

Impact of Sensor Selection on Signal Quality of Physiological Monitoring in Demanding Conditions

Aline F. Renz¹, Ekaterina Maevskaia¹, Frederik Bauer¹, Denis Bron², Andreas Stier³, René M. Rossi^{1,4}, Simon Annaheim¹

¹ Empa, Laboratory for Biomimetic Membranes and Textiles, 9014 St. Gallen, Switzerland

² Swiss Air Forces, Aeromedical Center, Dubendorf, Switzerland

³ Armasuisse, Bern, Switzerland

⁴ Department of Health Sciences and Technology, ETH, Zurich, Switzerland

aline.renz@empa.ch

Summary:

Monitoring vital signs becomes increasingly important beyond stationary medical settings for real world applications. With the rise of wearable sensor systems, monitoring over various time windows and in dynamic environments requires new evaluation of signal quality and suitable sensor selection. In this work we highlight the importance of evaluating the signal quality of wearable electrocardiography (ECG) derived data prior to further interpretation in the highly dynamic and demanding operational environment of fighter jet pilots.

Keywords: physiology, health monitoring, sensor, wearable, signal quality

Background, Motivation and Objective

Measuring physiologically important parameters such as heart rate and heart rate variability are widely adopted across the medical and physical performance field with different sensor interfaces widely available. However, in dynamic and demanding conditions, current sensors often lack the capability for highly accurate measurements beyond the heart rate itself. However, besides heart rate, the heart rate variability provides important insight to assess stress levels and potential fatigue. Here the sensor-skin interface as well as signal robustness in high-motion environments such as fighter jets with various noise sources become important.[1] Short-term recordings often pose an additional limitation in dynamic, real-world monitoring environments. Therefore, high signal quality is required to gain relevant insight for health and performance investigations in high-pressure and demanding tasks pilots face. Evaluating signal quality before interpreting sensor data is therefore a key step for non-stationary measurement conditions where sudden changes have to be identified fast and reliable to ensure pilot safety. In this study we assessed the signal quality of a commercial and a newly developed in-house wearable

sensor system [2] monitoring heart activity through textile-based electrodes under extreme conditions such as G-force exposure.

Tab. 1: The signal quality requirements based on Pearson correlation coefficient r for the collected ECG signals. [3]

	r of QRS complex	r of PQRST complex
Class 1	≥ 0.98	≥ 0.98
Class 2	≥ 0.98	< 0.98
Class 3	< 0.98	< 0.98
Class 4	any	any

Methodology

The signal quality was assessed using a previously established signal quality algorithm [3] for ECG measurements. The signal classification in table 1 show the specific requirements for the ECG derived QRS and PQRST complex. The signals were collected from a 2 lead (commercial) and a 1 lead (in-house) wearable sensor system, both equipped with textile-based electrodes placed across the chest area. 30-second time windows pre- and post G-force exposure

were selected for the signal quality analysis. The vital sign monitoring of fighter pilots was conducted using a standardized G-Force exposure protocol (15-second exposures to 4G, 5.5G, and 7G) in a dedicated centrifuge setup (Fig. 1.1).

Results

The signal quality for both systems was assessed by using the collected data and applying the signal quality assessment algorithm and evaluating the performance for each window of interest highlighted in Figure 1.1 in yellow.

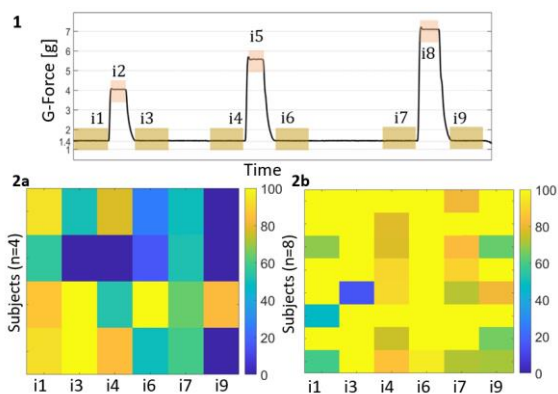


Fig. 1. Overview of G-Force profile (1) with the allocated 30-second time windows pre- and post-exposure (yellow). The corresponding ECG signal quality analysis Heatmap for the commercial (2a) and in house build (2b) wearable sensor system highlighting the percentage of data in class 1 and 2 for each subject and window.

Table 2. highlights a clear difference between the two systems across all classes, with almost equal distribution for the commercial system between class 1 and 2 to class 3 and 4. To further depict the signal quality a heatmap highlighting class 1 and 2 distribution across subjects and windows is mapped in Figure 1.2a. It shows that especially window i9 should be discarded for further heart rate variability interpretation as it would falsify the outcome. The overall low class 1 allocation for the commercial system should be considered when the aim is to investigate heart rate variability measures.

Tab. 2: Overview of Class allocation across subjects and time windows of interest for the commercial (C) and in-house (H) sensor system.

	M _C	SD _C	M _H	SD _H
Class 1	1.2%	5.8%	16.1%	29.8%
Class 2	52.7%	35.6%	72.8%	33.7%
Class 3	26.8%	31.9%	5.7%	14.9%
Class 4	19.3%	25.9%	5.5%	11.5%

Conclusion

As shown in Figure 1. (2a and 2b), the difference varies across subjects; hence, we can conclude that the superior performance of the in-house sensor system is not representative of population differences alone. In addition, the difference in signal quality couldn't be attributed to any specific subjects. This is important to note, as the two systems cannot be worn simultaneously and therefore limit the direct comparison.

Despite the better performance of the in-house solution, 20% of subjects for both sensor systems had to be excluded from the analysis due to contact issues of the sensors. This is mainly attributed to the additional gear worn on top of the sensor as well as body movements prone to errors in loose sensor-to-skin-contact. Although preliminary results, these findings highlight the importance of evaluating signal quality of sensors and potential noise sources prior to measurement interpretation, especially in human health context for dynamic conditions. Overall, the combination of our in-house developed textile-based sensor system with the consecutive signal quality analysis is a suitable tool for dynamic vital sign measures in extreme conditions. In future work a more in-depth investigation assessing the impact of dynamic parameters and environmental noise should be considered including an initial quality control prior to monitoring dedicated protocols to further reduce low signal quality recordings and subject exclusion.

References

- [1] BS. Bradke, TA. Miller, B. Everman, Photoplethysmography behind the Ear Outperforms Electrocardiogram for Cardiovascular Monitoring in Dynamic Environments, *Sensors* 21(13), 4543 (2021); doi: 10.3390/s21134543
- [2] F. Baty, D. Cvetkovic, M. Boesch, F. Bauer, NRA. Martins, RM. Rossi, O. Schoch, S. Annaheim, MH. Brutsche, Validation of a Textile-Based Wearable Measuring Electrocardiogram and Breathing Frequency for Sleep Apnea Monitoring, *Sensors* 24(19), 6229 (2024); doi: 10.3390/s24196229
- [3] NRA. Martins, F. Bauer, F. Baty, M. Boesch, MH. Brutsche, RM. Rossi, S. Annaheim, Introduction to electrocardiogram signal quality assessment and estimated accuracy for textile electrodes Acknowledgements, *Scientific Reports*, 15:41365 (2025); doi: /10.1038/s41598-025-25365-x