MASTER IN OCCUPATIONAL SAFETY AND HYGIENE ENGINEERING

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FATIGUE ASSESSMENT VS. MILITARY PERFORMANCE

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ABSTRACT

Fatigue is a complex and multifaceted phenomenon resulting from various factors, and it manifests itself in various forms. Indeed, a number of different definitions of fatigue exist, often dependent upon the experimental model employed and/or the conditions under which they occur.

Fatigue degrades performance and well-being leading to error, incident, and accident in operational settings. An operational setting is one in which effective human performance is crucial to a successful outcome. If the human fails, the system fails. Technological advances are enabling 24/7 operations and the integration of human activity around the globe, thus increasing exposure to the factors creating fatigue.

Military operations are not exempt from this. In fact, the physical demands of combat impose unique stresses on soldiers not seen with any type of civilian occupations. Besides typical operational stressors, soldiers, are exposed to extreme environments, heavy workload, inadequate sleep, information overload, dehydration and impaired nutritional status. The combination of these stressors can cause serious physiological impairments, therefore decreasing physical and military performance on the battlefield.

On the other hand, just as its definitions, assessments of fatigue have also taken various forms, ranging from objective measurements to subjective self-report assessments, and incorporating varying dimensions.

Therefore, the main objectives of the present study were stablished as follows: 1) To develop a fatigue assessment method based on physiological monitoring and, 2) To validate the proposed assessment method and demonstrate its applicability in occupational settings.

To fulfill these goals, 3 articles were elaborated. The first one corresponds to a systematic review developed with the objective of summarizing studies concerning fatigue assessment in the military context and the second, was a complementary review focused on highly intensity training scenarios, elaborated in order to determine the suitability of physiological variables to monitor different stages of fatigue and related conditions. For both cases, procedure was based in the guidelines of PRISMA Statement. Consequently, based on the found scientific evidence, the third article included a proposal of a fatigue assessment model and its validation in military occupational settings. Equipment, procedure, results and conclusions from the experience were also gathered along this final publication.

Results were able to show that the proposed alert-based system led to the successful identification of the most stressful and physically demanding activities and their direct impact on physiological parameters. Conclusions from the experience indicated that by providing a systematic and multivariate approach, this method has the potential to improve fatigue management, allowing early detection of potential physical impairments, reducing the number of medical evaluations performed and minimising unnecessary delays in treatment.

As a final remark, it was stated that this assessment method constitutes only a first approach in which several improvements can be made in order to enable not just a retrospective but also continuous and real time assessments for applications not just in military groups but also for any occupational considered sample.

TABLE OF CONTENTS

LIST OF FIGURES

Introduction Figures

Field Study Figures

LIST OF TABLES

Field Study Tables

LIST OF ABBREVIATIONS AND ACRONYMS

PSM - Physiological status monitoring systems

RPE – Rates of Perceived Exertion

HR – Heart Rate

AUTL - Army Universal Task List

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

CAC – Conduct After Capture training

EHS – Exertional Heat Stroke

Tco – Body Core Temperature

PA – Physical Activity

BCT - Basic Combat Training

CBRNE/CBRN training - Chemical, Biological, Radiological, Nuclear or Explosive training

SEM - Sensor Electronics Module

PART 1

1 INTRODUCTION

1.1 General Introduction

Fatigue is a complex and multifaceted phenomenon resulting from various factors, and it manifests itself in various forms (Saito 1999). Indeed, a number of different definitions of fatigue exist, often dependent upon the experimental model employed and/or the conditions under which they occur (Halson 2014).

Etymologically, the term fatigue has both Latin and French origin. According to The Oxford Dictionary of English Etymology (1966) the Latin word '*fatigare*', from which the word fatigue is derived, means "to exhaust as with riding or working, to weary or to harass". Likewise, the French word '*fatiguer*' means to tire (Ream and Richardson 1996).

From an occupational perspective, ISO 6385:2004 provides a definition of work fatigue in which it is described as a mental, local or general non-pathological manifestation of excessive strain, completely reversible with rest (ISO 2004).

Additionally, a concept stablished for nursing usage designates it as a subjective, unpleasant symptom which incorporates total body feelings ranging from tiredness to exhaustion creating an unrelenting overall condition which interferes with individuals' ability to function to their normal capacity (Ream and Richardson 1996).

Finally, taking in consideration a medical view, fatigue is explained as the state of tiredness that is associated with long hours of work, prolonged periods without sleep, or requirements to work at times that are "out of synch" with the body's biological or circadian rhythm (Flin, Winter, and Cakil Sarac 2009).

As it can be observed from the above definitions, ambiguities associated with the term are evidenced as there is not a unique or widely accepted concept for all areas. Mostly, they refer to a subjective state, symptom or manifestation of tiredness, generally reversible, and that affects mental and/or physical performance. However, neither of them gives an objective approach as to unequivocally define it or provides notions to determine its progress from those referred mental and physical affections.

Fatigue as a workplace hazard

As fatigue involves a condition involving decreased ability of individuals to perform activities at the desired level due to lassitude or exhaustion of mental and/or physical strength. (Ream and Richardson 1996, Hallowell 2010), it represents a workplace hazard because it affects the ability to think clearly and react appropriately. As a result, lowering of work efficiency, decrease in work amount, decrease in accuracy and inferiority rates of workers, prolongation of the time for one cycle of work and a great variation and increase in mistakes can be observed in any industrial context (Saito 1999).

Well-rested, alert employees are critical to safe and productive operations. Virtually everyone experiences some level of fatigue from time to time. However, excessive fatigue while working is an important condition in which the interrelationship of health, safety, and productivity can create a vicious or a virtuous cycle. Because of the potential impact of fatigue on health, safety, and productivity, any organization in which individuals work extended hours or hours during which people typically sleep can benefit from addressing fatigue in the workplace. This is particularly important for safety-sensitive operations such as the transportation, health care, and energy industries.

According to Lerman et al. (2012), fatigue risk factors, among others, are the following:

- Sleep deprivation
- Circadian variability
- Time awake
- Health factors (sleep disorders, medications)
- Environmental issues (light, noise)
- Workload

As for the consequences, fatigue can have several safety-related consequences, including slowed reaction time, reduced vigilance, reduced decision-making ability, poor judgment, distraction during complex tasks, and loss of awareness in critical situations (Lerman et al. 2012).

Assessment of Fatigue

Just as its definitions, assessments of fatigue have also taken various forms, ranging from objective measurements to subjective self-report assessments, and incorporating varying dimensions. This inconsistency will probably remain until this phenomenon is clearly delineated and understood (Ream and Richardson 1996).

However, when attempting to assess fatigue, some considerations must be highlighted: as fatigue manifests itself in various forms, it cannot be measured or indicated by a single test or a change of only one function; it is recognized as an overall state of the whole organism, even arising from the overuse of a certain organ or a muscle, it is generally considered to have negative effects and is a premonitory of maladaptation or impairment of the organism in the working environment. So, a mere comparison of the test results before and after operations is not sufficient to draw a conclusion (Saito 1999).

Furthermore, it is important in the assessment of fatigue, that not only measurements are made, but also findings to various factors which influence fatigue are related. This would make it possible to evaluate the grade of the obtained change in view of undesirable negative effects on health and well-being. Thus, fatigue should be evaluated by a multidisciplinary approach rather than simply measured.

As fatigue can never be measured itself directly, through the consequences of fatigue it is possible to point out this or that symptom, or at least measure indicators relevant to these symptoms. As a result, there can be mentioned a number of indicators which are generally applied in fatigue research: such measures representing cerebral cortical activity level as EEG, channel capacity or perceptual threshold such as flicker fusion frequency, some indications of vegetative functions, physiological parameters, biochemical variables relevant to metabolic changes or to endocrine regulation, motor skills and others.

Those measures can constitute invasive and non-invasive procedures: invasive methods include biochemical indexes of urinary excretion of protein, sugar, urobilinogen, creatinine, salivary analyses of salivary pH, liver functions, renal functions, etc. Some examples of non-invasive methods include: questionnaires on subjective feelings of fatigue such as Rates of Perceived Exertion (RPE), psychological tests such as the blocking test and measurement of perception time and physiological function tests of muscular strength, respiratory and circulatory functions, heart rate, near point distance, etc.(Saito 1999).

To conclude, from presented considerations, some inferences can be drawn: first, since fatigue affects the whole organism, it cannot be measured by one parameter or test; its assessment requires a multidisciplinary approach in which measurements are related to the various factors that might have influenced it. Additionally, as it is not possible to evaluate it directly, the grade of obtained consequences needs to be delimitated by relevant indicators. Lastly, being aware of the available procedures for different measurements, it would be beneficial to take advantage of non-invasive tools to define an assessment model in which, at the time of determining the level of negative occurred or potential consequences, advises on the necessity of deeper analysis.

Fatigue in Military operations

Fatigue degrades performance and well-being leading to error, incident, and accident in operational settings. An operational setting is one in which effective human performance is crucial to a successful outcome. If the human fails, the system fails. Technological advances are enabling 24/7 operations and the integration of human activity around the globe, thus increasing exposure to the factors creating fatigue (Belenky et al. 2014).

Military operations are not exempt from this. New technological complexity, the lethality of weapons systems, and rapid worldwide response capabilities make the performance of the individual soldier more critical to mission success than ever before. The near- and long-term health of individual soldiers is also potentially at risk from military technologies that can surpass operator capabilities and safety. Advances in warfighting technology and the changes in tactics and strategy that result from new capabilities make improved understanding of human limits critical to materiel and doctrine developers. No other agency or industry has a comparable need (Friedl 2012).

In fact, the physical demands of combat impose unique stresses on soldiers not seen with any type of civilian occupations. Besides typical operational stressors, soldiers, are exposed to extreme environments, heavy workload, inadequate sleep, information overload, dehydration and impaired nutritional status. The combination of these stressors can cause serious physiological impairments, therefore decreasing physical and military performance on the battlefield (Henning, Park, and Kim 2011, Lieberman et al. 2005).

A summary of these stressors, categorized in three main groups, namely environmental, metabolic and neuropsychiatric, are presented in Figure 1.

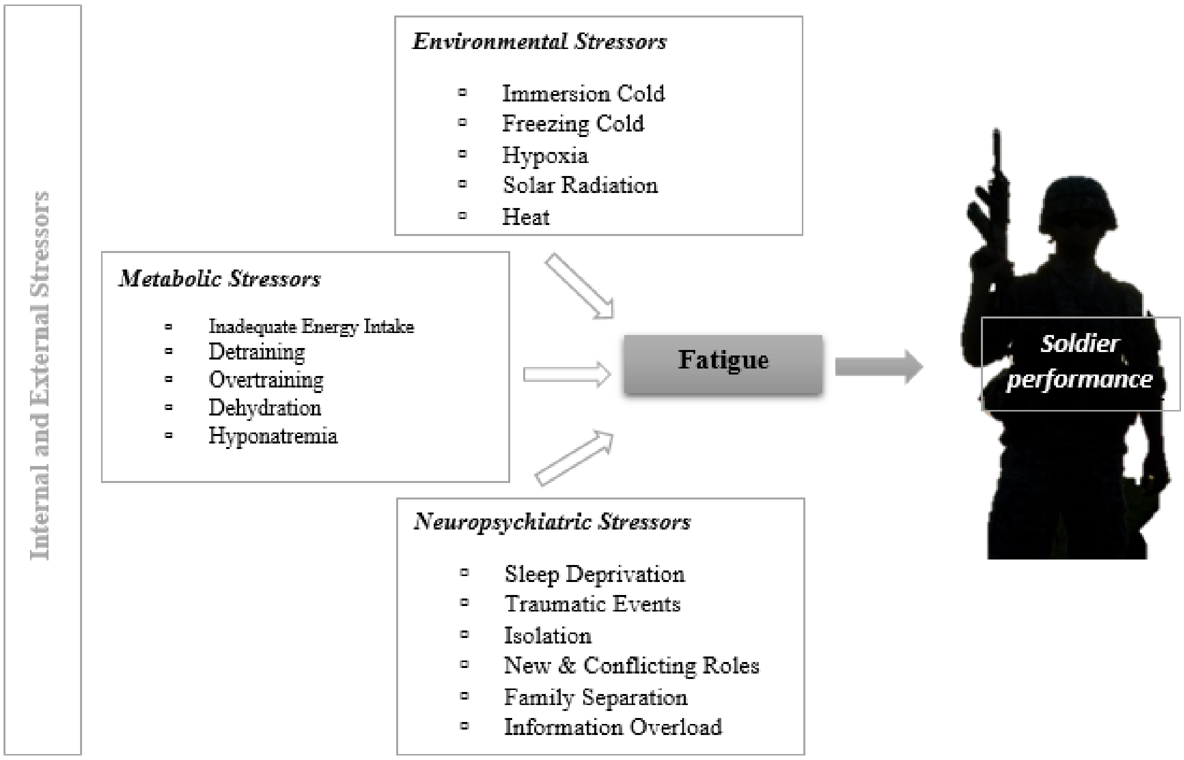

Figure 1 – Stressors of military performance.
(Henning, Park, and Kim 2011, Friedl 2012)

As physiological stressors compromise health and performance, human performance optimization involves strategies to sustain both in the face of these stressors. Physiological modeling defining human tolerance limits and the effect of moderating factors provides scientifically based strategies to interventions that ultimately involve the way individuals and teams eat, rest, train, and are equipped. It is important to consider models that combine multiple stressors because individuals are rarely subjected to only one stressor at a time (Friedl 2012).

Additionally, as Taylor et al.(2007) empathizes, comprehensive studies in realistically stressful environments are essential to expand the knowledge regarding the consequences or real-life stress exposure, facilitate development of operationally-useful techniques and promote the development of improved treatments as they differ greatly from more controlled settings in terms of environment, activity, equipment, and subject motivation (Taylor et al. 2007).

However, collecting the necessary physiological data in mission environments and activities has historically been hindered by lack of access to in-theater warfighters and difficulties associated with measuring parameters such as heart rate and core temperature in field. It is only with the development of non-invasive physiological status monitoring (PSM) systems, that such data can be collected effectively during military activities.

To conclude, it is clear that there are serious physiological decrements that occur during military operational stress which may impact mission accomplishment and jeopardize soldiers' lives. The physiological status before and during operations can have a strong impact on military performance in these missions conducted under high-stress environments (Henning, Park, and Kim 2011).

Thus, assessment of fatigue through multiple physiological parameters in the military context constitutes a relevant investigation opportunity, to focus on determining the associations between fatigue and physiological response in order to plan in the future adequate interventions to prevent related negative consequences.

1.2 Legal and Regulatory Framework

Relatively to Standards associated with the study focus of this work, there are not specific normative sources addressing fatigue assessment in military operations.

However, from a workplace perspective, some international standards (applicable to any type of organization) were taken in consideration as general references to the improvement of the military operational conditions.

- The **ISO 26800** *Ergonomics — General approach, principles and concepts* was consulted as it provides the principles that are fundamental to the design process wherever human involvement is expected, in order to ensure the optimum integration of human requirements and characteristics into a design. This International Standard considers systems, users, workers, tasks, activities, equipment and the environment as the basis for optimizing the match between them. The provisions and guidance given by this International Standard are intended to improve the safety, performance, effectiveness, efficiency, reliability, availability and maintainability of the design outcome throughout its life cycle, while safeguarding and enhancing the health, well-being and satisfaction of those involved or affected.
- Relevant concepts and terms were considered from the **ISO 6385**, *Ergonomic principles in the design of work systems*, as it establishes the fundamental principles of ergonomics as basic guidelines for the design of work systems and defines relevant basic terms to improve, (re)design and modify working situations to make the workplace safer, more comfortable and more productive. Concepts such as work fatigue, well-being and work stress are covered by this standard.
- Since mental workload is part of the total workload considered in ISO 6385, **ISO 10075,** *Ergonomic principles related to mental workload* was also taken into account as it determines the principles and requirements for the measurement and assessment of mental workload and specifies the requirements for measurement instruments. It provides information for choosing appropriate methods and provides information on aspects of assessing and measuring mental workload to improve communication among the parties involved.
- Finally, the **ISO 27500** *The human-centered organization — Rationale and general principles* was also consulted. This International Standard draws on that extensive body of ergonomics and human factors knowledge and presents the rationale and general principles

of human-centeredness in a concise form and explains the seven principles which characterize a human-centered organization. These principles are the following:

— capitalize on individual differences as an organizational strength;
— make usability and accessibility strategic business objectives;
— adopt a total system approach;
— ensure health, safety, and well-being are business priorities;
— value employees and create a meaningful work environment;
— be open and trustworthy;
— act in socially responsible ways.

It is intended to be useful to all types of organizations (whether large or small) in the private, public, and non-profit sectors. While not all parts of this International Standard will be of equal use to all types of organizations, the principles are relevant to every organization.

Additionally, from the military perspective, the following four field manuals developed by the US Army were gathered as a guidance to fully comprehend training characteristics, soldiers' functions and specific military operational conditions.

- **FM 4-02.17** *Preventive Medicine Services* was considered, and special attention was given to Chapter 2, in which roles of soldier and unit leader are detailed.
- **FM 7-22** *Army Physical Readiness Training*. This field manual was considered a relevant source of military operational functioning, as it prescribes the doctrine for the execution of the Army Physical Readiness Training System. It explains training requirements and objectives and provides a variety of physical readiness training activities that enhance military skills needed for effective combat and duty performance. Furthermore, it indicates that since the main goal is to develop soldiers who are physically capable and ready to perform their duty assignments or combat roles, training should instill confidence and the will to win; develop teamwork and unit cohesion; and integrate aggressiveness, resourcefulness, and resilience.
- **FM 7-21.13** *Soldier's guide* was consulted as a reference manual in which the individual soldier's role is discussed; duties, responsibilities and authority are specified, and some training characteristics are highlighted. It condenses information from other field manuals, training circulars, soldier training publications, Army regulations, and other sources. It addresses both general subjects and selected combat tasks.
- Lastly**, FM 7-15** *The Army Universal Task List*, is also included as it describes the structure and content of the Army Universal Task List (AUTL). The AUTL is a comprehensive listing of Army tasks, missions, and operations. For each task, the AUTL provides a numeric reference hierarchy, a task title, a task description, a doctrine reference, and, in most cases, recommended measures of performance for training developers to develop training and evaluation outline evaluation criteria for supporting tasks.

Finally, as a complementary consultation source, it was considered the following regulation developed by the Department of Army of the United States of America.

- **Code of Conduct, Survival, Evasion, Resistance, and Escape (SERE) Training, Army Regulation 350-30**, (1985) relevant for the purpose of this investigation because it describes the specific functions of military personnel and the characteristics involved in operations and training.

1.3 Thesis Structure

The present thesis project is divided in 5 chapters:

- Chapter 1 includes a brief introduction to the different concepts of fatigue, the importance of this phenomenon as a workplace hazard and its particular influence in military operational settings. Additionally, it enlists the legal and regulatory framework of the project.
- The state of the art is presented in Chapter 2. It includes two reviews elaborated following the PRISMA Statement guidelines. The first one corresponds to a systematic review developed with the aim of obtaining relevant information of previous fatigue assessments performed in field military conditions and the second, is a complementary review focused on highly intensity training scenarios, in order to determine the suitability of physiological variables to monitor different stages of fatigue and related conditions. Both were fundamental to delimit the topics, methods and parameters that should be part of the second stage of the project.
- Chapter 3 is a brief chapter in which the main conclusions of both reviews are addressed in order to provide the conceptual background to develop the practical part, including the reasons for selecting the assessment variables and monitoring methods, along with the theoretical foundation to stablish variables relationships and delimit different alarm levels that should be included for early detection of potential physical impairments. As a result, main objectives and methodology were correspondingly identified.
- Equipment, experimental protocol, data analysis, results and discussion of the practical study are presented in Chapter 4. Participants characteristics, monitoring procedures and the subsequent algorithm elaborated to analyse the data, are also described along this section. Conclusions regarding the relationships of physiological assessed parameters and the highly demanding military operations are presented, and the efficacy of the algorithm to detect alarm levels from assessed parameters is analysed. Finally, strengths and limitations of the followed methodology are equally described.
- Chapter 5 summarizes the main conclusions from the developed project, at the time of providing some future research opportunities derived from it.

2 STATE OF THE ART

Following the topics considered as the primary purpose of this project, and with the final goal of having the adequate scientific background for a development of a fatigue assessment model, the present chapter includes two reviews elaborated following the PRISMA Statement guidelines.

The first one corresponds to a systematic review developed with the aim of obtaining relevant information of previous fatigue assessments performed in field military conditions and the second, is a complementary review focused on highly intensity training scenarios, elaborated in order to determine the suitability of physiological variables to monitor different stages of fatigue and related conditions. Both were fundamental to delimit the topics, methods and parameters that were part of the second stage of the project.

Additionally, as the intended assessment model was being developed, this second review was augmented, and additional references were included in the experimental stage of the project.

2.1 Fatigue Assessment vs. Military Performance: A systematic review

Fatigue Assessment vs. Military Performance: A systematic review

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ABSTRACT: During military operations, soldiers often encounter extreme environmental, metabolic and neuropsychiatric conditions, which combined lead to a fatigue status that can cause serious physiological impairments, decreasing physical and military performance on the battlefield. Comprehensive studies in realistically stressful environments are essential to expand the knowledge regarding the consequences of real-life stress exposure, facilitate development of operationally-useful techniques and promote the conception of improved treatments.

This review, following the guidelines of PRISMA Statement, aims to obtain relevant information about fatigue assessment through multiple physiological parameters in the military context, to focus on determining the associations between fatigue and physiological response in order to plan in the future adequate interventions to prevent related negative consequences. Five databases, namely: Scopus, PubMed, Science Direct, Medline and Web of Science, are used to develop a data search based on the crosswords of keywords. A total of 12 publications are included in the systematic review. Topics such as sample characteristics, assessment context, main purpose and findings of each study, investigation parameters and equipment used, are analysed. Selected publications agreed on the risks that are associated to military duties and stablish the importance of a multi-variable fatigue assessment in order to obtain reliable results. Additionally, they mostly present similar conclusions regarding physiological alterations after intense training and operational activities.

Keywords: Fatigue, Physical Exertion, Monitoring, Military Performance, Military Operations, Military Training.

1. INTRODUCTION

Fatigue is a complex and multifaceted phenomenon. One of its most common definitions states it as a “failure to maintain the required or expected force” (Edwars 1983). A more descriptive definition explains it as a subjective, unpleasant symptom which incorporates total body feelings ranging from tiredness to exhaustion creating an unrelenting overall condition which interferes with individuals’ ability to function to their normal capacity(Ream and Richardson 1996).

In general, fatigue can be understood as a condition involving decreased ability of individuals to perform activities at the desired level due to lassitude or exhaustion of mental and/or physical strength (Ream and Richardson 1996, Hallowell 2010).

Fatigue degrades performance and well-being leading to error, incident, and accident in operational settings. An operational setting is one in which effective human performance is crucial to a successful outcome. If the human fails, the system fails. Technological advances are enabling 24/7 operations and the integration of human activity around the globe, thus increasing exposure to the factors creating fatigue (Belenky et al. 2014).

Military operations are not exempt of this. New technological complexity, the lethality of weapons systems, and rapid worldwide response capabilities make the performance of the individual soldier more critical to mission success than ever before. The near and long-term health of individual soldiers is also potentially at risk from military technologies that can surpass operator capabilities and safety (Friedl 2012).

The physical demands of combat impose unique stresses on soldiers not seen with any type of civilian occupations. Besides typical operational stressors, soldiers are exposed to extreme environments, heavy workload, inadequate sleep, information overload, dehydration and impaired nutritional status. The combination of these stressors can cause serious physiological impairments, therefore decreasing physical and military performance on the battlefield (Henning, Park, and Kim 2011, Lieberman et al. 2005).

A summary of these stressors, categorized in three main groups, namely environmental, metabolic and neuropsychiatric, are presented in **Figure 1.**

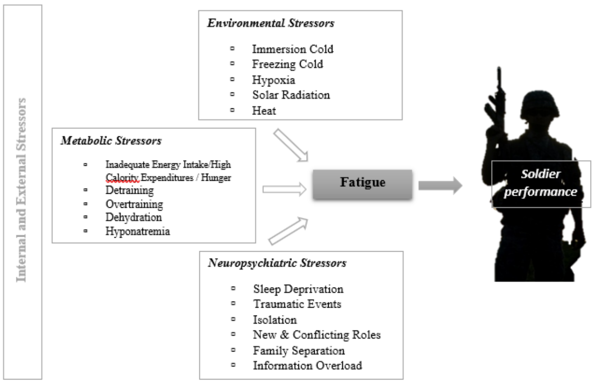

Figure 1. Stressors of military performance. (Henning, Park, and Kim 2011, Friedl 2012)

Intuitively, such stressors would be expected to have adverse physiological consequences (Nindl et al. 2013).

Previous studies suggest that physiological changes include increases in heart rate(HR) and blood pressure; alterations in skin and body temperature, elevations in electrodermal response and respiratory rate, and decreased heart rate variability (HRV) (Kudielka et al. 2004).

As physiological stressors compromise health and performance, human performance optimization involves strategies to sustain both in the face of these stressors. Physiological modeling defining human tolerance limits and the effect of moderating factors provides scientifically based strategies to interventions that ultimately involve the way individuals and teams eat, rest, train, and are equipped. Thus, it is important to consider models that combine multiple stressors because individuals are rarely subjected to only one stressor at a time-(Friedl 2012).

Additionally, as Taylor et al.(2007) empathizes, comprehensive studies in realistically stressful environments are essential to expand the knowledge regarding the consequences of real-life stress exposure, facilitate development of operationally-useful techniques and promote the conception of improved treatments as they differ greatly from more controlled settings in terms of environment, activity, equipment, and subject motivation (Taylor et al. 2007).

However, collecting the necessary physiological data in mission environments and activities has historically been hindered by lack of access to in-theater warfighters and difficulties associated with measuring parameters such as heart rate and core temperature (Tco) in field. It is only with the development of non-invasive physiological status monitoring (PSM) systems, that such data can be collected effectively during military activities.

Therefore, the main objective of this systematic review is the search of relevant information about fatigue assessment through multiple physiological parameters in the military context, to focus on determining the associations between fatigue and physiological response in order to plan in the future adequate interventions to prevent related negative consequences.

2. METHOD

This systematic review was conducted following the guidelines of The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) Statement.

2.1 *Search Strategy*

The search was developed through 5 databases, namely: Scopus, PubMed, Science Direct, Medline and Web of Science and based on the crosswords of keywords.

This systematic review aims to focus on literature that addresses fatigue assessment and military performance. Thus, selected keywords were categorized in two groups: group (A) with “Fatigue”, “Physical exertion” and “Monitoring”; and group (B) with “Military training”, “Military performance” and “Military operations”. These groups were stablished with the purpose of forming crosswords that were able to provide results that relate fatigue monitoring and assessment with the main aspects of the military activities.

A total of 9 combinations were formed and 10.204 first items were found (4911 from Scopus, 2193 from PubMed, 327 from Science Direct, 377 from Medline and 2396 from Web of Science).

2.2 *Screening criteria*

The search was initially conducted by inserting each combination and selecting, when possible, "Article title, Abstract, Keywords".

Three phases of exclusion were applied in this process. An initial phase was applied through the search filters of the databases to obtain relevant results. The first criteria were "Date": selected years were from 2013 to 2018. The second general criteria were "Type of Article": only Articles, Articles in Press and Reviews were filtered. However, reviews were not considered later in the final selection but as a source of complementary information. Additionally, only Journals were chosen when applying the "Source Type" filter. Finally, all articles but those written in English were excluded. As a result, 2084 items were gathered.

Since several of these items were duplicates, in a second phase, all these repeated articles were removed, leading to total amount of 1077 publications.

Lastly, the third phase in the screening process followed these guidelines:

a) Title and abstract were analysed. Studies were automatically excluded if one of these conditions was met: 1) studies were not applied on military; 2) studies involved only subjective methods of measurement.

b) Full text article was retrieved and considered. Whenever the title and abstract did not provide enough information to determine if the selection criteria were met, the article went through this step. If the article could not be retrieved, it was also excluded.

From this phase, a total of 34 articles were selected.

2.3 *Elegibility criteria*

Studies were included if both of the following conditions were met: 1) physiological parameters involving non-invasive measurements were objectively assessed (13 were excluded) and 2) measurements were developed in field, combat or training military conditions (9 were excluded).

This process led to a total of 12 articles. **Figure 2** displays the flowchart of the systematic review stages.

All selected articles have ethical considerations: informed written consent, assessment applied on human subjects and a committee ethic approval.

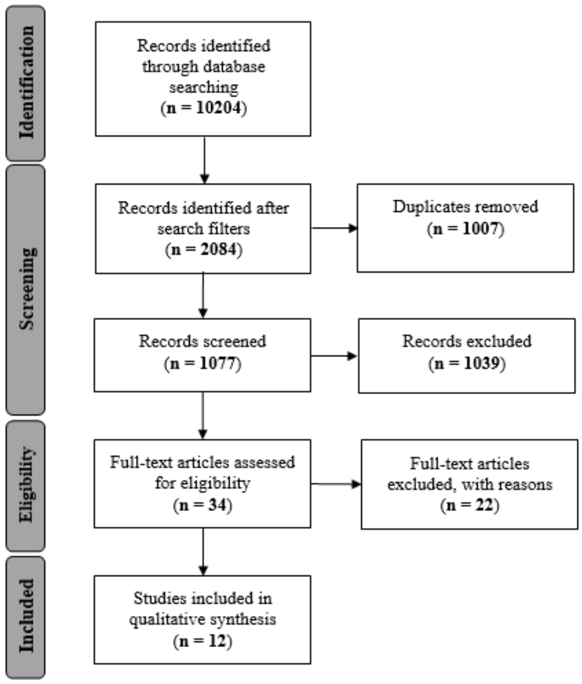

Figure 2 – Systematic Review Stages

3. RESULTS AND DISCUSSION

3.1 *General results*

By following the PRISMA Statement guidelines, the first identified articles (10.204) were reduced to 12 significant publications.

Throughout the Screening Stage, during an initial phase, a total of 6897 articles were rejected by date, 978 by type of article, 34 by Source Type and 211 by Language (**Table 1**).

Table 1. Summary of the first phase of the Screening Stage

Data Base	IA	Summary of rejected articles				Total left
		D	TA	ST	L	
Scopus	4911	3641	613	18	49	590

PubMed	2193	1293	0	0	144	756
Science Direct	327	191	0	16	0	120
Medline	377	257	0	0	2	118
Web of Science	2396	1515	365	0	16	500
Total	10204	6897	978	34	211	2084

IA*: Identified Articles D*: Date TA*: Type of article ST*: Source Type L*: Language.

After concluding this phase, 2084 articles were identified, of which 1007 were duplicates, leaving a total of 1077 articles for a third phase.

During this last phase, 1039 articles were excluded for not being applied on military or involving only subjective methods of measuring and 34 articles were left for a final full-text assessment.

Finally, following the Elegibility criteria, it was possible to identify 12 relevant publications and the process leading to this selection is summarized in **Table 2**.

Table 2. Summary of the Elegibility Stage

Criteria	Description	Filtered articles	Results after filters
1) physiological parameters with non-invasive measurements	Review Article	3	31
	Survey Method	1	30
	Not applied on military	1	29
	Does not include considered physiological parameters	8	21
2) measurements developed in field, combat or training military conditions	Developed on Laboratory conditions	9	12

3.2 *Studies characteristics*

Twelve studies were included. Data are presented in **Table 3** with a description according to the main purpose and findings of each, sample characteristics and a detail of the investigation parameters and measurement equipment relevant for this review.

From the final selected publications, it can be observed that 5 of the 12 are related to studies developed in the United States of America, 2 come from France; other 2 are from Finland, 1 from Poland and 1 from Switzerland.

The 12 articles included in total 2546 participants, of which approximately 2453 were men and 93 women (estimations were made for one study that did not provide specific gender numbers), representing 96.3% and 3.7%, respectively. The mean age ranged from 19.4 to 29.9 years old. It should be noticed that all participants were healthy active military personnel except those from one study (Jouvion et al. 2017) that developed an investigation with military subjects who had a history of Exertional Heat Stroke (EHS).

The studies duration varied widely, as they considered from 2 days of military field exercise (Pihlainen et al. 2014) to 7 months of sessions of a qualifying event for military service (Jouvion et al. 2017). Among them, only one had a control group of non-training soldiers (Charlot et al. 2017), whereas the rest used comparisons with previous or basal levels of the same soldiers.

As one of the selection criteria stablished the inclusion of studies developed in field, combat or training military context, it could be observed that 8 took part during different training activities (Captivity Survival, Chemical, Biological, Radiological, Nuclear, and Explosive materials defense – CBRNE, Basic Combat and Basic Physical training), 2 were applied during operations and 1 considered both scenarios.

Taking into consideration assessed parameters through non-invasive measurements, most of the studies evaluated heart rate (9 studies) and physical activity (6 studies). Additionally, it was found that 3 studies, besides considering at least one of the mentioned parameters, also developed core temperature measurements.

Table 3. Studies characteristics

Reference	Sample	Study goals	Conclusions	Related measured parameters	Equipment and Software
(Lieberman et al. 2016) **United States of America**	60 males Age: 21-34 years Weight: 65-103 kg, *4.4+-2.7 years on active duty.	To extend research on acute and chronic stress by examining classic markers of stress in combination with measures of cognitive performance, mood state and biochemical, nutritional and metabolic markers.	When exposed to simulated captivity, cognition mood, stress hormones, nutritional status and HR are simultaneously altered, and each of these subsequently recovers at different stages.	HR	EquiVital type 1 Sensor Electronics Module (SEM) (Hidalgo LTD.,Cambridge, U.K.). VivoSense version 2.0 software (Vivonoetics, Honolulu, HI). Statistical software SPSS 20.0; IBM, Inc., Armonk, NY, USA.
(Ralph et al. 2017) **Canada**	35 males, 1 female, age range 23-45 (CAF).	To quantify the effects of CAC training on specific aspects of psychological functioning and on specific neurohormones known to be related to stress responding.	CAC training induces significant but reversible effects on psychological and physiological function. Scores on all measures degraded but recovered after completion of training, and almost all measures were most degraded at the more intense interrogation role-play scenario.	Sleep, rest and activity periods based on actigraphy.	Wrist actigraphy (Ambulatory Monitoring, Inc., Ardsley, NY).
(Charlot et al. 2017) **France**	60 French Army soldiers in two groups: No Training (mean age 24.3 ± 3.6, height 178 ± 6 and weight 75.6 ± 7.4) and Training (mean age 24.3 ± 3.9, height 177 ± 7 and weight 74.0 ± 9.1)	To assess the effects of additional moderate, progressive training during short-term heat acclimatization during a very hot and dry spring period.	Low-volume training not sufficient to influence rectal temperature, but it enhanced decreases in thermal discomfort, RPE, sweat osmolality, and HR at exercise in personnel on a mid or long-term mission, proving that the addition of short-term training sessions to existing professional duties, comprised of light to moderate physical activities under conditions of heat stress, provides additional heat acclimatization in as little as 5 days.	HR, rectal temperature.	Chest belt and a heart rate monitor wrist receptor (RC3 GPS, Polar, Kempele, Finland). Electric thermometers (PX-TH 418, Pelimex, Ingwiller, France).

Table 3. Studies characteristics (Continuation)

Reference	Sample	Study goals	Conclusions	Related measured parameters	Equipment and Software
(Buller et al. 2015), United States of America	27 US soldiers (25 males and 2 females, age 29.9+-6.4).	To examine the performance of the Buller et al. (2013) Tc estimation algorithm in first responders wearing fully encapsulating PPE across three different field exercises with different environmental conditions and training scenarios.	The algorithm was able to provide reasonably valid estimates of Tc in different ambient environments. Thus, when this algorithm is used with a physiological monitoring system, individualized thermal–work strain can be estimated in real time and used to help prevent heat illness or injury and better manage work schedules.	HR, Tco.	Chest belt physiological monitoring system (Equivital EQ-02, Hidalgo Ltd., Cambridge, UK) with an associated ingestible thermometer pill (Jonah Core Temperature Pill, MiniMitter, Respironics, Philips, Bend, OR)
(Simpson et al. 2013) **United States of America**	24 recruits per company from 11 companies. (144 recruits at Fort Jackson and 120 at Fort Sill).	To measure and compare physical activity (PA) performed by recruits at 2 Army BCT (Basic Combat Training) sites	Army recruits at the 2 BCT sites spent similar amounts of time in each PA variable, regardless of the training site and measurement method.	Physical activity by 3 methods: instrumentation with an accelerometer, direct observation, and daily PA logs.	ActiGraph GT3X triaxial accelerometer (ActiGraph, LLC, Pensacola, FL). PAtracker. IBM SPSS Statistics (V 14.0) software (IBM Corp, Chicago, IL)
(Redmond et al. 2013) **United States of America**	24 recruits per company from 11 companies. (144 recruits at Fort Jackson and 120 at Fort Sill).	To determine the agreement among 3 different PA measurement instruments in the BCT (Basic Combat Training) environment: Actigraph Accelerometer, PAtracker and PA log.	The ActiGraph gave the best measure of the recruits' PA intensity while the PAtracker and daily PA log were best for capturing body position and type of PA in the BCT environment. The use of multiple PA measurement instruments was necessary to best characterize the physical demands of BCT.	Physical activity assessed by 3 methods: instrumentation with an accelerometer, direct observation, and daily PA logs.	ActiGraph GT3X triaxial accelerometer (ActiGraph, LLC, Pensacola, FL). PAtracker. IBM SPSS Statistics (V 14.0) software (IBM Corp, Chicago, IL).

Table 3. Studies characteristics (Continuation)

Reference	Sample	Study goals	Conclusions	Related measured parameters	Equipment and Software
(Jouvion et al. 2017) France	Forty subjects (38 males, mean age 28.4 ± 4.9 years, mean body mass index 24.9 ± 2.4) who had a history of Exertional Heat Stroke.	To determine the kinetics of increases in Tco among military subjects who had a history of EHS (Exertional Heat Stroke).	Subjects who had a history of EHS exhibited different Tco profiles at the end of an 8-km run. Laboratory studies will be necessary to identify the mechanisms underlying these profiles; future longitudinal studies can determine whether a Tco increase >0.5°C during the last 10 minutes is a risk factor for EHS recurrence.	Tco and HR	Ingestible temperature sensor (Cortemp HQ Inc., Palmetto, Florida). Chest belt (T31 Polar transmitter, Polar Electro, Kempele, Finland). Excel 2010 with Stata version 11 (Statacorp, College Station, Texas).
(Pihlainen et al. 2017) Finland	79 male soldiers, age 29.8±8.0, height 179.1±7.4 cm, body mass 79.4±8.1 kg, body mass index 24.5±2.4 kg/m2	To investigate the changes in body composition, stress biomarkers, PA, and heart rate (HR) responses of 79 male soldiers during a 6-month international crisis management operation.	Due to the operatively calm nature of the working environment, soldiers did not express any significant signs of physical overload during the study period.	HR and physical activity	Recordable memory belt (Memory belt, Suunto, Vantaa, Finland). Tri-axial accelerometer at a frequency of 100 Hz (Hookie AM20, Traxmeet, Espoo, Finland). Computer analysis software (Firsbeat PRO Firstbeat Technologies, Jyväskylä, Finland). Statistical software (IBM SPSS 22.0.0, Chicago, USA).
(Tomczak, Dąbrowski, and Mikulski 2017) Poland	15 air force cadets, average age 19.6±0.3 (SE) years; average height – 178.7±1.7 cm, body weight – 72.0±2.1 kg and BMI 22.5±0.4 kg/m2.	To assess the effect of long-term survival training on selected coordination motor skills in Air Force cadets.	36 hours of survival training combined with sleep deprivation mostly affected coordination performance (hand grip differentiation, results of Rotational tests, motor adjustment, heart rate), but not the shooting and psychomotor tests.	HR	NOT PROVIDED INFORMATION

Table 3. Studies characteristics (Continuation)

Reference	Sample	Study goals	Conclusions	Related measured parameters	Equipment and Software
(Welles et al. 2013) **United States of America**	10 male Marines (age 21.9 ± 2.3 years, height 180.3 ± 5.2 cm, and weight 85.2 ± 10.8 kg). Mission A: n=5, Mission B: n=4, Mission C: n=3.	(1) To characterize the thermal work strain, activity profiles, and Clothing and individual equipment (CIE) of warfighters performing dismounted mission activities in Afghanistan during March and (2) to use the observed mission profiles to predict the effects of conducting the same missions during typical July (summer) weather conditions in the same location.	(1) data can be successfully collected during in-theater missions, (2) small increases in ambient temperature and solar load are likely to lead to high thermal-work strain when combined with heavy work, and (3) similar modeling methods can be used to predict and compare the thermal burden resulting from various environmental conditions and CIE ensembles.	HR, Tco, accelerometry counts.	Equivital EQ-01 (Hidalgo, Cambridge, United Kingdom). Thermometer pills (Mini Mitter; Bend, OR).
(Wyss et al. 2014) **Switzerland**	1676 volunteers for injury data and 50 Volunteers at each of 12 Swiss Army BMT Schools for sensor data, mean age: 20.7 ± 1.2 years, body height: 177.6 ± 6.3 cm, body mass: 73.7 ± 10.6 kg, and BMI: 23.4 ± 3.0 kg/m2.	To investigate the impact of different physical training patterns on incidences of injuries in 12 Swiss Army basic military training schools	It was demonstrated that high physical demands (PAEE values and time spent on physically demanding material handling), decreasing distances covered on foot, low monotony in weekly physical demands, little time spent in sport-related PT, and little time for night rest are significant risk factors for injuries.	HR, physical activity parameters.	Heart rate monitors (Suunto Smartbelt and Comfortbelt; Suunto, Vantaa, Finland). Step and acceleration monitors (GT1M [ActiGraph LLC, Fort Walton Beach, Florida] and PARTwear [HuCE microLab, Biel, Switzerland]). SPSS (version 20.0, IBM, Chicago, Illinois) for statistical analysis.
(Pihlainen et al. 2014) **Finland**	15 male conscripts, age 19.4+-1.1, body height 179.7 ± 7.6 cm, body mass 72.8 ± 7.9 kg	To measure cardiorespiratory responses during military tasks in field conditions.	The mean work intensity of soldiers was close to 50% of their maximal aerobic capacity, which has been suggested to be maximal limit of intensity for sustained work.	HR	Recordable heart rate monitor (Polar S610, Polar Electro, Kempele, Finland). Heart rate monitors (Suunto t6, Suunto, Finland). Computer analysis software (Firstbeat PRO, Firstbeat Technologies, Finland). PASW Statistics for Windows, Version 18.0 (SPSS, Chicago, Illinois).

Furthermore, comparing assessment equipment, 3 of them used an EquiVital physiological monitoring system with ingestible thermometer pills, 4 used actigraphs (2 of them simultaneously using PAtrackers) to record physical activity and 5 utilized different chest belts and heart rate monitors.

The articles agreed on the risks that are associated to military duties, as they expose to stressors such as sleep deprivation, dehydration, adverse climatic conditions and physical fatigue, compromising physiological function (Lieberman et al., 2005), with potentially serious consequences for soldiers' performance. Therefore, they stablished the importance of a multi-variable fatigue assessment in order to obtain reliable results that could lead to provide skills to preserve optimal performance under such stressful conditions. Additionally, they presented mostly similar conclusions regarding which physiological alterations could occur after intense training and operational activities.

On the other hand, selected studies also involved other assessment approaches (Table 4) that even though are not the primary focus of this review, are relevant to support the analysis of results provided by the previous indicators. Evaluation of stress markers in saliva and blood samples such as cortisol, epinephrine, norepinephrine, neuropeptide-Y(NPY), dehydroepiandrosterone-sulfate (DHEA-s), prolactin, lactate and testosterone were included in 3 studies. Cognitive performance was assessed in 2 studies through the application of tests: Psychomotor Vigilance Test (PVT), Match-to-Sample, Grammatical Reasoning and N-Back.

Rates of perceived exertion (RPE), maximal oxygen uptake (VO_2) and environmental conditions were part of three investigations each, and mood states were monitored in one study.

As it was mentioned previously, three publications included an EquiVital equipment for respective assessment (Lieberman et al. 2016; Buller et al. 2015; Welles et al. 2013). Two of them were developed during training activities and the last one involved an operational context. The study duration was diverse in the three of them, Lieberman et al. (2016) considered 3 weeks of training, Buller et al. (2015) 3 training events that lasted in total 7 days and Welles et al. (2013) 3 days of in-mission activities. Similarly, sample size varied considerably, as one studied had a 60-male sample (Lieberman et al. 2016) and the other two considered 27 individuals divided in three training events (Buller et al. 2015) and 10 volunteers separated in three missions (Welles et al. 2013). Samples mean age ranged from 21.9 to 29.9 years.

Lieberman et al. (2016) developed a multi-dimensional assessment during a simulated captivity training that took place at the military Survival, Evasion, Resistance, and Escape (SERE) School. 60 males volunteered for the study, 15 of them were officers and 45 were enlisted personnel; there was no attrition among them. Training involved an academic phase in a first week, a stressful, field survival training in week 2 and a captivity simulation during a third and last week. Classic markers of stress in combination with measures of cognitive performance, mood state and biochemical, nutritional and metabolic markers were examined. Electrocardiographic data were collected at 256 samples per second during the academic phase (approximately for 12 hours) and the captivity phase (approximately for 2 hours). Results demonstrated significant increases during the two mock interrogation parts of the captivity phase; heart rate (HR) increased 42% from baseline when Interrogation 1 took place and 81% when Interrogation 2 was realized. From a research perspective, the highly standardized, structured nature of SERE training, provided a unique environment to systematically examine warfighters’ responses to stress. From this investigation, the main outcome was the evidence of the simultaneously altered parameters during the simulated captivity in all measured dimensions, as increases in heart rate were consistent with elevations in epinephrine and norepinephrine, and decrements in mood states, degraded cognitive function and substantial body loss were also evidenced during this phase.

Table 4. Other assessed parameters

Reference	Other measured parameters	Equipment and Software
(Lieberman et al. 2016) **United States of America**	Body weight. Stress markers in blood and saliva samples (cortisol, epinephrine, norepinephrine, NPY, DHEA-s, prolactin, testosterone). Cognitive performance. Mood States.	Calibrated electronic scale (A&A Scales, Prospect Park, NJ) Cognitive Tests: Psychomotor Vigilance Test (PVT), Match-to-Sample, Grammatical Reasoning,N-Back. Profile of Mood States (POMS).
(Ralph et al. 2017) **Canada**	Mood, fatigue, dissociation, PTSD symptoms, short-term memory and working memory(WM). Salivary cortisol and DHEA. Blood cortisol, DHEA, testosterone, NPY and lactate. Body weight.	Brief Trauma Questionnaire BTQ, The Childhood Trauma Questionnaire (CTQ), Clinician Administered Dissociative States Scale (CADSS), PTSD Symptom Scale PSS, Multidimensional Fatigue Inventory MFI, Profile of Mood States POMS, Delayed Matching-to-Sample dMTS, N-back. Salivette Cortisol tubes(SARSTEDTInc.,Montreal,QC). enzyme immunoassay kits per manufacturer's instructions (SAlimetrics, LLC, State COllege, PA) for salival cortisol and DHEA, immunoassay kits for lactate (Abnova, Taipei City, Taiwan), NPY (Abnova, Taipei City, Taiwan), and DHEA (Alpco, Salem, NH). Calibrated scale.
(Charlot et al. 2017) **France**	Sweat loss and osmolality. Thermal discomfort. Weight. Environmental conditions.	Self-made sweat collector. Freezing point osmometer (Osmomat 3000 basic, Gonotec, Berlin, Germany). Analogic scales and RPE. Balance (Mettler Toledo ICS 425d, Greifensee, Switzerland, accurate to 20 g). Weather meter (Kestrel Meter 440 Heat Stress Meter, Birmingham, MI, USA).
(Buller et al. 2015), United States of America	NO ADDITIONAL PARAMETERS	
(Simpson et al. 2013) **United States of America**	NO ADDITIONAL PARAMETERS	
(Redmond et al. 2013) **United States of America**	NO ADDITIONAL PARAMETERS	
(Jouvion et al. 2017) **France**	Maximum oxygen uptake (VO2max). Oxygen uptake, expired carbon dioxide and ventilation. Body composition. Anxiety.	Semirecumbent cycle ergometer (Lode Corival, Groningen, the Netherlands). Breath-by-breath analyzer (Quark, Cosmed Srl, Rome, Italy). 8-electrode bioelectrical impedance analysis of the body (Tanita BC-418, Tanita Corp., Tokyo, Japan). Y form of the Spielberger State-Trait Anxiety Inventory (STAI).

Table 4. Other assessed parameters (Continuation)

Reference	Other measured parameters	Equipment and Software
(Pihlainen et al. 2017) **Finland**	Average ambient temperature. Body height. Body mass, muscle mass, fat mass. In blood samples: Serum testosterone, sex-hormone binding globulin (SHBG), cortisol and insulin-like growth factor-1. Stress biomarkers in saliva samples: cortisol and α-amylase. Ratings of perceived exertion.	Thermochron iButton, Maxim integrated, San Jose, California, USA. Wall-mounted height board (Seca Bodymeter 206, Seca, Hamburg, Germany). Segmental multi-frequency bioimpedance analysis assessment (InBody 720, Biospace, Seoul, South Korea). Immulite 2000 XPi (Siemens Healthcare, Llanberies, UK). Konelab 20XTi (Thermo Fisher Scientific, Vantaa, Finland).
(Tomczak, Dąbrowski, and Mikulski 2017) Poland	Psychomotor factors: strength of forearm muscles and ability of its differentiation, running motor adjustment, reaction time, rotational test, exercise capacity, shooting performance. Estimated VO2.	MDAa 10/II dynamometer, APK 2/04 device (UNI PAR, Poland)
(Welles et al. 2013) **United States of America**	Meteorological data: air temperature (Ta), dew point and black globe temperature (Tbg). Clothing insulation (clo) and vapor permeability (im). Height, body weight, waist circumference at the navel, fighting weight. Estimated metabolic rate and body fat.	Collected at Kabul Airfield by the 14th Weather Squadron. Thermal manikin according to ASTM standards. Self-report and anthropometric tape measure.
(Wyss et al. 2014) Switzerland	To quantify training load: PAEE (Physical activity energy expenditure) and distance covered on foot (DOF). To quantify activity type and duration (time spent on physically demanding MHA-materials handling activities, sport-related PT, inactivity and night rest). To quantify periodization of physical activities (monotony and development in weekly PAEE and DOF). Body height, body weight.	Injury log and training reports. Stadiometer (Seca models 213 and 214; Seca GmbH, Hamburg, Germany), calibrated digital balance (Seca models 861 and 877; Seca GmbH).
(Pihlainen et al. 2014) **Finland**	Body composition: stature, BM, muscle mass, fat mass and fat percentage. VO2max. Metabolic measurements. O2 consumption, CO2 production and respiratory quotient. Ratings of Perceived Exertion. Distances moved, altitude differences and velocities.	Standarized wall-mounted height board, segmental multifrequency bioimpedance analysis assessment (InBody 720, Biospace, Seoul, South Korea). Vmax Spectra computerized metabolic system (SensorMedics, Yorba Linda, California). Portable devices (Oxycon Mobile, CareFusion, San Diego, California and MetaMax, Cortex, Leipzig, Germany). 6 to 20 scale questionnaires for RPE. Global positioning system (GPS)-based arm computers (FRWD Recorder, FRWD Technologies, Finland).

The other two studies had a different approach, as they were evaluating situations with possible heat strain of the participants. Both measured heart rate and core temperature with records every 15 seconds, Buller et al. (2015) with the main purpose of validating an algorithm that estimates core temperature from heart rate while wearing different levels of personal protective equipment, and Welles et al. (2013) to evaluate thermal work strain during operations in Afghanistan. Buller et al. (2015) considered a 27 sample from the US Army and US Army National Guard divided in three events of regularly scheduled CBRNE training and was able to obtain an overall performance of the algorithm similar to a previous study developed in laboratory conditions, suggesting that, despite ambient limitations, reliable measurements can be obtained in field situations. Likewise, Welles et al. (2013), but with a smaller sample: 10 male Marines divided in three missions with different work profile, concluded that data can be successfully collected during in-theater missions and determined that small increases in ambient temperature and solar load combined with heavy work are likely to lead to high thermal work strain.

Among these three studies, some limitations were found, mainly related to the expected difficulties of measurements in field situations: Lieberman et al. (2016) presented variations in testing times and differences in the number of subjects completing each test. Recording periods, small sample size and the fact of not having the same volunteers for each training event/mission to compare performances between the different scenarios, were observed as limitations in Buller et al. (2015) and Welles et al. (2013) studies. Additionally, it was reported a difficulty to ensure the proper functioning of the monitoring system in the Welles et al. (2013) investigation.

Using different monitoring equipment, two French studies also developed heart rate and core temperature assessments. Charlot et al. (2017) considered two groups of healthy soldiers; one developing a 5-day progressive and moderate training program, and a control group who performed usual outdoor military activities, while Jouvion et al. (2017) examined 3 days of training activities of subjects with a history of EHS (Exertional Heat Stress). Sample sizes were 60 and 40 subjects with mean age of 24.3 and 28.4 years, respectively.

Charlot et al. (2017), during a very hot and dry spring period, were able to prove that low volume physical training improves heat acclimatization as it enhances decreases in heart rate, sweat loss and osmolality, which are considered classical markers of heat acclimation, and in subjective measures such as RPE and general thermal discomfort, but concluded that it is not sufficient to influence rectal temperature. On the other hand, Jouvion et al. (2017) while monitoring Tco and HR every 20 seconds, performing an 8km run in full combat gear, were not able to obtain conclusive results, as the observed increase of 0.5°C in core temperature in the last 10 minutes of running was not sufficient to determine it as a risk indicator for EHS recurrence. Nevertheless, some methodological issues were encountered among these studies; Charlot et al. (2017) were not able to continuously monitor core temperature, which could have provided a more complete profile of individuals, and Jouvion et al. (2017), did not include a control group without a history of EHS for a better comparison of results. Additionally, as it was reported in this last-mentioned publication, a potential bias was present, as 42.5% of subjects had a BMI>25, which is considered an indicator of “overweight”, a risk factor for EHS.

Heart rate was also combined with physical activity measurements in two publications. Both used heart rate monitors and triaxial accelerometers but in different contexts. Pihlainen et al. (2017) examined 79 male soldiers during a 6-month crisis management operation in the Middle East and Wyss et al. (2014) considered a large sample from 12 Swiss Army schools: 1676 recruits to analyze injury data and 600 of them to evaluate their first 10 weeks of Basic Military Training. Mean ages among studies varied from 20.7 (Wyss et al. 2014) to 29.8 (Pihlainen et al. 2017) years old.

Wyss et al. (2014) investigated the impact of different physical training patterns on incidences of injuries in the 12 Army schools by monitoring physical activity, training demands and heart rate using a 2-second interval and concluded that high physical demands, decreasing distances covered on foot, low monotony, little time spent in sport-related PT, and little time for night rest were significant risk factors for injuries, as they explained 98.8% of the presented variances. Additionally, the study suggested that modifications in 3 of these variables: progressive development of distances covered on foot, at least 3 hours of physical training per week and an 8-hour night sleep, could be made in order to reduce risks without disrupting the content of the training program. In contrast, Pihlainen et al. (2017), while assessing the same parameters along with stress biomarkers from blood and saliva samples and RPE, were not able to get significant results in the evaluation of an international crisis management operation due to the operatively calm nature of the working environment, which was corroborated by the observed light physical overload and low HR responses. Finally, it is important to mention that some limitations with gathering all subjects' data were also found among both studies; not all soldiers were able to attend all measurements during the 6 months of operations in the first investigation and only data from Mondays to Thursdays was included in the second study as many volunteers from the training schools removed their sensors on Fridays.

Physical activity was also evaluated in three studies. One of them (Ralph et al. 2017) took place during a 4-day captivity survival course and analyzed actigraphic data of 36 subjects from the Canadian Armed Forces (35 males and 1 woman), while the other two (Simpson et al. 2013 and Redmond et al. 2013) were developed with the same sample from two US Basic Combat Training sites during a 10-week program and used more than one method of assessment, 24 recruits from eleven companies participated: 144 volunteers from Fort Jackson and 120 from Fort Sill.

Simpson et al. (2013) compared the activity from both sites by using instrumentation with an accelerometer, direct observation with a PAtracker and daily PA logs. Redmond et al. (2013) compared these 3 methods to determine the agreement among their measurement. Both studies considered times spent in various activity types, intensities, body positions and carried external loads and were able to prove the reliability of results from the 3 methods as outcomes were congruent among them. Simpson et al. (2013) concluded that, regardless of site and measurement method, training showed similar amounts of time spent in each PA variable. However, Redmond et al. (2013) provided some considerations between the methods, indicating that the actigraph gave the best measure of the recruits' PA intensity while the PAtracker and daily PA log were best for capturing body position and type of PA in the BCT environment.

Lastly, Ralph et al. (2017), having as a main objective the measurement of psychological functioning and neurohormones, also monitored sleep, rest and activity periods based on analysis of actigraphy data to quantify the effects of CAC training, which program and phases (Didactic, Practical and Recovery/debriefing) resemble some core features of the survival course of SERE school, analyzed in the Lieberman et al. (2016) study. Interestingly, despite the different sample characteristics and program duration (4 days vs. 3 weeks), Ralph et al. (2017) demonstrated that measures were mostly degraded with training, especially during the more intense interrogation, similar to what was concluded by Lieberman et al. (2016) previously. Nevertheless, inconsistency between results was found in the analysis of cognitive performance, as CAC training did not show an effect on short-term memory as SERE training observed.

Nevertheless, among these three studies, some methodological issues were encountered in the data collection, since not all participants completed training in the Ralph et al. (2017) investigation and recruits were not observed during the 10 weeks of training in the Simpson et al. (2013) and Redmond et al. (2013) studies; only the middle 8 weeks were considered. Additionally, in these last two, not all participants were evaluated by the three methods; only 1 recruit from each of the 11 companies was assessed with the PA tracker. Finally, sample characteristics were not specified, it was only reported that age was 18 years minimum, and exact number of male and female participants was not defined.

Lastly, two of the selected studies were developed considering similar general sample characteristics: 15 male subjects with mean age around 19 years old (19.6 and 19.4) and including measurements of heart rate. One investigation took place during 36 hours of survival training (Tomczak et al. 2017) and the other considered a 2-day military field exercise.

Tomczak et al. (2017), while aiming to measure psychomotor performance of Polish Air Force cadets, also developed heart rate measurements before and after prolonged exercise. The investigation determined that, when submitted to 36 hours of survival training combined with sleep deprivation, subjects significantly affected their coordination performance, which was evidenced by degradations of handgrip strength, corrected 50% max handgrip, maintenance of body balance and heart rate, but did not influence their short-term concentration, as reaction time, running motor adjustment and shooting performance levels maintained. Moreover, it determined that after one night of rest, none of the evaluated factors recovered to values presented before training, suggesting that a longer recovery period was required. Furthermore, it was proposed that to improve performance, more coordination and endurance strength training should be introduced in the program. On the other hand, Pihlainen et al. (2014), with the goal of measuring cardiorespiratory responses during 4 military tasks, was able to continuously monitor heart rate and other parameters such us oxygen consumption and RPE to conclude that military tasks leaded to a mean work intensity of soldiers close to a 50% to their maximal aerobic capacity, which had been suggested to be the maximal limit for sustained work. However, some limitations could be retrieved from these two publications: Tomczak et al. (2017) did not monitor continuously any of the considered parameters, which could have given a better profile of results. Likewise, not all variables were uninterruptedly recorded by Pihlainen et al. (2014) and the number of assessed subjects varied between measurements.

From the twelve publications, some conclusions could be gathered. First, it was proved that reliable measures can be collected in training activities and during in-theater missions (Buller et al. 2015, Welles et al. 2013). Secondly, two studies (Lieberman et al. 2016, Ralph et al. 2017) concluded that physical and psychological demands of simulated captivity survival training could simultaneously alter physiological functioning, stress hormones levels and most variables related to cognitive performance, as only short-term memory presented different outcomes between both investigations. Correspondingly, Tomczak et al. (2017) determined that 36 survival training without the possibility of sleep affected coordination performance but did not influence short term concentration. Lastly, when it comes to methods for measuring physical activity patterns, it was demonstrated by Simpson et al. (2013) and Redmond et al. (2013) that actigraphy provides the most accurate data of PA intensity and other methods such as PA tracker and PA logs are better for reporting body position and type of PA.

On the other hand, Charlot et al. (2017) established that low volume physical training improves heat acclimatization while Wyss et al. (2014) recommended modifications in variables such as distances covered on foot, sports-related physical training and night rest in training programs to reduce risks for injuries. In the same way, more endurance strength training was suggested by Tomczak et al. (2017) to improve performance.

In general, it was observed that publications enhance the assessment of stressors impact by physiological measuring in the face of other evaluation methods because it avoids the time consuming and labor intensive of in situ observations and provides more reliable results than the usage of subjective self-report questionnaires (Wyss et al. 2014).

Additionally, the importance of collecting multiple variables is highlighted in order to obtain a more complete characterization of the effects of fatigue on physiological functioning. Finally, it is emphasized that to improve performance, physical activity must be of the appropriate frequency, intensity and duration. If the volume is too low, little or no change in physical performance is achieved and if the volume is too high, it might lead to injury and health impairments (Simpson et al. 2013, Redmond et al. 2013).

It should be noted that, among studies, some general limitations were found, mainly related to the anticipated difficulties of measurements in field situations. Most of the studies presented differences in the number of subjects completing each test and some indicated that not all soldiers were able to complete all parts of the training programs. Additionally, two studies (Buller et al. 2015 and Welles et al. 2013) did not have the same volunteers for each training event/mission to compare performances between the different scenarios. In most, if a large number of volunteers would have been recruited, more robust effects may have been observed. (Ralph et al. 2017). Moreover, difficulties ensuring the proper functioning of the monitoring systems were also reported in one study. Furthermore, it was not always possible to continuously monitor all considered parameters, which could have given a more complete view of results. In addition, only one study had a control group, and in investigations like the assessment of soldiers with a history of EHS, comparisons between groups would have given a clearer perspective of obtained results. Finally, as Ralph et al. (2017) emphasizes, samples consisted primarily of men. Although it represents what is typically observed in the military context, caution must be exercised in drawing inferences and making generalizations to both genders.

4. CONCLUSIONS

The 12 articles included in this systematic review demonstrated that physiological parameters such as heart rate, physical activity and core temperature can be good predictors of fatigue, as they present alterations when submitted to environmental, metabolic and neuropsychiatric stressors. Additionally, and despite encountered limitations, this systematic review was able to prove that reliable data can be collected in field situations.

Finally, since only three studies included simultaneous assessment of physiological variables with the use of a non-invasive monitoring system such as EquiVital (the three with different approaches and considering diverse complementary variables) it can be concluded that there is a future research possibility by using this equipment to assess fatigue. This way, a multivariable assessment method can be executed, and supported fatigue measurements can be obtained in several military activities.

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2.2 Physiological Monitoring vs. Military Performance: A systematic review

Physiological Monitoring vs. Military Performance: A systematic review

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ABSTRACT: The physical demands of combat impose unique stresses on soldiers not seen with any type of civilian occupations. During military operations, soldiers often encounter extreme environmental, metabolic and neuropsychiatric conditions, which combined lead to a fatigue status that can later develop in overreaching and overtraining conditions. Comprehensive studies in realistically stressful environments are essential to expand the knowledge regarding the consequences of real-life stress exposure, facilitate development of operationally-useful techniques and promote the conception of improved treatments. However, collecting the necessary physiological data in mission environments and activities has historically been hindered by lack of access to in-theater warfighters and difficulties associated with measuring parameters in field. It is only with the development of non-invasive physiological status monitoring systems, that such data can be collected effectively during military activities. Nevertheless, there is not much evidence of non-invasive physiological monitoring during high training military activities.

Therefore, this systematic review, following the guidelines of PRISMA Statement, aims to identify evidence of the relevance of non-invasive physiological monitoring for detecting stages of fatigue, overreaching and/or overtraining and indicators of potential physical impairments in high intensity training scenarios that could be extrapolated and applied in a military context.

Four databases, namely: SCOPUS, PubMed, Medline and Science Direct, are used to develop a data search based on the crosswords of keywords. A total of 19 publications are included in this systematic review. Topics such as sample characteristics, assessment context, covered sports disciplines, main purposes and outcomes of each study and similarities among their outcomes, were analysed. Conclusions regarding the most suitable parameters to be extrapolated into a military operational context were gathered.

Keywords: Fatigue, Physical Exertion, Monitoring, Military Performance, Military Operations, Military Training.

1. INTRODUCTION

Fatigue is a complex and multifaceted phenomenon that has a variety of possible mechanisms (Edwars 1983). In general, fatigue can be understood as a condition involving decreased ability of individuals to perform activities at the desired level due to lassitude or exhaustion of mental and/or physical strength (Ream and Richardson 1996, Hallowell 2010).

All athletes, in any sport, must train hard in order to improve, and they experience minor fatigue as a consequence of the normal training process (Budgett 1998, Halson and Jeukendrup 2004). An improvement in performance capacity above what would be achievable after a normal training cycle is expected if the athlete is allowed sufficient recovery to permit the occurrence of the supercompensation effect (Bosquet et al. 2008).

When the balance between training stress and recovery is disproportionate, it is thought that overreaching and possibly overtraining may develop (Halson and Jeukendrup 2004).

Overreaching occurs when restoration of performance capacity takes from several days to several weeks. However, when intensified training continues, the athlete can develop a state of extreme overreaching (Non-functional overreaching), that will lead to stagnation or a decrease in performance capacity, which will not recover for several weeks. If restoration of performance takes from weeks to months, a possible state of overtraining may have been developed. Although the consequences of functional overreaching and non-functional overreaching on an athlete’s career can differ dramatically, simply in the time required to recover fully, the limit between these two states is very narrow. Thus, there is a need for athletes, coaches and sport scientists to have valid markers of functional overreaching at their disposal, so that appropriate rest can be provided before the development of non-functional overreaching and eventually overtraining (Bosquet et al. 2008).

Nevertheless, cases of overtraining or overreaching can occur in response to demanding training loads in all population groups, not just elite athletes. In fact, symptoms of overtraining have been documented during military training in many countries, including the United States, Spain, and Norway. Additionally, it is known that these symptoms are more likely to develop when physical training is combined with other stressors, such as psychological stress and inadequate nutrition (Booth et al. 2006). In this regard, it is pertinent to highlight that besides typical operational stressors, soldiers are exposed to extreme environments, heavy workload, inadequate sleep, information overload, dehydration and impaired nutritional status. In reality, the physical demands of combat impose unique stresses on soldiers not seen with any type of civilian occupations (Henning, Park, and Kim 2011, Lieberman et al. 2005). The combination of these stressors can cause serious physiological impairments, therefore decreasing physical and military performance on the battlefield (Henning, Park, and Kim 2011, Lieberman et al. 2005).

As physiological stressors compromise health and performance, human performance optimization involves strategies to sustain both in the face of these stressors. Physiological modeling defining human tolerance limits and the effect of moderating factors provide scientifically based strategies to interventions that ultimately involve the way individuals and teams eat, rest, train, and are equipped. Thus, it is important to consider models that combine multiple stressors because individuals are rarely subjected to only one stressor at a time (Friedl 2012).

Additionally, as Taylor et al.(2007) empathize, comprehensive studies in realistically stressful environments are essential to expand the knowledge regarding the consequences of real-life stress exposure, facilitate development of operationally-useful techniques and promote the conception of improved treatments as they differ greatly from more controlled settings in terms of environment, activity, equipment, and subject motivation (Taylor et al. 2007).

However, collecting the necessary physiological data in mission environments and activities has historically been hindered by lack of access to in-theater warfighters and difficulties associated with measuring parameters such as heart rate and core temperature in field. It is only with the development of non-invasive physiological status monitoring (PSM) systems, that such data can be collected effectively during military activities.

Nevertheless, there is not much evidence of non-invasive physiological monitoring during high intensity military training. Therefore, a systematic review is proposed in order to identify evidence of the relevance of non-invasive physiological monitoring for detecting stages of fatigue, overreaching and/or overtraining that would allow an early detection of pathological conditions in high intensity training scenarios, and could be later extrapolated and applied to a military context.

2. METHOD

This systematic review was conducted following the guidelines of The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) Statement.

2.1 *Search Strategy*

According to the stablished objective, a series of keywords were defined. In general, those keywords referred to physiological monitoring, training stages, overreaching conditions, physiological variables and risks associated to high intensity training. As a result, 21 combinations were formed among them.

In order to test the relevance of results provided, a first research was conducted using the Scopus database. Consequently, combinations were filtered as many of them presented results unrelated to the topics outlined in this work.

Finally, the combinations defined to conduct the review were formed by the following two groups of keywords: group (A) with 'physiological monitoring', 'physiological measurement' and 'life monitoring' and group (B) with 'fatigue', overreaching' and 'overtraining'.

The search was developed through 4 databases, namely: Scopus, PubMed, Medline and Science Direct, and based on the crosswords of keywords.

A total of 9 combinations were formed and 9955 first items were found (5513 from Scopus, 2302 from PubMed, 74 from Medline and 2066 from Science Direct).

2.2 *Screening criteria*

The search was initially conducted by inserting each combination and selecting, when possible, "Article title, Abstract, Keywords" (Scopus, Science Direct and Medline). All fields were considered in Pubmed.

Three phases were applied in this process. An initial phase of exclusion was applied through the search filters of the databases to obtain relevant first results. The initial criteria were "Type of Article": only Articles and Articles in Press were filtered. Additionally, only Journals were chosen when applying the "Source Type" filter. Next, all articles but those written in English were excluded. Finally, articles from journals related to Physiology, Sports, Medicine, Ergonomics, Health and Fitness were delimitated with the "Source Title" filter. No date restrictions were considered in order to collect all available information in the area. As a result, 2047 items were gathered.

Since several of these items were duplicates, in a second phase, all these repeated articles were removed, leading to total amount of 1787 publications.

Lastly, the third phase in the screening process followed this procedure:

a) Title and abstract were analysed: Studies were automatically excluded if one of these conditions were met: 1) studies were not developed in high intensity training context; 2) studies involved only subjective methods of assessment.

b) Full-text article was retrieved and considered: Whenever the title and abstract did not provide enough information to determine if the selection criteria were met, the article went through this step. If the article could not be retrieved, it was also excluded.

From this phase, a total of 78 articles were selected.

2.3 *Elegibility criteria*

Articles were included if all the following conditions were met: 1) they were applied on male samples (mean age over 18) with standard anthropometric characteristics, including average height and weight and normal IMC, 2) subjects were regularly physically active 3) they evidenced a representative sample size, case studies were not considered, and 4) they included a non-invasive physiological assessment method.

This process led to a total of 19 articles. **Figure 1** displays the flowchart of the systematic review stages.

All selected articles have ethical considerations: informed written consent, assessment applied on human subjects and a committee ethic approval.

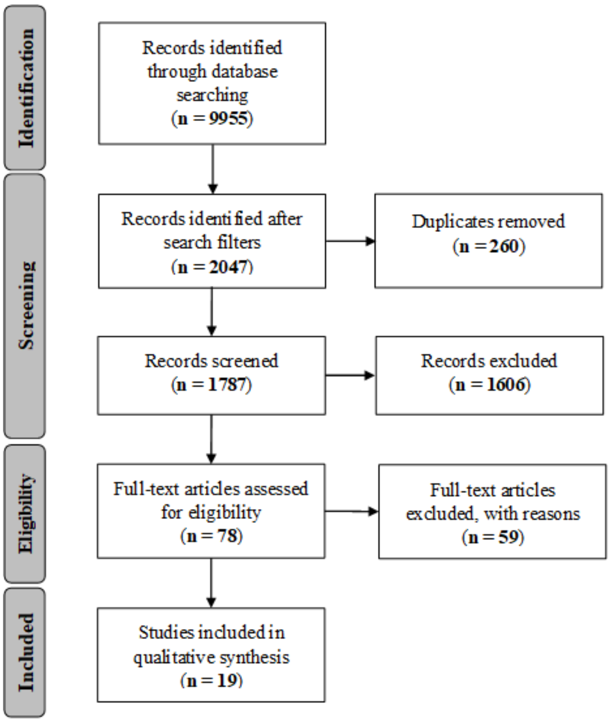

Figure 1 – Systematic Review Stages

3. RESULTS AND DISCUSSION

3.1 *General results*

By following the PRISMA Statement guidelines, the first identified articles (9955) were reduced to 19 significant publications.

Throughout the Screening Stage, during an initial phase (Table 1), a total of 3292 articles were rejected by Type of article, 112 by Source Type, 375 by Language and 4129 by filtering source titles.

Table 1. Summary of the first phase of the Screening Stage

Data Base	IA	Summary of rejected articles				Total left
		TA	ST	L	ST	
Scopus	5513	2450	112	229	2301	421
PubMed	2302	21	0	143	877	1261
Medline	74	0	0	3	28	43
Science Direct	2066	821	0	0	923	322
Total	9955	3292	112	375	4129	2047

IA*: Identified Articles TA*: Type of article S*: Source Type L*: Language ST*: Source title.

After concluding this phase, 2047 articles were identified, of which 260 were duplicates, leaving a total of 1787 articles for a third phase.

During this last phase, 1606 articles were excluded for not being developed during high intensity training or involving only subjective methods of assessment and, 78 articles were left for a final full-text assessment.

Lastly, following the Elegibility criteria, it was possible to identify 19 relevant publications. The process leading to this last selection is summarized in **Table 2.**

Table 2. Summary of the Elegibility Stage

Inclusion criteria	Reason for not inclusion	Filtered articles	Results after filters
1) Male sample with standard anthropometric characteristics.	Female sample.	13	65
2) Subjects regularly physically active.	Not regular athletes/players.	2	63
3) Representative sample size.	Case studies.	10	53
4) Include a non-invasive physiological assessment method.	Does not include considered physiological parameters.	4	49
5) Others	Developed in controlled conditions.	20	29
	Not available.	8	21
	Unrelated objectives.	1	20
	Review article.	1	**19**

During this last stage, studies were included if the following conditions were met: 1) Applied on male samples (13 excepted); 2) Participants regularly physically active (2 excepted); 3) Representative sample size (10 excepted); and 4) Involved a non-invasive assessment method (4 excepted).

Additionally, 20 studies were filtered for not being developed during high intensity training, 8 were not available for full-text assessment, 1 referred to objectives unrelated to the intended purpose of this review and 1 was identified as a review article.

3.2 *Studies characteristics*

As previously stated, nineteen studies were considered for this review.

Table 3 shows the main characteristics of these final selected articles including their objectives and respective conclusions, sample characteristics and assessed parameters.

From the final selected publications, it can be observed that most of them were developed in Australia and France (4 each) and 3 come from Denmark. The lasting 8 took place in different countries: Brazil, Finland, Greece, Italy, Poland, South Africa, Tunisia and the United Kingdom.

The 19 investigations included in total 385 male participants. Mean ages ranged from 18.5 to 36.6 years old. Additionally, as one of the selection criteria stablished the inclusion of studies in which the participants were regularly physically active, it was possible to identify athletes from a variety of sports disciplines; triathletes took part in three studies and soccer players were considered in other three investigations. Long distance runners, water polo players, football players, cyclists, road-race motorcyclists, handball field players, trail runners, wrestlers, futsal players, rugby union players and bowlers were also identified among studies. Furthermore, it is relevant to mention that two investigations were developed with military personnel: one with students of the Polish Air Force Academy (Tomczak, Gajewski, and Mazur–Różycka 2014) and the other one with Army officers and cadets (Vaananen 2004). All studies indicated participants were involved in regular physical training programs. However, 6 did not provide details on the average weekly training time or the participants' experience on the aforementioned disciplines.

The studies duration varied widely, as they considered from the four 7-min quarters of a water polo game (Galy et al. 2014) to three events along three years (Vaananen 2004) Among them, only three had control groups (Le Meur et al. 2012, Coutts, Slattery, and Wallace 2007, Hausswirth et al. 2014), whereas the rest used comparisons with previous or basal levels of the same participants.

Taking into consideration assessed parameters through non-invasive methods, 16 studies evaluated HR (heart rate) while 3 focused on activity patterns and one included both assessments. Only one investigation, at the time of recording heart rate changes, monitored Tco and Tsk (core and skin temperature).

As previously mentioned, two studies were developed with military personnel (Vaananen 2004, Tomczak, Gajewski, and Mazur–Różycka 2014). However, approaches and measured parameters differed. Vaananen (2004) performed a multidisciplinary research in which army officers, cadets and recreational endurance athletes were examined and, even though the experimental protocol was closer to a typical sports training than to a highly stressful military scenario, it evidenced the strong relationship between physical training intensity and %HRmax. On the other hand, Tomczak et al. (2014) considered 36 continuous hours of survival training with sleep deprivation when recording activity patterns to determine changes in physiological tremor. This context evidenced the real-life stressors to which soldiers are exposed to and, showed that along previously mentioned alterations, increasing fatigue and lack of sleep influenced psychomotor performance.

Three studies focused on assessing sleep patterns with wrist actigraphy (Hausswirth et al. 2014, Shearer et al. 2015, Robey et al. 2014). The first one also controlled training volume and intensity among triathletes by monitoring HR over the entire protocol. Notably, this investigation divided participants into a normal training group and an overload training group, which supported the feasibility of provided conclusions. In this regard, outcomes revealed sleep disturbances and increased illness in the functionally overreached athletes that where part of the second group. Similarly, Shearer et al. (2015) stablished significant differences in several sleep measures observed pre and post competition compared to reference values among 28 rugby union players. However, slightly different results were provided by Robey et al. (2014), in which investigation sleep quality and quantity were not affected by high intensity training in a 12 soccer-player sample.

Table 3. Selected articles

Reference	Sample				Study characteristics		
	Sample Size	**Age**	**Anthropometrics**	**Sport Discipline**	**Objectives**	**Assessed parameters**	**Conclusions**
(Saboul et al. 2016) **France**	11	32 ± 6	height = 182 ± 5 cm; body mass = 76.3 ± 10.2 kg; MAS = 18.9 ± 1.2 km/h	long-distance runners	To validate a HRV index (TL_{HRV}) that may be used to assess TL in field conditions.	HR (HRV, HRrest, HRmax), RPE.	HRV decrease during exercise strongly correlated with exercise intensity ($R = -0.70$; $p < 0.01$). TL_{HRV} correlated with Foster and Banister methods.
(Galy et al. 2014) **Tunisia**	Initial 14, final 8	26 ± 2.7	height = 180.2 ± 8.6 cm; body mass = 85.5 ± 11.7 kg	elite water polo players	To measure HR response during the four 7-min quarters of a water polo game and to check for relationships with physiological parameters of performance.	HR, VO2max, $Th1_{vent}$, $Th2_{vent}$	Mean game HR expressed as %HRReserve was significantly correlated with the player's VO2max which evidenced that intensity is influenced by the player's aerobic capacity.
(Buchheit et al. 2013) **Australia**	18	21.9 ± 2.0	height = 189 ± 8 cm; weight = 87.8 ± 9.1 kg	professional Australian Rules Football players	To examine the usefulness of selected physiological and perceptual measures to monitor fitness, fatigue and running performance during a pre-season, 2-wk training camp.	HR (HRex, LnSD1, post-exercise HRV). PV, TL, perceived ratings of wellness, salivary cortisol.	RPE based TL, HRex and wellness measures are the best simple measures for monitoring training responses to an intensified training camp; cortisol post-exercise and LnSD1 do not show practical efficacy. HRex changes are associated with changes in PV.
(Le Meur et al. 2012) **France**	24	NT group (8) = 32.4 ± 2.8. IT group (16) = 31.0 ± 1.4.	NT / IT: Height = 176.8 ± 2.1 / 178.7 ± 1.2 cm; Weight = 69.7 ± 2.6 / 70.6 ± 1.3 kg; V̇o2max = 64.9 ± 2.8 / 62.3 ± 1.5 ml·min−1·kg−1; MAS= 18.2 ± 0.4 / 18.3 ± 0.2 km/h	highly trained triathletes	To investigate OR using a multivariate approach, including physiological, biochemical, cognitive and perceptive monitoring.	HR, lactatemia, VO2, VE, biomechanical parameters (CK, plasma epinephrine, norepinephrine), RPE, kinetic and kinematic measures, cognitive performance.	HR and blood lactate concentration changes are the most important factors in discriminating between control and OR athletes.

Table 3. Selected articles (Continuation)

Reference	Sample			Study characteristics			
	Sample Size	**Age**	**Anthropometrics**	**Sport Discipline**	**Objectives**	**Assessed parameters**	**Conclusions**
(Lamberts et al. 2010) **South Africa**	14	G_{incr} (HRR increase) (8) = 34 ± 4; G_{decr} (6) = 25 ± 5.	Gincr / Gdecr: Stature(cm) = 182 ± 3 / 176 ± 9; Body mass (kg) = 76.9 ± 7.7 / 68.5 ± 6.0; Fat (%) = 16.0 ± 3.5 / 11.7 ± 2.0; Sum of skinfolds (mm) = 63.8 ± 23.0 / 49.8 ± 6.1.	well-trained cyclists	To retrospectively analyze the relationship between changes in HRR and cycling performance in a group of well-trained cyclists (n=14) who participated in a 4-week high-intensity training (HIT) program.	HR (beats/min, HRR), VO2max, speed (km/h), power output (W), cadence rpm.	HRR has the potential to monitor changes in endurance performance and contribute to a more accurate prescription of TL in well-trained and elite cyclists.
(D'Artibale, Tessitore, and Capranica 2008) **Italy**	34	26.2 ± 6.7		road-race motorcyclists	To evaluate the physical load of official international men's road-race motorcycling competitions.	HR(%HRmax), blood lactate.	%HRmax evidences road-race motorcycling imposes a high load on the riders who should have adequate fitness to maintain high speeds and delay the onset of fatigue during races
(Coutts, Slattery, and Wallace 2007) **Australia**	16	IT / NT: 33.4 ± 15.0 / 27.7 ± 7.6.	IT / NT: Body mass (kg) = 70.7 ± 5.2 / 80.6 ± 7.7; Skinfolds (mm) = 69.3 ± 18.1 / 100.8 ± 28.0.	experienced triathletes	To examine selected practical tests for monitoring changes in performance, fatigue and recovery of endurance athletes.	HR, VO_{2max}, VO_2, lactate threshold velocity, blood lactate concentration, RPE, psychological measures.	DALDA and 5BT may be practical tests for assessing changes in performance, fatigue and recovery of endurance athletes. It is difficult to distinguish adapting from non-adapting athletes through changes in VO_{2max}, lactate threshold and HR.
(Michalsik, Madsen, and Aagaard 2015) **Denmark**	41	26.4±3.1 (from players of the two top ranked teams N=26)	height = 188.9±6.3 cm; weight = 90.9±9.0 kg. (from players from the two top ranked teams N=26)	elite team handball field players	To examine the physical demands placed on male elite team handball players in relation to playing position.	HR, VO_{2max}, relative workload (RWL), blood lactate concentration, fluid loss, maximal aerobic capacity, maximal muscle strength, physical profiles.	Indications of temporary fatigue onset during match-play. Elite team handball imposes moderate-to-high demands on the aerobic energy system and high demands on the anaerobic energy systems during certain periods of the match.

Table 3. Selected articles (Continuation)

Reference	Sample				Study characteristics		
	Sample Size	**Age**	**Anthropometrics**	**Sport Discipline**	**Objectives**	**Assessed parameters**	**Conclusions**
(Easthope et al. 2014) **France**	11	34.7 ± 9.8	body mass = 72.3 ± 6.8 kg, height = 178.4 ± 7.0 cm, maximal oxygen uptake = 60.1 ± 6.5 mL min−1 kg−1	competitive trail runners	To test the reproducibility of running performance, neuromuscular fatigue markers and indirect muscle damage indicators in a field-based trail time-trial.	HR, running time, lactate concentration, RPE. Maximal voluntary contraction torque (MVC), counter movement jump height (CMJ), plasma creatine kinase (CK) activity, muscle soreness.	A short outdoor trail run is a reliable model for investigations of fatigue and muscle damage. MVC and CMJ are best suited as main outcome measures. Variability for RPE, lactate, CK and muscle soreness makes them insensitive to small changes and appropriate as auxiliary variables.
(Tomczak, Gajewski, and Mazur–Różycka 2014) **Poland**	15	19.9±1.3	Weight [kg] = 72.0 ± 8.0; Height [cm] = 178.1 ± 7.3.	students of the Polish Air Force Academy in Deblin.	To define the changes of the characteristics of physiological postural tremor under conditions of increasing fatigue and lack of sleep during prolonged military training (survival).	Tremor measurements by acceleration	Prolonged sleep deprivation and task demanding physical effort cause long-lasting changes of the amplitude of low-frequency tremor changes, which may influence psychomotor performance.
(Bendiksen et al. 2012) **Denmark**	12	24.2 ± 4.5	height = 181.2 ± 6.5 cm; body mass = 80.0 ± 7.5 kg; fat percentage = 15.8 ± 3.4; VO_{2max} = 4.93 ± 0.33 L/min.	Second and Third Division soccer players	1) To evaluate whether a simulated soccer game protocol: the Copenhagen Soccer Test (CST), elicited a similar physiological loading as a competitive game (CG). 2) To determine muscle metabolites, blood variables, and sprint performance in various phases of CST.	HR(%HRmax), VO_{2max}, recovery plasma creatine kinase, muscle glycogen, muscle CrP, sprint velocity, blood lactate, blood glucose, plasma FFA concentration plasma potassium, technical performance.	The test can be considered valid when investigating the effect of environmental temperature, nutritional supplementation, and training on the physiological response to and physical performance in soccer.

Table 3. Selected articles (Continuation)

Reference	Sample				Study characteristics		
	Sample Size	**Age**	**Anthropometrics**	**Sport Discipline**	**Objectives**	**Assessed parameters**	**Conclusions**
(Barbas et al. 2011) **Greece**	12	22.1 ± 1.3	height = 174.3±2.8 cm; weight = 72.1±3.6 kg; body fat = 7.6±0.9%; VO_{2max} = 56.8±3.8 ml/kg/min; maximal HR = 196.2±7.3bpm.	competitive wrestlers	To determine the effects of a simulated one-day Greco-Roman wrestling tournament on selected performance and inflammatory status indices.	HR (%HRmax), lactate, hormonal and metabolite functions. Performance: vertical jumping, hip-back strength. Muscle damage: CK activity, DOMS, and joints' range of motion. Inflammatory response: C-reactive protein, leukocyte counts, IL-6, oxidative stress markers.	A one-day wrestling tournament imposes significant physiological demands that may adversely affect performance and inflammatory status especially during the later stages of the tournament.
(Vaananen 2004) **Finland**	28	Study 1, 2 (n=6) = 36.6±7.7; Study 3, 4 (n=15) = 27.1±3.8; Study 5, 6 (n=10) = 34.8±9.7	Height (m) = 1.76 ± .08 / 1.81 ± .06 / 1.82 ± .05; Mass (kg) = 74.4 ± 8.1 / 79.4 ± 5.3 / 76.1 ± 6.6	Army officers, cadets, recreational endurance athletes	To examine the magnitudes and time courses of the physiological and psychological responses to various (intensity, duration, mode/type) daily repeated prolonged exercise.	HR (bpm, %HRmax), perceived pains, functional capacity of lower extremities (flexibility, functional strength, use of elastic energy and oedemic changes). CK, cortisol, testosterone, luteinizing (LH) and follicle stimulating hormone (FSH). Mood states.	Cardiorespiratory response to repeated walking over 8 hours was moderate (60% HRmax) and strenuous to repeated 3 skiing hours (90%). Multidisciplinary research allows for the collection of holistic data during field studies where physical and psychosocial competencies are present.
(Krustrup et al. 2003) **Denmark**	2 groups: 17 male subjects and 37 professional elite soccer players.	male subjects = 28 (range: 25–36). Soccer players = 26 (range: 22–32)	Male subjects / soccer players: Height = 182 (172–191) cm / 181 (169–193) cm; body mass = 78.2 (68.4–91.2) kg / 75.4 (67.5–90.1) kg; VO_{2max} = 50.5 (42.1–60.8) mL·min−1·kg−1	male subjects and professional soccer players.	To examine the physiological response and reproducibility of the Yo-Yo intermittent recovery test and its application to elite soccer	HR, lactate, muscle crP, glycogen, pH.	Fatigue during intense intermittent short-term exercise was unrelated to muscle CP, lactate, pH, and glycogen. Yo-Yo test was a valid measure of fitness performance in soccer. The aerobic loading approached maximal values, and the anaerobic energy system was highly taxed.

Table 3. Selected articles (Continuation)

Reference	Sample				Study characteristics		
	Sample Size	**Age**	**Anthropometrics**	**Sport Discipline**	**Objectives**	**Assessed parameters**	**Conclusions**
(Nakamura et al. 2016) **Brazil**	10	19.2 ± 0.8	height = 173.8 ± 6.2 cm; weight = 71.3 ± 6.6 kg	professional futsal players	To compare the weekly natural log of the root-mean-square difference of successive normal inter-beat (RR) intervals (ln $RMSSD_{Weekly}$) and its coefficient of variation (ln $RMSSD_{CV}$) in response to 5 wks of preseason training in futsal players	HR (HRV: ln $RMSSD_{Weekly}$, ln $RMSSD_{CV}$), RPE.	HRV monitoring on an individual basis may be useful to detect players deviating from expected responses to training.
(Hausswirth et al. 2014) **France**	initial 40, final 27	CTL group (9): 37 ± 6; overload group: AF (9): 35 ± 8; F-OR (9): 35 ± 5.	CTL group: 182 ± 6 cm, 72 ± 9 kg; overload group: AF group: 179 ± 9 cm, 73 ± 8 kg; F-OR group: 180 ± 5 cm, 72 ± 9 kg.	trained triathletes	To examine whether: i) objective markers of sleep quantity and quality are altered in endurance athletes experiencing OR in response to an overload training program ii) reduced sleep quality would be accompanied with higher prevalence of upper respiratory tract infections.	HR, sleep patterns, maximal aerobic power, VO_{2max}, blood lactate, mood states, incidences of illness, RPE.	This study confirms sleep disturbances and increased illness in endurance athletes who present with symptoms of F-OR during periods of high volume training.
(Shearer et al. 2015) **United Kingdom**	28	24.4 ± 2.9	weight = 103.9 ± 12.2 kg	rugby union players	To examine sleep patterns of professional rugby union players, prior and post-match-play, to assess the influence of competition.	Sleep patterns: time in bed, sleep latency, time asleep, time awake, sleep efficiency, actual sleep percentage, percentage of time moving, and sleep restlessness.	Sleep that is deprived post-match may have detrimental effects on the recovery process.

Table 3. Selected articles (Continuation)

Reference	Sample				Study characteristics		
	Sample Size	**Age**	**Anthropometrics**	**Sport Discipline**	**Objectives**	**Assessed parameters**	**Conclusions**
(Robey et al. 2014) **Australia**	12	18.5 ± 1.4	weight = 71.4 ± 7.4 kg	elite youth soccer players	To examine the effect of early evening high-intensity training on the sleep of elite male youth soccer players using wrist actigraphy	Sleep measures (bedtime, wake time, sleep duration, sleep onset latency, sleep efficiency and wake after sleep onset). RPE, fatigue, recovery	Early evening high-intensity training had no impact on subsequent sleep quality and quantity, nor was there any effect on sleep after performing CWI post-training.
(Minett et al. 2012) **Australia**	10	23 ± 8	Height = 189.8 ± 8.8 cm; body mass 84.9 ± 12.6 kg	well trained medium-fast bowlers	To examine physiological and performance effects of pre-cooling on medium-fast bowling in the heat.	HR, Tco, Tsk, sweat loss. Performance: ball speed, accuracy and run-up speeds. Physical: GPS monitoring, and counter-movement jump height. Biochemical: serum concentrations of damage, stress and inflammation. Perceptual: RPE and thermal sensation.	Mixed-method whole-body pre-cooling had no effect on the skill-based performance but improved thermoregulatory control.

Two additional studies were developed among soccer players (Bendiksen et al. 2012, Krustrup et al. 2003). Divergent in their aims, both assessed HR, muscle CrP (creatine phosphate) and lactate concentration along with other variables. Bendiksen et al. (2012) showed that this multivariate approach was able to distinguish the various phases of a simulated soccer game and compare them to a competitive setting. On the other hand, Krustrup et al. (2013) examined physiological responses from a group of players and regular males with the goal of determining the suitability of the Yo-Yo intermittent test for its application to elite soccer. While fulfilling its goal, the investigation demonstrated that aerobic loading approached maximal values, and anaerobic energy system was highly taxed. Finally, and contrarily to the aforementioned, it indicated that fatigue during intense intermittent short-term exercise was related to HR responses but not with muscle CrP and lactate.

Correspondingly to the cited study developed by Hausswirth et al. (2014), two more assessments (Le Meur et al. 2012, Coutts, Slattery, and Wallace 2007) were applied in a triathletes sample and identically to the aforementioned, both included a control group and an intensified training group. By a multivariate approach, Le Meur et al. (2012) concluded that HR and blood lactate concentration were the most important factors in discriminating between control and overreached athletes. Furthermore, Coutts (2007), at the time of examining selected practical tests for monitoring changes in performance, fatigue and recovery, was able to show significant changes in HR between the groups.

Taking in consideration diverse sports disciplines, Saboul et al. (2016), Buchheit et al. (2012) and Nakamura et al. (2016) also developed HR assessments but focused on analyzing HRV (heart rate variability) measures. What is more, one of them (Saboul et al. 2016) established as its main goal the validation of a HRV index to assess TL (training load) in field conditions. In this respect, the investigation evidenced that HRV was strongly correlated with exercise intensity within a long-distance runners' sample, and the proposed index provided correspondent results with other well-known methods (Foster and Banister). On the other hand, Buchheit et al. (2012) examined HRex and post-exercise HRV along with other physiological and perceptual measures in football players. As a result, these HR derived measures, TL and wellness measures were proved to be the best simple parameters for monitoring intensified training responses. Moreover, by evaluating two HRV variables (ln RMSSD Weekly and ln RMSSDcv) during a professional futsal team preseason, it was possible to conclude that HRV monitoring on an individual basis was useful to detect players deviating from expected responses to training(Nakamura et al. 2016).

Additionally, similar to Vaananen (2004) and Bendiksen (2012), three articles (Barbas et al. 2011, Easthope et al. 2014, D'Artibale, Tessitore, and Capranica 2008) determined the intensity of efforts from HR recordings expressed as a percentage of the participant's maximal heart rate (%HRmax). Samples included motorcyclists, competitive trail runners and wrestlers. In general, they demonstrated the adequacy of this variable to evidence the high loads on participants (D'Artibale, Tessitore, and Capranica 2008) and the significant demands of competitive scenarios(Easthope et al. 2014, Barbas et al. 2011). Additionally, and despite covering a variety of physical activities, percentages showed comparable results between all, as they evidenced from 85% during a simulated one-day wrestling tournament (Barbas et al. 2011), 86% through a simulated soccer game (Bendiksen et al. 2012), 87% during skiing (Vaananen 2004) and approximately 90% in both, field-based trail running (Easthope et al. 2014) and road-races of motorcycling competitions (D'Artibale, Tessitore, and Capranica 2008).

Similarly, an additional study (Galy et al. 2014) considered %HRmax values along with HRrest but with the aim of determining HRReserve, which is the difference between them. In this respect, at the time of examining this and other physiological parameters of performance during the four 7-min quarters of a water polo game, HRReserve was found to be significantly correlated with the player's VO_{2max}, indicating that physical intensity was influenced by the player's aerobic capacity.

Notably, one study (Lamberts et al. 2010) assessed another HR derived parameter, HRR (heart rate recovery), by examining a group of well-trained cyclists. Outcomes from this research revealed that this variable had the potential to monitor changes in endurance performance and contribute to a more accurate prescription of TL in this sports discipline.

Remarkably, Michalsik (2014) was able to prove the moderate-to-high-demands of the different periods of a handball match but, contrary to expected, did not obtain significant results when proving the influence of hydration, body weight loss and hyperthermia on the recorded HR values.

Finally, among all studies, Minett et al. (2012) were the only ones in considering HR recordings along with Tco and Tsk measurements. In this respect, while examining physiological and performance effects of pre-cooling on medium-fast bowling in the heat, was able to demonstrate the unique physical requirements of cricket fast-bowling and, proved the thermoregulatory control improvement obtained with pre-cooling, validating the suitability of HR, Tsk, Tco, sweat loss and RPE parameters to monitor physiological responses to training.

From the nineteen publications, some conclusions could be gathered. First, it was proved that reliable measures can be collected not only in laboratory conditions but also in field situations. Complementarily, it could be evidenced that incorporation of a multidisciplinary research allows for the collection of holistic information during these field studies in which physical and psychosocial competencies are present (Vaananen 2004). In fact, general outcomes revealed that performance is multidimensional (Galy et al. 2014), thus, monitoring various parameters is required in order to have a better perspective of responses to high physical demands and/or contextual stressors (Le Meur et al. 2012). What is more, the importance of identifying early markers of fatigue conditions, OR (overreaching) and OT (overtraining), is highlighted to limit the occurrence of these training maladaptation forms in population at risk (Le Meur et al. 2012). On the other hand, it is important to mention that observed large standard deviations of some outcomes indicates that significant inter-individual differences exist within a sample, which leads to the idea that information should be analyzed in an individual basis. Furthermore, since it was also observed that mean values of some results were compromised compared with population norms, it can also be emphasized the need of assessment models in which reference values are delimitated according to the population context to which they are intended.

Lastly, when selecting assessment parameters, it can be stated that HR and its derived measures are appropriate as they demonstrated to be good indicators of exercise intensity. Particularly, %HRmax evidenced its accuracy to identify the different phases of physical training and the high demands of certain disciplines. In this regard, HR expressed as $\%HR_{Reserve}$ also proved to be suitable for training contexts as it correlates with VO_{2max} evidencing the influence of the player's aerobic capacity (Galy et al. 2014). Likewise, other methods such as actigraphy and thermal response (Tsk and Tco), despite the reduced found evidence, also showed to be able to provide accurate data for monitoring physiological responses.

On the other hand, it should be noted that, among studies, some general limitations were found. Most of the studies presented differences in the number of subjects completing each test. Additionally, some studies reported difficulties to monitor all training events. To illustrate, missing monitoring weeks were reported in one investigation as it only considered from the third to the seventh week of a nine preseason futsal training due to the unavailability of portable HR monitors (Nakamura et al. 2016). Correspondingly, other study indicated to have used different actigraphs within the sample, which could have altered the generalization of obtained data (Robey et al. 2014).

Moreover, analyzing considered samples, only three of the included investigations used a control group (Le Meur et al. 2012, Coutts, Slattery, and Wallace 2007, Hausswirth et al. 2014), which would have allowed to better comparisons and supported the reliability of obtained results. Finally, it was observed that some relevant information about samples was not provided and, even though it does not necessarily bias the obtained outcomes, details about training background and regularity (which was provided only in six investigations), ethnics and nutritional habits would have helped to a more accurate contextualization of the developed research and a better understanding of potential factors influencing adverse outcomes.

4. CONCLUSIONS

The 19 articles included in this systematic review demonstrated that a multivariate approach is fundamental when assessing fatigue, overreaching and other related consequences during high training activities.

Additionally, most of the obtained results revealed the strong relationship, independent of age and sports discipline, between exercise intensity and the different HR derived variables encountered among studies. As a result, this parameter marks a focus point for an assessment of fatigue in any context. Furthermore, and despite the more reduced number of supporting investigations, activity patterns and core and skin temperature recordings proved to be accurate parameters when assessing response to intensified physical activity. Therefore, all these mentioned parameters demonstrated their suitability to be extrapolated into a military assessment context.

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3 DEFINITION OF OBJECTIVES AND METHODOLOGY.

3.1 Objectives

General Objetive

The main objectives of the present study were:

1. To develop a fatigue assessment method based on physiological monitoring.
2. To validate the proposed assessment method and demonstrate its applicability in occupational settings.

Specific Objectives

1. To identify fatigue physiological indicators that could be measured in an operational military setting through a review of literature.
2. To define a fatigue assessment method, suitable for military operations, based on physiological response monitoring.
3. To implement this method and validate its accuracy when detecting different levels of fatigue and alert status.
4. Determine respective conclusions and future research opportunities.

To fulfill the dissertation goals, 2 articles were elaborated. The first one corresponds to a systematic review developed with the objective of summarizing and analyzing studies concerning fatigue assessment in the military context and the second, was a complementary review focused on highly intensity training scenarios, elaborated in order to determine the suitability of physiological variables to monitor different stages of fatigue and related conditions. For both cases, procedure was based in the guidelines of PRISMA Statement and an explanation of it was presented in order to guarantee its reproducibility and traceability. Consequently, based on the found scientific evidence, the third article included a proposal of a fatigue assessment model and its validation in occupational settings. Equipment, procedure, results and conclusions from the experience were also gathered along this final article.

3.2 Methodology

Both developed reviews permitted a conceptualization of the experimental study that was later conducted. In this respect, an algorithm was proposed for the management of fatigue, in which assessment of monitored physiological parameters determines different categories of alert alarms with the aim of preventing further physical impairments caused by fatigue related conditions.

Through a practical experience, the performance of the algorithm was retrospectively evaluated in simulated occupational settings and military practices. A total of 5 participants were studied during a laboratory protocol. Blinded military training measurements from 2 subjects were also tested.

PART 2

4 FIELD STUDY

4.1 General framework

Fatigue is a complex and multifaceted phenomenon that has a variety of possible mechanisms (Edwars 1983). In general, fatigue can be understood as a condition involving decreased ability of individuals to perform activities at the desired level due to lassitude or exhaustion of mental and/or physical strength (Ream and Richardson 1996, Hallowell 2010).

Fatigue degrades performance and well-being leading to error, incident, and accident in operational settings. An operational setting is one in which effective human performance is crucial to a successful outcome. If the human fails, the system fails. Technological advances are enabling 24/7 operations and the integration of human activity around the globe, thus increasing exposure to the factors creating fatigue (Belenky et al. 2014).

Because of the potential impact of fatigue on health, safety, and productivity, any organization in which individuals work extended hours, or hours during which people typically sleep, can benefit from addressing fatigue in the workplace. This is particularly important for safety-sensitive operations such as the transportation, health care, and energy industries.

Military operations are not exempt from this. New technological complexity, the lethality of weapons systems, and rapid worldwide response capabilities make the performance of the individual soldier more critical to mission success than ever before. The near- and long-term health of individual soldiers is also potentially at risk from military technologies that can surpass operator capabilities and safety (Friedl 2012).

Besides typical operational stressors, soldiers, more than any other working group, must deal with particular stressful situations that may lead to a state of fatigue, non-functional overreaching and eventually overtraining.

As physiological stressors compromise health and performance, human performance optimization involves strategies to sustain both in the face of these stressors. Physiological modeling defining human tolerance limits and the effect of moderating factors provide scientifically based strategies to interventions that ultimately involve the way individuals and teams eat, rest, train, and are equipped. Thus, it is important to consider models that combine multiple stressors because individuals are rarely subjected to only one stressor at a time (Friedl 2012).

Through this chapter, with the purpose of providing guidelines to objectively define fatigue, an assessment model, in which different stages of fatigue are delimitated, was proposed. It was developed from the idea that by clearly defining fatigue’s progress it will be possible to plan adequate interventions in order to reduce and/or avoid negative related consequences.

The assessment approach was intended to fulfill previously stablished requirements, namely; to consider a multivariable evaluation, to define each stage with relevant indicators and to apply a non-invasive assessment method.

Focusing on this objectivizing aim, stages only considered the physical manifestation of fatigue, primarily through physiological noninvasive parameters.

As previously indicated, two systematic reviews were conducted. In this regard, determination of stages for this model was made after taking in consideration selected publications and references provided by both reviews. However, since the system was intended for the military field, information from studies developed in this area were primarily considered to assure the adequacy of selected ranges.

Additionally, as the projected assessment model was being developed, scientific evidence found in the reviews was augmented, and additional references were included in the experimental stage of the project.

As a result, an alert-based physiological assessment model was stablished and, with the aim of optimally analyse large data files from PSMs, a subsequent algorithm developed in python programming language was elaborated.

Consequently, an experience in which the proposed algorithm is validated, was performed and is presented in the following sections.

4.1.1 Objectives

In general, the present proposal aims to fulfil the following goals:

1. To develop a fatigue assessment algorithm based on physiological monitoring.
2. To validate its applicability in laboratory trials and using blinded military training recordings.

4.2 Methods

4.2.1 Participants

Included subjects were regular elements from the Portuguese Army.

For the purposes of this study, data from 5 male subjects during a VO_{2max} test, performed as part of a project executed from January 2014 to December in 2015, were compiled.

Additionally, recordings from 2 elements during a psychophysics military training were assessed.

All subjects gave their informed written consent prior investigative procedures and were briefed on the purpose, potential risks and benefits of the planned experiences.

In general, recruited subjects did not present cardiac, vascular, pulmonary, or any allergic medically diagnosed diseases, were considered mentally healthy and were not prescript with any regular medication.

4.2.2 Anthropometrics

A total of 5 soldiers were part of a laboratory experience. They were aged 22.4±1.14 (years ±SD) and weighted 78.1±14.41(kg ±SD).

Their general characteristics are presented in Table 1.

Table 1. Participants Characteristics

Assigned Code	**Birth Date.**	**Age (until 20.06.14)**	**Weight (Kg)**	**Height (m)**	**BMI* ($Kg.m^{-2}$)**	**Body Fat (%)**
M02	09.10.91	22	75.8	1.772	24.14	6.8
M03	27.04.92	22	71.5	1.708	24.51	13.7
M04	14.11.89	24	69.6	1.779	21.99	8.9
M05	23.09.92	21	70.1	1.736	23.26	6.1
M06	25.07.90	23	103.5	1.725	34.78	23.7

**BMI: Body Mass Index*

Additionally, blinded measurements from 2 male soldiers in operational conditions were gathered.

4.2.3 Equipment

4.2.3.1 Laboratory testing

- ***VO_{2max} test***

Maximum oxygen consumption (VO_{2max}) was assessed on a General Electric cycle ergometer (model T2100). The test was performed until complete exhaustion.

During experimental trials, oxygen concentration was continuously measured and monitored with a Cosmed K4b2 equipment. Additionally, physiological parameters were recorded as follows: skin temperature with temPlux thermometers, heart rate through ECG with a General Electric equipment and brain activity through EEG with an Emotiv EPOC EEG headset.

All trials were executed according to preestablished validated protocols, obtained data was saved in digital files and events chronology was recorded in log diaries.

- ***Perceived Exertion***

Ratings of perceived exertion (RPE) were measured verbally using the modified Borg's Scale (Borg, Hassmén, and Lagerström 1987). Subjects rated their level of fatigue on a scale from 0 (none at all) to 10 (Maximal exertion) during and immediately at the end of the maximal incremental test.

4.2.3.2 Military training

Physiological measurements were recorded every 15 seconds, through a chest belt physiological monitoring system: EquiVital LifeMonitor equipment (Hidalgo Ltd., Cambridge, U.K.), a "wear and forget" system type. The LifeMonitor senses, records and intelligently processes data measured from the person and is able to transmit this over a wireless or wired interface.

In both cases, for core temperature recordings, ingestible thermometer pills from Vital Sense were used. These pills travel along the digestive track harmlessly and leave the body naturally within 24 to 72 hours.

Finally, obtained data were analyzed by the annotated algorithm developed using Pandas, a Python 3.6 library for data analysis and statistics.

4.2.4 Experimental design

4.2.4.1 Laboratory testing

As described in the literature, the Maximum oxygen consumption (VO_{2max}) is an indicator of the aerobic power and the physical condition of a given subject (Impellizzeri, Rampinini, and Marcora 2005).

In this study, VO_{2max} was evaluated using an incremental treadmill protocol.

Initially the subjects performed a 5-minute warm-up run at low speed on the treadmill (8 km/h).

After resting (5 minutes at 4 km/h) subjects performed a progressive and continuous test, to exhaustion, on the treadmill without slope at an initial speed of 10 km/h, with load increments (1 km/h) every 2 minutes.

4.2.4.2 Military training

Physiological monitoring from psychophysical military practices were also assessed.

Contrarily to the aforementioned experience, in this case, there was not predefined experimental protocols and recordings were gathered during normal training conditions. It was only after obtaining the results from the algorithm that some specificities about training were asked and correlated with the performed assessment.

In general, these psychophysical exercises are designed to expose soldiers to limit conditions, in which they must deal with severe acute stress produced not only by the physical demands of training but also by neuropsychiatric and metabolic stressors such as sleep and food deprivation and short recovery periods. In addition, possible extreme environmental conditions may also be present.

4.3 Physiological Assessment Algorithm

Physiological monitoring records were assessed using a novel algorithm (Figure 1) that enables analysis and provides integrated assessment of parameters in 3 levels: per minute, per hour and in a daily frequency.

In general, the proposed algorithm takes the monitored data (from the EquiVital Manager) and uses recordings as input parameters. Initially, it uniformizes received values resampling them to a minute frequency and determines an alert alarm per minute according to 10 assigned categories (Table 2), that refer from a good overall health status (alarm 1) to 4 different levels of fatigue (alarms 2, 3, 4 and 5) and possible extreme scenarios of bad health status (alarm 6) or potential faint (alarm 7) or absence (alarm 8). Special consideration is also given when the sensor is not functioning properly (alarm -1). Later, from these determined alarms, it analyses continuous bad status and a possible death condition (alarm 9). Additionally, it is able to calculate the longest continuous time in which the subject presents a maximal effort status.

In a second level of examination, data is resampled to an hour frequency and, sustained fatigue alarm levels and related percentages per day are calculated. Finally, a third level of analysis is presented with mean values per day. All these three generated assessments are then exported to an xlxs file under the name of ‘Results’.

Complementarily, this proposed system presents graphical analytical information in 5 generated png-format charts: one displaying peak values from heart rate minute recordings, other presenting a bar graphic with alarms percentages per day, a third one with the evolution of parameters by minute, one more evidencing the different movement patterns and alert levels per minute and a last one with obtained hourly values from heart rate and core temperature recordings.

Table 2. Alert alarms

Alarm Codes	Alarm Description	Assessed parameters
1	**Overall Status: Good**	HR, BR, Tco
2	**Low Intensity Fatigue**	Overall Status: Good, BR, HR
3	**Moderate intensity**	HR, BR, Tco
4	**High Intensity**	HR, BR, Tco
5	**Maximal Effort**	HR, BR, Tco, Ambulation Status
6	**Overall Status: Bad**	HR, BR, Tco, Body Position, Ambulation Status, Maximal Effort, TimeMaxHR
7	**Faint**	BR, HR, Body Position
8	**Totally absent**	HR, BR
9	**Dead**	Absent, TimeNoHR
-1	**Sensor not working**	Datatag

4.3.1 Assessment criteria

4.3.1.1 Physiological variables

The main feature of this assessment algorithm lays on its ability to classify received physiological information into health alarm levels.

For this matter, three variables are considered as the most discriminating factors when determining every alarm stage.

- ***Heart rate***

Consulted literature in both, high intensity training scenarios (Hausswirth et al. 2014, Le Meur et al. 2012, Coutts, Slattery, and Wallace 2007) and military settings (Lieberman et al. 2016, Buller et al. 2015, Welles et al. 2013), revealed the strong relationship, independent of age and sports discipline, between exercise intensity and the different HR derived variables. As a result, initial filters were determined through this parameter.

However, since cardiac reactivity can vary greatly from one individual to another, and baseline measurements can also be diverse, fixed values of heart rate were not determined, as they would not be representative for all scenarios.

Alternatively, it was found that variations of heart rate expressed as percentages of the subject's theoretical maximal heart rate allowed a more accurate categorization on the intensity of physical activity (Barbas et al. 2011, Easthope et al. 2014, D'Artibale, Tessitore, and Capranica 2008) and the considered levels in D'artibale et al. (2008) study: (1) maximal effort (>90% maximal heart rate); (2) high-intensity (80–89% of maximum); (3) moderate-intensity (70–79% of maximum); (4) low-intensity (<70% of maximum) were selected as the primary premises for the four stablished fatigue alarm levels. A similar categorization was proposed in military settings (Pihlainen et al. 2014) suggesting they adequately adapt for applications in this context as well.

- ***Core temperature***

Along with heart rate measurements, literature from previously developed investigations (Minett et al. 2012, Charlot et al. 2017, Buller et al. 2015, Jouvion et al. 2017, Welles et al. 2013) and normative guidelines (ISO 9886:2015) have proved the relevance of correlating the aforementioned with core temperature values.

Referring to the ISO 9886:2015, thermal strain evidences through values from 38 to 39° C. However, during high intensity training, studies have shown that upper limits go above 39°C (Moran, Shitzer, and Pandolf 1998, Jouvion et al. 2017). As a result, fatigue alarms were set considering ranges from 38°C, for low intensity fatigue, to above 39°C, when maximal effort is reached.

Additionally, conditions of potential hypothermia were covered by taking as a reference the cited ISO standard, in which lower limits are set in 36°C, and values stablished for general occupational settings (ACGIH 2008). Lastly, this last consulted source also served to characterize cases of potential faint (alarm 7).

- ***Breathing rate***

Finally, and with the aim of validating the accuracy of settled alarm ranges, additional conditions were included with respiratory frequency references. Even though literature provides limited evidence of this parameter as a training measure, studies have shown it is currently measured as a vital sign by multiparameter wearable devices in the military field, clinical settings, and occupational activities (Nicolò, Massaroni, and Passfield 2017).

What is more, it has been proven to be strongly associated with perceived exertion during a variety of exercise paradigms (Nicolò et al. 2014, Nicolò, Marcora, and Sacchetti 2016), and under several experimental interventions affecting performance like muscle fatigue, glycogen depletion, heat exposure and hypoxia. This suggests that this variable is indeed a strong marker of physical effort. Furthermore, unlike other physiological variables, it is able to respond rapidly to variations in workload during high-intensity interval training (HIIT), with potential important implications for many sporting activities (Nicolò, Massaroni, and Passfield 2017).

For the purposes of this alert-based system, similarly to heart rate variations, breathing rate limits were stablished as percentages of the subject's maximal respiratory frequency and taking as a reference the categories provided by Nicolò et al. (2014) from their proven correlation with RPE. For instance, values of 80% and 88% of the maximum respiratory frequency corresponded to an exercise effort perceived as hard and very hard, respectively and, were correspondingly used in the algorithm to delimitate alarm levels 3 and 4.

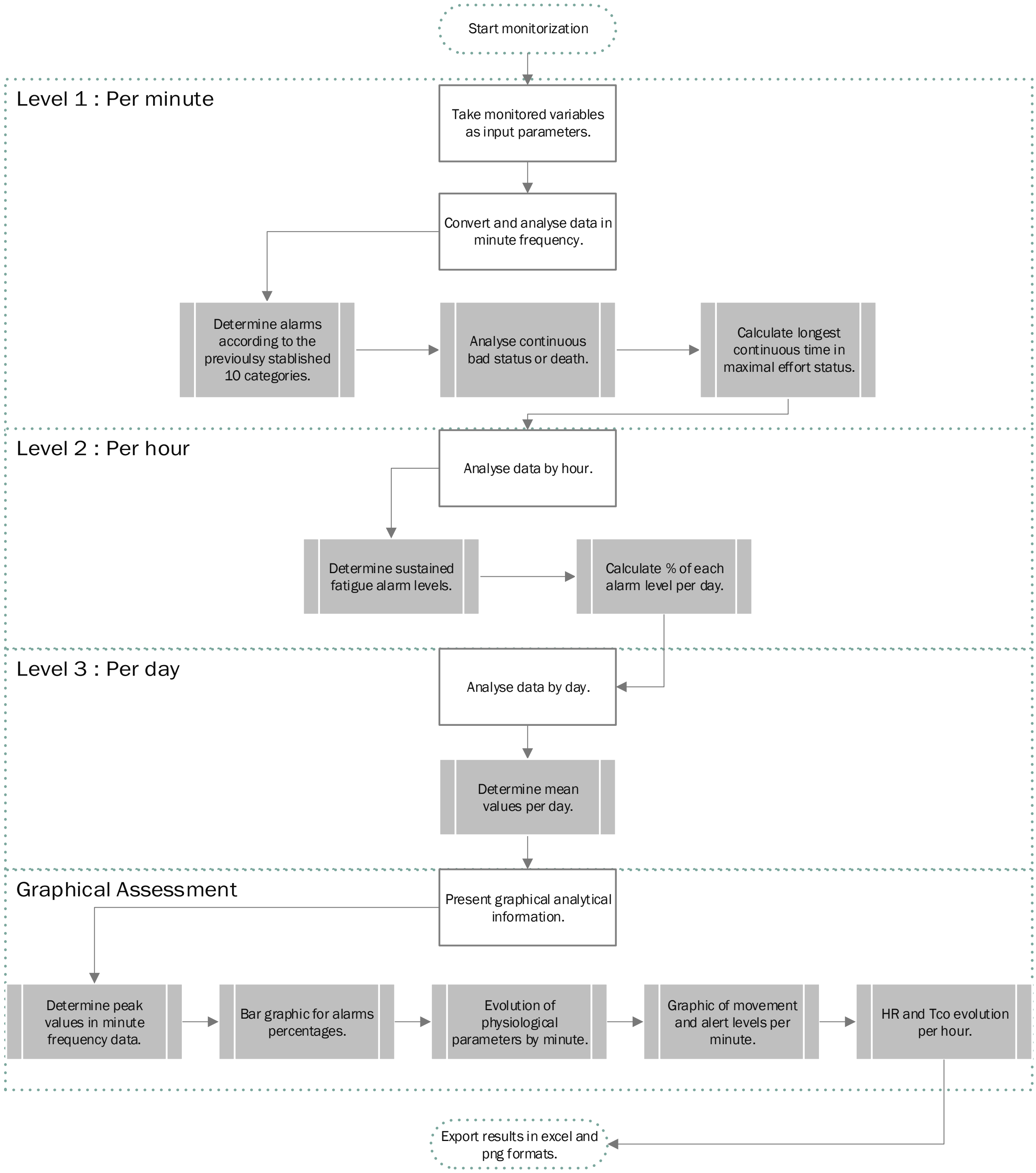

Figure 1 Algorithm Assessment Process

4.3.1.2 Alert Alarms

Taking in consideration aforementioned criteria and supporting monitored variables (movement patterns and sensors' data tags), 10 categories (Table 2) were established. For every alarm, more than one scenario was delimitated. Variables considered for each of them are detailed in Table 2.

In general, fatigue alarm levels are verified first and whenever one of the conditions is not met, fatigue alarm level undergoes one category. In other words, after verifying sensor status, categorization process begins from the highest fatigue alarm and only if none of the fatigue alarm conditions is fulfilled, the other alarm levels conditions are verified. Figure 2 synthetizes this process.

A brief description of each of the subprocesses undertaken for the definition of alarm categories are described in the next lines.

-1. Sensor not working. The first stablished filters are guided to determine the sensors' reliability. In this respect, the EquiVital system already detects possible sensor failures and provides a data classification under a column named 'Data Tag'. The algorithm sets this alarm each time this variable indicates a Data Warning. For posterior assessments, the algorithm does not consider any recording under this label and performs evaluations based only on Tco, as values of this variable are provided not by the SEM but by the associated core pill.

Fatigue Levels: alarms 3, 4 and 5. After verifying the validity of monitored data, stablished ranges of HR, BR, Tco and Ambulation Status are tested to verify any of the fatigue related settled scenarios. Conditions fulfilment are checked first for the 'Maximal Effort' alarm (alarm 5), then for the 'High Intensity' status (alarm 4) and finally for the 'Moderate Intensity' category (alarm 3). If data does not correspond to any of the proposed cases, conditions for alarm 1 (**Overall Status: Good**) are verified.

Given each category ranges of HR, BR and Tco, it is expected that an Alarm 5 is only determined in fatigue limit conditions that, when sustained, indicate a potential health impairment (alarm 6).

2. Low Intensity Fatigue. Since low intensity fatigue effects do not alter the subject's overall health status, only in the cases where data was classified by the aforementioned process as Alarm 1, conditions of a low intensity fatigue are evaluated. Even though this category does not provide evidence of high risk scenarios, it was stablished with the aim of detecting cases in which despite normal ranges, significant elevations in HR and BR are recorded.

6. Overall Status: Bad. The existence of extreme ranges of HR, BR and/or Tco are verified and classified under this alarm. Additionally, a case in which a 'Maximal Effort' (alarm 5) is sustained at rest, is also considered, as it would provide useful evidence on the potential development of non-functional or overreaching conditions.

Every time this alarm is determined, medical intervention is advised, as considered physiological ranges are indicators of a potential health impairment or high risk medical condition.

7. Faint. Cases in which low values of HR and BR are present and a lying body position is detected are considered under this category.

8. Totally absent. When null values of HR and BR are detected, data is labelled under this group.

9. Dead. At last, for the cases in which the above category (Absent) had been detected, time of null vital signs is verified and when sustained over time, alarm indicates this extreme condition.

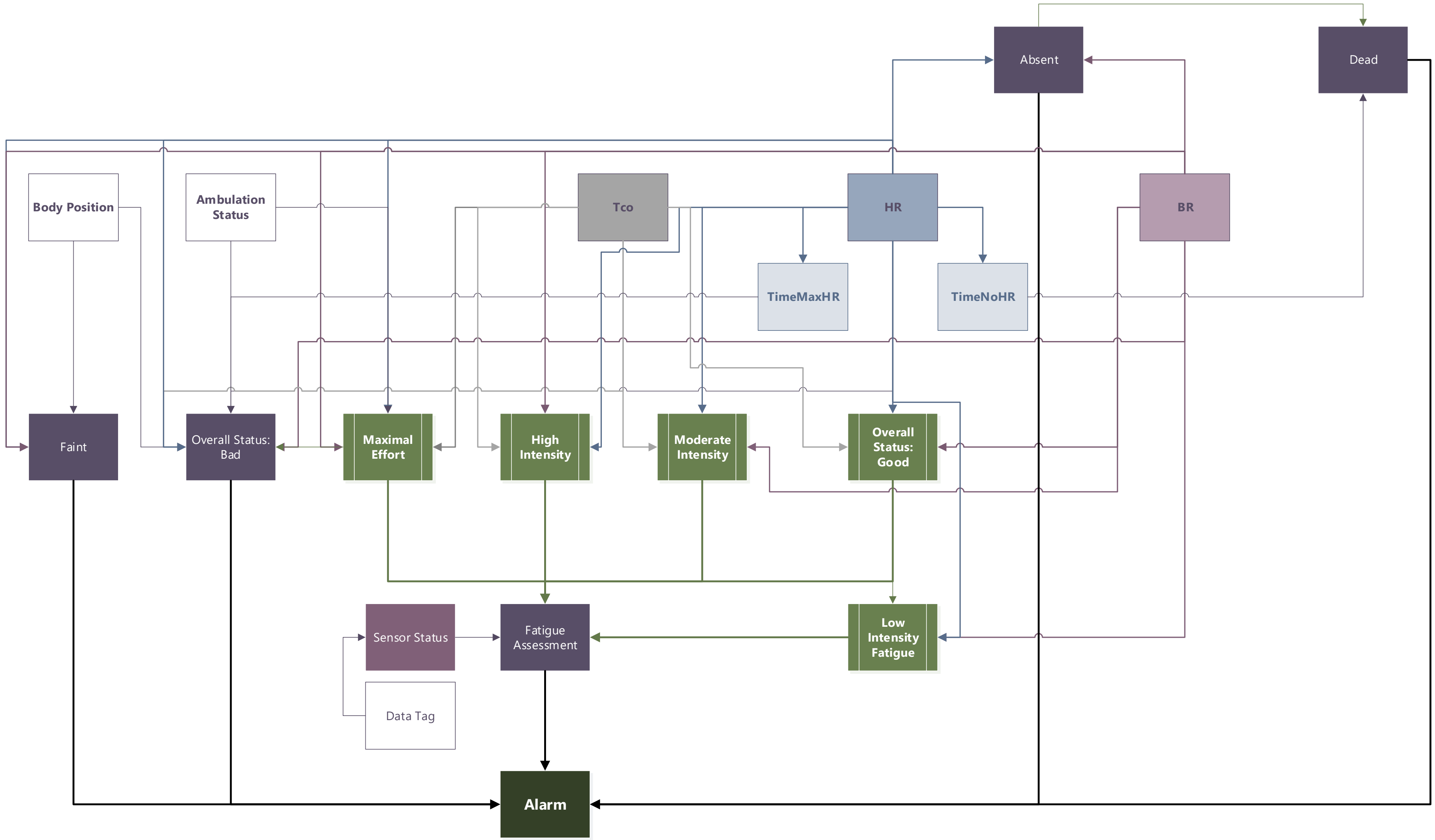

Figure 2. Assessment Model

4.3.1.3 Graphical Analysis

With the aim of providing a complete perspective on the evolution of the subjects' health status, several graphics are displayed. They permit a better visualization on the relationship of variables with the determined alarms and the identification of the most impairing periods of training. Additionally, and as a novelty approach, the system presents a graphic evidencing the peak values of heart rate and calculates the recovery time from them. By analysing these results, it is possible to detect the moments in which recovery is not reached and ultimately prevent development of further conditions, such as overreaching and overtraining (Bosquet et al. 2008).

4.4 Results

In general, outcomes demonstrated that despite the highly opposed considered scenarios, the algorithm was able to evidence the different stages of training and the resulting physical demands on subjects by means of their physiological response throughout the exercises. However, obtained alarms proved to be more conclusive for short periods of high physical activity than when analysing hours of intermittent training events.

4.4.1 Laboratory testing

In total, experimental data from 5 subjects were referred for assessment.

Using the algorithm, it was possible to evidence fatigue evolution during the designed up-to-exhaustion exercise.

Similar tendencies were observed among participants, as they gradually went from this first alert level (at the beginning of the trial) to a high intensity fatigue (alarm 4) at the end (Figure 3).

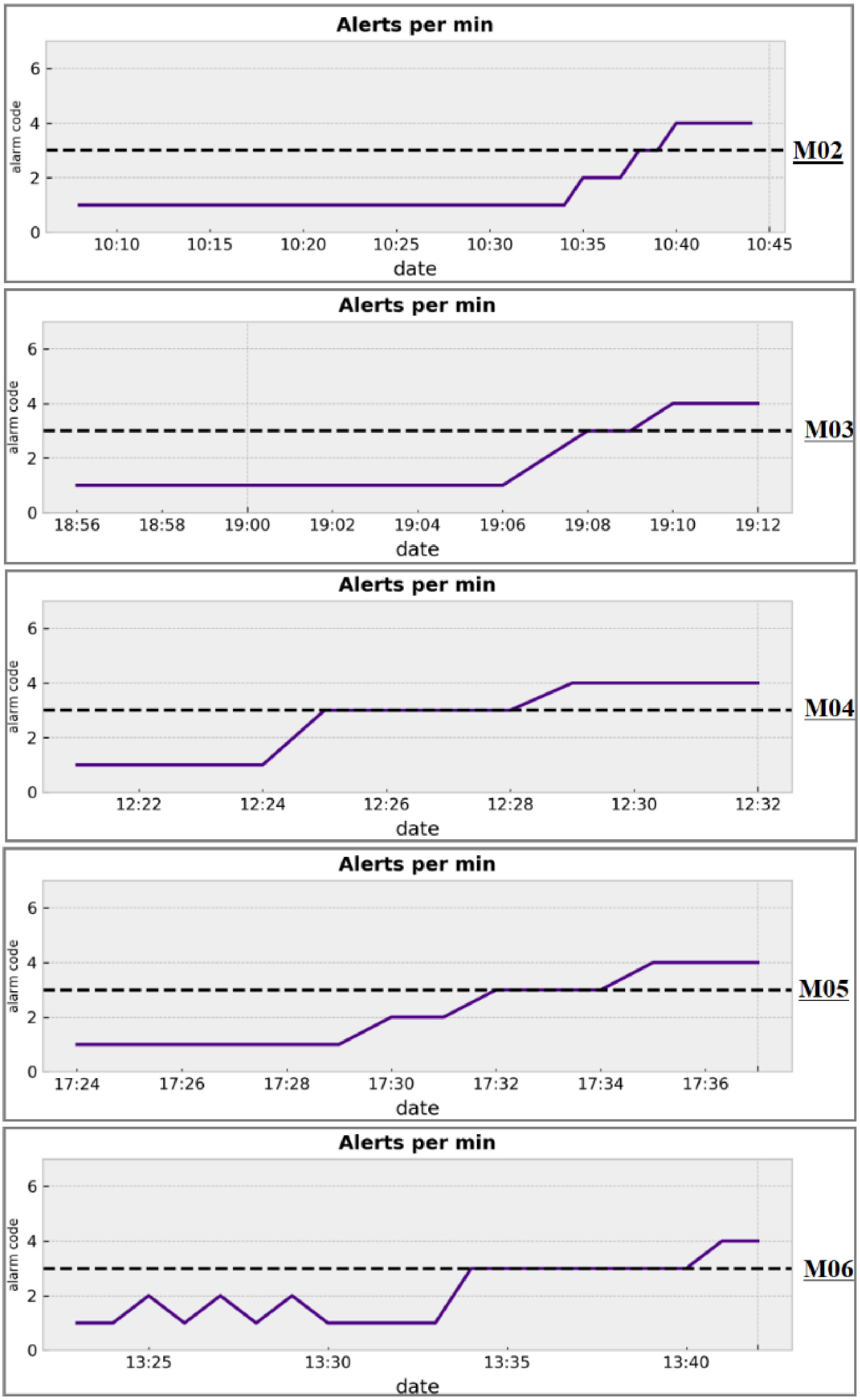

Figure 3. Algorithm-generated graphics with alerts results from 5 subjects during VO_{2max} test.

On the other hand, when considering results from Borg's Scale, Figure 4 evidences the expected increasing tendency of reported values from all subjects.

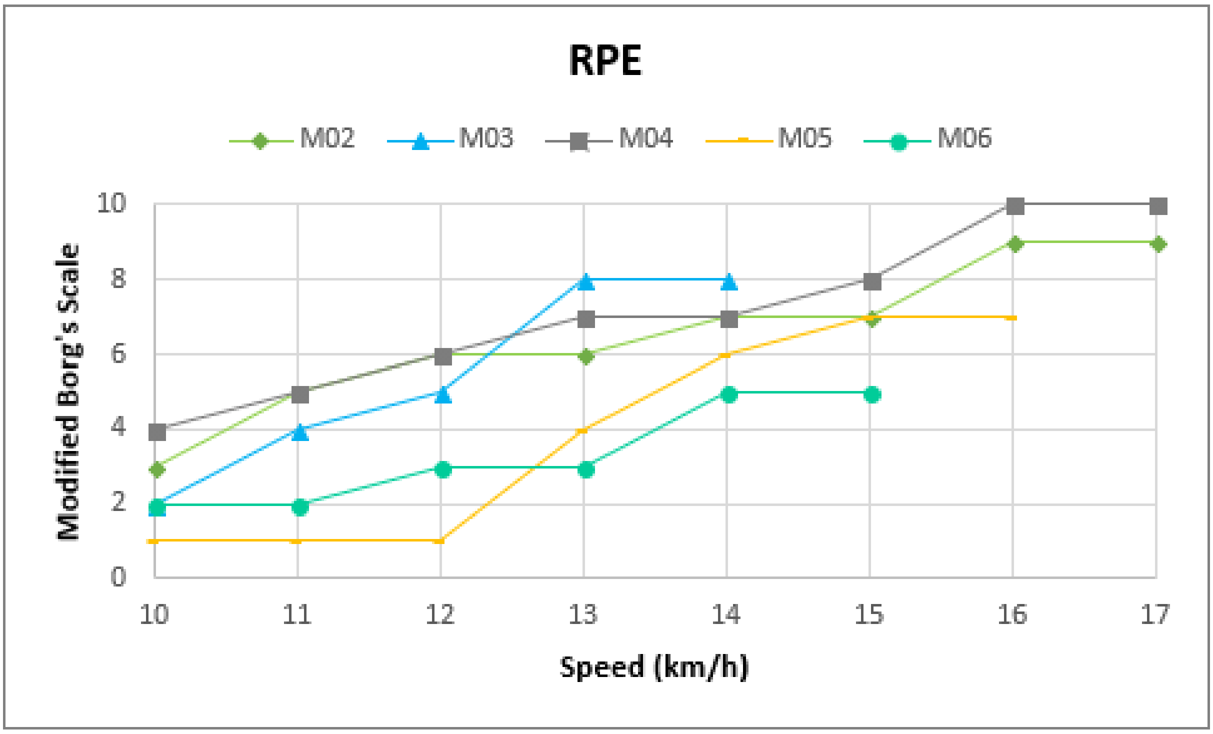

Figure 4. RPE from all participants.

Additionally, when correlating both outcomes; alert alarms with the obtained values in modified Borg's Scale, as Figure 5 evidences, comparable growing trends were observed.

And observing the correlation coefficient obtained in each case, the strong positive linear relationship between both outcomes was also proven.

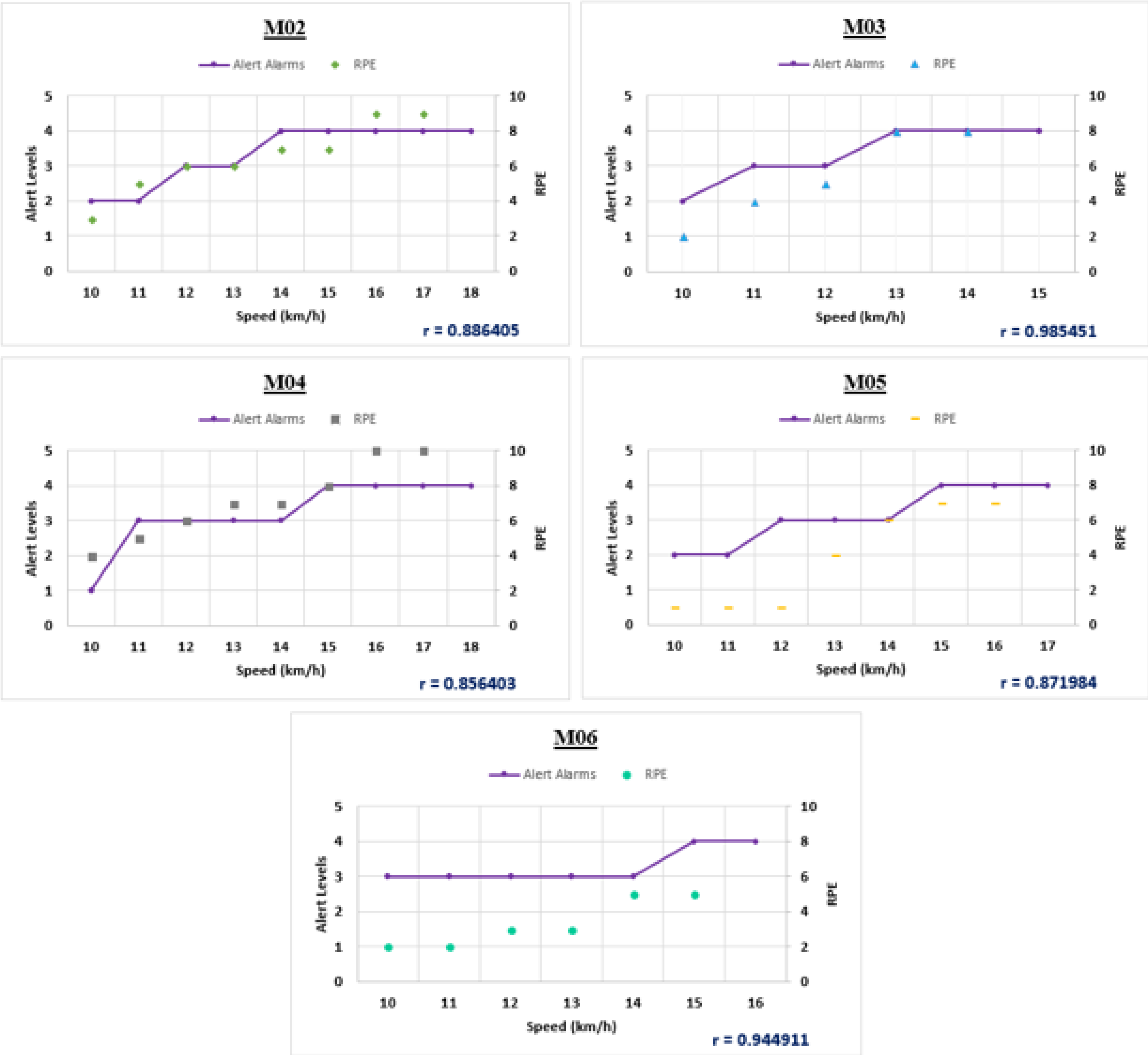

Figure 5. Alert Alarms vs. RPE.

4.4.2 Military training

2 physiological monitoring records were also assessed by the proposed algorithm.

Contrarily to the above cases, results from both subjects showed exposure to high risk scenarios as alarm 5 and 6 were evidenced during the last recorded hours (Figure 6).

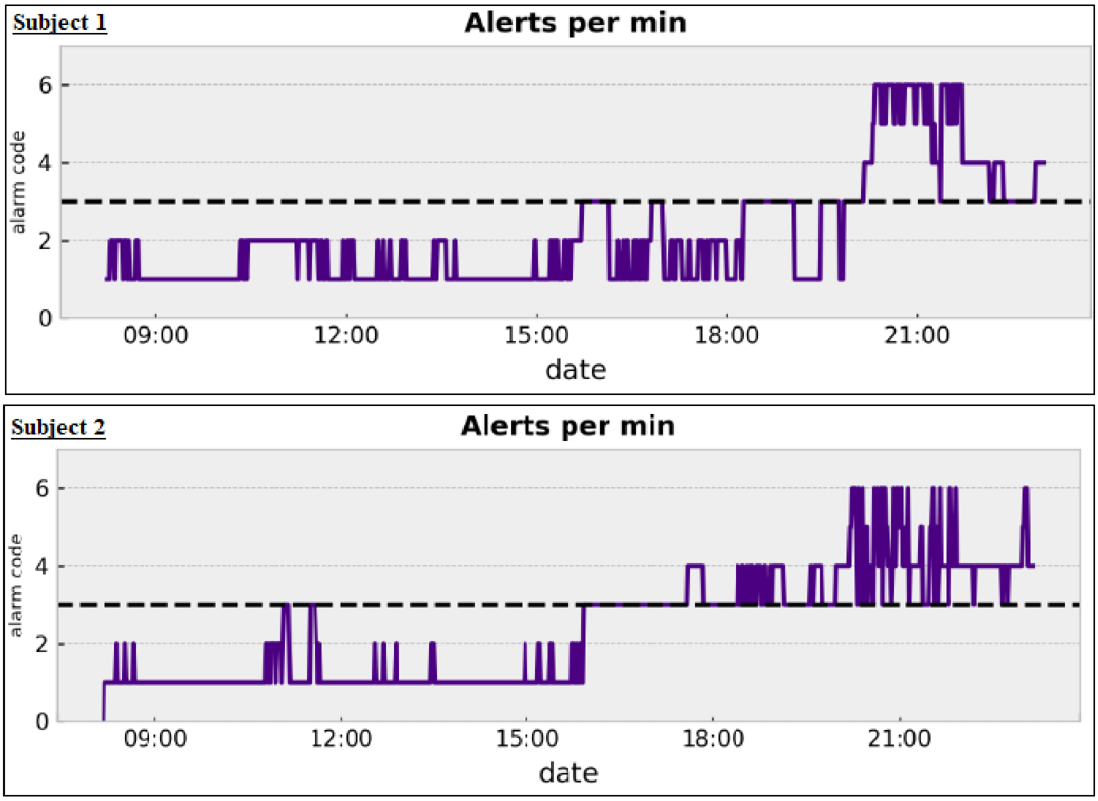

Figure 6. Algorithm generated graphics with alerts results from Subject 1 and 2.

However, conclusive alarm levels were not observed through time, as graphics obtained from the algorithm (Figure 6) evidenced several oscillations among results within alarms 5 and 6.

On the other hand, individual physiological responses, as presented by the algorithm (Figure 7), make possible to evidence the different stages in training and the most demanding periods of it. What is more, they make possible to observe that there were some periods in which the sensor indicated Warning labels and therefore, assessments for those cases were made only with core temperature recordings and values from HR and BR were eliminated. This fact might have been responsible for many of the above presented variations in results.

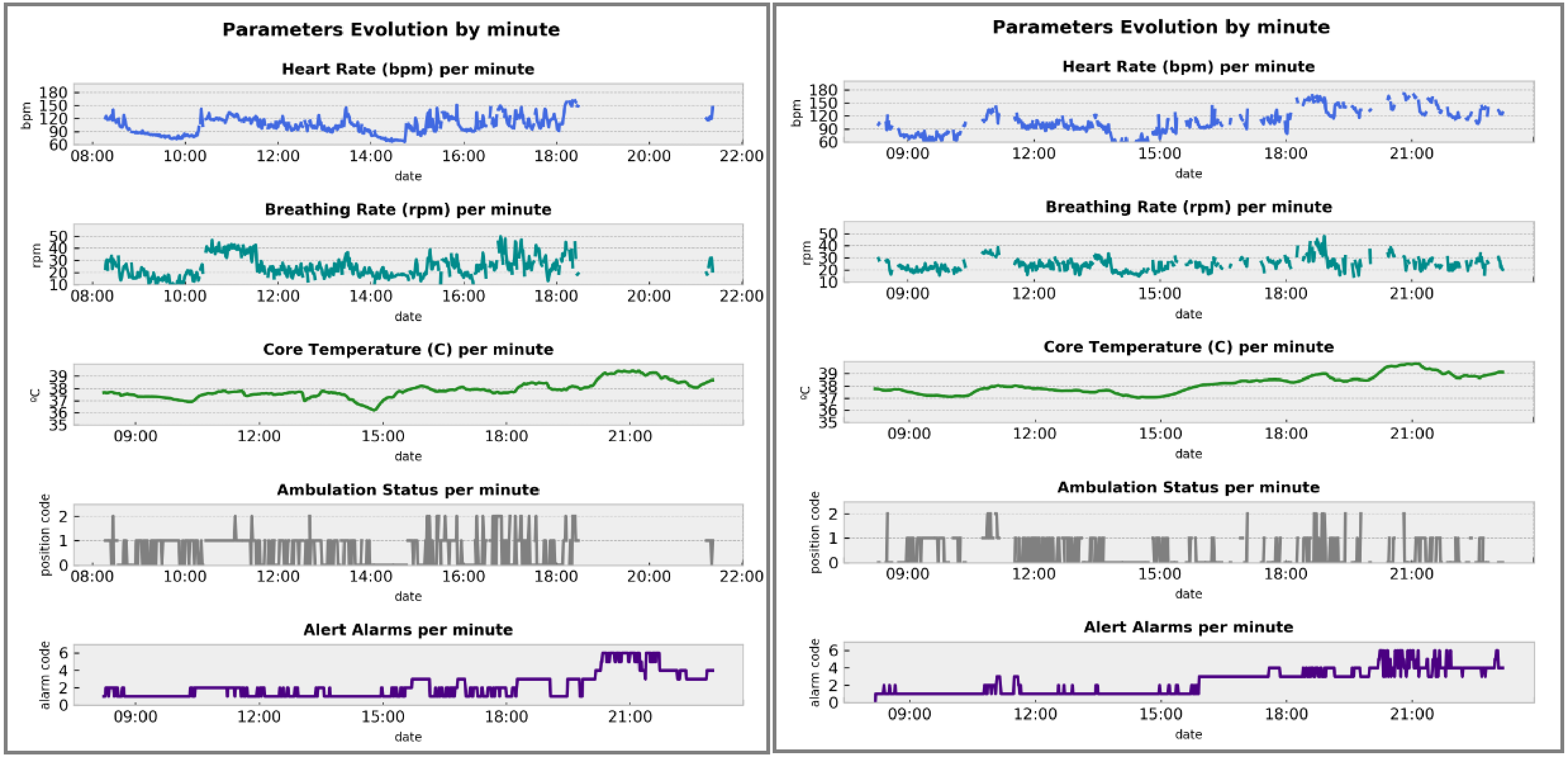

Figure 7. Algorithm-generated graphics from physiological responses of Subjects 1 and 2, respectively.

4.5 Discussion

In the present study, a novel algorithm for the assessment of fatigue through physiological monitoring was evaluated in both, a designed laboratory experience and blinded recordings from military training events.

Remarkably, the assessment approach was able to provide representative results during the laboratory testing. However, as alarms were determined every minute, it was not very precise when presenting results from big data sets of hours of intermittent activities.

Yet, in both contrasted scenarios, it proved to be a valid approach for detecting physically demanding periods and evidencing the physiological impairment resulting from the most stressful situations, which suggests it can be extrapolated to various occupational and physically intense training settings.

4.5.1 VO_{2max} test

Despite subjects' differences in time to complete the experience, some general considerations can be made among them.

As expected, they all presented a gradual increment in physiological recorded values and therefore, determined alarms also increased along the experience.

Given the characteristics of the experimental protocol, in which speed was gradually increasing every minute until a perceived exhaustion, evidenced patterns proved to be accurate and representative of the assessed scenario.

Since the exercise was short and performed in controlled climatic conditions, and subjects were physically active, it was anticipated that, fatigue levels were going to be present but extreme conditions of maximal effort or a bad overall status were not going to be registered. Consistently, alert alarms gradually increased along the exercise and reached a high intensity level (alarm 4) at the end of the experience in all cases.

On the other hand, from an individual perspective, some observations can also be described.

M06 registered the highest time in fatigue levels 3 and 4 and was the only one evidencing intermittent changes between levels 1 and 2 at the initial phase of exercise. When referring to his anthropometric characteristics, all these patterns were justified as the subject, alike the other four, evidenced an overweight condition, which helped to infer he did not have a physical condition as good as the other subjects. In contrast, M03 evidenced the best physiological response, as he presented the shortest period between levels 3 and 4. Furthermore, M04 showed the most stable tendency from all participants, as he underwent each stage of fatigue for similar periods of time. This fact was justified as he indicated to be a professional marathoner and therefore, potentially in better physical condition than the rest of the participants.

In conclusion, it was demonstrated that this proposed alert-based system was able to provide reliable outcomes from the considered experience.

4.5.2 Military training

From both assessed recordings, some observations can be gathered.

First, contrary to the laboratory experience, higher alert levels were expected since prolonged intermittent exercises are proved to be more physically demanding than continuous short practices (Edwards et al. 1972, Kraning 2nd and Gonzalez 1991, Edwards et al. 1973).

In fact, given the highly stressful characteristics of training, along with the extreme environmental conditions (maximum temperature reached values above 36°C) registered on that day, obtained levels 5 and 6 were representative of this high-risk scenario.

Furthermore, when observing physiological responses (Figure 7), despite not considered warning-labelled data, it could be observed there were periods in which values of HR exceeded 150 bpm and BR were above 40 rpm, evidencing fatigue stages in participants. However, the most significant values where observed in core temperature, as in both cases there were periods in which they went above 39°C and maintained those high-risk numbers over considerable time. This fact helps to comprehend the severe acute stress under which soldiers are exposed during these psychophysical tests and verifies what is evidenced in literature during military field practices (Ralph et al. 2017, Lieberman et al. 2016, Lieberman et al. 2005).

Nevertheless, even though determined alarms were mostly representative of the impaired health condition of participants and the extremely challenging scenario under which they are exposed, the observed oscillations in the higher alert levels suggest that some improvements are indeed necessary to precisely characterise alert situations along the training.

When designing the conditions to determine each of the covered alarms (Table 2), variations within the different fatigue levels were anticipated, since the system performs a minute-by-minute analysis and alarms need to reflect how the different stages of intermittent practices affect the subject's physiology. However, since alarm level 6 was stablished as an indicator for medical intervention, variations between this level and alarm 5 (Figure 7) impede a definite diagnosis in order to provide or not that annotated medical intervention and therefore, evidence the need of including an assessment of longer periods, potentially 5 or 10 minutes, to assure there is indeed a bad health condition that requires medical support.

Enhancement of assessment methodology

Following above mentioned considerations, some adjustments were included in the system.

To start with, an analysis of sustained extreme values over 5 minutes was included as the primary condition to determine an alarm 6 level.

When impaired physiological response does not maintain over this period, the system indicates an alarm 5 status, since it would represent a case of maximal effort but with a recovery from that condition.

On the other hand, if values do continue over the considered period and alarm 6 is determined, the system stops further assessments and keeps this level over the rest of the evaluated time, indicating the clear necessity of a medical examination, which was the intended aim when initially stablishing this alarm category.

Figure 8 compiles obtained results when applying improvements. In this respect, it can be evidenced that oscillations when determining alarms 5 and 6 were reduced and, the alert system is able to provide a clearer perspective of the evolution of impairing conditions as graphics denote how alerts intensify until an alarm 6 is reached and therefore, potentially allow a timely-precise medical intervention.

Overall, it was evidenced not only the high applicability of the proposed system but also opportunities of improvement that could be the foundation of future research studies.

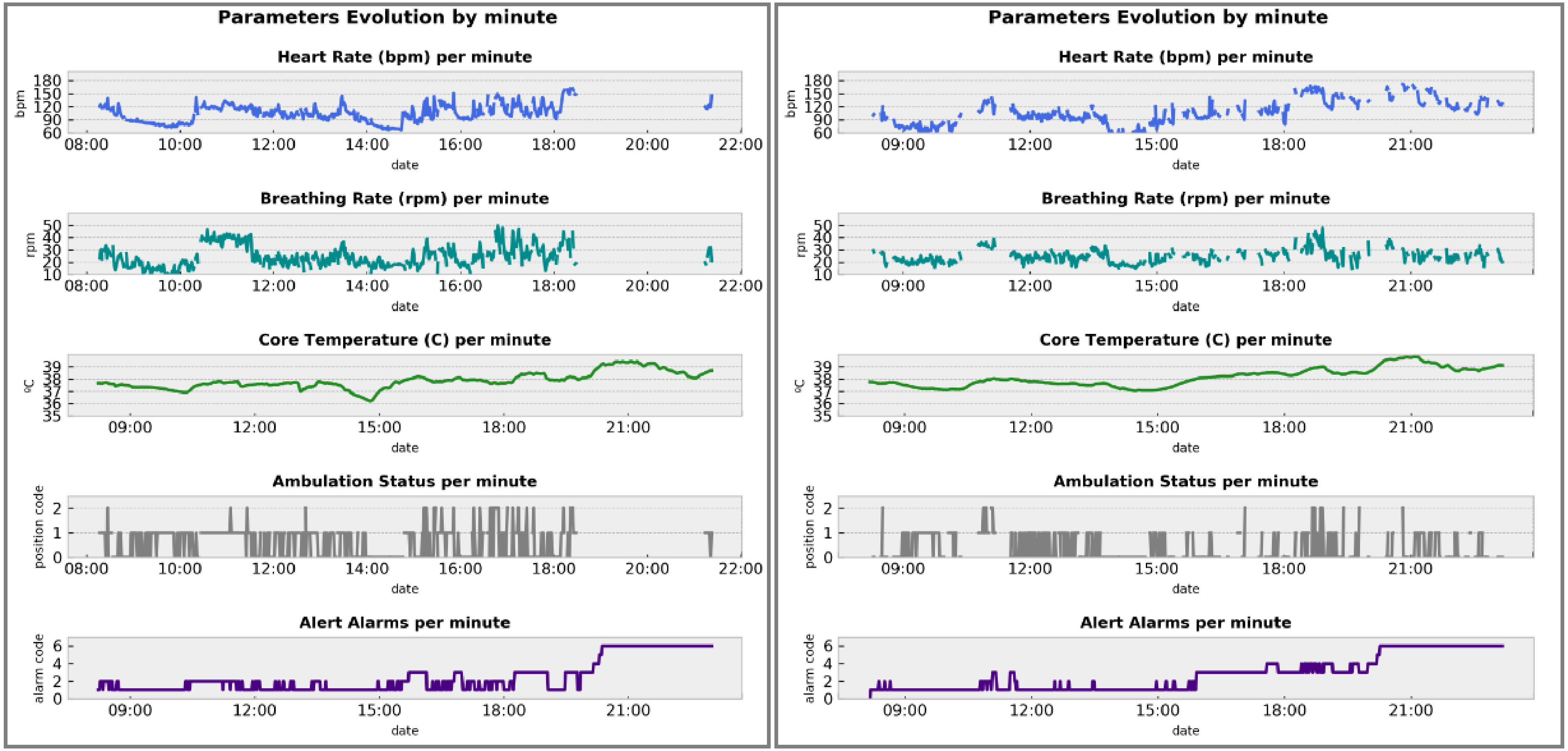

Figure 8. Algorithm-generated graphics from physiological responses of Subjects 1 and 2, after improvements.

4.6 Conclusions

In conclusion, the validation and applicability of an assessment algorithm for fatigue detection and management, within laboratory and training conditions, are reported.

It has been shown that the use of the proposed algorithm led to the successful identification of the most stressful and physically demanding activities and their direct impact on physiological parameters. However, the system proved to be more accurate during incremental short exercises than throughout several hours of intermittent training.

Overall, by providing a systematic and multivariate approach, it is believed that this developed assessment method, with further modifications, has the potential to improve fatigue management, allowing early detection of potential physical impairments, reducing the number of medical evaluations performed and minimising unnecessary delays in treatment. As a final remark, it is inferred it can also become economically advantageous as it potentially reduces the number of investigations performed, although economic outcomes were not evaluated in this present study.

4.7 Limitations and perspectives

- ***Algorithm Limitations***

Despite the proven applicability of the proposed algorithm, certain limitations were encountered.

Primarily, as it was evidenced when assessing the laboratory testing and military training measurements, the algorithm proved to be successful in its minute-by-minute analysis and provided reliable results in incremental short practices but, it presented some inaccuracies in outcomes from long intermittent training events, which suggests that, additional analysis of sustained alert levels over time, as the one proposed after analysing results, should be included.

Additionally, even though the stablished alarm categories consider an integration of various physiological parameters, literature evidences that other variables such as skin temperature and accelerometry counts, which are also recorded by the EquiVital system (Liu et al. 2013), are able to provide additional information on the impact of physically demanding activities (González-Alonso et al. 1999, Taylor et al. 1984, Tomczak, Gajewski, and Mazur–Różycka 2014), and their inclusion not only would have supported the reliability of developed analysis and potentially reduced observed oscillations in results, but also would have permitted a maximization in the utilization of the equipment’s features.

Consequently, and despite its demonstrated general efficacy, this algorithm constitutes only a first approach in which several improvements and validations within bigger samples can be made in order to enable not just retrospective but also continuous and real time assessments.

Finally, another opportunity of improvement was found in terms of how variables are treated, since physiological responses can differ greatly among individuals and measured values can also be diverse, recent studies have proved that variations of recorded parameters, such as core temperature (Morris et al. 2009, Sund-Levander et al. 2004), correlate better and are more sensitive to changes than direct recorded values. Thus, the possibility of considering this approach should also be evaluated.

- ***Algorithm Strengths***

This assessment methodology constitutes a novel approach that allows the categorization of fatigue levels for an early detection of further health impairments. As a result, it can become a useful tool for analysis and design of scientifically based strategies to interventions that ultimately involve the way individuals and teams eat, rest, train, and are equipped.

- ***Perspectives***

The algorithm from this study is not computationally complex and has the potential to be executed by the on-board processors present in many wearable devices with minor modifications. What is more, utilizing this approach, additional sensors and measurements can be integrated into wearable and connected devices, creating novel comprehensive remote monitoring systems.

To conclude, assessment methodology included in this proposed algorithm could be the first step towards developing a real time monitoring system that enables immediate assessments and provides continuous updates on the subject's health status, which would have a wide applicability in safety sensitive professions such as soldiers in the battlefield.

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PART 3

5 FINAL REMARKS

5.1 Conclusions

The current research provides: a solid understanding of fatigue development in high intensity training settings, the most accurate physiological indicators for its detection and assessment and the importance of its early identification in any occupational setting with focus on a particularly stressful occupational scenario: the military.

Initially, a significant literature background was gathered and presented in two articles. Since the investigation's main objectives were stablished for its applicability in military operations, a systematic review was performed to find relevant information on previously developed studies in this context. As a result, the final 12 articles included within this review demonstrated that reliable data can be collected in field situations and that physiological indicators evidence the different stages of training. From this review, as monitoring methods were also analyzed, a research possibility was found with the use of a non-invasive monitoring system such as EquiVital. However, evidence on assessment models among these studies was not found as they primarily focused on presenting results and correlating biochemical, physiological and cognitive variables.

Given previous literature results, the need on a complementary review surged. In this regard, a new research was conducted with focus on investigations developed during highly intensive training activities. Consequently, 19 publications were selected and in general, they demonstrated that a multivariate approach is fundamental when assessing fatigue, overreaching and other related consequences. Furthermore, most of the obtained results revealed the strong relationship, independent of age and sports discipline, between exercise intensity and the different HR derived variables encountered among studies. As a result, it was inferred that this parameter marks a focus point for an assessment of fatigue in any context. Furthermore, and despite the more reduced number of supporting investigations, activity patterns and core and skin temperature recordings proved to be accurate parameters when assessing response to intensified physical activity. Therefore, all these mentioned parameters demonstrated their suitability to be extrapolated into a military assessment context.

From both reviews, it was possible to observe the clear need of a model that takes advantage of the proven relationships between physiological monitoring and fatigue detection and, that provides an assessment method in which different stages of fatigue can be delimitated to allow early detection of potential health physical impairments not only within military personnel but any safety-sensitive professionals. Therefore, supported in references provided in both reviews and consulted normative guidelines, an alert-based physiological assessment model was established and, with the aim of optimally analyze large data files from PSMs, a subsequent algorithm developed in python programming language was presented.

Hence, the experimental part of this work focuses on the validation of this assessment algorithm with physiological recordings from the above mentioned EquiVital system. In this regard, results were able to show that the proposed alert-based system led to the successful identification of the most stressful and physically demanding activities and their direct impact on physiological parameters. Conclusions from the experience indicate that by providing a systematic and multivariate approach, this method has the potential to improve fatigue management, allowing early detection of potential physical impairments, reducing the number of medical evaluations performed and minimising unnecessary delays in treatment.

However, and despite the proven applicability of the proposed algorithm, certain limitations were encountered. Primarily, even though the stablished alarm categories consider an integration of various physiological parameters, literature evidences that variables such as skin temperature and accelerometry counts, which are also recorded by the EquiVital system, are able to provide additional information on the impact of physically demanding activities, and their inclusion not only would have supported the reliability of developed analysis but also would have permitted a maximization in the utilization of the equipment's features.

Additionally, despite its demonstrated efficacy, this algorithm constitutes only a first approach in which several improvements and validations within bigger samples can be made in order to enable not just a retrospective but also continuous and real time assessments.

As a final remark, it can be also stated that this assessment methodology constitutes a novel approach that allows the categorization of fatigue levels for an early detection of further health impairments. As a result, it can become a useful tool for analysis and designing of scientifically based strategies to interventions that ultimately involve the way individuals and teams eat, rest, train, and are equipped.

5.2 Future perspectives

The algorithm from this study is not computationally complex and has the potential to be executed by the on-board processors present in many wearable devices with minor modifications. What is more, utilizing this approach, additional sensors and measurements can be integrated into wearable and connected devices, creating novel comprehensive remote monitoring systems.

Additionally, assessment methodology included in this alert-based method could be the first step towards developing a real time monitoring system that enables immediate assessments and provides continuous updates on the subject's health status, which would have a wide applicability in safety sensitive professions such as soldiers in the battlefield. In this respect, future research possibilities were encountered within investigations from recognized international military institutions such as the U.S. Army Medical Research and Materiel Command, in which, by the application of Artificial Intelligence, homologous interdependencies between physiological variables have been stablished and represented by Bayesian Networks with the aim of developing algorithms that are able to automatically learn those relationships from data files and combine that prior knowledge and incoming data to the likelihood of a hypothesis of interest, such as a soldier being dead given his/her physiology and the sensory data time series (Savell et al. 2004). Thus, the novelty presented by this approach has the potential to provide the foundation to various future works not just for applications in military groups but also for any occupational considered sample.

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