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The Use of Wearable Systems for Measuring Biomedical Data in Special Units – Current State and User Evaluation

L. Leová[1*], V. Křivánek[2], H. Schvach[3], M. Sokol[1], P. Volf[1,3], J. Hejda[1,3], and P. Kutílek[1,3]

[1] *Department of Health Care and Population Protection, Faculty of Biomedical Engineering, Czech Technical University in Prague, Kladno, Czech Republic*
[2] *Department of Military Robotics, Faculty of Military Technology, University of Defence, Brno, Czech Republic*
[3] *Department of Military Medical Service Organisation and Management, Faculty of Military Health Sciences, University of Defence, Hradec Králové, Czech Republic*

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Abstract:

The service of special units demands high physical and mental endurance, exposing personnel to danger, stress, and CBRN threats that cause long-term exhaustion. Wearable systems offer a promising means to monitor biomedical data, enhancing intervention effectiveness and responder safety. This article reviews current wearable technologies, proposes a user evaluation procedure, and assesses their usability in operational contexts regarding ergonomics, functionality, and benefits. Five commercial systems (Garmin Tactix 7, Movesense Flash, Hexoskin Smart Shirt, Cosinuss° One, Ultrahuman Ring) were tested by the COMMANDOS unit. Results showed the Movesense Flash system had the best usability and reliability. Findings highlight the potential of commercial wearables for special operations, despite trade-offs between comfort, accuracy, and practicality.

Keywords:

wearable systems, special units, biomedical monitoring, comparative analysis, remote biomonitoring

1 Introduction

The service of special units is highly demanding and involves a wide range of tasks requiring precise coordination, quick decision-making, and a high level of physical

* *Corresponding author: Department of Health Care and Population Protection, Faculty of Biomedical Engineering, Czech Technical University in Prague, Sítná 3105 sq., CZ-272 01 Kladno, Czech Republic. E-mail: leovalyd@fbmi.cvut.cz. ORCID 0000-0002-3460-7914*

and mental preparedness [1]. These units are designated for combat operations, reconnaissance of enemy territory, counterterrorism missions, and hostage rescue, often operating abroad or in hostile environments [1, 2]. The units also face many risks, including direct physical danger during operations, psychological stress associated with high responsibility and both stress and health risks resulting from exposure to chemical, biological, or radiation threats, and the long-term consequences of physical and mental exhaustion [1-4]. The success of their operations depends on thorough training, modern equipment, and the ability to work as a team [2]. Realtime monitoring of physiological parameters and physical activity metrics can not only reduce the risk of human error during critical phases of an operation, but also provide valuable data for planning, evaluating, and optimizing tactical and training procedures [3].

Wearable systems appear to be a promising technology that can significantly increase the effectiveness of operations by remotely monitoring vital signs while improving the safety of units, especially in demanding and high-risk conditions [3-6]. Their rapid development in recent years, combined with the decreasing cost of available sensors, already enables the near mass deployment of this technology in practice. A large proportion of commercial products that monitor biomedical data were originally developed for fitness and healthcare applications [6, 7]. The aim of this article is to analyze the current state of wearable systems designed for monitoring biomedical data within special units. It also seeks to evaluate the usability of these technologies in the operational deployment of these units, particularly in terms of their user comfort, functionality, and practical benefits.

1.1 Overview of the Current State

The wearable technology market began to take shape in the 1970s. It has seen significant growth in recent years, mainly due to the popularity of fitness trackers, smart watches, and devices focused on users' health and physical activity [7, 8]. This trend has accelerated the development of technologies in the areas of miniaturization, wireless transmission, and the integration of multiple sensor units into a single device. Currently, wearable systems exist in various forms, and their specific uses vary according to specific needs. These include, for example, smart watches and fitness wristbands, chest straps, complex systems in the form of smart clothing, and innovative solutions of recent years such as ECG patches, smart rings, and ear sensors [8-10].

The most widespread category of wearable electronics are smart bracelets/watches [7, 11]. Basic fitness bracelets (e.g., Xiaomi, Fitbit) can be purchased at a relatively low price (€20–80), but their functions are quite limited [11]. Advanced models, such as Apple Watch, Garmin watch, or Huawei watch, allow monitoring of several parameters (HR, HRV, physical activity, stress, sleep tracking). However, their price is significantly higher (approx. €200–1 000) [11, 12]. Chest straps are widely popular among competitive athletes, as they can monitor heart rate and other parameters (HRV, breathing, etc.) with relative accuracy. Prices in this category vary depending on the type of design, brand, and features. For example, Polar and Garmin belts cost up to €120, while Movesense costs around €250 [11, 13]. Comprehensive wearable systems are also appearing on the market. These include smart T-shirts/vests with integrated sensors for recording ECG, movement, breathing, and other parameters. Examples of such solutions include Hexoskin from a Canadian company or Zephyr BioHarness from a British company. The price of these devices is several times higher than in the previous categories, with a base price ranging from €815

[6, 11, 14]. As already mentioned, in recent years, the focus has also been on miniaturizing electronics and developing alternative forms of wearable devices. ECG patch systems are also available on the market. These are either disposable or reusable self-adhesive sensors. An example is the VitalConnect system, which costs around €200 [6]. For civilian purposes, we can mention smart rings, which have similar functions to smart bracelets/watches. Examples of such solutions include the ŌURA Ring Gen 3, Ultrahuman Ring, and Circular Ring. The price of these devices ranges from around €245 to €400 [11, 15]. Ear sensors constitute a specific category. The Cosinuss° One device, for example, is available on the market at a price of around €285 [6, 16].

In recent years, large technology companies and research organizations such as the US Air Force Research Laboratory (AFRL), BAE Systems in the UK, and Rheinmetall in Germany have also focused on the development of wearable technologies, including complex systems for the military. These companies are developing advanced systems for monitoring and recording physiological functions. The AFRL research laboratory offers a mobile software tool designed for wireless monitoring of vital functions (finger sensor) and digital recording of soldiers' health status, known as the BADTOK (Battlefield Assisted Trauma Distributed Observation Kit) system [17]. This system is primarily intended for rescue missions and is part of the 711th Human Performance Wing. Currently, the Air Force Research Laboratory (AFRL) is working with JOMIS (Joint Operational Medicine Information Systems) to improve this feature so that it can be deployed across all branches of the Department of Defense [17]. BAE Systems [18] presents an innovative approach to integrating energy and data infrastructure directly into the textile structures of a soldier's equipment. This technology allows various electronic devices (e.g., radios, sensors, night vision devices) to be directly connected to a tactical vest, jacket, or belt via built-in connectors and USB interfaces [18]. Rheinmetall offers a comprehensive system called GLADIUS 2.0 [19]. It is a modular military system that can be adapted to different units, from light infantry to special forces to commanders. The system consists of several variants that differ in terms of equipment and expansion options. However, the basis is equipment with data and energy infrastructure that is connected via tactical radio, GPS, smart display devices, and headsets. The Multirole version, designed for special forces, also features smart textiles for biomonitoring [19].

2 Methods

2.1 Analysis

The aim of this method was to identify various design types of wearable systems that enable the monitoring of biomedical parameters relevant for use in extreme operating conditions. Products available on the market cover a wide range of technical solutions, i.e., smart textiles, devices with integrated sensors, various wearing locations, monitoring of countless parameters, etc. This analysis included commercially available products that differ mainly in the way they are placed on the body, in their design, and their ability to monitor biomedical data. The aim of this method was to include various approaches regarding their possible application in military deployment, especially for members of special units. The following products were selected for this analysis: Ultrahuman ring S10 [15], Garmin Tactix 7 [12], Hexoskin Smart Shirt [14], Movesence Flash [13], and Cosinuss° One [16]. This selection forms the basis for subsequent experimental verification and comparative analysis.

2.2 Experimental Testing of Systems

Experimental testing of the systems was conducted to verify the criteria established in the comparative analysis (Section 2.5), specifically to confirm their functionality and assess their potential for operational deployment. The results of the experiment made it possible to assess the differences between the theoretical properties of individual devices and their potential applicability under stress conditions. Pilot testing was carried out at the University of Defence, specifically during a technology presentation to a selected group of students participating in the COMMANDOS course. Demonstration testing of the developed technologies was conducted during a two-day training session. All tested sensors were deployed simultaneously on the same day, and the measurement was conducted on one representative participant, who wore all devices continuously throughout the experimental testing. The arrangement and position of all wearable systems on the body are shown in Fig. 1. The demonstration testing included complex tactical activities simulating combat deployment in an operational environment. During the two-day training, the following tactical activities were carried out in chronological order: assault on objective, mounted movement, trench clearing, ambush, and dismounted movement. The demonstration test was conducted in real conditions with variable terrain and climatic influences (humidity, dust, fluctuating temperatures). The training simulated typical conditions for the deployment of special forces in an environment without logistical support in the climate of Central Europe.

Fig. 1 Placement of Wearable Devices

2.3 Questionnaire Survey Design

To obtain feedback from the selected member of the COMMANDOS group, a personal questionnaire specifically designed for this purpose was created and administered after the experimental measurements were completed. The questionnaire was inspired by the standardized TAM (Technology Acceptance Model) [20] and WEAR Scale

(Wearable Acceptance Rating Scale) [21], which are commonly used to evaluate acceptance and user experience with wearable electronics. In view of the continuation of training and limited time, the questionnaire was simplified. The questions in the questionnaire were chosen so that, despite its simplified form, the questionnaire would provide relevant information about wearing comfort, perceived functionality, confidence in the accuracy of measurements, and willingness to use the device in a real operational situation. The questionnaire focused on individual devices, which were evaluated using a total of 8 questions. The evaluation was based on a Likert scale (1-7 points).

2.4 Data Analysis

The data obtained from the experimental test measurements were analyzed in equal time intervals (15 min), as the Ultrahuman ring device calculates the average HR (heart rate) for this interval. Based on this time interval, the time frame for each activity was divided into 15-minute segments. The average HR value for a given activity was then calculated as the average of the values within these time intervals. The data was then visually compared using a line graph showing HR trends over time and activity. For a quantitative comparison of individual devices, Pearson's correlation analysis was performed, where Pearson's coefficient was interpreted as 0.90–1.00 [very strong], 0.70–0.89 [strong], 0.40–0.69 [moderate], 0.10–0.39 [weak], and 0.00–0.10 [negligible] [22]. The results of the analysis are shown using scatter plots with a linear regression line.

2.5 Comparative Analysis

The comparative analysis was conducted to make a final comparison of five commercially available wearable devices representing different types of wearable systems in terms of design and potentially usable for monitoring physiological functions in the context of operational deployment by special units. A set of evaluation criteria was created for the purposes of comparison. Each criterion was evaluated on a scale of 1-5 points, where a higher value indicates better performance or greater suitability for operational deployment. The results of the evaluation are then presented in the form of a color matrix (heat map), which allows for a quick and clear comparison of the performance of individual devices across the specified criteria. The device functionality was assessed mainly through its ability to reliably record HR and HRV, maintain sufficient battery life throughout the training, export data for further analysis, and integrate effectively with other tactical equipment. The evaluation was based on the information from device producers (technical specifications and declared parameters), together with the results from experimental testing and user feedback from the questionnaire. Below is a detailed description of the evaluation criteria:

- Monitoring of Biomedical Data

The basic selection criterion was that the device should enable monitoring of key biomedical parameters, primarily heart rate (HR) and heart rate variability (HRV), which are basic indicators of the user's physical and mental stress [23, 24].

- Technical Parameters

From the perspective of the technical characteristics of the devices, the evaluation focused on battery life, methods of data recording, storage and transmission, and device durability. These parameters are critical given that the deployment duration of units may range from several hours to multiple days, often under extreme conditions. Battery capacity is therefore essential to prevent interruptions in data recording. Data recording and transmission were analyzed regarding the device's ability to store data internally or the need for a permanent connection to another device (e.g., a smartphone). Device durability included the ability to function in adverse conditions (e.g., humidity, dust), including the declared water resistance.

- Integration Capability, Open Access

Given the possibilities of specific requirements, such as stress load assessment, prediction of organism overload, patient health tracking, or even in cases where a high degree of control over data collection, processing, and analysis is required, the degree of openness of the device is also considered in the analysis. The assessment covered the availability of the application interface, the possibility of exporting raw data, access to development tools, support for firmware customization, etc.

- User preferences (ergonomics, comfort)

Five different types of devices were deliberately selected for this analysis, differing in terms of attachment (finger, wrist, chest, ear, torso). Primary attention was paid to aspects of wearability, i.e., comfort, robustness, suitability for long-term use, and overall usability in extreme conditions. As part of this, the ease of application of the device and its compatibility with other equipment (e.g., helmet, gloves, vest, etc.) were also evaluated. This criterion was verified through experimental measurements supplemented by a purpose design questionnaire.

- Price

The final evaluation criterion is the purchase price of the device. The basic version without additional accessories was considered, i.e., without the costs of repairs, administration, licenses, etc. From the perspective of protecting the life and health of the wearer, price is not a determining factor, but in the case of larger-scale deployment (e.g., equipping an entire unit), it is a crucial aspect in terms of economic efficiency.

3 Results

3.1 Analysis

Tab. 1 shows the basic technical and functional specifications of selected devices. The information is based on public sources provided by the manufacturer/seller.

3.2 Experimental Testing of Systems

The following key training activities were selected for data analysis: assault on the objective; mounted movement; trench clearing; rest/sleep periods; ambush; and dismounted movement. These activities were chosen because they represent activities that are part of the operational deployment of special forces. They are therefore suitable for training tactical procedures of the unit. At the same time, other activities were also analyzed, such as walking and mobile movements, including rest and sleep. These activities are also part of a real mission. The list of these key activities makes it possible to capture the physiological response of the body in various types of activities (stressful, regenerative).

Tab. 1 Basic technical and functional specifications of selected devices [12-16]

Parameter / Wearable device	**Ring**	**Garmin Tactix 7**	**Cosinuss° One**	**Hexoskin**	**Movesense Flash**
					
HR, HRV recording	Yes				
Type of Signal Recording	PPG-based			ECG-based (analog 256 Hz)	
Autonomous Recording Capacity	~1 week	~ 30 days (without the GPS)	~24 h	36 h battery (30 days memory)	> 60 h (depends on internal memory)
Need for Additional Device (e.g. phone, laptop, etc.)	No (synchronization only)		Yes (uploading, saving)	No	
Memory for Offline Recording	No	Yes	No	Yes	Yes
App	Yes (synchronization, display)		Yes (uploading, saving, display)	Yes	No
Water Resistance	Yes	MIL-STD-810 / 100 m	IP67	Yes	Yes
Development Potential	Limited (closed software)	Limited (Garmin CIQ)	n/a	n/a	Yes (open SDK, API)
Price [€]	400	1 000	285	733	250

The results of the average HR values recorded by individual devices during various training activities are shown in Tab. 2. The average values were then graphically represented in Fig. 2. The graphs (Fig. 3), show the results of the correlation analysis of these values in selected activities. The results of the average RMSSD (HRV) parameter values recorded by individual devices during various training activities are shown in Tab. 3.

Tab. 2 Results of average heart activity values

Activity/ Wearable device	Ultrahuman Ring	Garmin Tactix 7	Hexoskin	Movesence	Cosinuss° One
	Mean (Min-Max) [bpm]				
Baseline	55 (51–60)	85 (74–104)	69 (43–98)	79 (44–129)	n/a
Assault on objective	117 (109–125)	67 (62–73)	100 (89–115)	114 (89–138)	n/a
M.movement	94 (88–100)	77 (71–83)	68 (29–96)	66 (50–94)	61 (43–79)
Trench clearing	129 (126–133)	75 (60–84)	91 (81–106)	93 (83–106)	n/a
Rest/ Sleep period	65 (42–98)	63 (42–112)	65 (38–103)	56 (37–100)	n/a
Ambush	95 (85–99)	85 (87–105)	81 (61–107)	92 (57–127)	n/a
D.movement	78 (61–99)	74 (53–117)	83 (48–117)	85 (49–116)	n/a
Assault on objective	124 (122–127)	n/a	n/a	118 (54–171)	100 (42–159)
Baseline	95 (90–100)	n/a	n/a	68 (57–102)	n/a

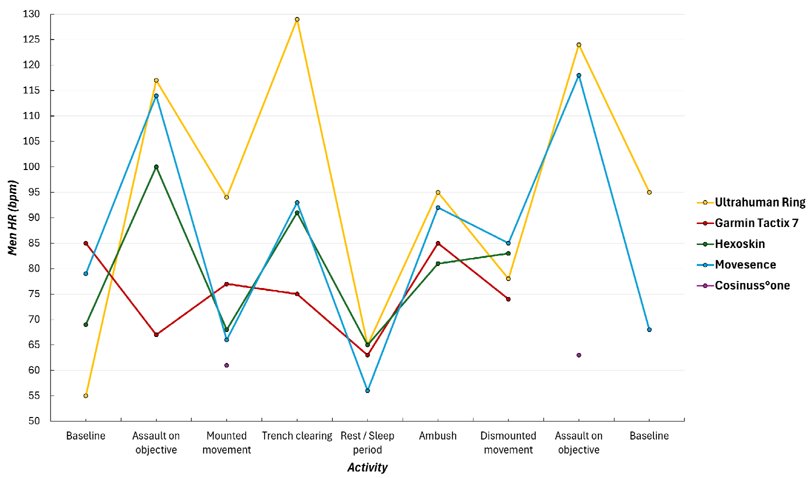

Fig. 2 Average heart rate (HR) values recorded by individual devices during various training activities.

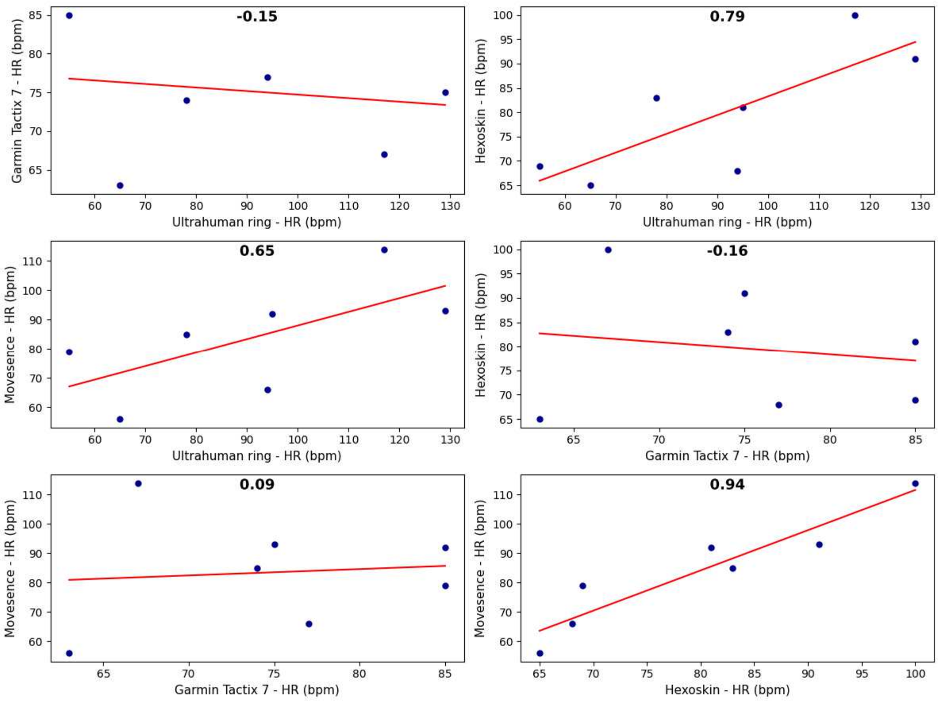

Fig. 3 Correlation analysis of average HR values between individual devices in selected activities (baseline, assault on objective, mounted movement, trench clearing, rest/sleep period, ambush, dismounted movement[1]).

To evaluate long-term continuous heart rate measurement, a correlation analysis of the average heart rate (HR) between individual devices was performed. A specific training period was evaluated, i.e., 4:45 p.m. to 8:45 a.m. This period was selected based on the availability of data from all devices. The graphs, seen in Fig. 4, show a summary of all activities, which included both active training phases (e.g., attack, movement, combat contact) and rest or planning activities (e.g., patrol, waiting, organization, preparation of materials, meal breaks, etc.). Each point in the graph (blue dot) represents the average HR value at 15-minute intervals. Data aggregation was chosen for methodological consistency, as the Ultrahuman ring device provides pre-processed data at this interval.

For the sake of comparison with the outputs from other devices, the same time frame was chosen for the remaining devices. The graph shows the overall course of the measurement and the relationships between the devices and serves as a supplement to the partial analyses of key activities, which were evaluated separately above.

[1] Note: The Cosinuss° One device was not included in the analysis due to insufficient data availability. Similarly, the last two activities (assault on objective, baseline) were not analyzed either.

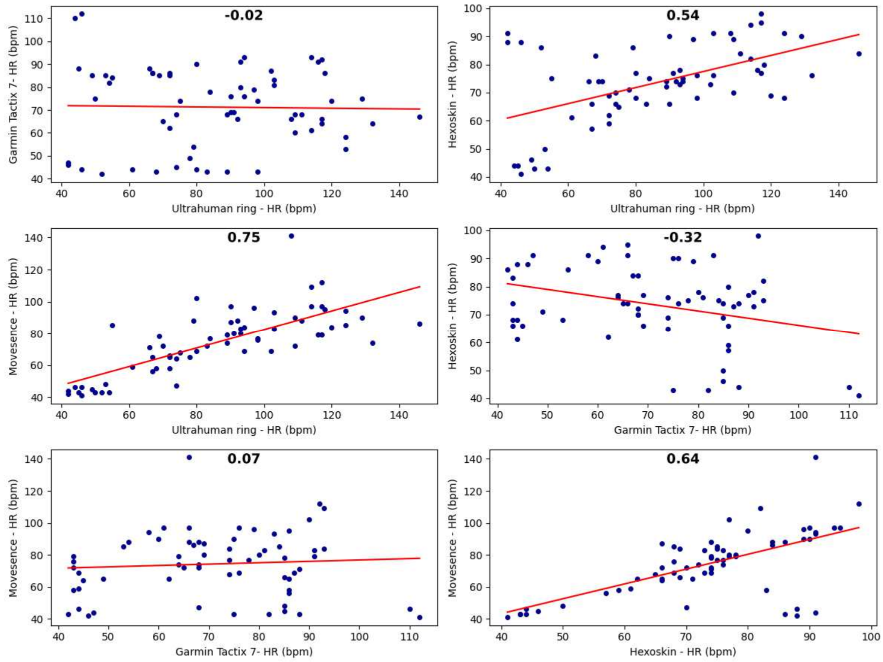

Fig. 4 Correlation analysis of average HR values between individual devices during the selected training phase[2] *(*4:45 p.m. *to* 8:45 a.m.*).*

Tab 3. Results of average HRV values

Activity/ Wearable device	**Ultrahuman Ring**	**Garmin Tactix 7**	**Hexoskin**	**Movesence**	**Cosinuss° One**
	Mean [ms]				
Baseline	62	n/a	57	101	n/a
Assault on objective	38	n/a	12	15	n/a
M.movement	30	n/a	118	110	n/a
Trench clearing	15	n/a	6	23	n/a
Rest/ Sleep period	100	122*	35	139	n/a
Ambush	n/a	n/a	40	41	n/a
D.movement	n/a	n/a	12	52	n/a
Assault on objective	n/a	n/a	n/a	33	n/a
Baseline	n/a	n/a	n/a	147	n/a
**note: measurement time 1:33-4:33 a.m.*					

[2] Note: The Cosinuss° One device was not included in the analysis due to insufficient data availability. Similarly, the last two activities (assault on objective, baseline) were not analyzed either.

The results from the purpose-designed questionnaire are shown in Fig. 5. The graph shows the subjective assessment of a COMMANDOS group member who evaluated wearable systems based on predefined areas: comfort, freedom of movement, integration with equipment, confidence in measurements, operational use, and overall assessment. Each parameter was rated on a 7-point Likert scale (1 = very poor, 7 = excellent).

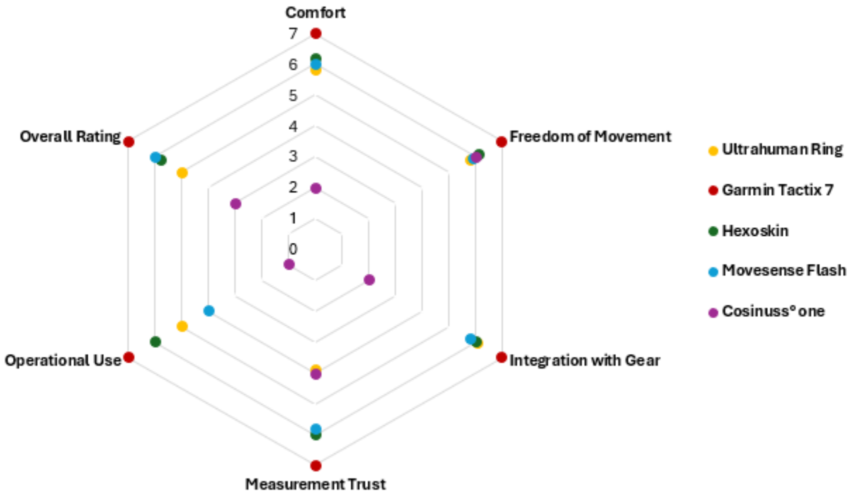

Fig. 5 Questionnaire results presented as a radar chart. Evaluation scale 1–7 *(7 indicates best rating).*

3.3 Comparative Analysis

Tab. 4 shows the results of the comparative analysis in the form of a color dot matrix (heat map), where higher scores (1-5) are marked with a darker shade of color and thus represent greater application potential for operational use by special units. The evaluation is based on objective technical parameters provided by the manufacturer/seller, subjective evaluation by potential users, including experience from experimental measurements.

4 Discussion

The aim of this article was to analyze the current state of use of wearable systems designed for monitoring biomedical data. At the same time, the aim was to evaluate the usability of commercially available technologies in the conditions of operational deployment of special forces, especially in terms of their user comfort, functionality, and practical benefits. Although many projects and prototypes of smart wearable systems for soldiers have been developed in recent years, these solutions have remained in the experimental use phase and their actual use by armies is unknown [3-5]. For these reasons, this article focused on commercially available systems that could potentially be an alternative for military use due to their availability, proven functionality, and compliance with technical and safety standards (e.g., ČSN, EN, ISO standards, etc.).

Tab. 4 Results of the comparative analysis presented as a heat map (evaluation scale 1–5; 5 indicates best performance).

	Ultrahuman Ring	Garmin Tactix 7	Hexoskin	Movesense	Cosinuss° One
Monitoring of biomedical data	3	2	5	5	1
Tech. Sp. – Durability (Certifications, Standards)	3	5	4	3	4
Tech. Sp – Recording Capacity, Internal Memory	2	4	5	5	1
Tech. Sp – Additional Devices, App	2	5	4	5	1
Development Potential / Open Access	1	2	4	5	2
***User Pref. – Ergonomics, Comfort, Wearability**	4	5	4	4	3
***User Pref. – Trust, Willingness to Use During Mission**	3	5	4	4	2
***User pref. - overall rating**	2	4	3	3	1
****Long-Term Deployment (Continuous Recording Without Intervention)**	5	4	4	5	2
****Recording Reliability (Complete Record, Data Consistency)**	3	2	4	5	1
****Ease of Deployment and Field Practicality**	2	5	3	4	1
Price/Performance Ratio	3	3	4	5	2

**based on the questionnaire*
***based on experimental measurement*

A large proportion of commercial products that monitor biomedical data were originally developed for fitness and healthcare applications, and their practical benefits in the field of military deployment are unknown. As part of this article, five commercially available wearable systems were selected, which differ mainly in their design. The selected devices represent different approaches to the solution, from the finger, through the wrist and chest, to the ear, which will allow comparison under the same conditions and evaluation of the advantages and limitations of each approach. At the same time, devices were selected that enable the monitoring of biomedical data, in particular heart activity and heart rate variability.

These documents [6, 10], which analyze the benefits of wearable systems for police work, emphasize the importance of monitoring the health of responders to increase their safety and effectiveness during operations. These metrics are of fundamental importance for military deployment, as HR data can provide information about a soldier's current workload during an operation, and HRV parameters can provide information about a soldier's overall recovery and determine their level of combat readiness [25].

Several studies have examined in detail the relationship between HRV and the effects of physical and psychological stressors in extreme conditions. This research confirms that a decrease in HRV is a reliable indicator of acute stress, exhaustion, or disruption of homeostatic balance and can therefore be used for real-time assessment of the stress response of individuals and entire teams. In this context, HR and HRV appear to be key and validated indicators of operational readiness in the extreme conditions of military and rescue operations.

As part of the verification of the practical applicability of selected devices in real conditions of special forces operations and to obtain feedback from end users, experimental testing measurement of selected systems was carried out. The results of the average heart rate (HR) recorded by individual devices during various training activities are shown in Tab. 2 and graphically represented in Fig. 2.

Only the Movesense and Ultrahuman ring devices measured throughout the entire training period. The Hexoskin and Garmin Tactix devices did not record the last two activities (Assault on Objective and Baseline). In the case of the Cosinuss° One device, there were major outages and only two activities could be evaluated. However, the devices were able to track the expected trends, i.e., all devices detected an increase in HR during exercise, peaks in heart rate during physically demanding activities, and subsequent decreases during rest/sleep. However, there are noticeable differences in the recorded values, especially for the Ultrahuman Ring device, which generally showed higher average HR values.

These differences are probably due to the influence of different sensor technologies, i.e., PPG vs. ECG recording methods, different sensor placement on the body, or artifact filtering algorithms. Pearson's correlation analysis was performed for a quantitative comparison of the average HR values from individual devices within key activities. The Cosinuss° One device was not included in the correlation analysis due to the small amount of data. The last two activities (Assault on Objective and Baseline) were also not included in the analysis, as values from all devices were not available for these sections.

The results of the analysis are shown in scatter plots with a linear regression line, see Fig. 3. In most cases, a moderate to very strong correlation was found between the Hexoskin, Movesense, and Ultrahuman ring devices. A very strong correlation was observed between the Movesense and Hexoskin devices ($r = 0.94$). In contrast, the Garmin Tactix 7 device showed negligible correlation across all devices ($r < 0.10$). As for HRV outputs, specifically the RMSSD parameter, data was not available for all devices, see Tab. 3. From the available data, especially from Movesence and Ultrahuman Ring devices, a trend can again be observed where the highest HRV values were recorded during rest/sleep, which in practice corresponds to parasympathetic dominance.

Conversely, during physically demanding activities (Assault on Objective, Ambush), there was a decrease in HRV values, which confirms sympathetic activation and indicates high physiological stress [1, 23]. As part of the evaluation of long-term continuous heart rate measurement, a correlation analysis of the average HR value in the period between 16:45–8:45 was also performed, see Fig. 4. The results show that in the context of longer-term observation, the differences between the individual devices are more pronounced than was the case for key activities. In this case, the Movesense and Hexoskin devices showed a moderate correlation (r = 0.64), while a strong correlation (r = 0.75) was recorded between the Movesense and Ultrahuman ring devices. As in the previous case, the Garmin Tactix 7 device showed a negligible (r = 0.07 for Movesence) to negative (r = −0.32 for Hexoskin) correlation with the others.

Differences between measured values, whether in key activities or during long-term monitoring, can be caused by several factors, i.e., from the measurement method and placement to the occurrence of motion artifacts. Another possible cause could be that poor synchronization occurred during data export. To determine the cause, a more detailed analysis of the raw signals is needed, including, for example, an assessment of the quality of the measured signal, a comparison of individual ECG/PPG curves, etc.

Based on the experimental measurements performed, it can be concluded that although the tested devices claim to be capable of measuring heart activity and its variability, their use in the context of special forces operations may be limited, particularly by the quality of the measurements, limitations in the data provided (HRV), and the duration of deployment.

As part of the measurement, feedback was also obtained from end users on selected systems. The results of the questionnaire are shown in Fig. 4. The Garmin Tacitx 7 smartwatch was the best-rated device in terms of perceived comfort, integration with equipment, confidence in measurement results, and willingness to accept these devices in practice. This result was to be expected, as similar types of wearable devices (smart bracelets, watches) are commonly used by soldiers in their daily and work activities and wearing them is natural for them. However, other devices, such as Hexoskin and Movesense, were also rated positively. There was only a minor complaint about Hexoskin, with one user reporting discomfort during inhalation. The worst-rated devices overall were the Ultrahuman Ring and Cosinuss° One. Although the Ultrahuman Ring was positively rated in terms of size, it was not as positively perceived in terms of the reliability of the measured data and willingness to use it.

The observed differences in user comfort and willingness to use the devices were mainly caused by their wearing position and design, which directly affected physical comfort and freedom of movement. Additional factors such as ease of application, compatibility with tactical gear, and users' perceived trust in data accuracy further influenced the overall acceptance of each device in operational conditions.

As a final step, a comparative analysis was performed that considered not only the technical parameters and characteristics of the individual devices, but also their real-world application during training and the subjective evaluation of the end user. The results of the analysis are summarized in Tab. 4. The analysis shows that the best-rated device is Movesense, which achieved high scores in most categories. Hexoskin came in second place. These devices were generally well rated, especially in terms of technical parameters, recording reliability, long-term use without user intervention, data accessibility, and price/performance ratio. Hexoskin's rating in the area of "ease of application and practical use" was lowered because, in terms of long-term missions (i.e., several days), this device may be impractical. The tight-fitting functional T-shirt is difficult to put on and take off, especially when sweaty. In addition, securing multiple pieces (2–3 per person) for replacement during multi-day deployments would represent a significant financial burden. The price of the shirt itself is around €200. With devices such as Movesense, it is sufficient to replace the chest straps, which cost up to €40. The Garmin Taxtic 7 device was well rated, especially in the user categories. Devices such as Ultrahuman Ring and Cosinuss° One were rated the worst across all categories. A comparative analysis showed that choosing the most suitable device for operational use depends on a compromise between user preferences and data accuracy and operational practicality.

Although the experimental testing was conducted in variable terrain and climatic influences (humidity, dust, fluctuating temperatures), the current data do not allow for a precise evaluation of how these environmental factors influenced device performance. Occasional data dropouts were observed, but their causes could not be clearly linked to external conditions. To determine such relationships, further testing would be necessary, ideally including simultaneous recording of environmental parameters such as ambient temperature, humidity, dust exposure, and movement context. Correlating these variables with sensor data quality would provide a better understanding of each device's robustness and stability under real operational conditions.

Despite the findings of this study, it is necessary to point out its limitations. A larger sample of participants is required to evaluate end-user feedback in a way that reflects the views of the broader special unit's community. Furthermore, differences in measured HR or HRV were mainly evaluated qualitatively, i.e., by visual comparison of curves and simple averages, rather than by detailed signal analysis or advanced statistical methods. An attempt was made to supplement the qualitative approach to evaluation by calculating Pearson's correlation coefficient, which may not be meaningful given the low amount of available data. The results should therefore be interpreted with caution as an exploratory insight rather than definitive conclusions about the accuracy of individual devices.

In addition, there is no comparison with an independent clinically verified reference system to evaluate the accuracy of the measured data. Although Movesence is classified as a medical device, it would be appropriate to correct the measured values against a fully certified medical device, such as a medical Holter ECG, clinical oximeter, etc. Furthermore, in order to draw final conclusions regarding the suitability of long-term operational deployment, it would be advisable to perform longer measurements and several measurements, e.g., over a period of several days, so that the user can fully test the interaction and handling of the device, including charging, maintenance, and replacement of structural elements (e.g., batteries, straps, etc.). Long-term measurements are desirable precisely from the point of view of wearability.

We did not include the criterion of monitoring multiple soldiers at the same time in the analysis due to the small number of sensors and the difficulty of implementing comprehensive training. The data was also analyzed only after the measurement was completed, i.e., the criterion of real-time monitoring was not evaluated. In practical use, it would also be appropriate to consider the transmission and display of data, e.g., by the unit commander, which could be used for planning activities during the training.

Furthermore, the article focused only on the possibility of monitoring biomedical data, not on methods for recording and evaluating it. The PPG-based monitoring method may not be suitable for continuous monitoring, as it is influenced by many factors, especially user activity. Some devices also allow HRV monitoring only during sleep, such as the Garmin Tactix 7 smartwatch. Although HRV monitoring during sleep is important for determining the degree of recovery, e.g., a soldier's combat readiness, it cannot replace 24-hour recording for identifying long-term trends.

In addition, most commercially available devices only evaluate the RMSSD parameter as an indicator of HRV, which may not be sufficient for a detailed analysis of stress response [26]. It would be appropriate for the device to have the ability to record

ECG signals and provide access to raw data. In the context of deeper analysis and understanding of stress, it would be appropriate to monitor other parameters, such as physical activity. Except for the Cosinuss° One device, all devices have the ability to record physical activity. This is important for defining the context of stress, determining its duration and intensity, and distinguishing mental stress from purely physical exertion. In combination with HRV parameters, it is thus possible to better assess the overall stress on the body, its regenerative capacity, and predict fatigue.

Finally, the article did not address legislative restrictions. When incorporating these technologies into real-world applications, it is desirable that the devices have the certifications required for military use (e.g., MIL-STD or NATO STANAG). These limitations open space for further research and emphasize that the presented conclusions should be verified on a larger sample and under different conditions.

5 Conclusion

This article deals with the possibilities of using commercially available wearable systems for monitoring biomedical data in the conditions of operational deployment by military special forces. Based on experimental measurements, end-user feedback, and comparative analysis, it can be concluded that the Movesence device appears to be the best option due to its technical parameters, recording reliability, long-term deployment without user intervention (up to 20 hours), data accessibility, and price/performance ratio. Other tested devices showed various compromises between comfort, measurement accuracy, and operational practicality. Although this article confirms the feasibility of monitoring heart activity and its variability using commercial technologies, it also points out the limitations. Future research should take these findings and limitations into account so that wearable sensors can become a standard part of the 21st-century soldier's equipment, such as radios, GPS, etc.

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