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Outlier Pulse Detection and Feature Extraction for Wrist Pulse Analysis

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***Abstract*—**Wrist pulse analysis for identification of health status is found in Ancient Indian as well as Chinese literature. The pre-processing of wrist pulse is necessary to remove outlier pulses and fluctuations prior to the analysis of pulse pressure signal. This paper discusses the identification of irregular pulses present in the pulse series and intricacies associated with the extraction of time domain pulse features. An approach of Dynamic Time Warping (DTW) has been utilized for the identification of outlier pulses in the wrist pulse series. The ambiguity present in the identification of pulse features is resolved with the help of first derivative of Ensemble Average of wrist pulse series. An algorithm for detecting tidal and dicrotic notch in individual wrist pulse segment is proposed.

***Keywords*—**Wrist Pulse Segment, Ensemble Average, Dynamic Time Warping (DTW), Pulse Similarity Vector.

I. Introduction

AN Ancient Ayurveda and Traditional Chinese Medicine use the pulse pressure signals observed over radial artery of both the hands for the identification of health status. The features associated with the pulse pressure signals are important from diagnostic point of view. Ancient Ayurveda identifies the health status by observing the wrist pulses in terms of ‘Vata’, ‘Pitta’ and ‘Kapha’ as the basic elements of human body [1] [2] while Traditional Chinese Medicine classifies the pulse types into twenty seven types based on the pulse characteristics like force, rate, rhythm, volume, regularity and contact pressure required to observe the pulse [3].

The pulse pressure signal generated in the arterial structure exhibit certain characteristics which involve percussion wave, tidal wave, dicrotic notch and reflected wave. It is required to identify these characteristics points on the wrist pulse correctly for the analysis of the pulse series. First derivative of the wrist pulse waveform is used for extracting these features [4]. Based on the pulse features, a quantitative system for pulse diagnosis has been proposed [5]. Wrist pulse series is segmented in to multiple pulses for extracting such features of individual pulse. A practical approach for pulse segmentation has been discussed by C. Xia et al.[6]. Prior to feature extraction and analysis of pulse series, pre-processing is essential to remove irregularities. When wrist pulse signal is acquired, few of the pulses may loose its character and seem to be irregular and irrelevant compared to most of the pulses present in the series. Such pulses are required to be removed before analyzing the wrist pulse series. Dynamic Time Warping (DTW) algorithm is used as similarity measure in time series analysis. It has been also utilized to classify the pulse based on its shape in wrist pulse classification [7]. DTW algorithm is particularly utilized here for identifying the most dissimilar pulses and thereby identifying regularity of the pulse series.

The systole phase of the wrist pulse shows upstroke with rising wave, while the diastole phase shows various transitions in the slope. This makes the identification of pulse features difficult in pulse segment, which is primary requirement in feature variability analysis. An approach based on first derivative of the segmented ensemble averaged wave is proposed to identify the characteristic points.

This paper is organized as V sections. In section II the wrist pulse characteristics and method of pulse acquisition are discussed. Section III discusses the issues related with the processing of wrist pulse. Section IV deals with the Dynamic Time Warping algorithm to search for outlier pulse in the pulse series as well as first derivative of ensemble average for identifying the pulse features. In Section V the article is concluded.

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II. Wrist Pulse Characteristics and Acquisition

A. Wrist Pulse Characteristics

The pulse pressure signal monitored on the radial artery follows a specific pattern. A wrist pulse of a healthy person is shown in Fig. 1. A steep rise in pulse pressure signal is observed due to systole phase of the heart. This action forms a percussion wave, which achieves the peak in the signal strength. Percussion wave is the forward wave generated in the arterial structure by pumping action of the heart. After this systolic wave, a secondary peak known as Tidal wave is observed. In the descending part of the wrist pulse a dicrotic wave appears due to shock of closure of the aortic valve, indicating start of diastole phase of the heart. The incisure present due to this is also referred as dicrotic notch. The peak amplitude H1 and its timing T1, amplitudes H2, H3 and their respective timings T2, T3 associated with Tidal wave as well as amplitudes H4, H5 and their respective timings T4, T5 associated with dicrotic wave of individual wave are helpful in the diagnosis. The pulse of an abnormal health status person shows different characteristics in terms of rate, rhythm as well as absence of tidal and/or dicrotic notch [8]. Hence identification of these features is essential in wrist pulse analysis.

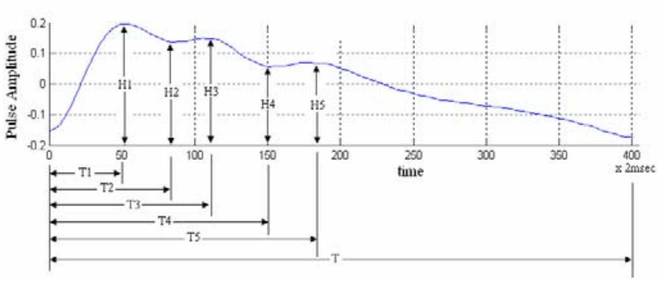

Fig. 1 Wrist pulse of a healthy person

B. Wrist Pulse Acquisition

A pressure sensor capable of measuring 350 mmHg of pressure is used for acquiring wrist pulse. The signal is amplified and filtered to obtain a clean pressure signal. The signal is then sampled with sampling frequency of 500 Hz with the help of USB-6009 Data Acquisition system from National Instruments. Since the wrist pulse contains most of the signal in the lower frequency band, the signal is filtered with the help of a low pass filter having appropriate cut off frequency. The signal also contains baseline fluctuations due to motion artifacts and respirations of the person. This baseline is removed using discrete meyer wavelet transform. [9].

III. Pre Processing of Pulse Series

A. Irregular Pulses in the Pulse Series

Due to physiology of the human body, wrist pulse series shows beat to beat variations. For the variability study of pulse parameters like pulse peak amplitude, tidal wave amplitude, dicrotic wave amplitude, their timings and pulse rate, they must be derived from each pulse segment. But due to motion artifacts in the pulse acquisition, few pulses loose their character and hence it becomes difficult to assign pulse features with them. Such outlier pulses need to be removed prior to further analysis as they have adverse effects on the analysis. An example of such pulse series is shown in Fig. 2 wherein the fifth pulse is loosing its character.

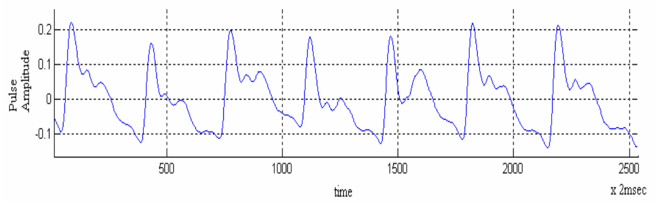

Fig. 2 Wrist pulse series

B. Intricacy with Pulse Feature Identification

Since wrist pulse is a combination of forward wave, generated by the heart and a reflected wave from the peripheral organs, it undergoes various slope changes in the diastole phase of the pulse. The first derivative of the pulse series shows these variations. The zero crossing points in the first derivative are helpful in identifying the tidal and dicrotic wave but minor variations around tidal and dicrotic wave give rise to multiple zero crossing points in the first derivative of pulse. These variations make identification of the characteristic points difficult. Fig 3(a) shows the first derivative of a pulse and Fig. 3 (b) shows an enlarged view of its small segment. The zero crossing points in Fig. 3(b) are helpful in identifying T1, T2, T3, T4 and T5. The minor variations like the one shown in circle in Fig 3(b) lead to false detection of these pulse features.

The above problem can be solved with the help of delta threshold technique, where delta is the allowable +/- slope in first derivative of wrist pulse series. The zero crossing point will be valid only if the slope crosses certain threshold value in the first derivative. But the amount of delta required will be different for each wrist pulse segment due to randomness present in the falling segment of the pulse. Hence some other approach needs to be adopted which can simplify the task of identifying the wrist pulse features.

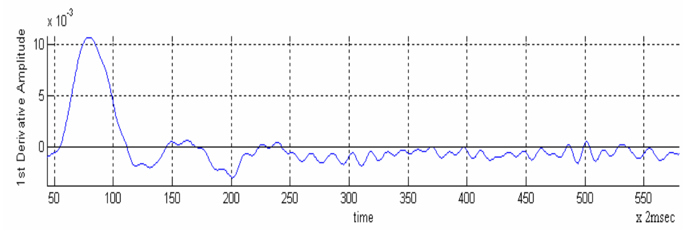

Fig. 3 (a) First Derivative of Wrist pulse series

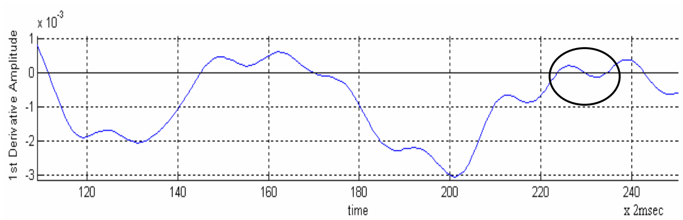

Fig. 3 (b) Enlarged First Derivative of Wrist pulse series

IV. Outlier Pulse Identification and Pulse Feature Derivation

A. Dynamic Time Warping Algorithm

Dynamic Time Warping (DTW) algorithm is used conventionally to align two time series of unequal lengths. The wrist pulse segments are derived from the wrist pulse series and two such segments are represented with time series P and Q.

$$P = P_1, P_2, \ldots\ldots\ldots P_n$$
$$Q = Q_1, Q_2 \ldots\ldots\ldots Q_m$$

A matrix'd' with nxm dimension is constructed to align two time series P and Q where ith and jth element of matrix is the distance between P_i and Q_j element of the series given by

$$d(P_i, Q_j) = (P_i - Q_j)^2 \quad (1)$$

A contiguous warping path 'W' through matrix elements is given as $W = w_1, w_2, ...w_k$ with boundary conditions as

$w_1 = d(1,1)$ and $w_k = d(n,m)$

where $x(m,n) \le k < m+n-1$.

In addition it follows the monotony condition

$i(k) \le i(k+1)$, $j(k) \le j(k+1)$

and the continuity condition

$i(k+1) - i(k) \le 1$, $j(k+1) - j(k) \le 1$.

Out of possible multiple paths an optimal warping path is selected based on minimizing following cost function

$$w_{i,j} = d(i,j) + \min\{w_{i-1,j}, w_{i,j-1}, w_{i-1,j-1}\} \qquad (2)$$

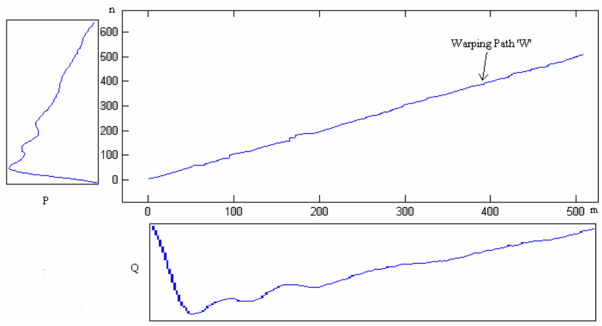

Fig. 4 Warping Path Calculation

B. Outlier Pulse Identification

Wrist pulse is segmented by identifying the onset sample using the first derivative of the pulse. Every pulse segment is normalized to its peak value. Warping path distance of individual pulse segment with all other pulse segments is calculated. For 'M' pulse segments in the wrist pulse series, a similarity distance matrix 'D' with dimension MxM is derived, where the matrix element D(i,j) is the warping path distance between i^{th} and j^{th} pulse segment. For each pulse segment the total warping path distance is calculated as follows:

$$\mathrm{P(j)} = \sum_{i=1}^{M} D(i,j) \qquad (3)$$

The vector 'P' used here as pulse similarity measure. Pulse segment 'j' for the maximum value of P(j) is searched, indicating the j^{th} pulse as the most irregular pulse in the series. Similarly pulse segment 'j' for minimum value of P(j) is searched indicating that pulse as the most similar pulse in the series. The mean of the pulse similarity vector 'P' was taken as threshold for the rejection of dissimilar pulses with P(j) lying above the threshold behaving as outlier pulse in the series.

As an example the distance matrix, 'D' for the wrist pulse of Fig. 2 is shown in Table I. The highest value of 5^{th} pulse in the P(j) vector indicates that the 5^{th} pulse is the most dissimilar in terms of pulse features. The minimum value of 7^{th} pulse shows maximum similarity with all other pulses. Mean and standard deviation associated with pulse similarity vector give information about the regularity of the pulse series.

TABLE I
SIMILARITY DISTANCE MATRIX 'D' FOR WRIST PULSE SEGMENTS OF FIG. 2

Pulse	P1	P2	P3	P4	P5	P6	P 7
P1	0	1.31	0.67	0.62	4.01	0.25	0.52
P2	1.31	0	4.69	1.00	4.72	0.58	0.31
P3	0.67	4.69	0	3.18	4.33	1.37	1.41
P4	0.62	1.00	3.18	0	5.44	0.54	0.85
P5	4.01	4.72	4.33	5.44	0	2.65	2.23
P6	0.25	0.58	1.37	0.54	2.65	0	0.17
P7	0.52	0.31	1.41	0.85	2.23	0.17	0
P	7.38	12.61	15.65	11.63	**23.38**	5.56	**5.49**

C. Pulse features derivation based on Ensemble Averaging

After rejecting the outlier pulses, the similar pulses are selected for further processing. As these pulses are of different length, the one with minimum length 'L' is identified and the rest of the segments are made of equal length by truncating the longer segments as shown in Fig. 5(a). All the pulse segments are aligned by their onset value. An ensemble average y(n) of M pulse segments is defined as

$$y(n) = \frac{1}{M}\sum_{k=1}^{M} x_k(n) \quad ; \quad \text{n = 1 to L} \qquad (4)$$

The ensemble average y(n) and its first derivative are shown in Fig. 5(b) and (c) respectively. The first derivative of ensemble average is smooth enough to predict about the pulse features. The differences between the sample numbers corresponding to the zero crossing points in this first derivative are calculated. These differences are used to predict actual zero crossing points in the first derivative of the individual wrist pulse segment, which are finally utilized in finding pulse features like amplitude and time associated with tidal notch and dicrotic notch.

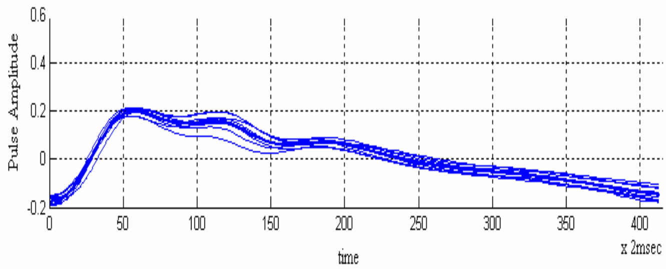

Fig. 5 (a) Similar Wrist Pulse Segments

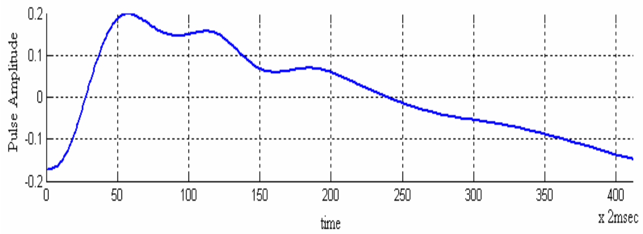

Fig. 5(b) Ensemble Averaged wrist pulse

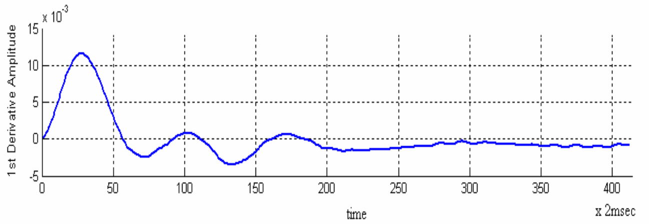

Fig. 5 (c) First derivative of wrist pulse in Fig. 5(b)

The algorithm shown below is elaborated by assigning 'A' as an array whose elements represent the zero crossing sample numbers in first derivative of the ensemble average y(n), while 'B' as an array which contains 'n' elements that represent the difference between consecutive elements of 'A' array. Let 'C_k' be the array which contains 'm' elements representing the zero crossing sample numbers in first derivative of pulse segment x_k. The algorithm searches for the valid zero crossing points in C_k array.

(i) i=1;j=1
Y:
(ii) sum = B(i) + C_k (j)
(iii) Search 'J' for which (sum – C_k (J)) is nearest to 0 for J = j+1 to m.
Select J as the valid zero crossing point in pulse segment.
(iv) j=J, i=i+1
(v) Repeat Y until i=n

The valid zero crossing points derived with the help of above algorithm gives appropriate timings for T1, T2, T3, T4 and T5 related to percussion wave, tidal wave and dicrotic wave. These parameters form a feature vector of the individual pulse segment as {H1,H2,H3,H4,H5,T1,T2,T3,T4,T5,T}. The feature vector can then be further used for variability analysis to obtain health status.

V. Conclusion

A unified approach for pre-processing of the wrist pulse series is presented. An approach of Dynamic Time Warping has been utilized for the identification of an outlier pulse in the wrist pulse signal and to remove it from the signal which is then taken for further processing. The ambiguities around zero crossing of first derivative are resolved by carrying out ensemble average of the series and leading to successful extraction of feature vector which can be used for further analysis.

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