and experiences. Complexity of this task brings a large number of referrals with normal hearts to the hospitals for cardiac examinations, after been examined by the general practitioners in the primary health care centers. This hugely inflicts unnecessary expenses and stress on the global health care system and the patients. On the other hand, a number of patients with cardiac diseases are overlooked due to the mentioned complexity. Therefore, the development of a noninvasive and inexpensive tool for screening heart disease is still a priority for the primary health care centers. Such a system can be used in hands of the nurses or practitioners to select proper candidates to undergo echocardiography which is a cumbersome

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and expensive approach. The main obstacle in creating an automatic screening system based on PCG is the development of a robust processing algorithm for interpretation and classification of the PCG.

In this paper, we present a supervised pattern recognition framework which preserves both the cyclic and dynamic characteristics of the time series, using a hybrid model boosted by discriminant analysis. The framework presents an iterative algorithm to learn cyclic characteristics of the time series using a joint combination the Fisher linear discriminant analysis and k-means clustering method. The outcomes of the iterative algorithm are employed by the hybrid model to perform binary classification. The hybrid method learns dynamic behavior of the time series within the cycles, using statistical machine learning methods. Although the two parts of the framework including the iterative algorithm and the hybrid model are discriminant, we have integrated them together to achieve a reliable classification in a demanding clinical application. The model combines different methodologies to extract efficient features that improve classification capacity. As a consequence, the dimension of the discriminative feature vectors is effectively reduced. It is well-known that "good, larger feature sets do not necessarily include the good small sets" [9]. As we will see in the sequels, the multiple mapping functions introduced by the methodologies, associate multiple design parameters with the model which appropriate its flexibility to be optimized for a specific case study. The framework proposes a systematic procedure to find an optimal set of the design parameters associated with the hybrid model.

The model is tailored to detect the changes of the HSRs, caused by aortic stenosis (tightening of the aortic valve), from the other three heart conditions: mitral regurgitation (leakage of the mitral valve after its closure), innocent murmurs (normal heart with extra sound) and no murmurs (normal heart without the extra sounds). It is important to note that aortic stenosis in mild cases can be easily confused by the conditions such as innocent murmur or mitral regurgitation (MR), during clinical auscultation since all initiate similar auscultatory sign. The model is evaluated by a database of real PCGs, prepared in two hospitals, in compliance with the Helsinki Declaration and Good Clinical Practices (GCP). The performance of the model is validated and compared with the dynamic support vector machine (SVM), using the SVM with the auto regressive kernel as the baseline. It is worth noting that the classification algorithms which involve dynamic time warping cannot provide a proper baseline for the performance due to their inefficiencies with the multidimensional time series, which has been addressed in a number of related studies [10–12]. The validation procedure employs different subsets of training and test data, randomly selected from the database, and repeated several times to obtain the statistically significant results. The average classification rate and sensitivity of the model is estimated to be 86.5% and 82.2%, respectively, while the perfect classification rate of 100% could be observed in a number of repetitions.

2. Medical background

A normal heart initiates two sounds in each cycle: the first and the second heart sound, denoted by S1 and S2, respectively, and the temporal interval between S1 and S2 is called the systolic period. In cardiac auscultation, the systolic period is divided into three intervals with equal duration: early, mid and late systole. A valvular heart pathology often causes extra sounds on the PCG which are in turn indications of the underlying pathology [13–15]. Systolic heart murmurs (SM) are by far the most prevalent extra heart sounds that could be either symptomatic or asymptomatic, namely pathological murmurs or innocent murmurs (IM), respectively [14]. Innocent murmur is one of the intricacies of the cardiac assessments, heard in 50–70% of children with normal hearts [16,7,8]. On the other hand, the pathological systolic murmurs could be heard in a broad range of the heart diseases including aortic stenosis (AS) and mitral regurgitation (MR). The AS is a heart disease in which the aortic valve is tighter than its normal size and therefore creates turbulence in blood flow. Intensity and duration of the turbulence depend on the degree of the stenosis, classified into three levels: mild, moderate and sever stenoses according to the findings of the ultrasound examinations. The systolic murmur initiated by the AS can cover early to late systole, depending on the severity of the AS [13]. In the MR cases, the turbulence is created by a backward blood leakage after cessation of the mitral valve, and its murmur mostly covers the whole systole [13]. Differentiation between the murmur caused by the AS and the one by the MR or IM is a complicated task, especially in the mild AS cases. Systolic periods of a PCG could be modeled as a non-stationary stochastic cyclic time series whose dynamic characteristics depend on the underlying pathology. Studies showed that frequency contents of the systolic murmurs serve as an indicative feature for the classification [17,18]. However, finding the frequency bands which provide an optimal segregation within a number of classes of the murmurs has been problematic, particularly when the mild pathologies are ruled in the study. Furthermore, the development of an efficient dynamic model for detecting a specific systolic murmur is still an open study. The non-stationary stochastic property of the systolic murmurs is considered as one of the difficulties of such a dynamic model. The non-stationarity is observed both over the recordings of a specific heart disease, and even on the cycles of a recording as the beat to beat variations. Consequently, it is a demanding challenge to detect the disease-related changes even for an expert physician in such situations where the signal has non-stationary and stochastic characteristics.

3. Related studies

Serious studies have aimed for developing powerful methods for modeling time series in the context of speech recognition and biomedical engineering, where the model parameters served as the design features to obtain a high-performance classification. multi-layer perceptron (MLP) neural network and Hidden Markov Model (HMM) broadly received interests and recognitions from the researchers as the two distinct methods in the context of the artificial intelligence and statistical classification, respectively [19,20]. Although the link between the multi-layer perceptron and HMM was later discovered, they are still considered as the two distinct approaches [21,22]. Time-Delayed Neural Network (TDNN) was first introduced as the transition invariant back-propagation for noisy speech recognition tasks, propounded as an alternative to the HMM [23]. However, a main drawback of the TDNN is the large size of the feature vector needed for the classification, since the feature sets are simultaneously extracted from multiple windows to preserve dynamic properties of the signal. Recurrent neural network is another alternative applied to the time series to provide a probabilistic modeling [24]. An advantage of the neural networks is the ability of quick learning in terms of the training data size, comparing to the statistical classifiers e.g. HMM. On the other hand, a negative aspect of the neural networks is the presence of the local minimum along with their high structural risks [25].

Hybrid modeling has been proposed as a combination of the artificial intelligence and statistical methods to improve quality of the classification, employed in the data intensive domains such as