A Controlled Study for Measuring Stress Induced Changes of Physiologic Tremor with a Wearable Activity Sensor

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Keywords: Activity Sensor, Accelerometer, Context Recognition, Emotional Stress, Tremor.

Abstract: This work presents the results of a controlled study with the aim to quantify the effect of emotional stress on physiologic tremor. A paced auditory addition test is utilized to induce emotional stress. The tremor is measured by means of a wearable activity sensor (GENEA), were empirical mode decomposition is used to extract the tremor signal. An autoregressive model and the fractal dimension of the signal are used to construct tremor features. The result of an ANOVA test provides evidence that the stress condition increases the tremor strength compared to the control. The observed changes of the spectral properties indicate that emotional stress affects intentional tremor. These findings support the usage of wearable activity sensors for the investigation of stress-related tremor changes and the evaluation of emotional context.

1 INTRODUCTION

At its simplest level, physiologic tremor can be said to consist of two main components: mechanical and centrally nervous driven (Elble, 1986; Hallet, 1998). The contribution from each is still subject to debate, and reported values in the literature concerning this split may in part be due to the lack of standardization in experimental approach. Physiologic tremor is present in everybody, but under particular conditions its amplitude may increase by over an order of magnitude compared with standard physiologic tremor (Elble, 1986) which is referred to as enhanced physiologic tremor. Using an autoregressive model and cross-spectral analysis it has been found that enhanced tremor involves central structures (Timmer et al., 2000). Factors which may instigate an enhanced tremor state include fatigue, caffeine, and stress.

Stress is an interesting context variable in the measurement of human activity, as it affects the well-being and the performance of the individual. Emotional stress is usually assessed with the help of questionnaires. The quantification of stress levels using methods such as galvanic skin response, however, is still a challenging task which requires high expertise from the data analyst. With the advent of ubiquitous computing, digital approaches have been tested which involve mobile phone use patterns and speech analysis (Lu et al., 2012). These methods allow the identification of certain stress symptoms, while a quantification of stress levels is still elusive. Tremor, on the other hand, is relatively easy to measure, as it is well separated from the spectrum of voluntary movements. The most commonly used objective measurement techniques are accelerometry and Electromyography (EMG) - or a combination of the two (Timmer et al., 2000; Mansur et al., 2007; Godfrey et al., 2008). In this paper we measure hand tremor by means of a wearable accelerometer, and study the impact of emotional stress on the tremor features. By means of bespoke processing and analysis methods we show that the measurement of physiologic tremor by means of wearable sensors promises to be an efficient method for the real-time assessment of emotional context.

2 THE STUDY

The most commonly used experimental approach to measuring tremor is to record postural or resting tremor using accelerometer sensors (Mansur et al., 2007). This approach is adopted in the present study which investigates the increase of the tremor amplitude in healthy subjects exposed to emotional stress. The study was designed as single blind study, randomized with respect to a) the stress condition: a paced auditory addition test (PASAT) (Tombaugh, 2006) and b) the control: listening to a piece of classical music (Rachmaninov adagios). The study design

Zillmer R., Newby B. and Treloar R..
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DOI: 10.5220/0004789701780182
In *Proceedings of the International Conference on Bio-inspired Systems and Signal Processing* (BIOSIGNALS-2014), pages 178-182
ISBN: 978-989-758-011-6

is summarized in Figure 1.

A total of 15 subjects (5 male and 10 female, age 25-35) with no pathologic tremor conditions were recruited. All subjects were screened as per confidential medical questionnaire. During the test the panellist was seated, with the right arm placed on the rest of their chair. The tremor response was measured by means of a 3-axis GENEA device attached to the back of the subject's hand. The GENEA is an acceleration sensor developed by Unilever Discover (Colworth, UK) which is now distributed by Activinsights Limited (Kimbolton, UK). The reliability and performance of this sensor has been validated in several studies (Esliger et al., 2011; Zhang et al., 2012). The sensor is wireless, storing all measured data in a flash memory. Data download and initialization of the sensor is accomplished by means of a bespoke hub. During the exploratory analysis it was found that one panellist is a potential outlier. An inspection of the study records revealed that this panellist did not follow the PASAT protocol - thus this panellist has been removed from the subsequent analysis, leaving data from 14 subjects (8 control, 6 intervention).

3 SIGNAL PROCESSING AND FEATURE EXTRACTION

The accelerations were recorded with a sampling rate of 80 Hz. For the following only the vertical acceleration of the hand, a_z, is considered. After smoothing the signal by means of a moving average, the empirical mode decomposition (EMD) is used to extract the tremor signal (see (de Lima et al., 2006)). Because EMD employs an adaptive process to compute the signal envelope, it is appropriate for the analysis of nonstationary signals such as tremor. It is not *a priori* clear which intrinsic mode functions (IMF) contain the tremor signal. An inspection of the resulting frequency spectra was used as a guide, whereupon it was decided to use the sum of the first two IMF as tremor signal.

Typical tremor signals appear as noisy oscillations with one or two dominating frequencies (see Fig. 2). Such time series $s(t)$ can be modelled by a damped noise-driven oscillator model (Timmer et al., 2000). To accomodate spectra with two peaks we adopt a 4th order autoregressive model as follows:

$$s(t) = a_1 s(t-1) + a_2 s(t-2) + a_3 s(t-3) + a_4 s(t-4) + \xi(t) \; ; \quad (1)$$

where $\xi(t)$ is the driving noise. A test using the partial autocorrelation of the signals confirmed the validity of this model. The coefficients a_i reflect mechanical properties of the hand and attached muscles, which is not of interest here. The strength of the driving noise, however, defines the amplitude of the tremorous oscillations, which suggests to use the variance as measure of the tremor strength:

$$SD = \mathrm{Var}(\xi) \; . \quad (2)$$

The noise variance is estimated by standard statistical methods.

To measure changes of the tremor signal structure, the fractal dimension FD for one dimensional time series can be used. This measure is related to the roughness of the signal. The fractal dimension equals 1 for smooth signals, however, for rough signals it takes values between 1 and 2. It has been used successfully for the modelling and analysis of multi-scaled random processes and ecological data (Halley et al., 2004). A change of the fractal dimension may indicate a change in the underlying mechanism of tremor generation. For the computation of the fractal dimension we used the R package *fractaldim*, selecting the *madogram* estimator (Gneiting et al., 2010).

4 RESULTS

Typical frequency (power) spectra of the tremor signal before and after the stress intervention are shown in Figure 2 for the control and stress condition. The effect of the the stress intervention is clearly visible, resulting in an increase of the total power and an enhancement of lower frequencies around 6 Hz. In contrast, the control condition (listening to classical music) leads to a reduction of the total power.

The effect of the stress intervention on the tremor strength SD is compared with the control in the boxplot Figure 3. Here SD_1 and SD_2 are the tremor strength before (baseline) and after the intervention. These results confirm that the stress condition increases the magnitude of SD, in contrast to the control condition that tends to decrease the tremor strength. In order to validate the effect of stress on the tremor strength SD, ANOVA (analysis of variance) is used to quantify the difference between the log-ratios $\log(SD_2/SD_1)$ of the stress and the control condition. The ANOVA, based on 1 and 12 degrees of freedom and $F_{1,12} = 8.34$, results in a p-value of 0.014, i.e., good evidence that the stress condition indeed increases the strength of tremor. We now consider the fractal dimension FD. As shown in Figure 4, the stress condition leads to a decrease of FD. Because the distributions of FD are slightly skewed and have different variance for stress and control, we first use the non-parametric Kruskal-Wallis

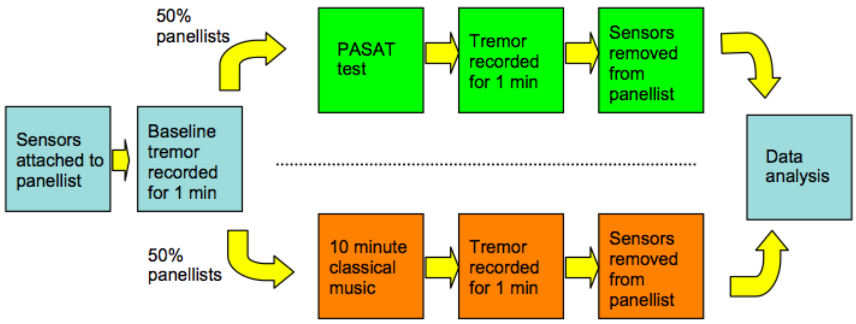

Figure 1: The design of the study to measure stress induced tremor.

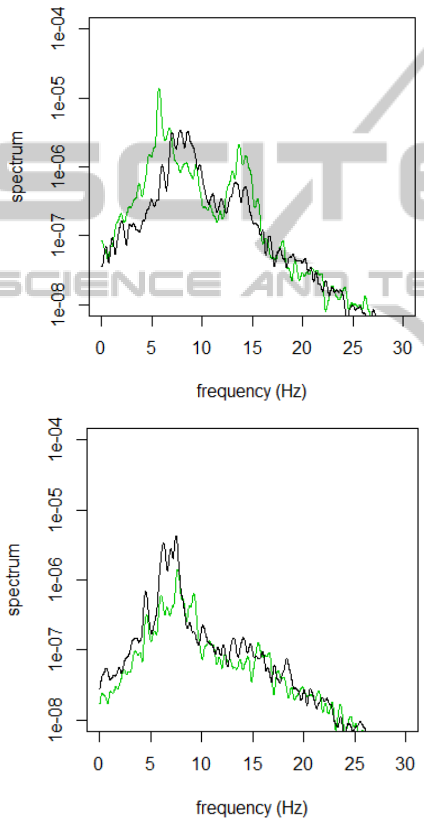

Figure 2: The tremor frequency spectrum of a panellist who was exposed to the stress (top panel) and control condition (bottom panel). Shown is the spectrum before (black) and after the intervention (green).

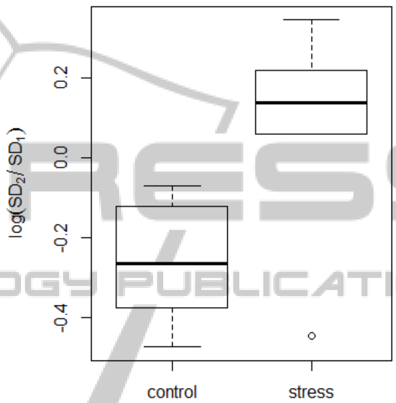

Figure 3: Boxplot of the log-ratio, $\log(SD_2/SD_1)$, for the control and stress (PASAT) condition. SD_1 and SD_2 are the tremor strength before (baseline) and after the intervention. The thick lines indicate the median while the lower and upper box edges indicate the 25th and the 75th percentile, respectively.

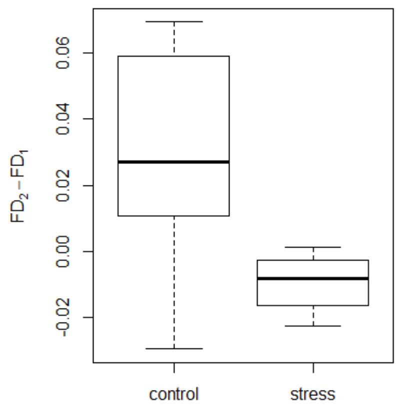

Figure 4: Boxplot of the change of the fractal dimension for the control and stress (PASAT) condition.

test (Kruskal and Wallis, 1952). The resulting statistics are $\chi^2 = 4.82$ on 1 degree of freedom and a p-value of 0.028. Additionally we use Welch's ANOVA for unequal variances, which results in a p-value of 0.014. In summary, both methods give good evidence that the stress condition decreases the roughness of the tremor signal. It could be argued that the change of the fractal dimension is related to changes of an underlying low-dimensional dynamical system. In order to test this hypothesis, signal surrogates were constructed by means of phase randomization. By construction, the surrogates have the same frequency spectrum as the original signal, while any dynamical memory is removed by the randomisation step (Kantz and Schreiber, 2005). The results for the surrogate signals are shown in Figure 5. There is no significant

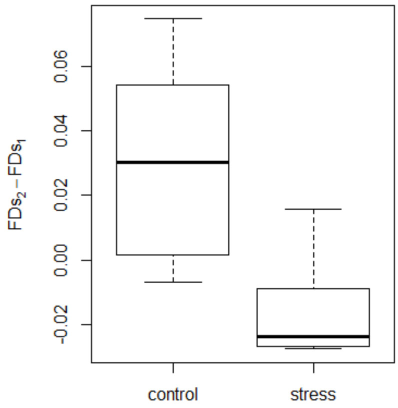

Figure 5: Boxplot of the change of the fractal dimension as computed from surrogate signals.

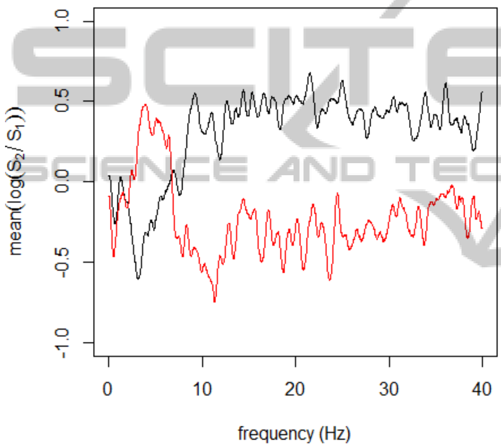

Figure 6: The average change of the normalised spectrum for the control (black) and stress group (red).

change compared to Figure 4, which indicates that the change of the signal roughness is related to changes of a linear stochastic process (as modelled by Eq. (1)).

The decrease of the signal roughness should be reflected in qualitative changes of the frequency spectra. Indeed, as shown in Figure 2, the stress condition leads to an increase of a low frequency peak around 6 Hz. To make this observation more precise, we compute the average change of the spectrum as follows:

1. For each panellist compute the normalized spectra S_1 and S_2 of the tremor signal before and after the intervention, respectively.
2. Compute the average change of the log-spectrum, $\text{mean}[\log(S_2/S_1)]$, for the control and the stress group.

The result shown in Figure 6 confirms that the stress condition enhances the power for low frequencies between 3-7 Hz.

5 CONCLUSIONS

We have presented the results of a controlled study which investigates the change of physiologic tremor as a result of emotional stress. Tremor was measured by means of a wearable accelerometer attached to the hand of the panellists. The stress group performed an auditory addition test while the control group listened to classical music. To quantify the tremorous oscillations we compute the strength of the driving noise, estimated by an autoregressive model, and the fractal dimension of the tremor signal. A comparison of the signals recorded before and after the intervention shows that stress leads to qualitative and quantitative changes of tremor. On the one hand, stress increases the overall magnitude as measured by the tremor strength. On the other, the fractal dimension (roughness) of the signal decreases as a result of the stress condition. Statistical tests confirm the validity of the observed changes. A test with surrogate signals shows that the change of the roughness can be explained by parameter changes of a linear stochastic process. The inspection of the change in the average spectra reveals that the reduction in roughness is related to an increse of spectral power of low frequencies between 3-7 Hz. This indicates that emotional stress increases the magnitude of intentional tremor, which has been observed in the same frequency range (McAuley and Marsden, 2000).

Our results show that physiologic tremor, as measured by an accelerometer, is a marker of emotional stress. However, although we observe statistically significant changes of mean quantities, there are considerable variations between subjects. Thus, in order to construct reliable stress scores based on accelerometer data, the model has to be extended to allow for additional factors such as age, gender and physiological parameters. To this end, a larger study would be required, which is beyond the scope of the pilot study presented here.

Finally, the investigation was based on measurements in a controlled lab environment. However, as physiologic tremor occurs at relatively high frequencies, its separation from voluntary activities appears feasible even in real-life settings. Thus, the usage of wearable activity sensors for the investigation of emotional stress as well as for the evaluation of emotional context is a promising topic for further research.

ACKNOWLEDGEMENTS

The authors are indebted to Sarah Paterson and Ian Mahers who helped with the design and analysis of

the study.

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