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Iterative two-dimensional signal warping—Towards a generalized approach for adaption of one-dimensional signals

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ABSTRACT

The assessment of subtle morphological changes in noisy signals is a common challenge in the field of biomedical signal processing. Concerning the electrocardiogram (ECG), it may yield novel risk factors for cardiac mortality. Here, we describe an iterative two-dimensional signal warping algorithm (i2DSW), which morphological analyses even in case of noise ratios. i2DSW adapts a generalized iterative template adaptation process that yields a more flexible template and allows for better fitting of subtle variations of signal shapes. Moreover, the template segmentation is not dependent on signal morphology. We test its performance, by measuring beat-to-beat repolarization variability in simulated and clinical ECG. Simulation studies show higher robustness of i2DSW in presence of typical ECG artefacts compared to previously proposed methods including the existing two-dimensional warping technique (26% improvement). Comparison of short-term ECG recorded in normal subjects versus patients with myocardial infarction (MI) confirmed increased repolarization variability in MI patients ($p < 0.0001$). Results obtained with long-term ECG show improved waveform adaptation of i2DSW (overall 19%, up to 33%). The assessment of subtle morphological changes by i2DSW may yield novel and more robust risk factors for cardiac mortality. By avoiding a fixed template segmentation, the generalized design of i2DSW has the potential to be also powerful in the application to other quasi-periodic signals.

1. Introduction

Extracting quasi-periodic features from noisy signals is a common challenge in the field of biomedical signal processing. To track beat-to-beat changes in cardiovascular variables over time, template matching algorithms have evolved [1–3]. A widely used technique to determine beat-to-beat changes of QT intervals relies on homogeneously stretching the ST-T segment of the beat under consideration until it matches best a ST-T template [1]. To consider temporal changes of the QRS complex the time shifting algorithm has been introduced [2]. The main idea is to construct separate QRS and T wave templates and shift them in time to determinate the QT interval. From a physiological point of view, these techniques might not be able to capture all morphological changes within the QT interval.

The description of subtle morphological changes in electrocardiograms (ECG) may yield novel risk factors for cardiac mortality [4,5], but the low signal to noise ratios imposes practical challenges. To address these issues, we introduced a technique that adapts one-dimensional (1D) templates in a two-dimensional (2D) manner, so-called two-dimensional signal warping (2DSW) in 2014 [3]. A 2D mesh superimposed on the signal, allows subtle segmentation of the template taking into account inhomogeneous variations of waveform morphologies.

Several clinical research studies and multiple systematic investigations have demonstrated the power of 2DSW in applications related to QT variability (QTV) assessment [6–11]. We further proposed a simple formula to correct for the inverse relationship between QTV and T wave amplitude. Using this correction, predictive value of QTV for all-cause mortality in patients with non-ischemic cardiomyopathy has been demonstrated [11]. Nevertheless, analysis of long-term ECG recordings showed limitations of 2DSW to adapt to large shape variations, e.g. caused by circadian rhythm [6]. These limitations in the template adaptation are mainly due to the fixed 2D mesh segmentation. As a consequence, we further developed 2DSW, referred to as iterative 2DSW (i2DSW), to remove these limitations. With respect to the enhancements of

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i2DSW, we were faced with the tradeoff between generalization of the technique for all quasi-periodic signals on the one hand, and achievement of robust and sensitive results in the application of QTV measurement on the other hand.

This article is structured as follows: Section 2 covers a summary of the 2DSW warping concept published in [3]. The iterative implementation and generalization of 2DSW is introduced in Section 3. Section 4 applies the iterative 2DSW algorithm to waveform variability assessment in ECG and QTV evaluation, in particular using simulated and real data. The results are shown in Section 5. Section 6 discusses i2DSW in comparison to standard 2DSW and common algorithms.

2. Warping concept

2DSW [3] aims to adapt a template to a waveform by minimizing the distance between both. This is realized by superimposing a 2D mesh of warping points on the template to be adapted. The 2D mesh, the so-called warping grid, is built of N_C columns and N_R rows. Each intersection defines a warping point P_i with $i = 1, 2, \ldots, N_P$, where N_P is the number of warping points in the warping grid. The area spanned by a quadrangle of four warping points is called warping area, denoted as A. Warping points are active warping points $P^{(1)}$, if at least one of the up to four surrounding areas contains part of the template to be adapted. Otherwise, these warping points are denoted as passive warping points $P^{(0)}$. To modify the template in A, a 2D shift of one or more adjacent active warping points is necessary. Each absolute coordinate of the template $[x, y] \in A$ has a relative coordinate $[x^{(rel)}, y^{(rel)}]$, see Fig. 1. Each relative position remains unchanged in the 2DSW deforming process, so that all template coordinates $[x, y] \in A_j$ with $j = 1, 2, \ldots, N_A$, where $N_A = (N_C - 1)\cdot(N_R - 1)$ is the total number of areas in the warping grid, belong to an warping area A_j. Thus, a drift of template coordinates to neighboring areas is not possible. The template adaption is achieved by minimizing the euclidean distance

$$d^{(2n)}(Y^{(1)}, Y^{(2)}) = \frac{\sqrt{\sum_{l=1}^{|\mathcal{Y}|}\left(y_l^{(1)} - y_l^{(2)}\right)^2}}{|\mathcal{Y}|} \tag{1}$$

between template $\mathcal{Y}^{(1)}$ and waveform $\mathcal{Y}^{(2)}$ normalized by the signal length $|\mathcal{Y}|$. The signals $\mathcal{Y}$ are defined as a set of vectors $[x, y]$, $\mathcal{Y} = \{[x, y]| \in \mathbb{R}\times\mathbb{R}\}$. X and Y represent the series of x and y values. To compute $d^{(2n)}(Y^{(1)}, Y^{(2)})$, the domains $X^{(1)}$ and $X^{(2)}$ have to be identical, otherwise interpolation/resampling is applied. The shifting of warping points underlies two constraints: (1) the functional character of the template has to be preserved, i.e. each x value has one single corresponding y value. (2) The maximum of the two-dimensional shift is restricted in x and y direction. This prevents warping areas from reducing below a given size or cut across neighboring areas. In the original design 2DSW is implemented by applying a predefined warping grid to adapt the waveform (further details are given in [3]). The parameterization of this grid involves limitations in the deforming process. To remove the limits an iterative 2DSW algorithm is proposed in the following section.

3. Iterative implementation

3.1. Iterative generalization

Iterative two-dimensional signal warping realizes the basic concept of 2DSW by applying a divide and conquer strategy. By repeating 2DSW multiple times, starting with a warping grid of a single warping area A and refining that grid in each iteration *iter*, a stepwise template adaption is realized. The refinement of the warping grid is implemented by dividing each warping area in subareas, illustrated in Fig. 2. Because macroscopic morphological adjustments can be made in the first iteration, passive shifting of

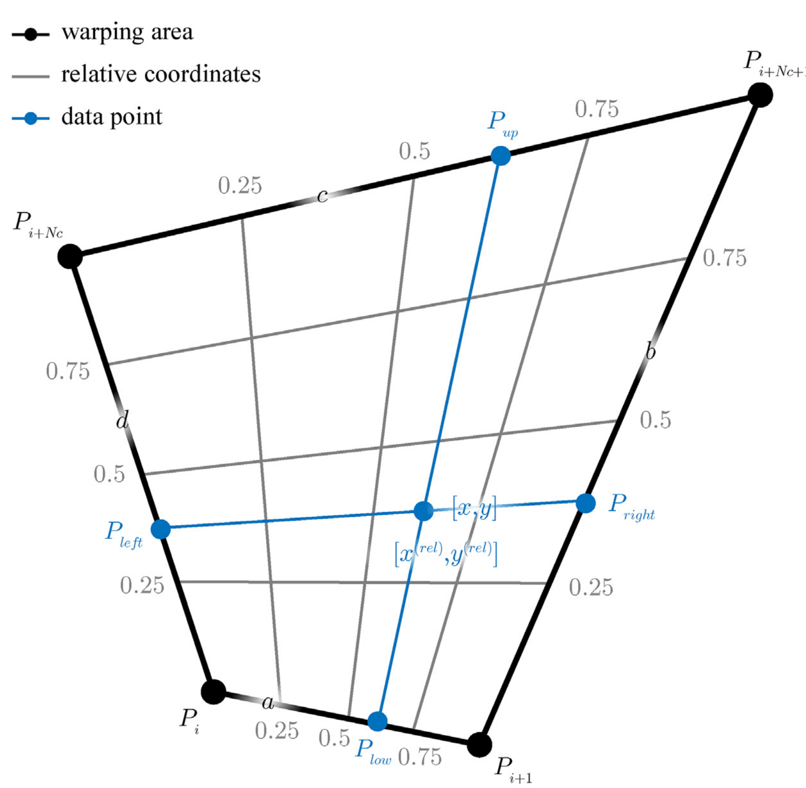

Fig. 1. Illustration of the relative position $[x^{(rel)}, y^{(rel)}]$ of an arbitrary point in a non-rectangular warping area. Four warping points P_i spawn a warping area. The borders are denoted as vectors a, b, c and d.