35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Are standard heart rate variability measures associated with the self-perception of stress of firefighters in action?

P. Gomes[1], M. Kaiseler[2], B. Lopes[1], S. Faria[1], C. Queirós[2] and M. Coimbra[1], *Member, IEEE*

***Abstract*— Stress is a major factor for the degradation of cardiac health in first responder professionals such as firefighters. Monitoring stress during real events might be the key for controlling this problem. In this paper we inspect how standard heart rate variability (HRV) measures are associated with the self-perception of stress of firefighters in action, supported by an advanced technological solution to acquire this data. Results obtained from more than 94 hours of annotated ECG recordings of firefighters in action are promising, showing positive association with various standard HRV measures. Given the richness of the gathered data, we have also measured the association of the HRV measures with the stage of a firefighting event (pre, during, post), obtaining some interesting results that hint that the psychological impact of the post-event may be one of the most concerning situations for a firefighter, motivating further studies on this in the future.**

Fig. 1. Images of a version of the Vital Jacket®, specially made for the firefighters, and the Vital Analysis framework running on a smartphone.

I. Introduction

Research has shown that Firefighters (FF) have the highest mortality ratios of ischemic heart disease compared to other populations. In fact, FF are trained to perform under dangerous and high-pressure situations such as forest fires, vehicular accidents or rescue missions, and experience combinations of physical and psychologically demanding challenges (e.g., physical danger, physiologic exertion, heat, mental stress, etc.) while fulfilling their occupational responsibilities. These factors are likely to be associated with psychological and physical illness [1]. Hence, it seems crucial to develop systems that can monitor psychological and physiological stress responses of FF in action.

The Vital Responder project has addressed this problem (http://www.vitalresponder.pt) by exploring the synergies between innovative wearable technologies, sensor networks and precise location services to provide secure, reliable and effective first response systems in critical emergency scenarios. Using a specially made shirt capable of colleting continuous electrocardiogram (ECG) signal and a smartphone based framework (see Fig. 1) we were able to collect a rich dataset consisting of physiological data, psychological reports, self-assessment after emergency events and its context.

The estimation of stress in real environments using wearable sensors has been mainly focused on driving scenarios [2] or on monitoring regular people during physical exercises [3]. Although, some relevant results were obtained by analyzing the sympathetic activity and vagal activity of the heart using heart rate variability measurements [4], we believe that these scenarios do not represent a significant stress scenario, when compared to FF in action.

In this paper we will analyse the standard heart rate variability measures acquired from FF during real emergency scenarios, in order to access if these have any association with a FF's self-assessment of how stressful an event was. Furthermore, we will inspect how these measures are associated with the various stages of an event, namely pre, during and post event.

The methodologies used to annotate stress levels will be presented in Section II, followed by associating heart rate variability (HRV) measures with self-perceived stress on Section III. Section IV will show the results and conclusions will be made in Section V.

II. Annotationg Stress Levels of Firefighters in Action

In this section we will address the definition of stress, followed by an explanation about the methodologies used to annotate it during emergency events. Finally we will describe the dataset acquired with this setup.

A. Annotating Stress Levels

For the purposes of this paper, stress conceptualization will follow the transactional model of stress, defined as ”a situation that taxes or exceeds one's personal resources or threatens the person's well-being has the potential to cause stress” [5]. Thus, the emotions experienced and physiological responses are initiated due to the person interpretation of the event and its perceived meaning to their well-being [6].

This work was supported by FCT projects PTDC/EEIELC/2760/2012 and PTDC/EIA-CCO/100844/2008

[1]P. Gomes, B. Lopes, S. Faria and M. Coimbra are with the Instituto de Telecomunicações in Faculdade de Ciências da Universidade do Porto, Portugal (email:{ptmgomes, brunolopes, sergiofaria, mcoimbra}@dcc.fc.up.pt)

[2]M. Kaiseler and C. Queirós are with the Laboratório de Reabilitação Psicossocial from FPCEUP/ESTSIPP, Portugal (email:{mkaiseler, cqueiros}@fpce.up.pt)

Previous research on stress has been plagued by problems in defining and measuring the concept [7]. Traditional stress assessment procedures are often reliant on retrospective recall, crossectional methodologies, self-report measures and/or laboratory simulations. But, relying merely on retrospective memory recall can jeopardize validity and reliability of the reports and its ecological validity [8]. In an attempt to overcome these limitations, Stone and Shiffman [9], recommend research methods such as Experience Sampling (ESM) and Ecological Momentary Assessment (EMA), also known as "momentary studies" to assess stress. These are daily tools for assessing a within-person variation, in participant natural environment and contemplating an idiographic approach [10]. Although the terminology used to define these research methods does not seem unanimous in the literature, the core idea underlying the methods is consistent. Since our study aims to assess a combination of psychological (self-reports) stress combined with the physiologic stress responses (heart rate variability) among FF working in real world environments, EMA will be used. As suggested by Segerstrom and OConnor [8] when aiming to analyze the stress process, studies should include daily assessments of stress and physiological outcome measures, which strongly motivated the creation of the Vital Analysis framework.

B. Vital Analysis Framework

The Vital Analysis framework (VA) [11] is a smartphone based application designed to gather context from the daily routines of a firefighter, without distracting him from them.

With this framework the firefighters were asked to start their day by dressing the Vital Jacket® (VJ) (see Fig. 1) instead of their official firefighter shirt. Then they were required to start the VA application in the smartphone and to choose to connect to the VJ via Bluetooth. During the calibration period they answered to a set of questions to evaluate their physical and psychological states, and after that they were ready for their normal day [12].

To collect context data from the emergency event occurred during the work day, the VA provides an annotation methodology that allows the firefighter to change the state of the event from going to the event (PRE), to at the event (IN) and then leaving the event (POST) with a simple press of a button in the smartphone. This way, we can analyze our data differently assuming that in each of these states a firefighter can have different behavior. We also allow the firefighter to make voice annotations and to take photos of the scenario to increase context. At the end of the event, when they return to the headquarters, they are prompted to self-evaluate how difficult the event was for them, focusing on: control over the event, impact of the situation on themselves and power to make decisions.

When their work day is finally over, they are requested to answer the same questions at the beginning of the day.

C. Dataset

We have gathered around 94 hours of ECG signal of firefighters in action, from which around 20 hours were collected during real life emergency events. The data was collected from 4 firefighters with an average age of 39 years (ranging from 37-41 years old) and at least 5 years of experience as a professional firefighter. These signals were collected during 39 days of work and from 29 different emergency events.

According to the self-evaluation given by the firefighters to each individual event we have ranked our events into three different categories: low stress events; medium stress events and high stress events. In table I it is possible to see the distribution of the dataset according to each firefighter and category.

TABLE I
DISTRIBUTION OF THE DATASET ACCORDING TO EACH FIREFIGHTER AND CATEGORY

	All	No Event	Low Stress	Medium Stress	High Stress
FF1	50:28:26	38:42:49	07:24:30	02:33:30	01:47:37
FF2	35:43:57	28:51:53	03:44:55	01:14:56	01:52:13
FF3	07:09:03	06:13:50	00:00:00	00:00:00	00:55:13
FF4	00:49:50	00:36:45	00:00:00	00:00:00	00:13:05
Total	94:11:16	74:25:17	11:09:25	3:48:26	4:48:08

III. ASSOCIATONG HRV MEASURES WITH SELF-PERCEIVED STRESS

To compare the features gathered by the analysis of the heart rate variability (see subsection III-B) during real emergency events and the self-perceived stress, according to the firefighters, we have used the process in Fig. 2. Section III-C will describe the calculations of the association measures used in this paper.

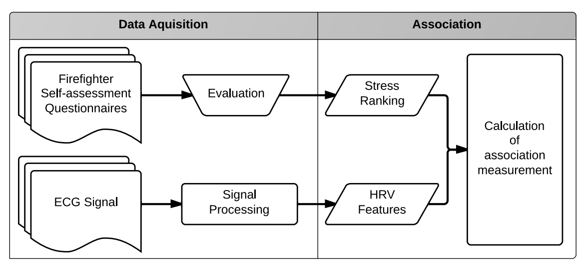

Fig. 2. Data processing scheme

A. QRS Detection

QRS detection for the gathered ECG recordings was based on the algorithm by Pan and Tompkins, implemented with some improvements by the open source EP Limited QRS detection software [13].

B. HRV Analysis

Heart rate variability (HRV) represents a promising marker in the relationship between the autonomic nervous system and the cardiovascular system [4]. Besides instantaneous heart rate (HR) measured in beats per minute (bpm), we have used 9 standard derivations of the HRV.

TABLE II

P_k ASSOCIATION MEASURE AND MEAN VALUES FOR 5 MINUTES SEGMENTS ACCORDING TO THE FIREFIGHTERS SELF-ASSESSMENT

Categories	HR	SDNN	RMSSD	HRVti	HF	HFnorm	LF	LFnorm	LF/HF	VLF
No event	62.782	628.641	816.303	14.059	0.331	0.388	0.516	0.337	1.799	0.234
Low stress	69.897	813.615	1101.769	15.319	0.503	0.477	0.420	0.307	0.744	0.182
Medium stress	65.525	1147.111	1595.593	14.624	0.830	0.530	0.667	0.318	0.642	0.132
High stress	66.168	1105.407	1478.795	14.539	0.697	0.497	0.626	0.318	0.818	0.160
P_k	0.623	0.675	0.681	0.553	0.685	0.671	0.668	0.464	0.372	0.313

In the time domain we have used:

- SDNN: Standard deviation of all NN (normal to normal beat) intervals in ms.
- RMSSD: The square root of the mean of the sum of the squares of differences between adjacent 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.

To obtain the frequency domain measurements the series of NN intervals was transformed to a power spectral density (PSD) using the Lomb Periodogram implemented in Matlab using an open source implementation [14]. Thereafter, we have analyzed the spectrum using the following derivations:

- Low frequency (LF): ranging from 0.04-0.15 Hz.
- High frequency (HF): ranging from 0.15-0.4 Hz.
- Very low frequency (VLF): $\leq$ 0.04 Hz
- LF/HF: ratio between the LF and HF components

Both LF and HF were also be measured in normalized units, which represent the relative value of each power component in proportion to the total power minus the very low frequency component. The representation of LF and HF in normalized units emphasizes the controlled and balanced behavior of the two branches of the autonomic nervous system [4]. Moreover, the normalization tends to minimize the effect of the changes in total power on the values of LF and HF components. Following the task force's suggestions [4], all measures were calculated in consecutive windows of five minutes, until the whole record was covered.

C. *Measures of Association*

Association measures are important and useful in the field of evaluating a predictive relation between two variables [15]. 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 categories that we have defined) these popular measures could not be applied. The ideal measure, in our study, should describe the stress as a monotonically nondecreasing mathematical function of the HRV measurements. Although other methods are advised [15], we choose the P_k measurement by Smith et al. because it is easier to interpret 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 categories) 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.

IV. RESULTS

According to the self-assessment given by each firefighter on how stressful each event was, 3 categories were defined: low stress, medium stress and high stress events. In addiction to these categories we added another category with all the remaining ECG as data where no events were occurring.

Results for the association measures between all 4 categories and all 9 HRV measures (see subsection III-B) plus heart rate, can be observed in Table II.These results show that various features are positively associated with stress, with probabilities reaching 68% for the strongest predictors such as SDNN, RMSSD and HF.

The HR measure increases when you compare a ”no event” scenario with an ”event” one. However, this increase is not observed as the perceived-stress also increases, which may be explained by the HR also being strongly associated with the body's adaptation to the physical activity present during events. The SDNN and the LF are usually related to the body capacity to respond to a situation, and the increase of these values is expected, but we should theoretically be seeing higher values in the high stress events [4], which does not happen. A possible explanation is that the interpretation of the difference between a medium and a high stress situations on the self-evaluation might not have been straightforward for the participating FF of this study, since the differences between no event, low stress and medium/high stress seem to be relevant.

Furthermore, we have analysed the associations between the different stages of an event. With the annotation methodology that we have implemented (see subsection II-B) we are able to parse an event into 3 different stages: going to the event (PRE), which represents the trip to the scene where the emergency is occurring; at the event, which represents the actual emergency (IN); and leaving the event, which represents the trip back to the headquarters (POST). Association measures between these stages and some HRV measures can be seen in Table III.

These 3 stages can be interpreted differently from a psychological point of view. In the PRE stage the FF is anxious and has some uncertainty of what will be expecting him. When he arrives, he faces the scenario and focuses on his tasks, sometimes oblivious the danger and emotional

TABLE III

P_k ASSOCIATION MEASURE AND MEAN VALUES FOR 5 MINUTES SEGMENTS, FOR THE 3 STAGES (PRE, IN AND POST) OF AN EVENT, ACCORDING TO THE FIREFIGHTERS SELF-ASSESSMENT.

	PRE event				IN event				POST Event			
Categories	HR	SDNN	HF	LF	HR	SDNN	HF	LF	HR	SDNN	HF	LF
Low stress	71.438	517.700	0.250	0.270	78.700	497.007	0.228	0.143	71.757	629.149	0.311	0.162
Medium stress	78.380	495.499	0.154	0.065	66.030	1234.907	0.914	0.952	73.551	151.148	0.010	0.006
High stress	75.632	611.502	0.242	0.111	65.539	1300.717	0.847	0.977	96.548	78.747	0.002	0.002
P_k	0.619	0.636	0.624	0.624	0.270	0.732	0.717	0.735	0.675	0.088	0.087	0.095

impact of these situations. And finally, when he leaves, the impact of what he has went through starts to affect him, especially when an event was stressful.

During the event, almost all the measures show a positive strong association, which supports that the FF has higher sympathetic activity and vagal activity, as expected when stress increases. Nevertheless, the HR has a negative association, which from a cognitive point of view is expected. These professionals are prepared to face this kind of events, and when faced with danger they try to adapt their physiological condition to endure and be ready to act. We can also have the frustration, in the low stress events, of being called to act in a not emergency scenario, which can explain the differences in the HR values.

Focusing on the POST stage, the HR measure increases with the increase of perceived stress, which can be connected to the impact of the event on the FF, and pointing out that this stage can be the one where we need to worry most about the health of these professionals. Also, the low HF is usually connected to the incapacity to recover and the low LF, since the firefighter does not need to act anymore, is usually connected to exhaustion [4]. These values hint that the FF may be recovering in a way that can lead to heart problems [16], motivating further research on this topic.

V. CONCLUSION

The results presented in this paper show that the self-perception of stress, in real life emergency scenarios, can be associated with standard heart rate variability measures. Furthermore, these results support that future studies should also focus on the measure and analysis of the before, during and after stages of an event. These results, despite of being part of an exploratory approach, already show interesting phenomena that can lead to a better understanding on how the uncertainty before an event can provoke stress, how firefighters react when facing danger, but more concerning, how their bodies react and recover after the event.

ACKNOWLEDGEMENT

We are thankful to Cmdt. Rui Ribeiro, from Bombeiros Voluntários de Amarante, as well as to Cmdt. Eng. Salvador Almeida, from Companhia de Bombeiros Sapadores de Gaia, and their teams, for their collaboration. We are also thankful to Ana Castro and Johannes Pallauf for all the help and support.

REFERENCES

[1] C. A. Reynolds and L. Shannon, "Stress and first responders: The need for a multidimensional approach to stress management," *International Journal of Disability Management Research*, vol. 2, pp. 27–36, 2008.

[2] J. Healey and R. Picard, "Detecting stress during real-world driving tasks using physiological sensors," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 6, no. 2, pp. 156 – 166, 2005.

[3] E. Jovanov, A. O'Donnell Lords, D. Raskovic, P. Cox, R. Adhami, and F. Andrasik, "Stress monitoring using a distributed wireless intelligent sensor system," *Engineering in Medicine and Biology Magazine*, vol. 22, no. 3, pp. 49 – 55, 2003.

[4] T. F. of the European Society of Cardiology the North American Society of Pacing Electrophysiology, "Heart rate variability: Standards of measurement, physiological interpretation, and clinical use," *Circulation*, vol. 93, pp. 1043–1065, 1996.

[5] R. S. Lazarus and S. Folkman, *Stress, Appraisal, and Coping*. New York: Springer, 1984.

[6] W. R. Lovallo and W. R. Lovallo, *Stress & health: Biological and psychological interactions*. Sage Publications, 2005.

[7] S. Monroe and J. Roberts, "Conceptualizing and measuring life stress: problems, principles, procedures, progress," *Stress Medicine*, vol. 6, pp. 209–216, 1990.

[8] S. Segerstrom and D. OConnor, "Stress, health and illness: four challenges for the future," *Psychology & Health*, vol. 27, pp. 128–140, 2009.

[9] A. Stone and S. Shiffman, "Capturing momentary, self- report data: a proposal for reporting guidelines," *Annals of Behavior Medicine*, vol. 24, pp. 236–243, 2002.

[10] T. Conner, H. Tennen, W. Fleeson, and L. Barrett, "Experience sampling methods: a modern idiographic approach to personality research," *Social and Personality Psychology Compass*, vol. 3, pp. 292–313, 2009.

[11] P. Gomes, B. Lopes, and M. Coimbra, "Vital analysis: Field validation of a framework for annotating biological signals of first responders in action," in *EMBC*, 2012.

[12] P. Gomes, M. Kaiseler, C. Queirs, M. Oliveira, B. Lopes, and M. Coimbra, "Vital analysis: Field validation of a framework for annotating biological signals of first responders in action," in *EMBC*, 2012.

[13] J. Pallauf, P. Gomes, S. Bras, J. Cunha, and M. Coimbra, "Associating ecg features with firefighter's activities," in *EMBC*, 2011.

[14] C. Saragiotis, "Lomb normalized periodogram." http://www.mathworks.com/matlabcentral/fileexchange/22215-lomb-normalized-periodogram, last visited January 2013.

[15] G. Norman and D. L. Streiner, *Biostatistics: The bare essentials*. Peoples Medical Publishing house, 2008.

[16] S. A. E. Geurts and S. Sonnentag, "Recovery as an explanatory mechanism in the relation between acute stress reactions and chronic health impairment," *Scandinavian Journal of work environement & Health*, vol. 32, no. 6, pp. 85–123, 2006.