Detecting Exercise Induced Stress using the Photoplethysmogram

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Abstract

The effect of exercise on the cardiovascular system has been studied extensively using a wide range of physiological sensors. Athletes now commonly use EKG-based monitors to ascertain heart rate, but these devices cannot directly monitor the level of physical stress. We hypothesize that the low frequency spindle waves seen in the photoplethysmographs (PPG) of exercising individuals may be useful for noninvasively detecting hemodynamic stressors to the human vascular system. In a clinical trial with nine healthy subjects performing the Bruce Protocol treadmill test these low frequency spindle waves were observed in the forehead and ear PPG in all subjects before the onset of volitional fatigue. As volitional fatigue approached, the spindle waves become more pronounced, decreased in period and then within several seconds of the cessation of the protocol they disappeared. Using a software-based detector, these distinct spindle waves can be reliably detected. This technique holds promise for the automatic detection and characterization of exercise induced physical stress.

Introduction

While moderate exercise in an individual can easily be detected by monitoring increases in heart rate and respiration, it is more difficult to ascertain the their degree of physical and hemodynamic stress. In many professions, such as fire fighting and military operations, excessive hemodynamic stress can lead to failure in completing a task. If reliable algorithms for detecting fatigue can be developed, it should aid in the management of human resources in critical activities and potentially prevent unnecessary deaths.

Recent studies have focused on analyzing low-frequency oscillation of arterial blood pressure and blood flow to the skin, with a period between five and fifteen seconds, as a metric of physical fitness [1, 2], and relaxation [12]. Instead of using laser-Doppler flowmetry, our study analyses the photoplethysmogram (PPG) from a pulse oximeter.

Using a modified Bruce treadmill protocol subjects were exercised until volitional fatigue. We detected a low frequency phenomena, seen in Figure 1, with a longer period than respiration in each subject. We refer to these waveforms, characterized by periodic pinching in the PPG, as spindle waves. These distinct waveforms with undulating amplitude and envelope, without a corresponding shift in the baseline of the cardiac pulse, have not been previously reported [7].

Whereas most recent PGG research analyzes the signal using frequency-domain techniques, our research shows that these spindle waves can be detected more easily using morphological techniques. Moreover, these techniques allow for the detection and characterization of even a single spindle wave. As seen in Figure 1 these may have a smooth sinusoidal envelope as in (a) and (b), or a more ragged envelope with distinct periodic pinching as in (c) and (d).

PPG Waveform

A pulse oximeter illuminates the skin with light from a Light Emitting Diode (LED), and measures the amount of light either transmitted or reflected to determine changes in volume, the PPG. Though the cardiac pressure pulse is damped by the time it reaches the skin, it is sufficient to distend the arteries and arterioles in the subcutaneous tissue and produce a distinct pulse in the PPG. A reduction of pulsatile amplitude can be directly attributable either to a loss of central blood pressure or to constriction of the arterioles perfusing the dermis[13].

Respiration affects the cardiac cycle by varying the intrapleural pressure. When the frequency and depth of respiration increase, the venous return increases, leading to increased cardiac output[8].

Vasoconstrictive and vasodilative systems of the skin used to mediated temperature and arterial pressure also contributes to the morphology of the PPG waveform. Exercise increases the core temperature which results in vasodilation and an increase in skin blood flow. The amount of vasoconstriction typically increases until about 38° C before the onset of vasodilation. Trained athletes have been described to have a higher temperature threshold before vasodilation begins [5].

Low frequency oscillation in arterial pressure and peripheral blood flow, often called Traube-Hering-Meyer (THM) waves [3, 9] may also contribute to oscillations in the PPG. THM waves often manifest themselves as a rhythmic rising and falling in the baseline of blood pressure and vascular blood flow (as measured by laser Doppler) with superimposed cardiac and respiratory cycles. The THM waves are currently thought to be a manifestation of multiple physiological phenomena, influenced by thermoregulation, respiration, and cardiac pulse [12].

Methodology

All nine subjects were nonsmokers, physically active, normotensive, without significant past medical history and screened for medications that would influence the results of the study. The experiments were approved by the IRB of Dartmouth-Hitchcock Medical Center. The treadmill-based Bruce Protocol Stress Test was used to elicit cardiac stress [10]. We exercised nine subjects to volitional fatigue.

FDA-approved Nonin® pulse oximeters were placed on the subject's finger and ear using the standard clip, and the forehead using a standard Nonin-supplied holder. A serial RS-232 interface allowed a personal computer to record data at 75 Hz using a Java-based program. The annotated data was saved in text files for later analysis using Matlab®. The respiration rate was measured using a impedance pneumography with analysis using Matlab®-based algorithm.

Using Matlab®, a spindle wave classifier was developed that detected the morphological characteristics of two types of THM spindle waves: those with a smooth sinusoidal envelope and those that have more pronounced pulse amplitude pinching. This technique is based on a related method developed for detecting morphological features of the PPG indicative of hypovolemia[6] .

Results

All nine subjects completed the Bruce protocol with the following distribution of completed stages: Stage 4: 2; Stage 5: 1; Stage 6: 4; and Stage 7: 2. We detected THM spindle waves in the forehead and ear PPG of all nine subjects during the final stage before volitional fatigue, and with all subjects the spindle waves disappeared immediately when the treadmill was slowed to a walking pace. All subjects showed an increase in PPG amplitude as the trial progressed, with spindle waves becoming more pronounced after large increases. Shown in Figure 1 are the PPG of four subjects with the time of volitional fatigue marked with a dotted vertical rule.

In seven of the nine subjects, spindle waves appeared before the final stage, with the earliest stage being Stage 3. Four of the seven subjects had spindle waves appear two stages before termination, and three had them appear one stage before. The period of the spindle waves shortened as the subjects became more fatigued, except for the subject shown in Figure 2 where the spindles' periods lengthened after the final stage began.

Spindle waves were also detected in the ear PPG for eight subjects but in the finger PPG of only one subject. In all subjects the spindle waves were of a longer period than breathing. Minimum breathing rate for Stage 5, the first stage that requires running, is 28 bpm and the maximum of 81 bpm which is consistent with studies done with road runners[4].

As an example Subject 1, shown in Figure 2, has a respiration of 60 breaths/min, a period of 1 sec, and a steady heart rate 168 bpm, while the spindle have a period of over 10 sec. As with all subjects, when she approached her maximum heart rate, the variability in heart rate disappeared. All subjects showed a normal EKG during the stress test.

Discussion

The PPG spindle waves were detected in all subjects under cardiac stress in the forehead and ear PPG. As with low frequency arterial pressure waves described in other studies, the origin of these waves is unknown. One possible hypothesis is that the periodic decrease in the blood flow to the skin, causing a pinching in the PPG, is a mechanism to increase blood flow to the other organs.

Nominally, the baroreflex maintains cerebral perfusion by increasing the heart rate and constricting the periphery. However, under sufficient exercise-induced stress the heart rate cannot be easily increased, and the vasodilation of skin is required to shed heat.

Exercise increases vascular conductance in the muscles, and because the blood supply to the viscera has already been suppressed [14], the only way to increase the cranial and muscular blood supply is to shunt blood from else where. Perhaps by periodically shunting blood from the skin where it is only needed cool the blood this can be done. This hypothesis is supported by the spindle waves becoming more pronounced as the PPG amplitude increases, implying increased blood flow to the skin, as well as a general absence of spindle waves in the finger PPG [11]. The finger PPG showed no significant increase in amplitude during exercise, and then only increasing in am-

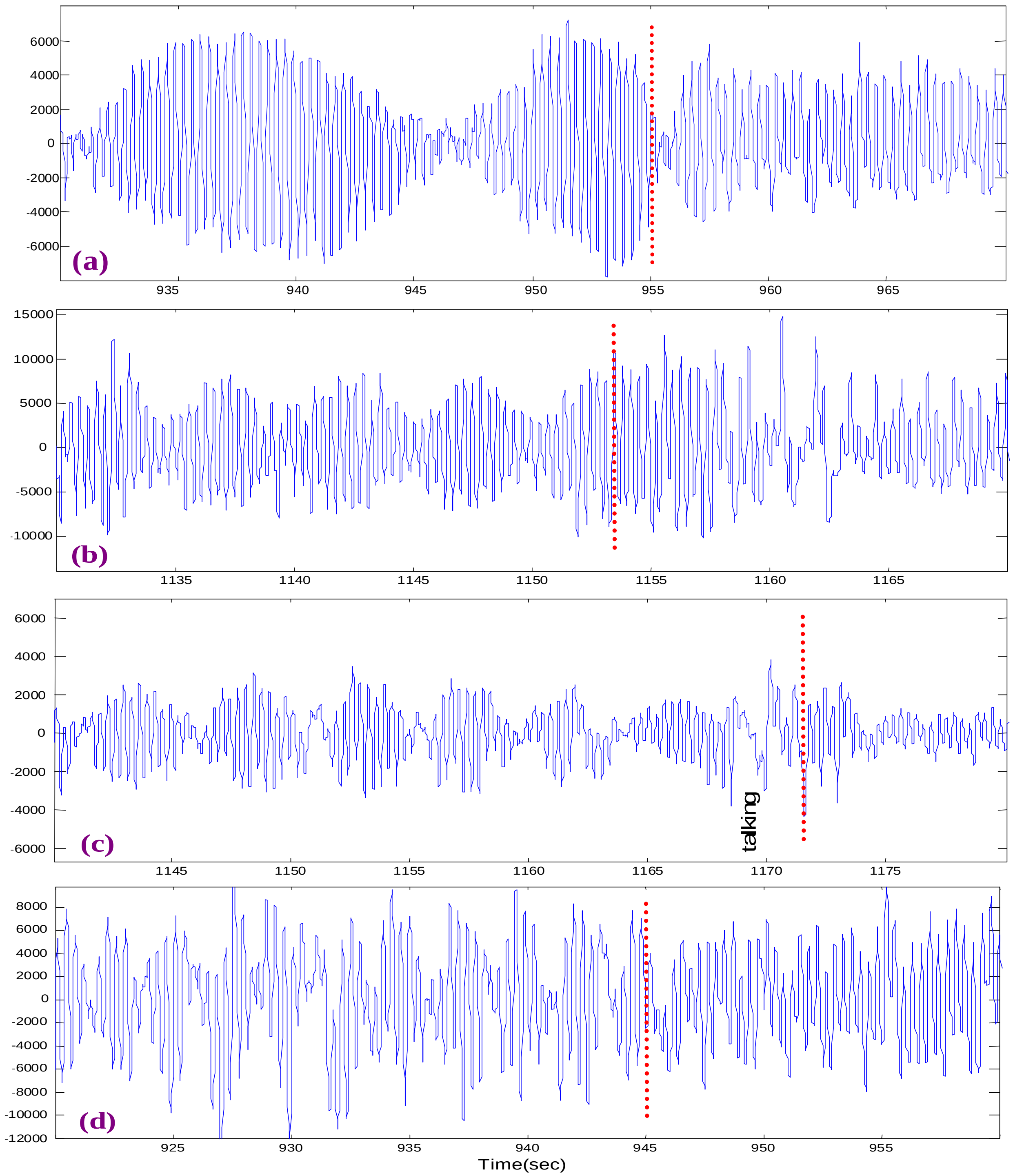

Figure 1. Photoplethysmogram showing vasomotor spindle waves from four subjects just before volitional fatigue at the end of Bruce protocol stress test. The red dotted line indicates the slowing of the treadmill.

plitude after the termination of the trial. The corresponding decrease in spindle wave period as the PPG amplitude increases and the subject becomes more stressed, could also indicate reduced average blood flow to the skin.

Future research will refine the PPG spindle wave detection algorithm so that it will not only detect the spindle waves but also characterize them. Statistics may allow us to quantify the level of physical stress by measuring the period and smoothness of the spindle waves and the mean reduction of blood flow.

Additional study will be needed to better under-

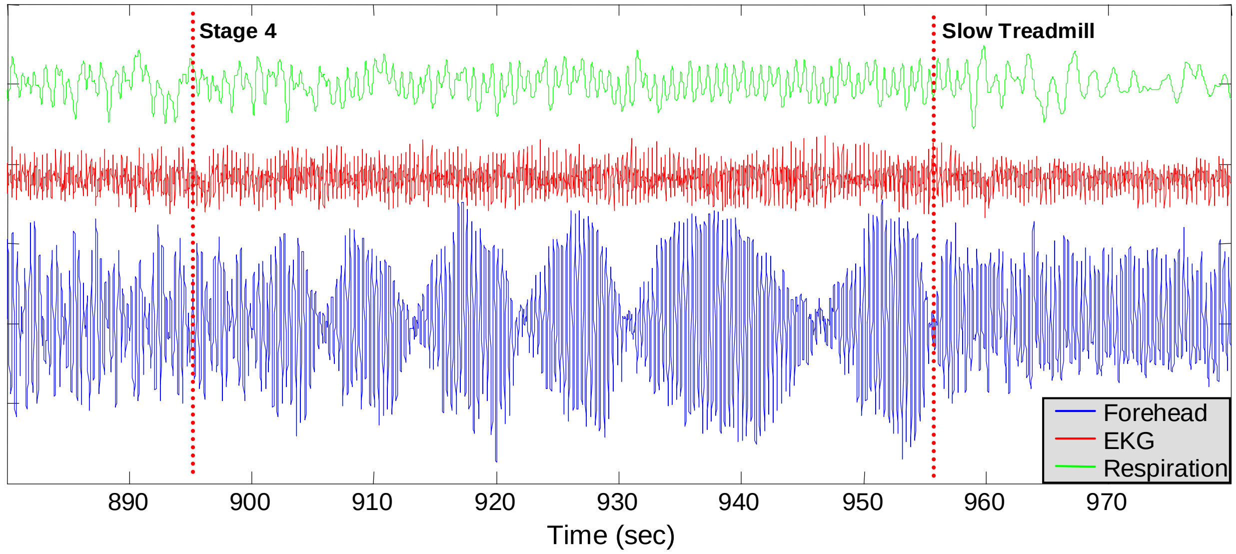

Figure 2. Forehead PPG (blue), EKG (red) and respiration from impedance pneumography (green) for subject 1 with the start of Stage 4 marked at 895 seconds and the slow down of the treadmill at the onset of volitional fatigue at 955 seconds. Notice the period of the spindle waves increases from a period of less than two seconds to a period of over six seconds within 5 seconds of the start of the Stage 4 and eventually lengthening to 16 seconds. The spindle waves are always of a longer period than respiration and the EKG shows that the heart beats normally when the PPG amplitude pinches.

stand the physiological genesis of the spindle waves. Studying the effect of pharmacologically-induced stress should eliminate the complicating factors of physical and respiratory motion on the data and help determine the morphological changes of the spindle waves when cardiac output is increased without the effects of direct exercise.

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