Photoplethysmogram Morphology in Stress: from Mental to Pain to Physical Activity-induced Stress

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Abstract

Stress is a fundamental aspect of modern society that has a significant impact on both personal and work life. The ability to indicate mechanisms through which stressors affect the body is crucial to determine between various stressors. This would allow the application of unsupervised stress monitoring during daily living. The aim of this study is to disclose morphological changes in photoplethysmogram (PPG) during mental stress, pain stress, and physical activity-induced stress to facilitate stress monitoring and diagnosis. Three databases with PPG and electrocardiogram biosignals were used in this study, covering all three types of stress. Heart rate and six morphological PPG parameters were evaluated. The results revealed that mental and pain stress reduced the amplitude of PPG by 60-77%, while physical activity-induced stress, on the contrary, increased it by 17-44%. In terms of time-related PPG parameters, mental stress is more similar to physical activity-induced stress than pain stress. This is most visible in the time interval from systolic to diastolic peak. PPG morphology changes caused by mental and pain stress are related but distinctly different from those caused by physical activity stress. It can be concluded that different types of stress cause specific changes in the PPG morphology and have distinct effects on the cardiovascular system.

1. Introduction

Stress is an inescapable experience that affects most people worldwide. However, long-term chronic stress is the main cause of numerous stress-related diseases, which have impacted a large part of the population [1]. Namely, World Health Organization reports that the COVID-19 pandemic increased the prevalence of anxiety and depression by more than 25% [2]. Mental stress can manifest in various ways, e.g., anxiety, depression, poor quality of sleep, and impacts overall well-being and work life [3].

From a physiological perspective, stress is a response to a stressor or stimulus that activates mainly the sympathetic nervous system with the associated changes in different biosignals such as photoplethysmography (PPG) [4]. Stress assessment methods typically employ algorithms that rely on detecting physiological changes associated with increased stress levels. This is usually achieved by means of analyzing changes in PPG pulse morphology, heart rate (HR) variability, or respiration. However, although numerous studies have been conducted to identify mental stress [5,6]; the main limitation of existing methods is inability to distinguish mental stress from stress caused by pain or physical activity.

Most wristbands have the capability to record PPG data which has been demonstrated to be sensitive to various types of stress, e.g., mental [7, 8], pain [9], and physical activity [10]. Typically, a PPG signal is recorded in periphery (usually finger or wrist) where systemic vasoconstriction occurs during mental and pain, resulting in a reduction of the amplitude of the cardiac PPG component [11]. However, during physical activity-induced stress, the amplitude is expected to increase due to systemic vasodilation, caused by increased local metabolism and thus increased core temperature [10]. While most types of physical activities can be detected using an accelerometer or altimeter, activities like cycling or certain gym exercises are more difficult to detect. Additionally, the difference in physiological responses between mental and pain stress is not fully explored. The aim of this study is to disclose morphological changes in PPG during mental stress, pain stress, and physical activity-induced stress to facilitate stress monitoring and diagnosis.

2. Material and Methods

Three well-known stress-causing tests were used in the study:

1. Trier social stress test (TSST) to induce mental stress;
2. Cold pressor test (CPT) to induce pain stress;
3. The Young Men's Christian Association (YMCA) bench step test to induce physical activity stress.

2.1. Databases

Thirty-three healthy volunteers (13 women), from 18 to 32 years old (22.6 $\pm$ 3.5 y) participated in the TSST study (for details see [12]). Two phases of the protocol were used in this study: 1) baseline lasting 10 min in the sitting position and 2) arithmetic task in which a participant was requested to perform successive subtractions of 13, starting from the number 1022.

Forty-nine healthy volunteers (22 women) from 20 to 32 years old (25.7 $\pm$ 3.6 y) participated in the CPT study [13]. Two phases of the protocol were used in this study: 1) the first rest phase lasting 10 min in the sitting position and 2) the cold-water phase, in which the participant immersed his left hand into cold water (7.0 °C $\pm$ 0.1 °C) for 2 min. The cold water phases lasted 2 min, except in cases when a volunteer ended the phase prematurely.

Forty-six healthy volunteers (20 women) from 20 to 32 years old (22.5 $\pm$ 3.2 y) participated in the YMCA bench step test study [14]. During the YMCA test, volunteers performed the standard YMCA bench step test [15]. Two phases of the protocol were used in this study: 1) rest phase before the YMCA test lasting 3 min in the sitting position and 2) rest phase after the YMCA test lasting 2 min in the sitting position. The post-test rather than during-test rest phase was chosen due to movement-induced noise in PPG.

An infrared wavelength PPG signal from the index finger and standard three-limb lead electrocardiogram (ECG) signals were recorded during all tests by using specific devices and sampling frequencies:

1. TSST: Medicom system (Medicom MTD Ltd., Russia), the sampling rate of PPG – 250 Hz, ECG – 1 kHz;
2. CPT: multimodal recording system Nautilus II (Biomedical Engineering Institute, Lithuania), the sampling rate of PPG – 1 kHz, ECG – 2 kHz;
3. YMCA: wrist-worn device (Biomedical Engineering Institute, Lithuania), the sampling rate of PPG – 100 Hz, ECG – 500 Hz.

2.2. Data analysis

The instantaneous HR was assessed from evaluated RR intervals. A 4th-order bandpass Butterworth filter with cutoff frequencies 0.4 to 9 Hz was used to filter PPG. All signals were resampled to 250 Hz and six morphology parameters were evaluated according to previous studies [5, 16], including three amplitude-related and three time-related parameters (Fig. 1): 1) amplitude A_{s} of systolic peak; 2) amplitude A_{d} of diastolic peak; 3) ratio A_{sd} of A_{s} to A_{d}; 4) time interval T_1 from foot point to the following systolic peak; 5) time interval T_2 from systolic peak to diastolic peak; and 6) time interval T_3 from the diastolic peak to the end of cardiac pulse (foot point of next impulse).

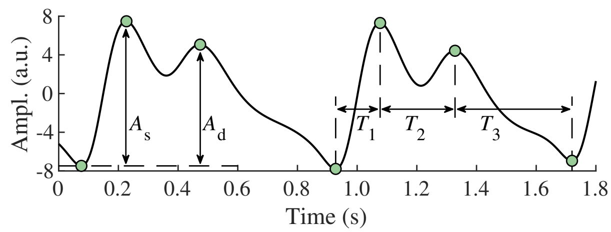

Figure 1. Definition of morphological PPG parameters.

The average percentage of pulses with detected parameters were 79.3%, 83.4%, and 87.7% for mental, pain, and physical activity stress respectively. Time-related parameters were evaluated from normalized PPG impulses along the time axis to eliminate the influence of the individual HR. All parameters in rest and stress intervals were normalized with respect to the individual value of the preceding rest interval. The values of all parameters were calculated in 30 s window intervals to account for their variation over time. The results are summarized using boxplots with medians and quartiles.

3. Results

PPG signals before and during different stress stimuli are exemplified in Fig. 2. The amplitude of the signal decreases during mental and pain stress while increases during physical activity-induced stress.

The boxplot diagrams of median values of HR (normalized by rest intervals) during different stress are shown in Fig. 3. Mental stress and physical activity-induced stress tend to increase medians of HR from 11 to 26%. In contrast, pain stress causes smaller changes in HR. The first three 30 s long intervals increase the median HR by 3-8% while the 4th interval decreases the median of HR by 1%.

The boxplot diagrams of median values of amplitudes and ratio parameters (normalized with rest intervals) during different stress are shown in Fig. 4. Medians of amplitudes A_{s} and A_{d} decreases respectively by 67-72% and

60-77% during mental and pain stress; in contrast, A_{s} increases by 17-44% and A_{d} decreases by 0-21% during physical activity-induced stress. The ratio A_{sd} shows minimal changes for mental stress (1-6%), larger changes for pain stress (-16-+3%), and the largest changes for physical activity-induced stress (33-46%).

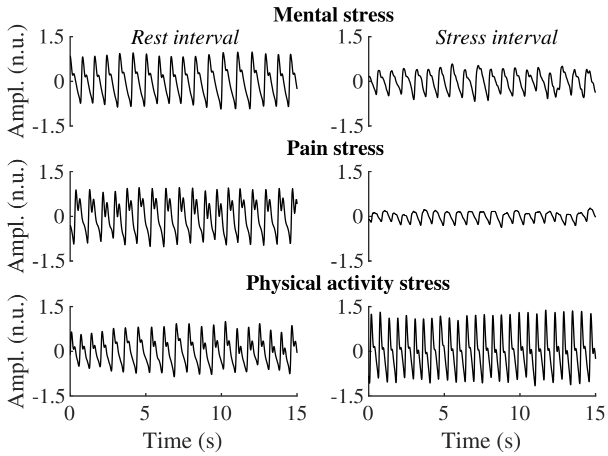

Figure 2. An example of PPG signals during rest and different stress stimuli. Amplitudes are normalized by preceding rest intervals.

The boxplot diagrams of median values of time-related parameters (normalized by rest intervals) are shown in Fig. 5 during different types of stress. Median values of T_1 increase by 21-27%, 1-6%, and 5-17% for mental, pain, and physical activity-induced stress, respectively. Median values of T_2 increase by 5-18% for mental and physical activity-induced stress, those for pain stress decrease by 1-14% (except the first 30 s interval). Median values of T_3 decrease by 0-12% for all types of stress.

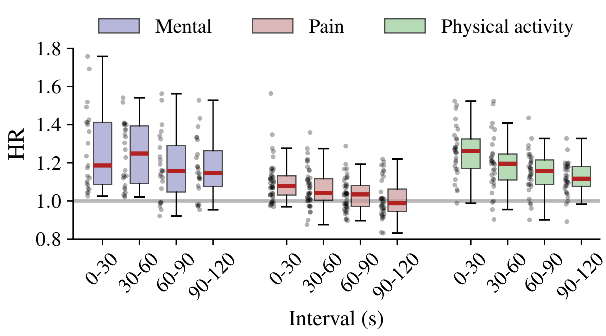

Figure 3. Relative changes of HR during mental, pain, and physical activity-induced stress.

4. Discussion

Irrespective of the induced stress type, our study shows that the human body adapts to stress, i.e., HR decreases over time to approach resting HR values (Fig. 3). Correspondingly, most of the amplitude-related and time-related parameters of PPG converge towards or oscillate around their respective resting values (of "1", Fig. 4 and 5).

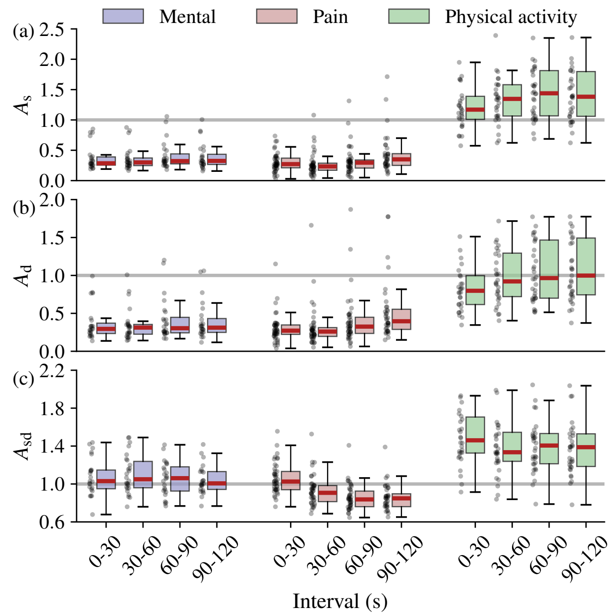

Figure 4. Relative changes of PPG amplitude-related parameters (a) A_{s}, (b) A_{d}, and (c) A_{sd} during mental, pain, and physical activity-induced stress.

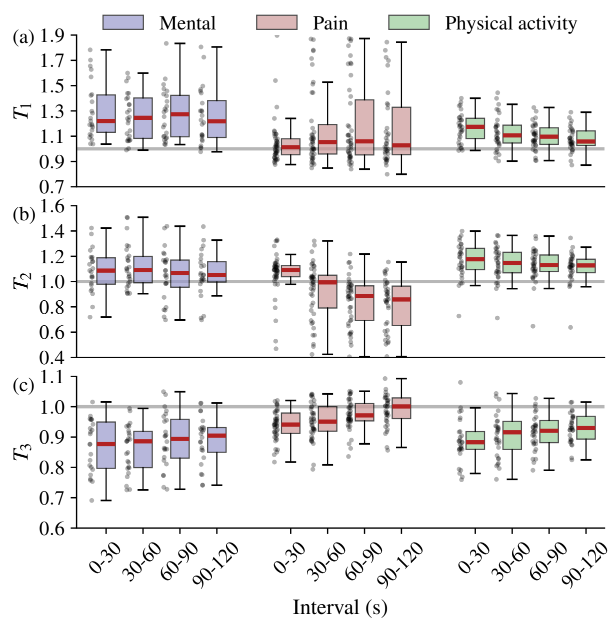

Figure 5. Relative changes of PPG time-related parameters (a) T_1, (b) T_2, and (c) T_3 values during mental, pain, and physical activity-induced stress.

Amplitude-related parameters (Fig. 4) indicate a similarity between mental and pain stress, in contrast to physical stress. The opposite behavior in the amplitude-related A_s when comparing mental and pain stress versus physical stress highlights systemic vasoconstriction for mental and pain stress and systemic vasodilation for physical activity-induced stress. These results are in line with previous studies which showed that the PPG amplitude decreases during mental- and pain-induced stress [7–9] and increases during physical activity-induced stress [10].

Time-related parameters (Fig. 5) indicate the strongest changes for pain stress, especially for T_2 and T_3. The time-related parameter T_1 (Fig. 5a), the systolic rise time of PPG, shows values higher than 1 indicating increased stiffness of arterial vessels, which inhibits their quick opening. Here the adaptation towards the resting state (T_1=1) seems to be strongest for physical stress. The opposite behavior of T_2 and T_3 (Fig. 5b, c) is more prominent during pain stress (T_2 decreases and T_3 increases) than mental and physical stress, showing an earlier diastolic wave with progressing stress duration. Please note that T_3 is mostly negative while T_1 and T_2 are mostly positive, which indicates the shortening of the cardiac period (Fig. 3) at the cost of T_3 shortening.

The strongest limitation of the study is the fact that the three separately collected databases were used (even though age-matched). In the future, biosignals during different stresses should be recorded for the same subjects to obtain more accurate results and to evaluate subtle changes in physiology.

5. Conclusion

This paper compares morphological changes of PPG during mental, pain, and physical activity-induced stress. Changes in PPG morphology caused by mental and pain stress are related but distinctly different from physical activity-induced stress. The difference of mental and pain stress is more visible in parameters A_{sd}, T_2, and T_3. Different types of stress have distinct impacts on the cardiovascular system, leading to specific alterations in PPG morphology. To effectively monitor mental and pain-induced stress separately, it is recommended to combine PPG with other physiological signals and parameters since PPG alone may not provide comprehensive information on these two distinct types of stress in specific conditions.

Acknowledgments

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