DIGITAL SIGNAL PROCESSING METHODS FOR THE EVALUATION OF BLOOD VOLUME PULSE (BVP) WAVEFORM CHANGES DUE TO EXERCISE

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ABSTRACT

Previous research by our group has revealed that the Blood Volume Pulse (BVP) waveform recorded using an infrared finger photoplethysmograph (PPG) undergoes changes as the subject performs physical exercise. In particular, a reduction in the depth of the Dicrotic Notch has been observed. There is an interest in characterizing those changes through a single parameter to measure the level of exercise the subject has reached, at any time during an exercise session. This paper reports on the comparison of three Digital Signal Processing approaches designed to reflect the BVP waveform changes through a single parameter, which could be obtained automatically from the digitized BVP signal. The first approach derives a single parameter from the distribution found in the average histogram of several time-aligned and averaged BVP beats. Our second approach analyzes the ratio observed between the first harmonic and higher harmonics in the BVP signal. The third approach evaluates the Dicrotic Notch depth directly from the BVP waveform, tracking sample values about the local minimum defined by the Dicrotic Notch. Our study, involving observations from 10 subjects, ranks these three approaches according to their ability to reflect the changes in BVP due to exercise.

INTRODUCTION

Finger photoplethysmography (PPG) is a non-invasive monitoring technique, which does not require costly equipment or specialized personnel. Traditionally, the Blood Volume Pulse (BVP) has been used to determine the heart rate [1]. However a more detailed analysis of photoplethysmographic BVP variations may indicate circulatory changes that take place in an individual due to exercise. Further research has shown that the changes in the single BVP signal through an exercise session (before exercise, immediately after exercise, and after a recovery period) can be measured, characterized, and quantified through signal processing methods [2].

In our previous research, we recorded the BVP signal for each subject at three states A, B, C (representing "before exercise", "immediately after exercise", and "after recovery", respectively). The data gathered showed changes in BVP waveforms from the three states, which showed a decrease in the Dicrotic Notch in stage B[3]. Our objective is to use three Digital Signal Processing methods to find a parameter that reflects the cardiovascular system changes due to exercise, beyond the heart rate modifications.

METHODS & RESULTS

I. Data Gathering Protocol:

The recording procedure used consisted of three measurements: A, B and C, through a total time of about 18 minutes. Ten healthy volunteers with ages between 22 and 40 participated in the recordings. Seven of them are male and three of them are female.

Each subject was requested to sit comfortably, resting the right arm on a table. At this point, a first photoplethysomgraphic Blood Volume Pulse record was obtained from the tip of the right index finger (Stage “A”, “Before exercise”). After recording for about 30 to 60 seconds, the subject was asked to begin performing continuous lifting of a 6.6-pound dumbbell with the left arm. At the end of 1-minute intervals, the subject was asked to alternate the arm used to lift the dumbbell. This process lasted for 8 minutes. Then a second BVP measurement was taken (Stage “B”, “Immediately after exercise”). After this, the subject was asked to rest, allowing for his or her cardiovascular system to recover, for 8 more minutes. After the recovery period, one last BVP measurement was taken from the right index finger (Stage “C” or “After recovery”).

All of these measurements were obtained with a custom-made infrared finger photoplethysmograph. The signal obtained from the phototransducer was amplified. The DC component was removed and a low-pass filter (second order) with a corner frequency of 10 Hz was used to remove interference components, particularly those derived from residual interference from the fluorescent lamps installed in our laboratory. The resulting analog signal was sampled at 500Hz, with a 12-bit resolution for a range of -5.0 V to +5.0V.

Figure 1 shows the BVP waveforms recorded from one of the subjects (S1) at stages A, B and C, respectively. As we can see, in stages A and C, the dicrotic notch is very pronounced, while in stage B the Dicrotic Notch is less obvious, because of the changes in the cardiovascular system caused by the exercise. This is probably due to a combined effect of the increased cardiac output and decreased peripheral resistance associated with exercise [4]. Our objective is to find methods to derive a single numerical parameter from the BVP signal, which will reflect those cardiovascular changes.

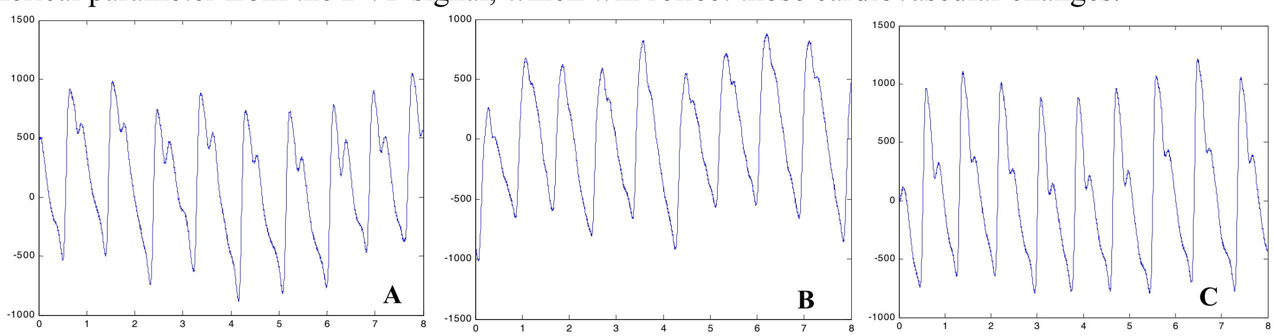

FIGURE 1. BVP waveform from Subject S1 at stages A, B and C (The horizontal axis is time in seconds)

Three approaches were tested to quantify the changes introduced in the photoplethysmographic Blood Volume Pulse waveform by exercise. The first approach attempted to summarize the changes in depth and position of the Dicrotic Notch immediately after exercises by averaging histograms of pre-aligned individual beats from the BVP signal and comparing the area under the histogram in different amplitude ranges. A second method was tried, by which the changes were observed in the frequency domain. A peridogram from each selected segment was obtained and the amplitudes of the fundamental and second harmonics in the signal were compared at the three recording stages in the protocol. Lastly, the dicrotic notch depth was measured and used to characterize the changes in the BVP waveform. A more detailed explanation of each one of these approaches, as well as a summary of the results obtained for each, follows.

II. Average Beat Histogram Analysis:

Preliminary observation of the records obtained for the study indicated that the dicrotic notch tends to be less pronounced in the measurement taken right after the exercise (Stage B). This led us to implement a signal processing scheme that separates individual beats in the signal, aligns them according to their maxima and computes a normalized histogram for each of them. In this histogram the full amplitude range of each beat is divided into 100 bins and the number of values within each amplitude bin is found. We found that there is a significant change in the percentual concentration of samples in the upper two fourths of the normalized histogram in the measurement obtained immediately after exercise. Before the exercise session (A) and after the recovery period (C), the presence of dicrotic notch results in a large number of samples detected in the range R1: (50% - 75%) of the total amplitude of the beats, which tends to predominate over R2: (75% - 100%). On the other hand, immediately after the exercise session the Dicrotic Notch is normally less pronounced and it now appears in the upper 1/4 of the amplitude of each beat (i.e., in R2). Thus, the predominance between ranges R1 and R2 in the histogram tends to revert at this point. The ratio of the histogram accumulation for range R1 and the histogram accumulation for R2 was selected as the single index to summarize the changes in the histogram [3]. The following table indicates the ratios found for the ten subjects at the 3 different stages of the procedure, normalized to the value found in stage A:

	A	B	C
S1	1.00	0.7935	1.9410
S2	1.00	0.7751	0.7645
S3	1.00	0.3572	0.8703
S4	1.00	0.5471	0.8969
S5	1.00	0.5583	0.9303
S6	1.00	0.2121	0.8748
S7	1.00	0.8314	0.3183
S8	1.00	0.9115	0.9704
S9	1.00	0.5260	0.9167
S10	1.00	0.3693	0.3903

TABLE I: Histogram Method Results

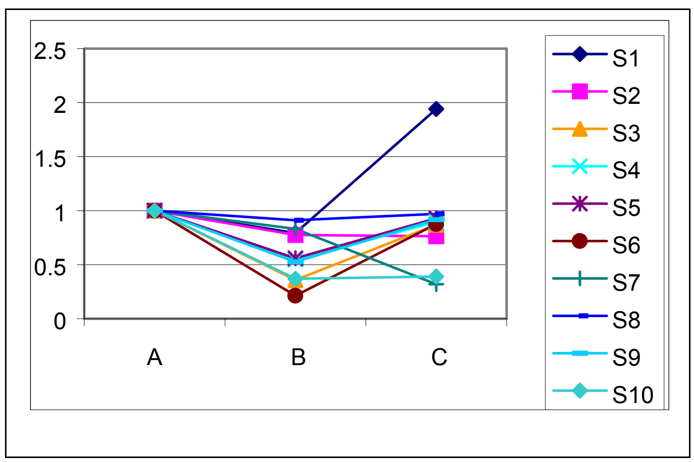

FIGURE 2: Histogram Method Results (plot)

III. BVP Harmonic Composition Changes:

The presence of the Dicrotic Notch in the BVP wave is represented in the frequency domain as a significant component corresponding to the second harmonic of the fundamental BVP frequency. This second harmonic component is normally very significant in comparison with the fundamental for stages

A and C (i.e., at rest or after recovery). In contrast, the second harmonic contribution is small at stage B (right after the exercise session), since the Dicrotic Notch is less well defined. To detect these changes we propose the determination of the ratio Pf2/Pf1, where Pf2 is the amplitude of the second harmonic and Pf1 is the amplitude of fundamental in the averaged periodogram of the BVP segment recorded at each stage of the procedure. The values of this ratio, normalized to the ratio measured in stage A are shown in Table II and Figure 3.

	A	B	C
S1	1.00	1.1565	0.5661
S2	1.00	0.6553	1.1001
S3	1.00	1.1527	0.8583
S4	1.00	1.2002	1.4372
S5	1.00	1.1184	0.5557
S6	1.00	1.8228	1.2160
S7	1.00	0.9878	1.0727
S8	1.00	0.9487	0.6098
S9	1.00	1.3652	1.6916
S10	1.00	0.6992	0.6181

TABLE II: Harmonic Ratio Method Results

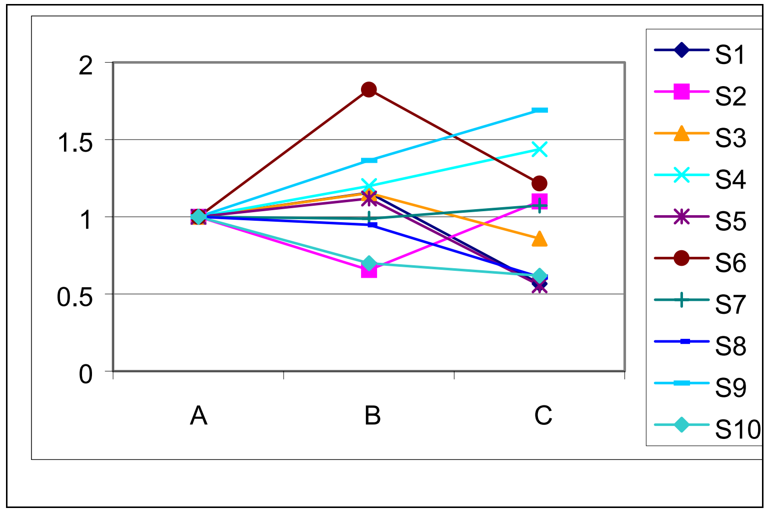

FIGURE 3: Harmonic Ratio Method Results (plot)

IV. Dicrotic Notch depth method:

The algorithm for this approach isolates each individual BVP beat and identifies the local minimum and local maximum associated with the presence of the Dicrotic Notch. The difference between these two levels is used as the estimation of the Dicrotic Notch depth for a particular beat. The ratio of the Dicrotic Notch depth to the total amplitude of each beat is found and an average of this ratio is calculated for all the beats in the BVP segment under study. Table III and Figure 4 show the results for the 10 subjects studied, at the 3 stages of the protocol, normalized to make stage A for every subject 1.0:

	A	B	C
S1	1.00	0.0648	0.5127
S2	1.00	0.0183	0.1549
S3	1.00	0.1028	0.4486
S4	1.00	0.4583	0.7344
S5	1.00	0.2825	1.2696
S6	1.00	0.2248	1.0661
S7	1.00	0.5193	0.8619
S8	1.00	1.5185	4.7778
S9	1.00	0.0860	0.6822
S10	1.00	2.2500	5.9375

TABLE III: Dicrotic Notch Depth Method Results

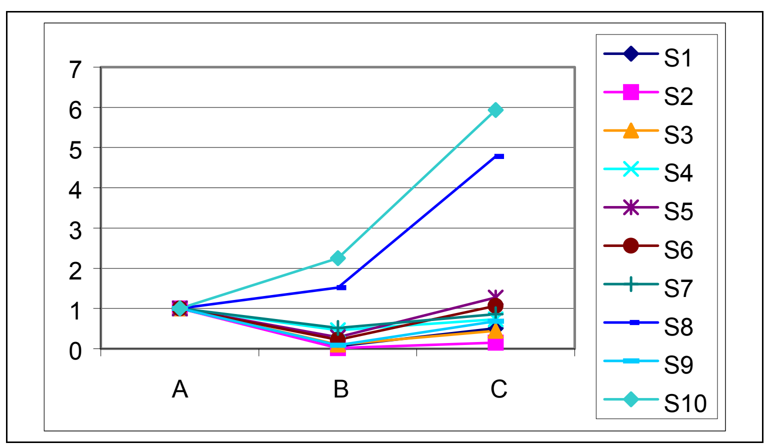

FIGURE 4: Dicrotic Notch Depth Method Results (plot)

DISCUSSION

Tables I – III and Figures 2- 4 show that there is significant variability in the BVP responses recorded from different individuals through the exercise protocol used in this study. Figure 3 shows that the evolution of the harmonic ratio measure was particularly different for different individuals. It is important to assess if these differences are primarily due to the methods used to evaluate the changes in BVP waveforms or whether they arise because the waveforms themselves varied in different ways through the 3 recorded stages (A, B and C) for different individuals. By visual inspection of the waveforms recorded, we realized that for seven of the ten experimental subjects the waveforms at the different stages showed the anticipated changes very clearly. However, the waveforms from three of our subjects (S7, S8 and S10) showed much less pronounced changes. An example of these less conspicuous changes is shown in Figure 5, which displays the sequence of BVP waveforms for subject S8. The first panel in this figure shows that the Dicrotic Notch for this subject is not pronounced even in stage A, before any exercise has been performed. Therefore, the additional BVP smoothing observed in stage B does not result in a dramatic difference in the depth of the notch. Stage C brings about the enhancement of the Dicrotic Notch in just some of the beats recorded.

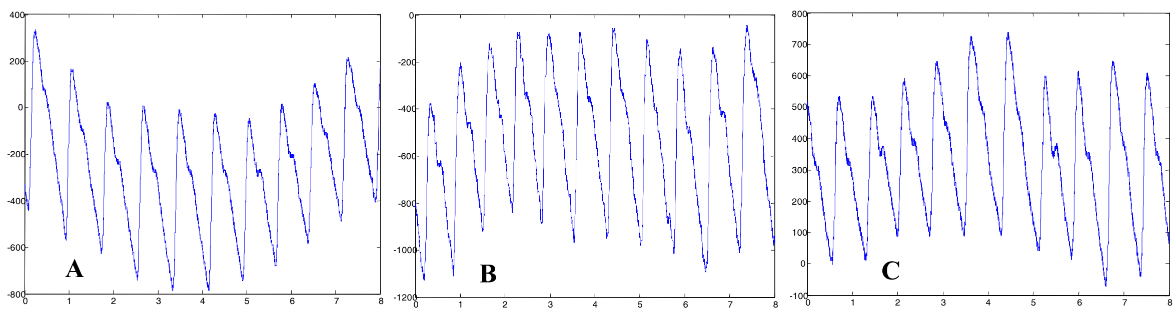

FIGURE 5. BVP waveform from Subject S8 at stages A, B and C (The horizontal axis is time in seconds)

Overall, the visual inspection of the BVP waveforms for subject S8 actually confirms and explains the corresponding traces in Figure 2 (Histogram method results), where the data point for the second stage is very close to the point for the first stage, and the point for the third stage is above the point representing the second stage.

In order to compare the efficiency of each one of the signal processing approaches used in the study to represent the changes in the BVP waveform induced by exercise, we will focus on the records obtained from the seven subjects for whom BVP waveform changes were clear, i.e. we will exclude from consideration the results from subjects S7, S8 and S10. Looking at this subset of the data we appreciate that both the Histogram method (Table I and Figure 2) and the Dicrotic Notch depth method (Table III and Figure 4) provide results that are consistent with our expectations. For both methods the lessening of the Dicrotic Notch observed immediately after exercise (stage B), is represented by a reduction of the numerical index derived through the methods, with respect to the values obtained at stages A and C. For the Histogram method this pattern is only disrupted for subjects S7, which has a lower value for stage C than for stage B, and for S10 whose value for stage C is only slightly higher than for stage B. These are, however, two of the three subjects with non-representative BVP waveforms. For the Dicrotic Notch depth method the pattern is modified for subjects S8 and S10, in that the value at stage B is higher than that at stage A. In this case, also, the subjects displaying atypical patterns for the measure obtained belong to the three-subject subset of non-representative BVP waveforms.

In contrast, the values in Table II and the traces shown in Figure 3, for the harmonic ratio method indicate a lack of consistency of this measure, even within the set of seven subjects whose BVP waveforms appeared typical according to visual inspection.

CONCLUSIONS

Photoplethysmographic BVP records obtained from 10 healthy volunteers confirm that the BVP waveforms change as the subject performs exercise. In our study seven of the 10 subjects studied displayed clear BVP waveform changes of the type that we had originally expected. In the remaining 3 subjects the BVP changes were subtler. The Dicrotic Notch depth method and the Histogram method were successful in consistently representing the BVP changes of the seven subjects whose data was typical. The results from the Harmonic Ratio method were the least consistent of the three methods considered. Overall, the Dicrotic Notch depth method seems to be the most promising for the intended application, due to the consistency of the results obtained and its relatively low computational cost.

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