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Associating ECG features with firefighter's activities

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Abstract— **In this paper we associate features obtained from ECG signals with the expected levels of stress of real firefighters in action when facing specific events such as fires or car accidents. Five firefighters were monitored using wearable technology collecting ECG signals. Heart rate and heart rate variability features were analyzed in consecutive 5-min intervals during several types of events. A questionnaire was used to rank these types of events according to stress and fatigue and a measure of association was applied to compare this ranking to the ECG features. Results indicate associations between this ranking and both heart rate and heart rate variability features extracted in the time domain. Finally, an example of differences in inter personal responses to stressful events is shown and discussed, motivating future challenges within this research field.**

I. INTRODUCTION

A recent study on firefighters in the United States [1] showed that 45% of the deaths that occur among U.S. firefighters, while they are on duty, are caused by heart disease. This number is twice as high as for police officers and three times as high as the average incidence of heart disease at work. Furthermore the study shows that the risk of death from coronary heart disease during fire suppression is approximately 10 to 100 times as high as that for nonemergency events. These facts clearly show that for a firefighter the most life threatening condition besides factors such as direct contact to fire or chemicals, is the condition of his heart. Factors that have an obvious high impact on the cardiovascular system are stress and fatigue, which might also be triggering factors for its overload.

The Vital Responder project is an interdisciplinary research project formed by teams from Institute of Electronics and Telematics Engineering of Aveiro (IEETA), Carnegie Mellon University (CMU), Instituto de Telecomunicações (IT) in Porto and Aveiro, and BioDevices, S.A. The goal of the Vital Responder research project is to explore the synergies between innovative wearable technologies, scattered sensor networks, intelligent building technology and precise localization services to provide secure, reliable and effective first-response systems in critical emergency scenarios. For this goal the estimation of stress and fatigue in first responders is a main concern to prevent cardiac failure and addressed by using a wearable technology (Fig.1) to obtain information on the firefighter's cardiovascular status via electrocardiography (ECG).

Fig. 1. The Vital Jacket is a wearable vital sign monitoring device. Due to its design in form of a light T-shirt it allows to record a one lead ECG with a sampling frequency of 200 Hz without restricting the freedom to move.

So far the estimation of stress in real environments using wearable sensors has been mostly focused on driving scenarios [2,3] or to estimate stress during high performance jet flights [4]. Some interesting results were obtained by analyzing the sympathovagal balance between sympathetic and parasympathetic activity using heart rate variability (HRV) measurements [7].

We are however concerned that in these scenarios the individual being monitored is not under significant amounts of fatigue or short-term physical stress, which is not the case of first responders in action. Our aim is thus to inspect how these cardiac features obtained from ECG signals behave in a scenario where both high levels of fatigue and stress are expected. In order to accomplish the objective, we present in this paper the two following contributions:

- A methodology for the data collection and annotation necessary for a comparison of a firefighter's working day with features extracted from a wearable device recording ECG signals;
- A measurement of the associations between HRV features and certain types of emergency and non-emergency events in which varying degrees of stress are expected.

The data collection and annotation methodology will be presented in Section II, followed by the signal analysis and feature extraction on Section III. Section IV will show the results of the association of ECG features and conclusions will be drawn in Section V.

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II. Data Collection and Annotation

The data used for this paper consist of records from five male firefighters from the Bombeiros Voluntários de Amarante, which is a team of volunteer firefighters based in Amarante, Portugal. To collect the data, in the beginning of the working day the firefighters put on a shirt under their clothes with the ability to collect clinically valid ECG signals during very long periods (Vital Jacket™) [8]. The Vital Jacket then records the firefighter's ECG signal together with a time stamp until the end of his shift, which in most of our recorded cases takes 8 to 12 hours. Afterwards the ECG signal is transferred from the internal memory of the Vital Jacket to a database.

A. Vital Jacket

Vital Jacket (Fig. 1) is a product from BioDevices S.A. that is mainly a very light and comfortable T-shirt with embedded microelectronics that allows the monitoring of cardiac activity from ECG up to five days. The ECG is recorded using two electrodes recording one lead plus an additional electrode to reduce noise. An embedded box processes and stores the signal on a SD memory card and transmits it directly to a personal computer or a mobile device using a bluetooth connection. The ECG signal is recorded with a sampling frequency of 200 Hz and a resolution of 8 bit. Additionally the Vital Jacket provides a time-stamp for the signals using an internal real-time clock. Due to its design the Vital Jacket does not interfere with the user's daily activities and is therefore ideal for the use with firefighters where any restriction caused by such a monitoring device is unacceptable.

B. Data Annotation

Together with the ECG data recorded by the Vital Jacket the timestamps and types of activities occurred during a specific shift were logged. We have used the official daily log of each firefighter that participated in this study. The Portuguese law implies that these logs include the following information: date and time of the beginning and of the end of every event; type of event, according to a national scheme for classifying events; and the tactical position within the team.

The categorization of events is divided into nine main classes with a varying number of sub classes. The main classes are: Fire, Car Accident, Infrastructures/ Communications, Pre-Hospital Assistance, Legal Conflict, Technological/ Industrial, Services, Activities and Civil Protection Events.

C. Dataset

With this setup around 447 hours of ECG were recorded between February 2010 and July 2010 from five firefighters. The average age for these firefighters was 35.4 years, with a maximum of 41 years and a minimum of 24 years and at least five years of experience in firefighting. The harsh environment and unexpected situations that these individuals face led to a substantial amount of bad signal recordings due to inadequate electrodes, broken hardware, and incorrect time stamping of the data. Although it is an issue beyond the scope of this paper, this study led to a clear improvement of the data collection system, which is now much more robust and reliable. After this screening, 238 hours of recordings were selected, out of which 59:25 hours were collected during missions. The distribution of these 59 hours divided by types of events can be seen in Fig. 2. The ECG data which was recorded outside of events was not used for the experiments presented in this paper, because no information about the actual activities performed was available.

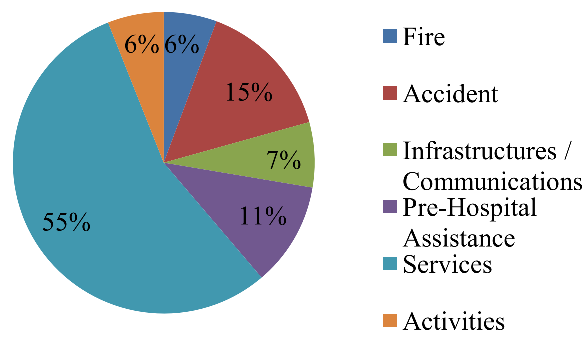

Fig. 2. Distribution of the 59 hours of collected ECG signal divided by type of event

D. Questionnaires

A simple questionnaire was given to 25 firefighters to get a better idea of their self-assessment of stress and fatigue during each type of event. The average of the individual responses to the questionnaires was used to rank events in three levels of stress and fatigue, being respectively low, medium and high.

III. Methods

A. Data format

To have a standardized format and to benefit from the numerous functionalities and algorithms provided by Physionet [5], the WaveFormDataBase format was used to save and process the collected ECG signals.

B. QRS Detection

The detection of QRS complexes used is based on the algorithm by Pan and Tompkins [6] implemented together with further improvements in the open source EP Limited QRS detection software [7] which was used to detect R peaks in the ECG recordings.

C. HRV Analysis

Besides instantaneous heart rate (HR) measured in beats per minute (bpm), six standard measurements proposed by the task force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology [9] were used for the heart rate variability (HRV) analysis. The following three time domain measurements were used:

- **SDNN:** Standard deviation of all NN (normal to normal beat) intervals in ms;

- **RMSSD:** Square root of the mean of the sum of the squares of successive differences between NN intervals in ms;
- **HRV triangular index (HRVti):** Total number of all NN intervals divided by the height of the histogram of all NN intervals measured on a discrete scale with bins of 7.8125 ms.

Together with the time domain measures, three frequency domain measures were also used. To obtain these measures the series of NN intervals was transformed to a power spectral density (PSD) using the Lomb Periodogram [10] implemented in Matlab (Version 7.10.0) using an open source implementation [11]. The spectrum then was analyzed using:

- **Low frequency (LF) part**: ranging from 0.04-0.15 Hz;
- **High frequency (HF) part**: from 0.15-0.4 Hz.

The two previous measures were then divided by the total frequency in the 0-0.4 Hz frequency band. Finally, the third measure is:

- **LF/HF**: ratio between the LF and HF component.

All measures were calculated in consecutive windows of five minutes, until the whole record was covered.

IV. ASSOCIATING ECG FEATURES

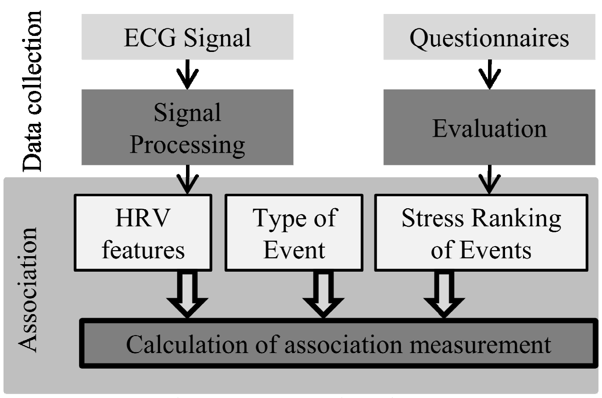

Fig. 3. Data processing scheme

For comparing features gathered by HRV analysis during certain types of events and their position in the ranking of stress levels, estimated by the questionnaires, the processing scheme shown in Fig. 3 was used. The results of the data collection part are passed on to a measure of association which was then applied to the data.

A. Measure of Association

Association measures are important and useful in the field of evaluation a predictive relation between two variables [12]. The most used measures are the correlation measures, which are adequate for continuous variables, e.g. Pearson correlation. However, in the presence of discrete variables (such as the stress ranking) these popular measures could not be applied. In this special case, another kind of association measures should be used. The ideal measure, in our study, should describe the stress/fatigue as a monotonically nondecreasing mathematical function of the HRV measurements. The Kim's d_{yx} measure is described as adequate for the present problem [12]. However, the P_k measurement by Smith et al. [13] was used which is an easier to interpret modification of the underlying d_{yx} measure by Kim [14] and often used to evaluate the quality of indicators of anesthetic depth. Briefly, when comparing indicator values (in this case the HRV measurements) to an ordinary scale (the stress ranking) the value of P_k with a range from 0 to 1 can be interpreted as the probability of a concordant relationship of both sides, which means that if the indicator value increases, the assigned level of the ordinary scale is also increasing.

B. Results

Due to the answers given in the questionnaires the categories were ranked from low to high stress as following: 1) services, 2) activities, 3) pre-hospital assistance, 4) infrastructures / communications, 5) fire and 6) car accidents. This ranking method produced the same ordering for stress and for fatigue.

Calculating the P_k measure for all six classes and the mentioned HRV measurements including heart rate resulted in P_k values around 0.5 which means a probability of 50% to predict an increased stress level according to an increased value of the measure. But considering only the extreme levels of low stress and high stress at both ends of the scale showed interesting results, as observed in Table I. The mean values over all five minute segments for the five firefighters are shown divided into the three extreme types of activities: services, fires and car accidents.

Although this is a rather generalized approach, it can be seen that the average heart rate, as the strongest predictor, clearly distinguishes differences between these types of activities and in 76% of all cases supports the order estimated by the questionnaires. Also, the time domain features, mainly HRVti and SDNN, show a negative association with our ordering. This means that the HRV tends to go down during events, which were ranked as more stressful, like fires and car accidents, compared to a low stress service activity, like cleaning route, unblocking passageways or patient transportation.

TABLE I
P_k ASSOCIATION MEASURE AND MEAN VALUES FOR 5 MINUTE SEGMENTS OVER FIVE FIREFIGHTERS ACCORDING TO THREE DIFFERENT ACTIVITES

Ranking position	Classes	HR (bpm)	SDNN (ms)	RMSSD (ms)	HRVti	LF norm	HF norm	LF/HF	random
1	Service	87.07	77.44	44.69	12.79	0.35	0.11	5.56	
5	Fire	101.54	65.12	31.01	10.21	0.34	0.09	4.71	
6	Car accident	103.96	57.71	30.63	9.47	0.41	0.10	5.30	
P_k		0.76	0.39	0.43	0.32	0.57	0.49	0.54	0.53

These findings agree with the expected increased sympathetic activity of the autonomous nervous system during stressful situations [2].

The frequency domain features do not show significant concordance to the stress ranking used, presenting similar P_k values as the control random feature shown in the last column.

Furthermore, differences in the inter-personal reactions to the different scenarios were observed by inspection of an individual case. Fig. 4 shows the most promising HRV measures (HR, HRVti and SDNN), during two working shifts of two different firefighters, which included in both cases only service events and accidents. By the inspection of the single example in Fig. 4, it is observed that the absolute HRV values for both firefighters are different according to both types of events. Also, the variation of the three measurements between the two events is stronger for FF1 compared to FF2. Knowing that FF1 is the youngest team member (24 years old) and FF2 the oldest (41 years old), either age or experience might be explanations for these variations. This isolated example proves nothing by itself but since this is a unique window into the reality of vital signals of firefighters in action, it gives us motivation enough to argue that both these factors should be further studied as a possible covariate in the stress/fatigue stratification, when looking at inter-personal reactions to different events.

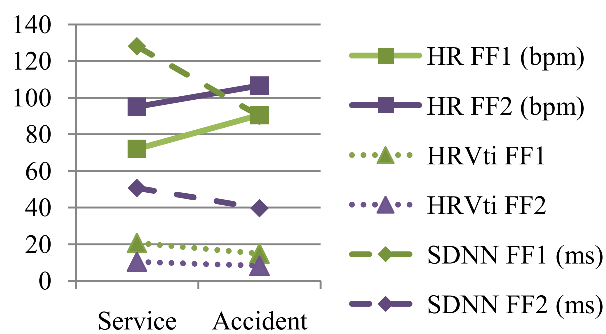

Fig. 4. Two selected working days of two different firefighters and their HRV response to these days which only included service and accident events.

V. DISCUSSION AND CONCLUSIONS

Although a rather coarse classification of events was used as basis for the stress ranking of the events, an association between the activities which were ranked as least stressful and most stressful was observed as an increased heart rate and decreased HRV in the time domain. In previous studies [2], the standard frequency domain HRV features, especially the ratio between LF and HF, showed to be a promising parameter as an estimation of the sympathovagal balance. However, in this study it turned out not to be a potential indicator of stress, at least using the standard definition under the uncontrolled conditions of a firefighter's working day, which implies a high level of physical activity. The reason behind this could be that during most of the events the largest part of the power spectrum does not lie within the HF or LF band, but in lower frequency parts. These parts probably should be assessed in more detail in future works.

The distinction between fatigue and stress was not possible by asking the firefighters directly to assess their perception of stress and fatigue with a simple questionnaire as used in this work. Therefore a subtler questionnaire might obtain more differences between both kinds of stress. Using psychological methods of questioning the levels of stress and fatigue might reveal a more complex model of these measures in ECG features. Especially if a level of fatigue and stress can be assigned to every single event and separated for every firefighter. Inter personal variations are always present, so the event analysis between firefighters might provide more insight into the problem of stress and fatigue estimation together with personalized inferring of stress and fatigue using aforementioned questionnaires. This approach will provide a possible adaptive model that would therefore be preferable to a general categorization.

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