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A review of implementations in wearables to detect stress

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ABSTRACT

In this era where robustness is in high demand, relying on medical professionals for your regular health checkup is a bit tedious. One of the major concerns in today's world is the stress experienced by a user, which can have adverse effects on health, also known as cognitive stress, psychological stress or psychosocial stress. There are a lot of devices present to monitor and record rudimentary information of a user's physiology. Groundbreaking and advanced technologies such as Polyplethysmography (PPG), which provides a wide spectrum of features, which can be used to observe physiological, changes and compute the stress level of a person. Use of wearable devices in health monitoring has increased exponentially over the past few years. In all these devices PPG sensor has been a key component. In this paper uses of PPG sensors are discussed for obtaining values for parameters such as blood flow, heartbeat, oxygen consumption etc. These features are further used to derive complex features, e.g. heartbeat is used to get heart rate variability, which in turn can be used to detect sleep stages. Other sensors in smart watches can provide skin conductance which when collaborated with features like body temperature can provide hydration level of the body. In this paper, multiple algorithms and state-of-the-art researches that use PPG technology in wearables to monitor the above mentioned features are mentioned. It is discussed that stress can be detected using sleep history, hydration, heart rate variability and oxygen consumption.

Keywords: *Polyplethysmography, Cognitive Stress, Heart Rate Variability, Sleep, Hydration, Health Monitoring*

1. INTRODUCTION

Human health has been the primary concern since the evolution of scientific methods. Doctors and scientists have worked enthusiastically to analyze the diseases and created corresponding medicines. Diseases are still a great threat for humans but even if a body is free from diseases there are conditions, mental and/or physical, which, if not checked, can lead to deterioration of the body. For the last couple of decades the study has also been focused on detecting these physical and mental conditions. Neil Schneiderman et al. [1] argued in their work that health of a person is greatly affected by the presence and severity of stressors. Stressors can be workload, critical emotional situation or individual biological complexity. As it became necessary to monitor these mental and physical conditions, study has been evolved to create artifacts to help such monitoring. Various technologies have been evolved in recent years. Moraes et al. [2] described the use of Polyplethysmography (PPG) signal processing to detect the Heart Rate Variability (HRV) of a person.

These days, people are looking for technologies as small as possible. Carrying heavy equipment all day long for basic data monitoring such as heartbeats, blood flow is not practical. So the researchers are trying to figure out a way to minimize the burden of such devices. Chung et al. [3] proposed a non-intrusive healthcare system, which uses integrated sensors for electrocardiogram, accelerometer and oxygen saturation. It includes chest belt and smart watches to record data. Smart watches are being used heavily in health care sectors for data collection. There are sensors available, such as PPG, which are small enough to fit inside smart watches. Thomas et al. [4] in their work described a BioWatch, which uses two sensors, ECG and PPG. These sensors collect data from user's wrist and the gathered data can be used to determine various physiological parameters such as heart rate, blood oxygenation, blood pressure etc. There are various other research works performed in past few years for integrating sensors in smart watches. Today the health care industry is trying to obtain the fundamental sign of wellbeing of a user without disturbing his or her daily routine. In this paper, the PPG sensor will be explored in terms of its uses, requirements and benefits.

2. BACKGROUND LITERATURE

Changes are essential part of human life. The human body is evolved in such a way that it can adapt according to the changes happening around him or her. Stress in a person's life is basically an outcome of such changes. These changes are known as stressors. They may include physical incidents, emotional incidents, workspace environment, and social pressures. These can cause physical, chemical and mental responses in humans.

The changes happening around us not always give a negative impact on us. Stress is a necessary evil. A little amount of stress is always appreciated as it provides motivation to perform a given task or achieve a certain goal. For example, if a student is under pressure of qualifying an examination then he or she will try to study hard. But in same scenario, if the pressure is too high then the performance might decline. This kind of acute stress is coined as positive stress. There have been very few studies, which takes the stress as a positive factor. Selye et al. [19] has discussed some stressful situations, which provides positive reinforcements in the performance of a person. This type of stress is termed as eustress. Hay et al. [20] says that stress maintains alertness and ability to respond to pressure. Be it negative or positive stress the body always shows some signs related to the stressors. The signs mainly include change in heart rate, blood volume, oxygen saturation etc. Taelman, Joachim, et al. [5] observed Heart Rate (HR) and Heart Rate Variability (HRV) under stressful conditions. In their study, the results suggested that the mental tasks done by a person has significant effects upon HR and HRV. Malmo et al. [6] performed a study on psychiatric patients under stress focusing on their blood pressure changes. Different types of stress and pain were stimulated in the patients and it was found out that in some cases blood pressure is higher than others.

Eui-Joong Kim and Joel E. Dimsdale [7] wrote a review on effect of psychosocial stressors on sleep. They focused their study on the work, which used polysomnographic measures of sleep. The results showed that stress is responsible for decrease in slow wave sleep, REM sleep as well as increase in awakenings. There has been various studies to find dependencies between sleep and stressors. Minkel et al. [8] tried to evaluate the stress in the volunteers when their last night sleep was interrupted. Kundsen et al. [9] conducted a study over 1715 American full time employees and related poor quality of sleep over past month with the job stressors. The participants were subjected to various stressors such as work overload, role conflict, autonomy and repetitive task. In the results it is found that work overload is positively associated with poor sleep quality, role conflict is positively associated with difficulty in initiating sleep and non-restorative sleep. Job autonomy was negatively associated with non-restorative sleep. Some of the results are included below. In the table, the Mean represent the average number of days when a particular type of sleep difficulty is experienced.

Table 1: Average days corresponding to particular difficulty

Types of Difficulty	Mean ± SD (%)
Initiating Sleep	5.34 ± 8.37
Maintaining Sleep	6.59 ± 9.85
Non-restorative Sleep	5.00 ± 9.29

Stress affects multiple physiological parameters simultaneously. So changes in one parameter can be used to predict the changes in other parameters. Tobaldini et al. [10] in their study talked about various systems of body that are active during sleep. Their main focus was on Autonomic Nervous System (ANS). The different components of ANS are responsible for the variation in the heart rate and hence the HRV. During sleep the ANS modulation regulates the cardiovascular functions. Thus observing the HRV patterns different sleep stages can be determined. Aldredge et al. [11] in their paper described the patterns observed in HR of a person during different sleep cycles. Stein et al. [12] proposed a method to identify sleep apnea using cyclic HRV values. The data is collected from ECG obtained from overnight polysomnography. Studies have not been focused only on finding relations between different physiological parameters of human body, but also on how these relations can be utilized to predict stress in user. Vrijkotte et al. [13] conducted a study on white-collar employees and monitored their heart rate, heart rate variability and blood pressure for two working days and one non-working day. The results suggested that the work stress causes variations in above-mentioned parameters. These parameters measurements under stress conditions mildly point towards hypertension. It was observed that high imbalance of work is responsible for increase in heart rate.

Use of sensors in detecting physiological parameters such as HRV, oxygen consumption, sleep etc. has shown outstanding results. There are various methods to detect these physiological parameters separately and in combination. Lee et al. [14] filed a patent in which they claimed to provide a method to record heartbeat of a person using polyplethysmography (PPG) sensor. Pinheiro et al. [15] in their study focused on the problem of getting HRV without ECG. According to them the PPG optical sensor can provide Pulse Rate Variability (PRV), which is 82% similar to HRV. For correct HRV the detection of R peak is important in order to record RR intervals, which can easily be done by ECG. But ECG is not convenient always and there was a requirement for a less intrusive way. PPG sensor can be used easily in a wrist worn device, which then can be programmed to observe the changes in blood flow in veins. A wide range of information related to user's health could be extracted from the blood flow data. It acts as a fundamental parameter to derive other parameters such as HRV, oxygen consumption. The sleeping patterns are again can be derived by detecting specific patterns in HRV. Seshadri et al. [21] proposed in their work various methods to monitor different physiological parameters. Their main focus was to unobtrusively detect the biomarkers such as hydration, cortisol level etc. in the body. Sweat is known to be a great source for various hormones secreted by the body. The motivation behind their study was to monitor the biomarkers of the athletes during their workout session and compute mental stress. Thus various studies have been done to relate these physiological parameters with each other and collectively used in different combinations to predict stress of the user.

3. MODERN IMPLEMENTATION

The science of health monitoring has been evolving since always. There is always some new method to extract data for physiological parameters from human body. Many experiments have been done to get better results like adding new sensors or using existing sensors in various combinations. In this section, some of those researches are described in detail. Mainly the focus will be on finding stress level based on physiological parameters recorded using sensors present in wearable devices.

Ciabattoni et al. [16] proposed a method to detect real time stress detection using wearable smart watch. They recorded Galvanic Skin Response (GSR), RR Interval and Body Temperature (BT) to classify stress. A set of cognitive tasks was provided to the participants and their mental efforts were analyzed using the recorded data. A questionnaire is also done to validate the self-reported stress level. A total of 27 features were generated using GSR, HRV and BT. Using the Mutual Information concept top 10 features ranked in decreasing order of mutual information were selected. A K-NN classifier is then trained to classify the dataset into stressed and not stressed classes. This study included those features, which are directly related to Autonomous Nervous System (ANS). In general scenario ANS affects the working of various vital processes in human body including cardiac movements, digestive tracts, eye movement, breathing etc. During mental stress ANS is mostly affected and hence significant changes can be observed in these physiological processes. Due to these reasons, GSR, RR Interval and BT were used to analyze stress.

If looked at the market solutions, Firstbeat Technologies is working in health sector for a long time. They are focused on measurement of daily life activities such as exercising, training, sleeping etc. They have released several white papers related to their research in these areas. Recently algorithms designed by them commonly known as Firstbeat Algorithm is being used for commercial purposes. They have collaborated with Xiaomi and implemented these algorithms in smart watches [17]. These algorithms include Sleep Detection, Sleep Analysis, All-day Stress & Recovery, and Calories Burned etc. Here a brief description is provided about the methods and implementation done for Stress detection and recovery during the day.

In the white paper [17] titled "Stress and Recovery Analysis Method Based on 24-hour Heart Rate Variability" by Firstbeat researchers stress is detected from the HRV features recorded using smart watch. The main motivation was Autonomic Nervous System (ANS), which is a key component in maintaining physiological functions of the human body. According to this paper the two parts of ANS, Sympathetic and Parasympathetic works simultaneously to manipulate the HRV. The patterns in HRV data is used as input to a neural network model to determine various physical activity and their pattern such as respiration rate, oxygen consumption etc.

The main hurdle for stress detection is to separate those part of HRV data which are recorded during non-stationary states i.e. exercising, running etc. The aforementioned parameters help to distinguish between three states that are physical activity, recovery state and stress detection state. The HRV data is divided into segments and all the segments are classified into these three states. In stress detection state, using the HRV values, it is decided that whether sympathetic nervous system is dominant or not. User will be considered under stress if sympathetic nervous system is found to be dominant. The algorithm also considers the time span of different states to analyze the stress to recovery ratio of the user.

There are other smart watches in the market, which also uses Firstbeat algorithm. These include Huawei, Garmin, Google smart watches etc. Apart from full day stress and recovery monitoring, they also provide different tracking features provided by the Firstbeat algorithms. Though other competitors such as Apple and Fitbit provide heart rate monitoring but they do not give any particular score for stress yet. They do provide breathing and relaxation exercises and other fitness trackers. Samsung has been providing stress monitoring in its high-end smart phones, bands and smart watches. Currently in these devices instantaneous data for heart rate and oxygen consumption is used to predict stress. It takes approximately 30 seconds of data and performs its analysis. There have been many reviews on how efficient and accurate these watches are in providing heart rate or stress as per their claims [18].

4. PROPOSED SOLUTION

A lot has been done in stress detection in wearable industry. There are various devices, which provide scoring for real time stress using different features. While there are a lot of physiological parameters which are directly or indirectly affected by the stress experienced by a person, most of the work done so far has been primarily focused on heart rate, heart rate variability and oxygen consumption. In terms of research various physiological parameters are tested and implemented successfully with satisfying results but only few of them are carried out in practice. As seen in previous sections, HRV is directly affected by stress level and it is used in almost all the wearable devices. In addition with HRV, sleep and hydration level of the body are also useful in detecting stress as mentioned in earlier studies.

Stress is not a virtue that comes or goes instantaneously. It is an effect of the sum of events happening over a long period of time. If not kept in check it increases continuously with time and so do its effects on human body. Up till now it is observed that all the practical implementation focuses on the instantaneous values of these parameters. But it will be fair to say that if the effects keep increasing over the time the history of these parameters will be more useful and will contribute constructively towards the scoring of current stress level of the user.

It is observed in several studies on healthy persons as well as persons suffering from cognitive diseases that if stress is imposed on them their sleeping efficiency deteriorates. In other words if sleeping pattern is observed for a person and its overall efficiency is calculated it can predict the amount of stress he or she is in. Drinking sufficient water can help reduce the negative psychological and physiological impacts of stress. Hence, hydration level can also be utilized to detect stress level. In the following sub-sections aforementioned features are described in detail.

4.1 Sleep History

There are four stages of sleep and during sleep these stages occur in a particular pattern. Penzel et al. [23] investigated the dynamics of sleep stages and concluded as follows. In normal scenarios a person spends a fixed amount of time in each sleep stage. At the onset of sleep the person enters in awake stage followed by light sleep. After light sleep, the person enters deep sleep. REM sleep follows it. This sequence is termed as sleep cycle and it has duration of 90–110 minutes. This cycle is observed five to six times in a healthy person during night sleep. With each cycle the deep sleep duration decreases whereas the duration of REM sleep increases.

If looked for Samsung devices they provides trackers for sleep and its stages. This sleep tracker is totally unobtrusive. There is no input required from the user other than the requirement of wearing the smart watch while sleeping. In sleep tracking various sleep parameters are observed. They include duration of total sleep in one go, which is called a Sleep Instance, the detection of various stages of sleep including awake, light sleep, deep sleep and Rapid Eye Movement (REM) sleep and the duration of each stage. The data is collected in an organized manner for all these stages. Each sleep instance has its unique id and same is applicable for sleep stages as well. The start and end time for sleep instances and stages are recorded. Using this data various features can be extracted which are described below.

Below is an example of how sleep is recorded using Samsung smart watch. Here, two different instances of sleep and their respective stages along with their timings are provided. Efficiency of each sleep instance is also mentioned.

In a study conducted by a Research Center in Canada [22] the duration and quality of sleep is directly related to stress. The participants self-evaluated their sleep quality while the sleep duration is monitored and based on several questionnaire and clinical factors stress score is generated. The findings are as follows.

Fig. 1: Different sleep stages recorded using Samsung Galaxy Watch 2. The figure on the left describes first instance while the figure on the right describes the second instance.

Table 2: Stress score against sleep quality

Sleep Quality	Stress Score (Mean ± SD (%))
Very bad	24 ± 0.69
Bad	15 ± 0.71
Mild	14.75 ± 0.29
Well	9.62 ± 0.28
Very well	5.4 ± 0.34

Table 3: Stress score against sleep duration

Sleep Duration (hours)	Stress Score (Mean ± SD (%))
4	46 ± 0.63
5	35.75 ± 0.58
6	25.42 ± 0.42
7	17.6 ± 2.3
8	13.06 ± 0.26
More than 8	16.73 ± 0.85

4.2 Hydration

Stress is dependent on body hydration level. Often hydration is related to heat stress or in severe cases heat stroke but cognitive stress or mental stress is also an effect of dehydration in the body. Water is like a nutrient for brain. If water is not available in sufficient amount some of the brain functionalities may slow down or even completely shut down. Brain produces serotonin, which is a kind of neurotransmitter, in presence of amino acid tryptophan and sufficient amount of water. The level of serotonin in the brain can be helpful in predicting depression. Using a wearable device it may not be possible to accurately provide the amount of above mentioned chemical produced, but if the water level in the body is known then it can be related to the production of the said chemical. Thus low water level in the body can be assumed to be a cause of cognitive stress.

If looked in reverse order, cognitive stress can also cause dehydration in the body. While the body is in stress, cortisol, the stress hormone, is produced by adrenal glands. In condition of chronic stress adrenal glands can exhaust themselves which can lead to dehydration. This is the main reason behind using hydration level for stress prediction as dehydration and stress are related.

Currently in smart watches the water intake is input manually by the user. Hence hydration level will be calculated manually, as till now there are no automatic sensor in smart watches dedicated to measure hydration level in the body. Though there are researches which claim to detect such parameters. Studies have shown that the dehydration in the body affects the cognitive abilities of the user. A goal of water intake will be set on daily basis and the current value of water intake will be used to calculate the stress score. It will not be assumed to complete the goal at the start of the day instead it should be broken down in regular intervals as per the requirements of the body. The use of hydration level is quite important for prediction of stress as both are related to each other.

4.3 Heart Rate Variability

This feature has been the top priority for the researchers from the beginning. Its instantaneous value is as important as its history. Different users have different patterns in normal scenarios as well as when under excessive amount of physical or mental stress. For example, HRV of an athletic person will be low most of the time due to high heart beat from exercise and activities compared to a person on a desk job. As there are studies for personalizing the device for each user this paper does not emphasize on this. Here the idea is to record HRV for a specified period of time and use it in collaboration with HRV history i.e. the count of events when HRV had crossed a set threshold, to get a stress score.

4.4 Oxygen Consumption

The human body cells produce reactive oxygen species and their counterpart antioxidants. There is a balance, which should be maintained always in lack of which the brain functions can perform poorly as the oxygen consumption for these functions is very high. In cognitive stress the brain is functioning more than the usual and hence the current oxygen consumption is high. Using PPG sensor the current saturation of oxygen is calculated. If the saturation is not very low, it means the brain is not putting extra efforts or in other words the user is relaxed. In contrast when a user is under stress the saturation is very low indicating the high consumption of oxygen. This feature indicates the instantaneous state of the brain and can be used straightforward. The current consumption of oxygen will determine how much the user is putting mental efforts in present condition and this value can be used to compute stress level.

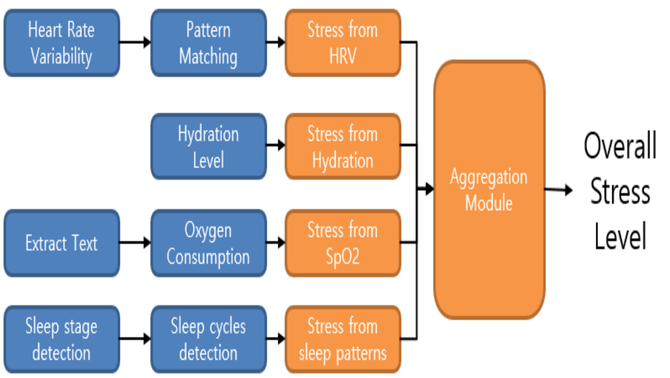

Fig. 2: Workflow diagram for the proposed solution. Here individual features are used to get a score which is then aggregated based on their relevance to obtain final value.

The solution proposed in this paper makes the use of these four features i.e. HRV history, oxygen consumption, sleep history and hydration level. HRV history will basically provide the percentage of time when the sympathetic nervous system was dominant over the last 27-72 hours. In the same way, sleep history for last 5-10 instances will be used. First using each feature stress is predicted in percentage then a machine learning model can be trained to predict overall stress level.

For training the model a dataset will be created. In the process of dataset creation four features will be calculated at a time. The actual stress at that time will be the value currently provided by the smart watch itself. Using these actual values the model will be trained. Once the model is trained it will use the features to predict stress level. A flowchart for the training model might be similar to this.

5. CONCLUSION AND FUTRUE WORK

As discussed up till now, it is clear that using HRV and oxygen consumption, in practical implementation, gives an approximate idea of stress amount in a user. In theory other features such as sleep and hydration level are also important and contribute significantly towards stress detection. It is also clear that not only the instantaneous value but also the history of these physiological parameters are significant and can be used in stress detection. As the aforementioned parameters are responses of simultaneous functions happening inside body, including such parameters will increase the accuracy.

According to recent researches hydration level in the body can be detected using sensors unobtrusively. This will remove the requirement of manual entry of water intake by the user and the goal setting. If used, such real time detection methods will provide accurate value of hydration level and will be more helpful. Further in terms of improving the stress detection other factors might also be included such as location, voice analysis etc. These can be used to rule out false positive and false negative cases and thus increase the accuracy.

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