Headquarters Papers
#UOET Proceedings 2023
https://www.milak.at/nike/uoet

doi: 10.5281/zenodo.10673024

Stress Modelling based on Specific Stress Characteristics of Various Military and Civil Forces for a Real-Time Stress Monitoring

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Abstract: In recent decades, the development of autonomous cyber-physical systems for a wide range of tasks has been the focus of research activities for military organisations. Humans are still at the center of deployed sociotechnical systems and therefore extensive development projects have been launched for the psycho-physiological monitoring, with new possibilities arising from innovative developments in the field of biosensor technology. The aim is to optimise human performance in the field and the interaction between man and machine with intelligent mission equipment.

Key Words: Real-Time Physiological Stress Monitoring, Wearable Biosensors, Physiological Stress Model, Core Body Temperature, Load-Speed-Index.

1. Introduction

The well-being and effectiveness of soldiers or civilians in military or first responder operations are of central importance. Monitoring their psychophysiological state of stress plays a crucial role in ensuring their safety and increasing their effectiveness. One cutting-edge technology that has revolutionised this aspect is the Real-Time Psychophysiological Status Monitoring (RT-PSM). Using wearable sensors and advanced data analysis techniques, the system can track key indicators such as heart rate, core body temperature, respiratory rate and stress markers. This continuous monitoring provides a comprehensive understanding of stress levels, enabling timely intervention and preventative measures.

Reduced concentration and reaction can lead to delayed or even incorrect decisions, which can have fatal consequences (Witzki et al., 2011). Statistical evaluations by the US Army Combat Readiness Center (Thomas et al., 2006) show that approximately 80-85% of all military accidents are directly related to cognitive performance impairment. High physiological stress can degrade cognitive performance in critical situations (Hancock and Vasmatzidis, 2003; Bermejo et al., 2019). By analysing psychophysiological data in real time, the RT-PSM system can detect and identify high-stress situations experienced by soldiers. By identifying these stressors in a timely manner, commanders and medical personnel can take appropriate action, such as providing immediate stress-reduction techniques, modifying mission parameters, or providing necessary rest and recovery periods.

The research project *VitalMonitor* therefore focuses on the development of (I) a real-time monitoring system that analyses changes in physiological parameters such as heart rate, heart rate variability, skin conductance, core body temperature, etc., (II) development of a stress model considering load characteristics of different military branches, (III) a communication solution for real-time data transfer, (IV) a data management and

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interactive real-time visualisation module to support decision processes for mission commanders in determining optimal work/rest cycles to avoid physical overload during training and missions, and (V) an expert interface to visualise sensor data streams (low-level data) together with model-based analysis results (high-level data) in a graphical interface as a commanders' interface for decision making.

This paper gives an overview of the main developments and results implemented and achieved within the Austrian *VitalMonitor* project.

2. Methods

a. Sensor Evaluation

As part of the project, a comprehensive evaluation of potentially applicable sensor technology was carried out to test the existing smart shirt solution in combination with selected additional sensors according to the operational requirements. A step-by-step plan was devised to examine the sensor technology's effectiveness and practicality for military operations by subjecting it to different conditions. The plan consisted of four distinct phases, ranging from laboratory evaluations, to evaluations in standardized military exercise scenarios, up to a realistic training and exercise scenarios in the field. The first two phases involved laboratory testing on moderately trained individuals. The aim was to evaluate the accuracy of the smart shirt solution for measuring heart rate (HR), respiratory rate (RR) and skin-based core body temperature (CBT) under (i) standard climatic conditions during an incremental exercise test on an ergometer followed by (ii) an incremental exercise test on a treadmill under hot and humid conditions (room temperature 34-36°C; humidity 60-80%). The data obtained from the advanced sensor technology were compared to established benchmarks for accuracy.

Subsequently, the evaluation progressed to military personnel, starting with a controlled exercise during an annual CBRN-defense training simulation involving active soldiers. The soldiers wore the sensor setup beneath their full CBRN personal protective equipment. To ensure the accuracy of the sensor data, a data verification and validation pipeline was developed. This pipeline involved several checks, such as assessing signal quality, identifying missing data, ensuring adherence to reasonable boundaries, and verifying the expected behavior of the sensors under various external stressors, such as physiological strain or recovery.

In addition, usability tests to determine the optimal fit of the sensor equipped smart shirt were conducted with two different groups of soldiers (infantry, CBRN-defense) from the Austrian Armed Forces. Participants completed a branch-specific scenario designed by infantry and CBRN-defense experts, respectively. Infantrymen marched 4-6 kilometres with full personal and platoon equipment (average additional load 54.9 ± 7.6 kg = 70 ± 14% of body weight). Subsequently they approached a target area and attacked an urban area for 2 kilometres at 0.5 km/h (average additional load 43.5 ± 3.7 kg = 55 ± 9% of body weight). The CBRN-defense soldiers performed various CBRN-defense specific tasks for a full duration of sixty minutes, wearing full CBRN personal protective equipment and the necessary kit (average additional load: 28.6 ± 1.7kg = 35.0 ± 4.8%). After completing the branch specific scenarios, the participants were asked to complete a questionnaire developed by the Austrian Armed Forces Sports Centre, which contained eleven questions with space for additional comments on specific questions.

b. Load Model Development

The *VitalMonitor* project aimed to create a model that could objectively evaluate the physical stress experienced by military personnel during training and exercise scenarios. This assessment considered both internal factors, such as heart rate, respiration rate, and core body temperature, as well as external factors like activity level, movement speed, external load, and ambient temperature. These factors interacted with each other and influenced the individual's physical response. Initially, the project focused on identifying the most suitable parameters for monitoring the physical condition of soldiers in specific military branches, including CBRN-defense, light infantry, and explosive ordnance disposal personnel. Established literature (Wonisch & Ledl-Kurkowski, 2017; Godehardt, 2018; Hunt et al., 2016) and input from military experts were used to define thresholds and zones for each parameter. Based on this, the load model categorized each parameter into six different zones and applied a specific logic to combine them. The initial model was further refined to allow for weighting of individual parameters based on the activities being performed. Parameters associated with more physically demanding activities could be assigned higher weights to account for increased physiological stress.

3. Results

a. Evaluation

In the first study the measurement accuracy of the smart shirt for determining heart rate, respiratory rate and core body temperature under standard climatic conditions during an incremental exercise test on an ergometer was performed. The results of the sensor evaluation revealed that the proper fitting of the smart shirt and an adequate warm-up phase were crucial for optimal conductivity of the ECG electrodes integrated into the shirt. In the second phase of the sensor evaluation tests, exercises were performed on the treadmill under hot and humid conditions (room temperature of 34-36 °C; humidity of 60-80%) (Figure 1). The aim of the work was to evaluate the measurement accuracy under hot and humid conditions and increased upper body movement. However, no heat or movement related decrease in measurement accuracy was observed for either the smart shirt or the skin-based core body temperature sensor. The results under hot and humid conditions coincide with the results of the testing under standard climatic conditions for the first two test phases in a laboratory setting.

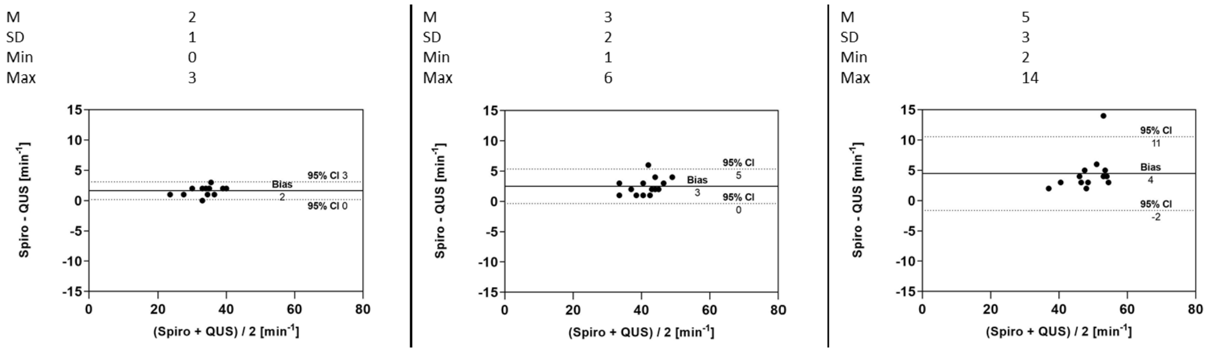

Figure 1: Absolute differences for respiratory rate expressed in mean, standard deviation, min and max values for LTP1 (ri), LTP2 (mid), and maximum load (le). Reference system Cortex MetaMax 3B spiroergometer.

During the annual CBRN-defense training simulation some participants experienced partial data loss or overall noisy ECG signals, leading to inaccurate readings of heart rate and heart rate variability. Similarly, the accuracy and signal quality of the temperature sensor improved with a longer warm-up phase. The recorded and averaged CBT measurement values were found to be reasonable (Table 1). However, real-time measurements exhibited a slight delayed increase in core body temperature compared to the reference values obtained from the ingestible capsule (*BodyCAP eCelsius*).

Table 1: Non-invasive CBT measurements via skin sensor (*greenTEG CORE*) compared to ingestible capsule (reference)

	n	Approach	Sampling	Separating sources	Decon	March back
CBT + HR	18	**37.63** ± 0.09	**37.87** ± 0.05	**37.96** ± 0.03	**38.08** ± 0.03	**38.18** ± 0.03
CBT	18	**37.68** ± 0.04	**37.87** ± 0.07	**38.02** ± 0.03	**38.11** ± 0.03	**38.25** ± 0.05
Reference	18	**37.52** ± 0.05	**37.64** ± 0.05	**37.81** ± 0.05	**37.91** ± 0.03	**37.93** ± 0.01

Values expressed as °C mean ± standard deviation. CBT + HR: algorithm additionally uses heart rate (HR)

The usability evaluation of the smart shirt solution showed that infantrymen and CBRN-defense personnel were generally satisfied with the solution. Three areas were identified as tending to be problematic, although the means of the responses were below the median (continuous scale from 0-10: zero = strongly disagree to ten = strongly agree): poor comfort (mean 2.7 ± 2.8), problems with additional equipment (mean 2.5 ± 3.6) and increased perspiration (mean 4.8 ± 3.7) (see Table 2). There were isolated written comments about skin irritation due to the sensors in the smart shirt, increased pressure on the back of the neck due to the processing unit and increased perspiration. In summary, participants found the smart shirt solution to be usable and comfortable to wear. To increase comfort and reduce perspiration, a reduced version of the smart solution was used for the CBRN-defense tests. This reduced version of the shirt is similar to a woman's bra. CBRN-defense personnel still cited increased perspiration as the main problem.

Table 2: Mean values for selected questionnaire answers by Infantry, CBRN-defense and combined

	n	poor wear comfort	shirt causes discomfort	shirt affects movement	poor mobility	problems with additional gear	restricted breathing	increased sweating	poor operability
Infantry	59	**2.9** ± 2.9	**1.1*** ± 2.4	**0,7** ± 1.1	**0,5** ± 1.2	**2,9*** ± 3.8	**0,9** ± 2.1	**4,9** ± 3.8	**0,7** ± 1.9
CBRN-defense	22	**2,1** ± 2.6	**0,1*** ± 0.2	**0,7** ± 1.2	**0,5** ± 0.9	**1,0*** ± 2.2	**0,9** ± 1.6	**4,5** ± 3.6	**0,3** ± 0.8
combined	81	**2,7** ± 2.8	**0,8** ± 2.1	**0,7** ± 1.2	**0,5** ± 1.1	**2,5** ± 3.6	**0,9** ± 1.9	**4,8** ± 3.7	**0,6** ± 1.6

Values as mean ± standard deviation; scale 0-10 → 0 = strongly agree; 10 = strongly disagree; * measured Infantry vs. CBRN: Student's unpaired t-test t = -3.389 (*p* <0.001) and Welch test t = -2.694 (*p* = 0.010)

b. Load Model

After several test runs in different training and exercise scenarios and the subsequent evaluation of the collected data, certain parameters of the load model turned out to be very suitable, others partly unsuitable, in order to survey the individual stress of the soldiers and to adapt the stress model individually to the different requirements. For the CBRN-defense e.g. walking speed was negligible whereas for the light infantry it turned out to be a significant parameter. Therefore, a new index "Load-Speed-Index (LSI)" based on walking speed and payload was implemented. The LSI can be used as a predictor on how long the soldier can endure this particular situation with a constant load (Drain et al., 2016). Also parameter thresholds were adapted (CBT, RR) based on these tests and empirical knowledge from military experts. The final model for the determination of psychophysical stress includes the parameters body-core temperature (CBT), heart rate (HR), respiratory rate (RR) and the load-speed-index (LSI). The measured values are weighted to each other and combined using a predefined logic, making it adaptable to different military activities (Figure 2). An overall score can be determined, allowing for a quick assessment on the soldiers' state, which is also highlighted in a certain colour scheme in an interactive visualization described in the following chapter.

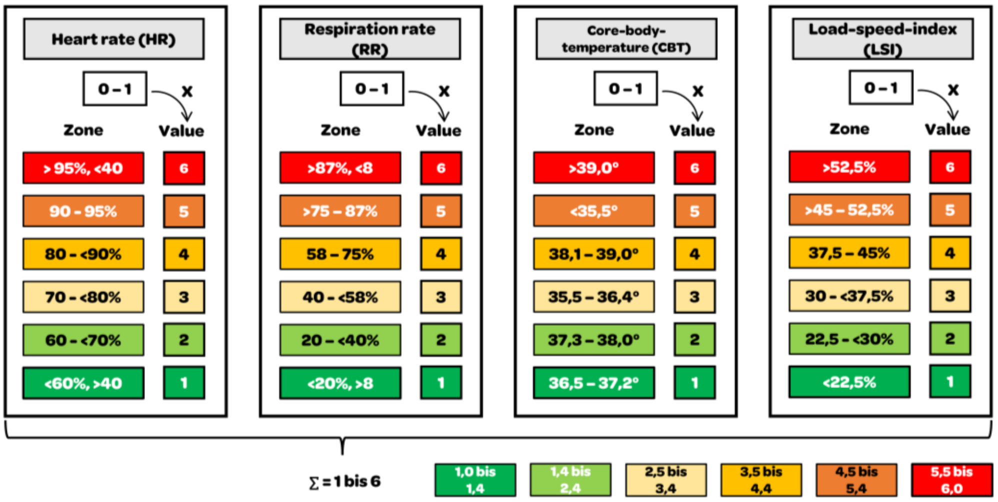

Figure 2: Load model with parameters, zones and overall load score.

c. Interactive Real-Time Visualization

In *VitalMonitor*, a RT-PSM system to support time-critical decisions was developed together with domain experts of the Austrian Armed Forces and the Federal Ministry of Denfence. It provides real-time monitoring the physiological status of the soldiers, implementing the previously described individual load model. The RT-PSM offers various functionalities organized into different levels of detail (Figure 3). The first tab provides an overview of the physiological status of all soldiers in the field, with a specific focus on four vital parameters. The overview incorporates the load model, presenting an overall load score through a six-stage traffic light system and corresponding pictograms. Thresholds are predefined according to given anthropometric data and data from standardized performance tests, but can be adapted individually to the branch or scenario by domain experts. Additionally, a historical graph is available to track individual load score over time. For a more detailed analysis, a second tab displays a line graph for each recorded vital parameter. Below the graph, a timeline presents the history of traffic light states for each individual parameter, as well as the Load Stress Index (LSI) and the overall score of the load model. This comprehensive representation allows for an assessment of the future direction of the physiological status, both on a parameter-specific and an overall score level.

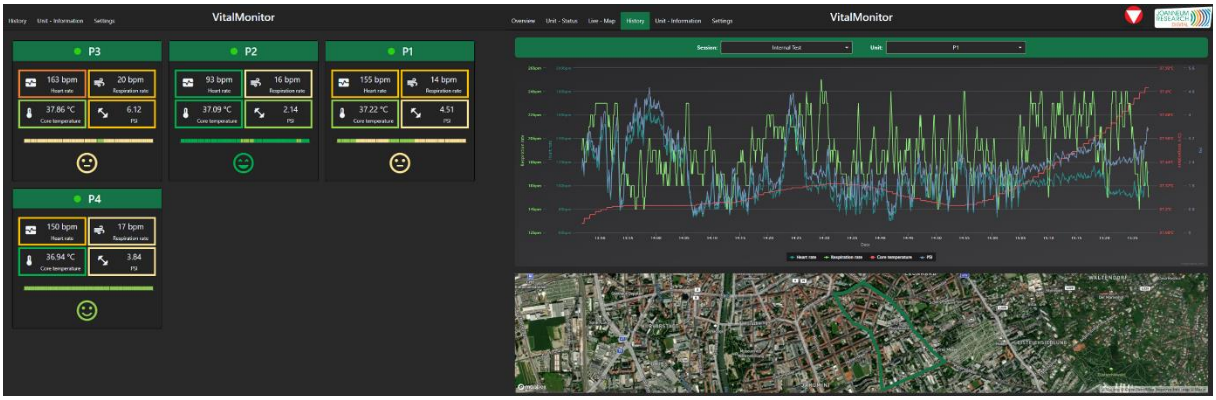

Figure 3: Examples of VitalMonitor real-time visualisation of vital parameters, thresholds, stress index and location.

The *VitalMonitor* system underwent a rigorous evaluation during a large-scale international CBRN-defense live exercise held in Suffield, Alberta, Canada. This exercise, known as "Precise Response," has been conducted annually since 2004 and focuses on CBRN reconnaissance and decontamination capabilities serving also as a platform for testing new developments in a multinational setting. The exercise posed a specific challenge due to the physical demands of working in protective gear under high temperatures, which can lead to an increase in core body temperature of the soldiers. To analyse the resulting stresses and mitigate heat-related emergencies, the *VitalMonitor* system was tested as part of the exercise. It implemented novel methods and procedures to assess the real-time physical condition of soldiers, thereby providing valuable information for decision-making by military commanders. This allowed for a comprehensive evaluation of the system's performance in a realistic operational environment with the aim of enhancing operational effectiveness and soldier safety.

Figure 4: VitalMonitor at the exercise Precise Response in Suffield, Alberta, Canada.

4. Conclusion and Outlook

The implementation of RT-PSM systems in monitoring the psychophysiological stress state of soldiers in military units, such as the infantry or CBRN-defense, brings significant benefits. By continuously monitoring and analysing soldiers' psychophysiological parameters, the system enables timely interventions, optimized resource allocation, and informed decision-making. This ultimately ensures the safety of soldiers and enhances operational efficiency. The real-time nature of the system allows for immediate responses to high-stress situations, enabling commanders to provide necessary support and reduce the risk of injuries and illnesses. Furthermore, the long-term data trends collected by RT-PSM offer insights into training effectiveness, mission planning, and soldier well-being, facilitating continuous improvement in military operations. The use of RT-PSM systems for monitoring the psychophysiological stress state of soldiers is a rapidly evolving field, and its future holds promising advancements. Continued research and technological innovations can further enhance the capabilities of these systems, leading to even more precise monitoring, analysis, and intervention strategies. Integration with Artificial Intelligence and Machine Learning algorithms can provide more focused as well as integrated data analysis in order to enable predictive capabilities, enabling commanders to anticipate and address stress-related issues proactively. Additionally, advancements in wearable sensor technology and data transmission systems may lead to more seamless and unobtrusive monitoring, enhancing soldier comfort and usability. The impact of physiological stress on cognitive performance is specifically relevant in decision–making (Schneeberger et al., 2022) and substantiates a future research trajectory that is of high importance for the success of complex missions. Immersive simulation environments for first responder training provide performance results that are comparable to field trials (Reim et al., 2022). In this context, first results of AI-supported research demonstrate that wearables with biosensors provide substantial information to predict situation awareness as a key feature of cognitive readiness (Paletta et al., 2022). Furthermore, the integration of RT-PSM with other military systems and networks can create a comprehensive battlefield awareness and health management ecosystem. By sharing real-time psychophysiological data with commanders, medical personnel, and tactical decision-making platforms, a holistic understanding of soldiers' stress states can be achieved, enabling optimized resource allocation and mission planning.

5. Acknowledgment

This work was funded from the Austrian Defense Research Programme FORTE, the Austrian Research Promotion Agency (FFG) and the Austrian Federal Ministry of Finance.

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