Bio-Medical Materials and Engineering 24 (2014) 3605–3611
DOI 10.3233/BME-141187
IOS Press

Morphology variability of radial pulse wave during exercise

Lisheng Xu[a,b,*], Yang Yao[a], Hao Wang[a], Dianning He [a], Lu Wang[c] and Yongsheng Jiang[a]
[a]*Sino-Dutch Biomedical and Information Engineering School, Northeastern University, Shenyang 110819, China*
[b]*Key Laboratory of Medical Image Computing (Northeastern University), Shenyang, Ministry of Education, 110004, China*
[c]*College of Information Science and Engineering, Northeastern University, Shenyang 110819, China*

Abstract. Pulse wave contains much information on a cardiovascular system. Pulse wave variability during exercise is of great significance as it reflects more information combining with pulse wave under stationary state. This paper studied the morphology variability of radial pulse wave during exercise. Radial pulse waves were collected from 30 subjects with two pressure pulse sensors worn at the wrists of the right and left hands, respectively. Electrocardiography (ECG) was also detected synchronously. After data preprocessing and feature point extraction, the variability of several parameters of pulse wave and ECG were analyzed. It is notable that pulse rate (PR) and heart rate (HR) change synchronously. During the exercise period, both systolic phase and diastolic phase of a radial pulse shorten but the latter is more obvious. The amplitude of the dicrotic notch decreases and even turns negative. Aligning the radial pulse waveforms together, the radial pulse waveforms prior to, during and after exercise coincide with each other except for some details like the tidal wave which fades away during exercise.

Keywords: Pulse morphology, exercise, radial pulse wave

1. Introduction

Cardiovascular diseases are the leading cause of death among all noncommunicable diseases globally [1]. Pulse wave contains much information on cardiovascular system. Thus accurate interpretation of pulse wave is of great significance. In recent years, work on how to quantify the state of the cardiovascular system from the parameters of pulse wave has been reported [2–6], one of which is to change the working condition of cardiovascular system by taking exercise, and study the variability of the pulse wave. A. Figueroa studied the influence of acute exercise with whole-body vibration on wave reflection and leg arterial stiffness [4]. A. P. Avolio investigated the role of blood pressure measurement and pulse wave analysis in enhancing cardiovascular assessment [5]. V. Almeida explored the application of machine learning on pulse wave analysis [6].

*Corresponding author: Lisheng Xu, Sino-Dutch Biomedical and Information Engineering School, Northeastern University, No. 11, Lane 3, Wenhua Road, Heping District, Shenyang 110819, Liaoning Province, China. Tel.: 86-24-83683200; Fax: 86-24-83681955; E-mail: xuls@bmie.neu.edu.cn.

This paper studied the morphology variability of the radial pulse wave during exercise. The following of this paper is organized as follows: Methods including data acquisition, data preprocessing and feature point extraction were displayed in the second section; Results of the experiment were illustrated in the third section and discussed and concluded in the fourth section.

2. Methods

2.1. Data acquisition

Data presented in this paper are collected from 30 subjects aged 23±2. Radial pulse was collected by two pressure sensors respectively fixing on the right and left wrists. For electrocardiography (ECG) acquisition, bipolar leads were chosen, with three electrodes on the right and left shoulder and lower abdomen of the subjects, respectively. Cycling was chosen to make it easier for the subjects to keep their upper body still during exercise. The process of the experiment is as follows:

1. At the beginning of the experiment, subjects were advised to keep still for three minutes.
2. Subjects pedaled the training bike for ten minutes. As the signal quality can be affected by body motion artifact, subjects were advised to keep upper body still when pedaling.
3. After the 10-minute exercise, subjects had a 5-minute rest to recover.

Pulse and ECG data were collected continuously and synchronously in the whole process. Both the pulse and ECG signals were digitized at 1150Hz.

2.2. Data preprocessing

2.2.1. Outliers elimination

Outliers may be introduced during the acquisition of pulse wave, causing distortion of the pulse wave and the ECG waveform during the baseline wander removal and the de-noising procedure. The outliers were detected by thresholding the first derivative of the pulse and ECG signals, and were replaced by the mean value of their neighboring points.

2.2.2. Baseline wander removal

Baseline wander may be introduced by body motion artifact. ‘sym7’wavelet decomposition and reconstruction at level 10 was applied to the ECG and pulse signals. In this process, approximate coefficients of the pulse signal at level 10 were eliminated. For the convenience of extracting R wave crest, more low frequency components should be removed. Hence both the approximate coefficients of the ECG signal at level 10 and detail coefficients at level 10 and 9 were set to zero.

2.2.3. De-noising

In the data acquisition process, noise may also be introduced. Db7 wavelet decomposition and reconstruction at level 5 were applied to the ECG signal, eliminating all the five detail coefficients. Thus, the components above 36Hz were removed. Similarly, the pulse signal was de-noised by decomposing the pulse signal at level 4 and eliminating all the details.

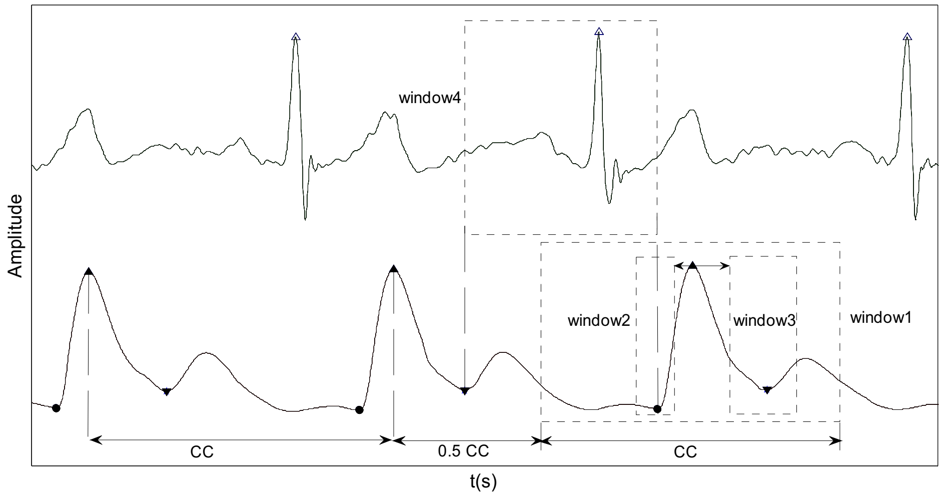


Fig. 1. Windowing methods in feature point extraction.
Note: '△': peak of ECG; '●','▲' and '▼': onset, peak and notch of pulse wave, respectively.

2.3. Extraction of feature points

To facilitate further analysis, feature points (onsets, peak points and dicrotic notch points of radial pulse wave and peak points of ECG) were extracted by windowing methods.

Pulse rate and heart rate change significantly during exercise, which means that the crest-crest interval (CC) of the pulse wave has significant variation during the whole exercise procedure. Thus, the window used to detect the peak points (window 1) should automatically change based on the CC. Thus, as shown in Figure 1, window 1 was defined in the range of [0.5, 1.5] times CC of the former two pulse waves. Then the onsets and the notch points of the pulse wave could be extracted based on the position of the peak points by using window 2 and window 3, respectively, as shown in Figure 1.

Since the ECG signal and the radial pulse signal are recorded synchronously, and the pulse wave signal has a comparatively higher quality, the peak points of ECG can be extracted based on the feature points of the pulse wave. As the peak points of ECG are always located between the positions on the ECG waveform corresponding to the onset of the pulse wave and the dicrotic notch of the former one, the peak points of ECG waveform are extracted by finding the maximum of the duration in window 4, as shown in Figure 1.

3. Results

3.1. Pulse rate and heart rate analysis

In this paper, pulse rate (PR) was calculated by the CC of the pulse wave, and heart rate (HR) was calculated by the R-R interval (time interval between the peak points of two adjacent R wave of ECG) of the ECG signal. PR and HR are always of little difference. When the subject begins to exercise, PR and HR synchronously increase rapidly at first, and then the increase slows down. Similarly, when the exercise stops, they decrease rapidly at first and then slowly until reaching their respective resting value. Figure 2 shows the variability of the PR prior to, during and after exercise.

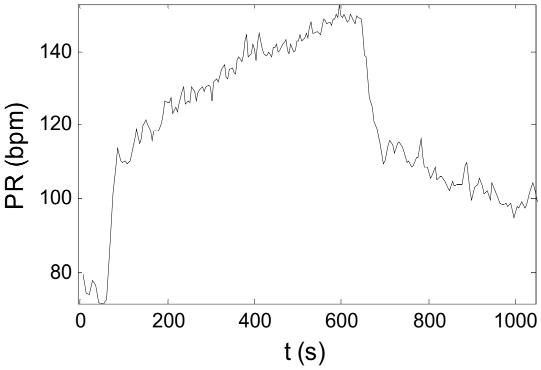


Fig. 2. Pulse rate (PR) prior to, during and after exercise.

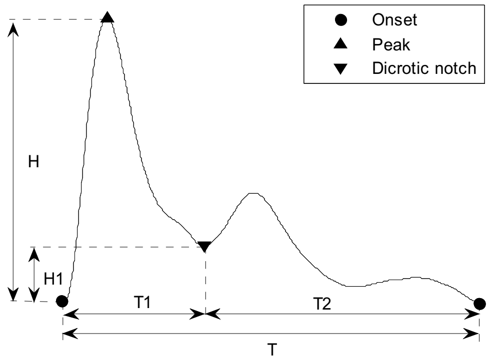
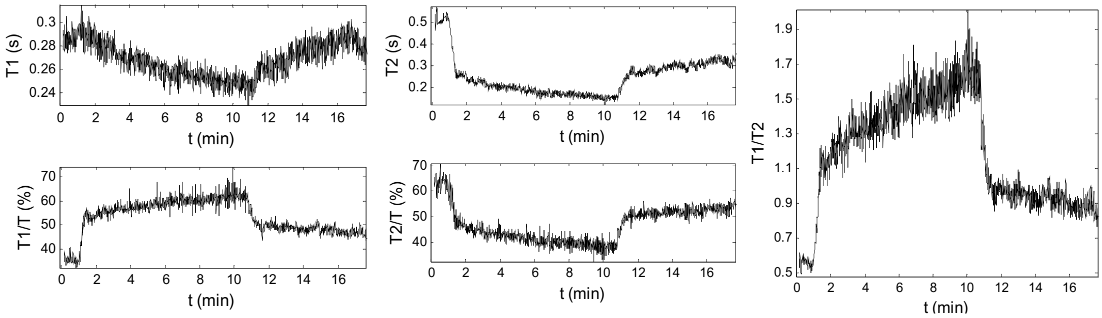


Fig. 3. Parameters of the radial pulse wave.



(a) (b) (c)

Fig. 4. Change of T1, T1/T (a), T2, T2/T (b) and T1/T2 (c) prior to, during and after exercise.

3.2. Radial pulse morphology analysis

Pulse morphology changes a lot during exercise. In this paper, this change is demonstrated in terms of both time and amplitude. As shown in Figure 3, T is defined as the time interval from the onset of one pulse to the onset of the next. T1 is the time of systolic phase, which is the time interval from the onset to the dicrotic notch, while T2 is the diastolic phase, the time interval from the dicrotic notch to the onset of the next pulse. H1 is defined as the amplitude difference between the dicrotic notch and the onset of the pulse wave, and H represents the amplitude difference between the peak point and the onset of the pulse wave.

As shown in Figure 4(a), T1 changes little (about 0.05s) in the whole procedure, while T2 changes apparently (about 0.3s) as depicted in Figure 4(b). Also, Figure 4(c) shows that during the whole process, the ratio between T1 and T2 has an evident change from 0.6 to 1.6.

The amplitude variability of the dicrotic notch is also studied. As shown in Figure 5, the parameter H1/H decreases rapidly at first and then this decrease slows down. Similarly, when exercise ends, H1/H recovers rapidly at first and then slowly until reaching its resting value. The parameter H1/H even goes negative during exercise corresponding to Figure 6, in which the dicrotic notch of the pulse wave during exercise is lower than its onset.

Then the waveforms of the three periods were put together with their peak points coincident to measure the similarity between them. In this process, the amplitudes of the three typical pulse

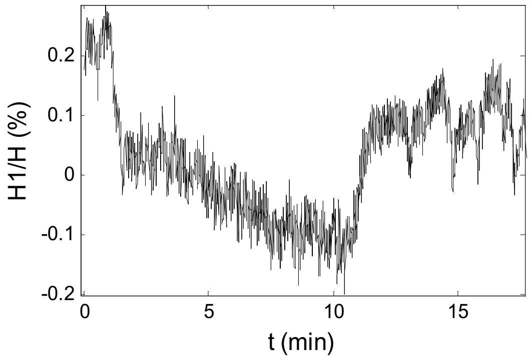


Fig. 5. Change of H1/H prior to, during and after exercise.

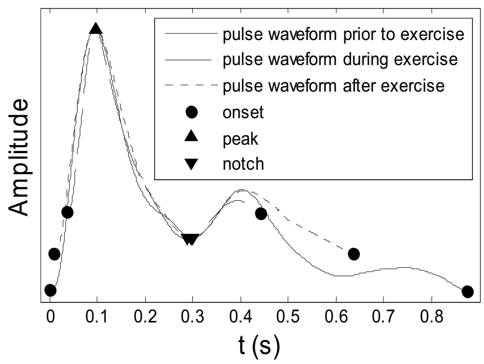


Fig. 6. Comparison of pulse wave prior to, during and after exercise.

waveforms were normalized by calibrating the amplitude difference between the peak and the notch points to one. Then, the percent root-mean-square difference (*PRD*) was used to measure the similarity between any two waveforms in the three periods. The two signals should have the same length, thus, the long one should be cut to fit the short. The *PRD* can be expressed as:

$$PRD = \sqrt{\sum_{i=1}^{N} \left| S(i) - S_c(i) \right|^2 \Big/ \sum_{i=1}^{N} S_c(i)^2} \qquad (1)$$

where $S(i)$ and $S_c(i)$ are the two waveforms, and N is the number of samples, $S_c(i)$ is the cut one.

However, the *PRD* requires the two signals of the same length, and it does not tolerate time warping. Dynamic time warping (DTW) is a similarity measure which allows elastic shifting of the time axis between two time series to accommodate similar sequences, except the locally out of phase [7]. D represents a distance matrix in which each element $D(x_i,y_j)$ represents the distance between two sample points x_i, y_j of two signals $X_n=[x_1, x_2, \ldots, x_n]$ and $Y_m=[y_1, y_2, \ldots, y_m]$, respectively.

DTW distance is the minimal cumulative distance from (x_1, y_1) to (x_n,y_m), which is defined as [7]

$$DTW(X_n, Y_m) = D(x_n, y_m) + \min\left\{ DTW(X_{n-1}, Y_m),\ DTW(X_{n-1}, Y_{m-1}),\ DTW(X_n, Y_{m-1}) \right\}. \qquad (2)$$

Figure 7 shows the DTW of the pulse wave prior to and during exercise. Once a warping path W is found, the quadratic sum of the distances in W would be used to fix the PRD by defining the PRD_{dtw} as

$$PRD_{dtw} = \sqrt{\sum_{W} D(x_i, y_i)^2 \Big/ \sum_{i=1}^{n} X(i)^2} \qquad (3)$$

In this process, longer pulse waveform was cut to the same length as the shorter one. Table 1 shows the *PRD* and PRD_{dtw} between the waveforms of the three stages of 10 subjects.

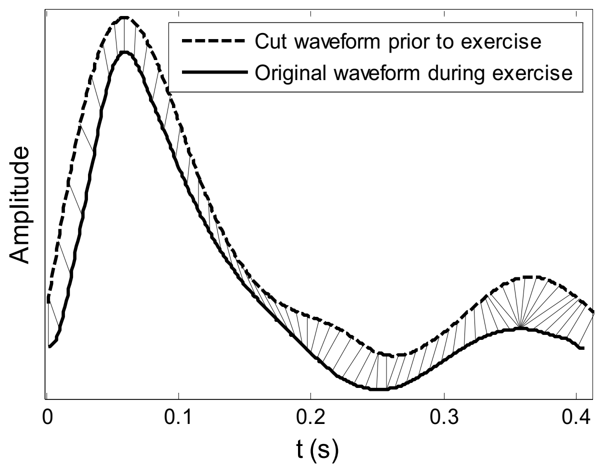


Fig. 7. Elastic similarity measure of the pulse wave prior to exercise and the pulse wave during exercise.

Table 1

PRD and of pulse waveforms of 10 subjects

	PRD12 (%)	*PRD23* (%)	*PRD13* (%)	$PRD12_{dtw}$ (%)	$PRD23_{dtw}$ (%)	$PRD13_{dtw}$ (%)
Subject1	8.697	10.297	10.026	0.040	0.041	0.035
Subject2	8.857	9.837	4.001	0.079	0.089	0.505
Subject3	4.949	6.270	5.040	0.079	0.041	0.434
Subject4	14.042	9.289	10.204	0.218	0.231	0.129
Subject5	13.426	6.650	10.104	0.255	0.198	0.918
Subject6	13.230	4.606	10.226	0.061	0.025	0.273
Subject7	14.755	14.305	9.426	0.086	0.303	0.843
Subject8	16.492	6.284	15.789	0.084	0.236	1.276
Subject9	21.792	13.406	12.757	0.121	0.172	0.368
Subject10	17.311	14.377	4.930	0.144	0.056	0.040

4. Discussion and conclusion

During exercise, radial pulse morphology has apparent variations in terms of both amplitude and time. Compared with diastolic phase, systolic phase is the main cause of the PR change. It means that during exercise, the increase of PR is due to the decrease of the heart's resting time. The H1/H even goes negative during exercise, which means that the dicrotic notch gets lower than the onset. It is also notable that the pulse waveforms during and after exercise are as if cut from the pulse wave prior to exercise. The mean *PRD12*, *PRD23* and *PRD13* are 13.36%, 9.53% and 9.25%, respectively. And the mean $PRD12_{dtw}$, $PRD23_{dtw}$ *and* $PRD13_{dtw}$ of the 10 subjects are 0.12%, 0.14% and 0.44%, respectively. The main reason why the *PRD* and the PRD_{dtw} of the subjects7-10 are so large is that the tidal waves change a lot during exercise. The invariant components of the pulse wave during exercise may reflect some features of the cardiovascular system. The exact reason is still unknown and worth more future work.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (No. 61374015, 61202258), the Ph.D. Programs Foundation of Ministry of Education of China (No. 20110042120037), the Fundamental Research Funds for the Central Universities (No. N110219001) and the Liaoning Provincial Natural Science Foundation of China (No. 201102067).

References

[1] World Health Organization, Global status report on noncommunicable diseases 2010, Geneva, 2011.

[2] F. Su, Z. Li, X. Sun et al., The pulse wave analysis of normal pregnancy: investigating the gestational effects on photoplethysmograhpic signals, Bio-Medical Materials and Engineering **24** (2014), 209–219.

[3] Z.C. Luo, S. Zhang and Y.M. Yang, Basic properties of pulse wave, in: Engineering Analysis for Pulse Wave and Its Applications in Clinical Practice, Science Publishing House, Beijing, 2006, pp. 8–20.

[4] A. Figueroa, F. Vicil and M.A. Sanchez-Gonzalez, Acute exercise with whole-body vibration decreases wave reflection and leg arterial stiffness, Am. J. Cardiovasc. Dis. **1** (2011), 60–67.

[5] A.P. Avolio, M. Butlin and A. Walsh, Arterial blood pressure measurement and pulse wave analysis-their role in enhancing cardiovascular assessment, Physiol. Meas. **31** (2010), 1–47.

[6] V. Almeida, J. Vieira, P. Santos, T. Pereira, H. Pereira, C. Correia, M. Pego and J. Cardoso, Machine learning techniques for arterial pressure waveform analysis, Journal of Personalized Medicine **3** (2013), 82–101.

[7] C. Qian, H. Guyu, G. Fanglin and X. Peng, Learning optimal warping window size of DTW for time series classification, Proceedings of the 11th International Conference on Information Science, Signal Processing and Their Applications (ISSPA), 2012, 1272–1277.