Smart vest for real-time measurements of physiological data

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Short abstract: Future Sky Safety is a Joint Research Programme (JRP) on Safety, initiated by EREA, the association of European Research Establishments in Aeronautics. The Programme contains two streams of activities: 1) coordination of the safety research programmes of the EREA institutes and 2) collaborative research projects on European safety priorities.

This deliverable is produced by the Project P6 "Human Performance Envelope". The main objective is to report on the testing and demonstration of a smart vest for real-time measurement of physiological data and its potential use in future cockpits.

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Acronyms

Acronym	Definition
HRV	Heart rate variability
SNS	Sympathetic nervous system
PNS	Parasympathetic nervous system
ECG	Electrocardiogram
HR	Heart rate
SDNN	Standard deviation of RR intervals (time domain HRV feature)
RMSSD	Root mean square of successive RR intervals (time domain HRV feature)
LF	Relative power of the low-frequency HRV band (0.04–0.15 Hz)
HF	Relative power of the high-frequency HRV band (0.15–0.40 Hz)
LF/HF	Ratio of LF and HF power, estimating balance between SNS and PNS

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EXECUTIVE SUMMARY

Problem Area

Physiological data allow the determination of the state of several Human Performance Envelope factors. To enable the determination of the states of the Human Performance Factors, physiological data need to be measured. As part of Future Sky Safety (FSS) Project P6 Human Performance Envelope, a smart vest has been developed to measure various physiological data. It has been used in both simulator experiments with pilots conducted in the first and third year of the Project P6. There is now a need to further develop the smart vest in order to allow a real-time measurement and analysis of physiological data. This was not possible before. The smart vest will then need to be demonstrated and shown/exhibited to stakeholders.

Description of Work

The objective of this study is to further develop the smart vest in order to allow a real-time measurement and analysis of physiological data, and to demonstrate and show the smart vest to stakeholders and users. As part of this study, the following activities are conducted:

- Development of smart vest interface module
- Visualization of physiological data
- Testing of smart vest
- Demonstration of results

Results & Conclusions

The smart-vest for the real-time measurement was successfully tested and demonstrated. Furthermore, an analysis and visualisation software was developed and tested. The results of the performance tests are provided. Overall, the new smart-vest system allows the real-time estimations of various physiological data and thus the determination of the state of different Human Performance Envelope factors.

The system is consisting of two independent sensors with Bluetooth connection, one garment (vest) with sewn slots linked together with a wire integrated into the garment, one USB charger and one Smartphone App (Android) to control the system, perform real-time signals visualization and upload recorded data from the sensors. Dedicated algorithms are embedded in the sensors in order to estimate in real time the workload as well as the stress level of the pilot.

The smart vest was demonstrated at a P6 workshop in Rome and exhibited during the Aerodays 2019 in Romania, at the Future Sky Safety stand, located in the exhibition area of the EC. It is planned to also demonstrate the smart vest during the FSS Final Event (19/20 June 2019) and the Paris Airshow 2019.

Applicability

This study addresses the usage of a smart vest in the future cockpit and what is required or best to have in order to facilitate the integration into the cockpit, and also to make the pilots eager to accept and use it.

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1 INTRODUCTION

1.1. The Programme

The European Council Flightpath 2050 vision aims to achieve the highest levels of safety to ensure that passengers and freight as well as the air transport system and its infrastructure are protected. Trends in safety performance over the last decade indicate that the Advisory Council for Aeronautics Research in Europe (ACARE) Vision 2020 safety goal of an 80% reduction of the accident rate is not being achieved. A stronger focus on safety is required.

Future Sky Safety, established under coordination of EREA (Association of European Research Establishments in Aeronautics), is a transport research programme built on European safety priorities that brings together thirty-three European partners to develop new tools and new approaches to aviation safety. The programme links the EASp (European Aviation Safety plan) main pillars (operational issues, systemic issues, human performance and emerging issues) to the Flightpath 2050 safety challenges through four themes:

- **Theme 1** (new solutions for today's accidents) aims for breakthrough research to address the current main accident categories in commercial air transport with the purpose of enabling a direct, specific, significant risk reduction in the medium term.
- **Theme 2** (strengthening the capability to manage risk) conducts research on processes and technologies to enable the aviation system actors to achieve near-total control over the safety risk in the air transport system.
- **Theme 3** (building ultra-resilient systems, organizations and operators) conducts research on the improvement of systems, organisations and the human operator with the specific aim to improve safety performance under unanticipated circumstances.
- **Theme 4** (building ultra-resilient vehicles) aims at reducing the effect of external hazards on vehicle integrity as well as reducing the number of fatalities in case of accidents.

Together, these themes and the institutionally funded safety research intend to cover the safety priorities of Flight Path 2050 as well as the ACARE Strategic Research and Innovation Agenda (SRIA) (in particular the challenges brought forward by ACARE Working Group 4 "Safety and Security"). The programme will also help coordinate the research and innovation agendas of several countries and institutions.

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1.2. Project context

Future Sky Safety P6 addresses theme 3 (building ultra-resilient systems and operators) focussed on strengthening the resilience to deal with current and new risks of the humans and the organizations operating the air transport system.

P6 builds on a concept previously proposed in the air traffic management domain, extending it to the human operators in the cockpit. The aim of the project is to define and apply the Human Performance Envelope for cockpit operations and design, and determining methods to recover crew's performance to the centre of the envelope, and consequently to augment this envelope.

The HPE is to some extent a new paradigm in Human Factors. Rather than focusing on one or two individual factors for example situation awareness or fatigue, the HPE considers a range of common factors in accidents and maps how they work alone or in combination to lead to a performance decrement that could affect safety. The safe region on the envelope is defined by human performance concepts, which can be signalled and measured, allowing the pilots to detect and recover, or enabling external agencies to prompt recovery, or allowing automation to kick in and take over.

The objectives of the project P6 are to define the Human Performance Envelope, to conduct preliminary experiments in order to select and assess sensors for measuring the Human Performance Envelope, to conduct first flight simulator experiments in order to validate the Human Performance Envelope, to validate the sensors and to identify performance decrement limits of the pilots, to develop new Human Machine Interfaces in order to recover the performance of the pilots, and finally to conduct second flight simulator experiments in order to validate the new Human Machine Interfaces.

1.3. Research objectives

The overall aim is to further develop the smart vest in order to allow a real-time measurement and analysis of physiological data, and to demonstrate and show the smart vest to stakeholders and users.

More specifically, this study has the following objectives:

- To develop the smart vest interface module
- To visualize physiological data
- To test the smart vest
- To demonstration the results

1.4. Structure of the document

Section 2 describes the smart vest, including the interface module and visualization methods used, and the results of the performance tests. A summary of the workshop demonstration is provided. Section 3 contains the conclusions and recommendations. Appendix A contains the presentation on the smart vest.

2 SMART VEST FOR REAL-TIME MEASUREMENTS OF PHYSIOLOGICAL DATA

2.1. Introduction

The present chapter reports on the development of the smart vest system which allows for real-time measurements of physiological data in view of online workload monitoring of pilots. Thanks to the exploitation action the existing smart vest system could be extended with a new interface module and a visualization tool, enabling the real-time measurement and visualization of physiological data.

We first describe the system and each of its components (smart vest, interface module, visualization tool). Then we give a brief background on the physiology of the signals measured, followed by a report on the system performance by means of an example measurement. Finally, we provide a summary report of the workshop where this system was presented.

2.2. System Overview

The smart vest system is shown in Figure 1 and each of its three components is described in more detail in the following sections.

Figure 1: Smart vest system consisting of (Left) the vest itself with two embedded sensors, (Middle) a battery-powered interface module, (Right) the visualization via a web browser on a smartphone, tablet or computer.

2.2.1. Smart Vest

The smart vest itself consists of a garment with two embedded sensors (each equipped with a battery) which allow for the acquisition of the following data:

- Electrocardiogram (ECG)
  - Measures the electrical activity of the heart. Used to determine heart rate (HR) and heart rate variability (HRV)
- Transthoracic bioimpedance
  - Used to determine the breath rate derived from the electrical resistance of the lungs.
- Skin temperature
- Accelerometer to measure activity
  - Posture: sitting, lying, standing
  - Activity class: walking, running, rest
  - Step count and cadence
  - Energy expenditure

2.2.2. Interface Module

The data measured via the smart vest is streamed wirelessly (via Bluetooth) to the interface module. This battery-powered module ensures the automatic data collection from the smart vest once it is worn and in the vicinity of the interface module. Besides doing automatic recording of the physiological signals, the interface module acts as core component for data visualization. To this end it provides a network connection (either via cable or the internal WiFi access point) which allows the connection of any web-browser-capable device such as smartphone, tablet or computer to visualize the physiological signals as described in the next section.

2.2.3. Visualization

Data visualization can be performed in any web browser on several devices in parallel. An example of data visualization is show in Figure 2. The interface shows the following signals:

- Top row, center: ECG tracing (temporal plot)
- Top row, right: HR derived from ECG
- Middle row, center: Temporal evolution of HR and time-domain HRV features SDNN and RMSSD (see section 2.3)
- Middle row, right: BR derived from transthoracic bioimpedance
- Bottom row, center: Temporal evolution of frequency-domain HRV features HF and LF (see section 2.3)
- Bottom row, right: Skin temperature

All these data are shown in real-time and updated about ten times per second.

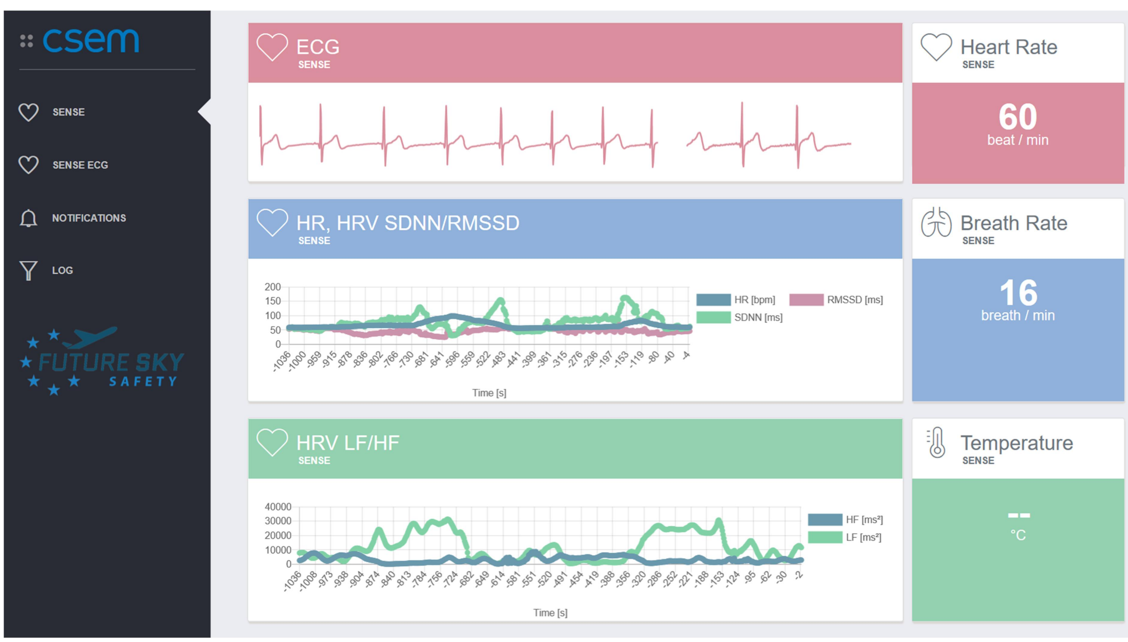

Figure 2: Visualization example of physiological signals from the smart vest via a simple web browser.

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2.3. Physiological Background

The monitoring of workload and stress of the pilots in this part of the project was mainly based on the ECG-derived heart rate (HR) and in particular its variations (HRV) [1].

HRV analysis can be used to estimate the activity of the autonomic nervous system (ANS), which is composed of the sympathetic- (SNS) and the parasympathetic nervous system (PNS). While the SNS is more active during stressful situations (*fight or flight*), the PNS is dominant during calmer situations (*rest and digest*). The relation between the ANS and HRV is due to the differences in speed at which the PNS and the SNS induce changes in HR. In brief, variations in HR due to PNS occur faster than those induced by the SNS [2,3]. Analyzing HRV thus provides an estimate for ANS activity, in particular the balance between SNS and PNS. Moreover, HRV has been shown to be a surrogate measure for stress [4,5].

Prior to HRV analysis the ECG’s R-peaks are detected and the intervals between each successor are calculated (RR intervals). Then, the so-called NN intervals are being calculated. These are RR intervals where artifacts of non-physiological origin (e.g. due to a wrongly detected R-peak), arrhythmias or ectopic beats were removed. Based on these intervals a myriad of HRV features can be extracted, as also summarized in [2]. The four HRV features provided by the smart vest are the following:

- Time-domain features
  - SDNN: standard deviation of the NN intervals. Often described as the total variability;
  - RMSSD: the square root of the mean squared difference of successive NNs;
- Frequency-domain features (via spectral analysis of different bands of frequency)
  - HF: High frequency (0.15 – 0.4 Hz), describing parasympathetic modulation;
  - LF: Low frequency (0.04 – 0.15 Hz), describing sympathetic modulation;

Note that in view of real-time visualization these features were computed over a short duration within 1 minute sliding windows (*ultra-short term* HRV [2]). While standard HRV features are mostly based on 5 minute windows (*short-term* HRV [2]), these are less suited for real-time visualization. However, as all physiological signals are being recorded by the interface module, these can be processed after each measurement in order to perform a more detailed, offline analysis.

2.4. System Performance Test

To validate the system performance an 18 minute measurement was performed on a healthy human volunteer (male adult, 33 years). During the measurement the subject underwent the following protocol targeted to induce changes in HR and HRV:

1) 3 minutes sitting, normal breathing
2) 3 minutes sitting, deep and slow (~0.05 Hz) breathing
3) 3 minutes walking around in office
4) 3 minutes lying in supine position, normal breathing
5) 3 minutes lying in supine position, deep and slow (~0.05 Hz) breathing

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The physiological signals resulting from this measurement are shown in Figure 3. The following observations confirm a successful implementation of HR and HRV analysis. First, the HR is at baseline of approximately 60 bpm during most of the measurement while it increases during walking and during the transition from lying to sitting. Second, the slow and deep respiration leads to a clear increase in the LF power as also suggested in [2]. Third, the SDNN feature shows a clear increase during HR transitions.

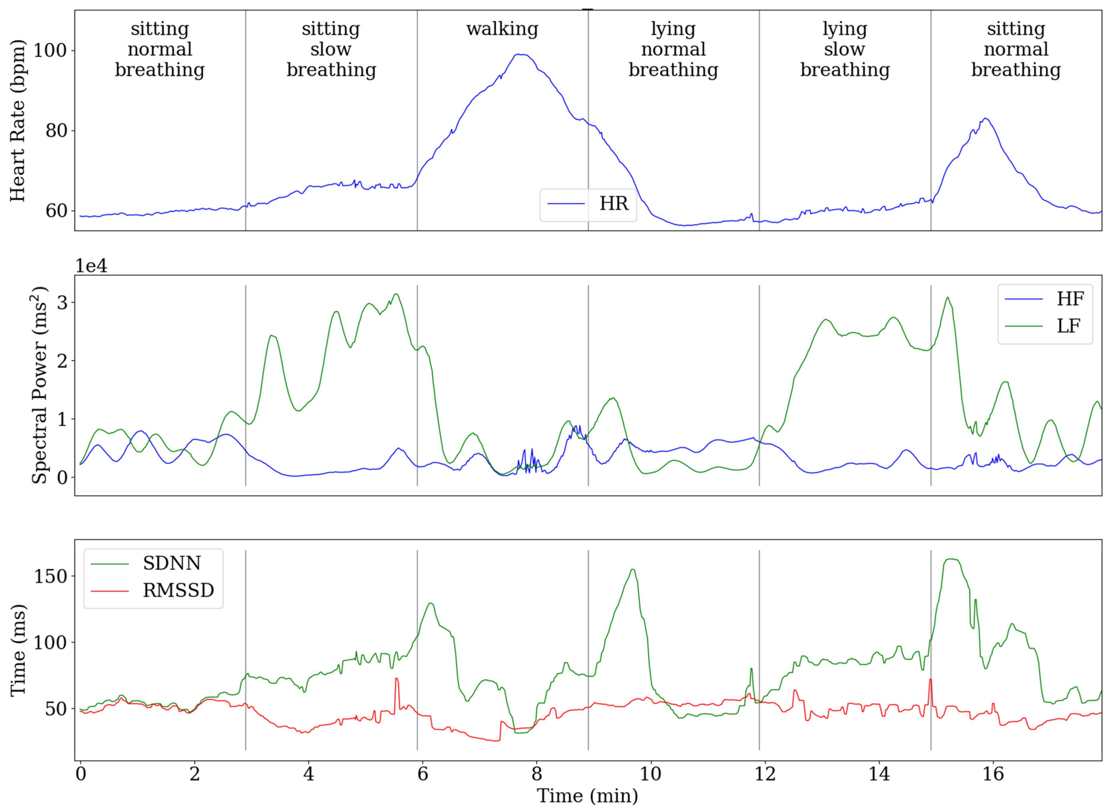

Figure 3: Temporal evolution of HR and HRV signals during the example measurement performed for validation purposes. (Top) heart rate (HR). (Middle) frequency-domain HRV features: LF and HF. (Bottom) time-domain HRV features: SDNN and RMSSD.

This example demonstrates the successful use of the smart vest under controlled conditions. HR and HRV did not vary due to stress but due to specific postural changes and orchestrated breathing exercises.

2.5. Workshop Summary

The smart vest system was presented at a workshop in mid-Mai held at DeepBlue in Rome, Italy. Besides a real-time demonstration of the system, its performance validation (see section 2.4) was also presented and discussed.

In addition there was a discussion regarding the most appropriate physiological signals to assess the pilot's workload. HR and HRV alone might not be enough to provide a proper assessment and it is known that the relationship between workload and physiological signals can be quite complex, i.e. there is not

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one single measurement modality which allows for a straightforward assessment of a pilot's workload [6]. The following combination of measurement modalities has been proposed to be used in future investigations:

1) Respiratory rate;
2) Galvanic skin response (GSR) / electro-dermal activity (EDA);
3) HR and HRV;
4) Blood pressure.

In future work these parameters should be investigated in wearable devices, e.g. using a smart watch.

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3 CONCLUSIONS AND RECOMMENDATIONS

3.1. Conclusions

We report on the successful development of the smart vest system which allows for real-time measurements and recording of physiological data in view of online workload monitoring of pilots.

The functional system provides real-time estimations of HR and HRV, related to the pilot's workload. It was successfully tested and demonstrated at the final workshop of P6 in Rome.

Furthermore, the smart vest was demonstrated at various Future Sky Safety meetings and to external parties at the second external Future Sky Safety workshop in November 2018 and at the AEROdays 2019 in Bucharest.

3.2. Recommendations

The relationship between workload and physiological signals is complex and not straightforward [6]. Besides HR and HRV, other physiological signals – such as respiratory rate, galvanic skin response and blood pressure – should be investigated in the future to improve the physiology-based workload estimation.

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4 REFERENCES

1. Silvagni S, Graziani I, Berberian B, Grossenbacher O, Kirwan B, Le Blaye P, et al. Development of the Human Performance Envelope Concept for Cockpit Operations. 6th EASN International Conference on Innovation in European Aeronautics Research. Porto, Portugal; 2016.
2. Shaffer F, Ginsberg JP. An Overview of Heart Rate Variability Metrics and Norms. Frontiers in Public Health. 2017;5. doi:10.3389/fpubh.2017.00258
3. Ernst G. Heart rate variability. London, UK: Springer; 2014.
4. Kim H-G, Cheon E-J, Bai D-S, Lee YH, Koo B-H. Stress and Heart Rate Variability: A Meta-Analysis and Review of the Literature. Psychiatry Investigation. 2018;15: 235–245. doi:10.30773/pi.2017.08.17
5. Castaldo R, Melillo P, Bracale U, Caserta M, Triassi M, Pecchia L. Acute mental stress assessment via short term HRV analysis in healthy adults: A systematic review with meta-analysis. Biomedical Signal Processing and Control. 2015;18: 370–377. doi:10.1016/j.bspc.2015.02.012
6. Charles RL, Nixon J. Measuring mental workload using physiological measures: A systematic review. Applied Ergonomics. 2019;74: 221–232. doi:10.1016/j.apergo.2018.08.028

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APPENDIX A SMART VEST PRESENTATION

Below are the slides of the presentation of the smart vest given at the final workshop of P6 in Rome.

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Background

- Many safety critical domains rely on human operators (**Air traffic control**, **Aviation**, Maritime, Rail, Military, Medical, etc.)
- Need to know when human operators are approaching the **edges of acceptable performance**, e.g. when should automation take over?
- One way to track human operators' performance is to **monitor significant physiological signals.**
- Equip operators with **wearables containing sensors.**
- **Evaluate** measured signals **and alarm in critical situations.**

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CSEM's smart vest

- **1-lead electrocardiogram (ECG):**
  - **Heart rate**
  - **Heart rate variability (HRV)**
- Trans-thoracic **bio-impedance**
  - Breathing rate
- **Skin temperature**
- **Activity**
  - Posture: Sitting/Lying/Standing
  - Walking/Running/Rest
  - Steps/Cadence
  - Energy Expenditure

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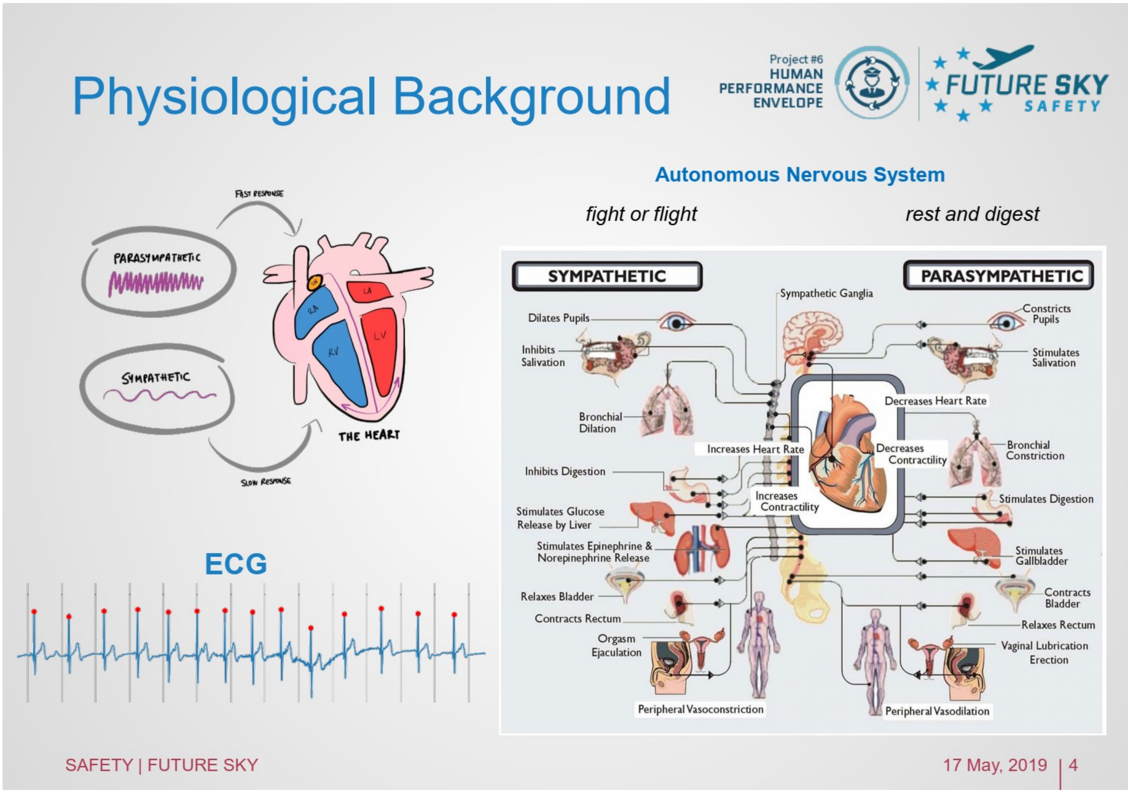

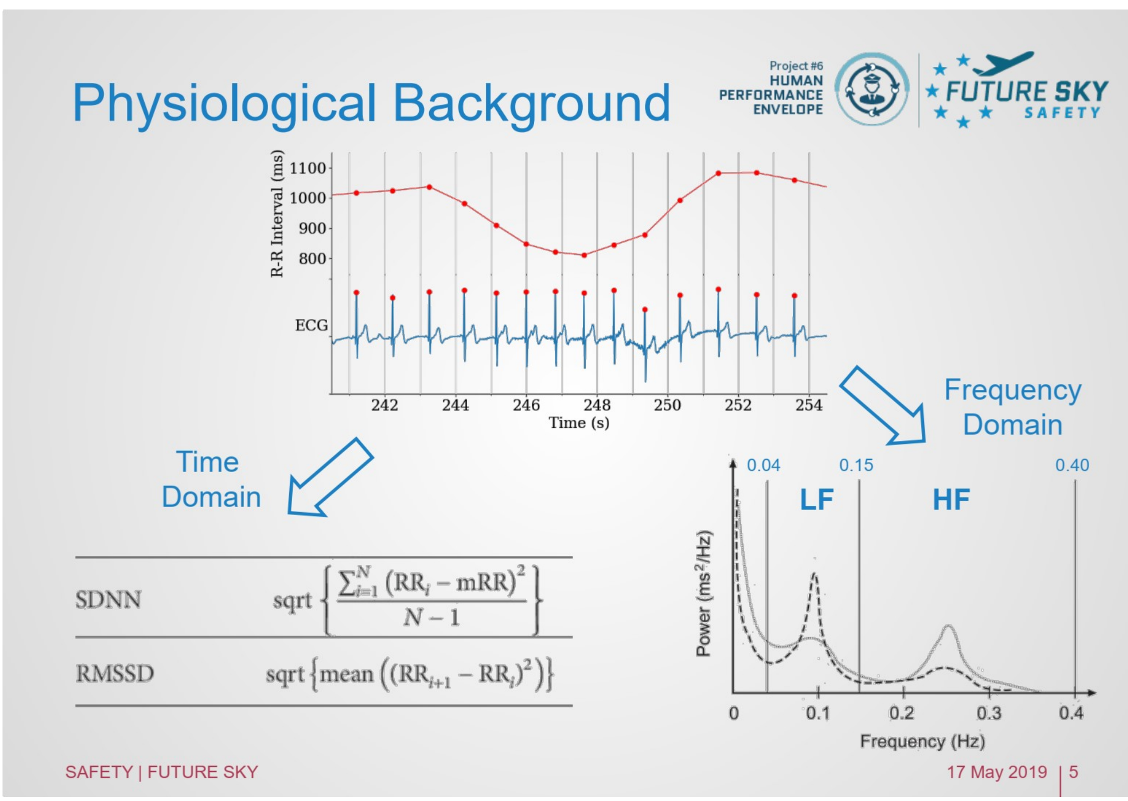

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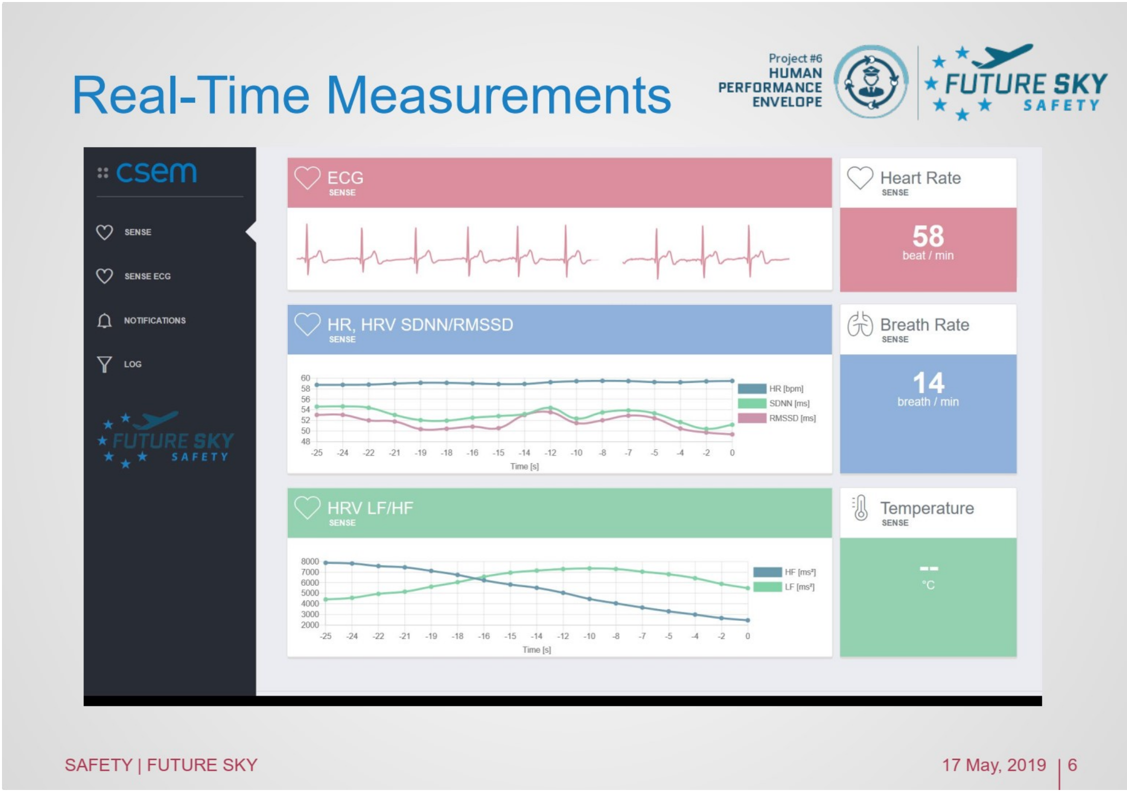

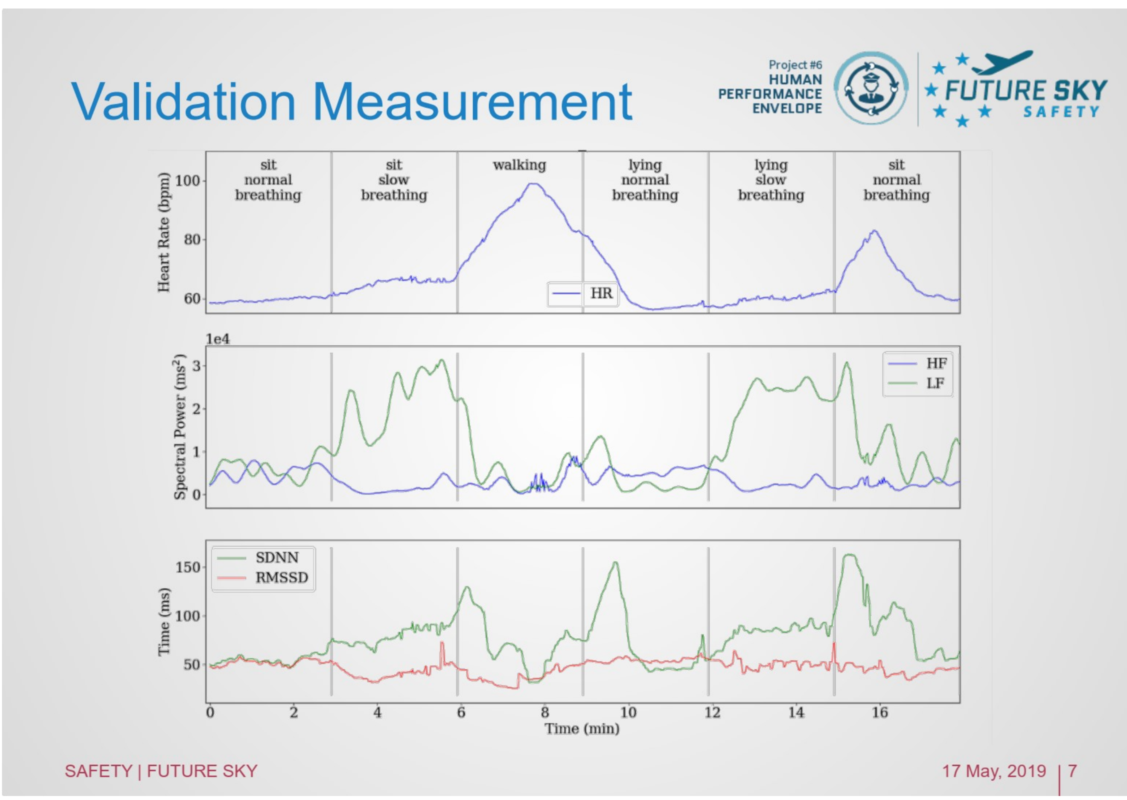

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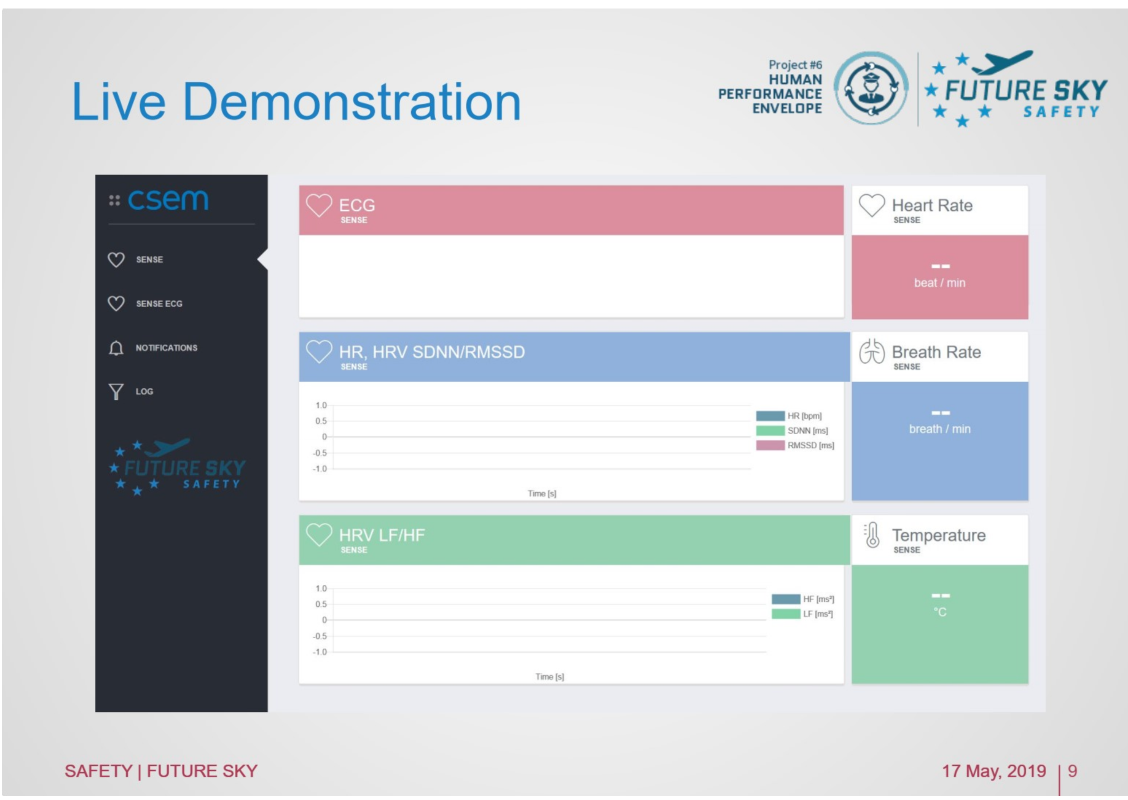

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