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Research of Human Fatigue and Measurement Parameters for Workability Assessment

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***Abstract*—Human fatigue is reduced working capability for certain period of time as the result of unusual or prolonged workload. Fatigue arises when the body's energy requirements exceed its supply. Fatigue first manifests as reduced concentration capability causing movement coordination and precision disruption leading to decreasing workability. Fatigue is an object of research in physiology, psychology, work ergonomics, medicine, and biotechnology where each domain has a focus on mental fatigue. The functional state in the context of professional activity is defined as a complex of characteristics of functions and qualities that determine the fulfilment of labour activity. Furthermore, a comprehensive estimation of subject functional state in combination with other factors like subject self-assessment and objective performance tests (cognitive load tests) is a necessary input for the evaluation of workability and efficiency on task. The heterogeneous nature of fatigue as a systemic manifestation requires analysis of multiple key parameters which are relevant to the specific type. The current feasibility study focuses on human biological signal from electrical activity of heart, brain, muscles and skin potentials as well as temperature, position, and respiration to obtain diagnostic parameters reflecting the state of cardiovascular, muscles, and central nervous systems for physiological monitoring of vital signs. The fatigue physiological parameter and feature formalization aim to support the development of a platform with complex passive multi-level fatigue monitoring system and workability evaluation system designed in order to provide an integrated service.**

Keywords—human fatigue, functional state, workability.

I. Introduction

Human fatigue is a construct of multiple components that are characterized from experience, physiology or performance [1] leading to the effects of fatigue on operations safety, mental performance, and attention. A wide range of sensors and methods designed for biomedical applications of monitoring vital parameters and algorithms for analysis of human physiological states exist to this date [2]. The areas of research focus on the pathological causes of fatigue as a symptom in differential diagnostics and evaluation of workability based on the physiological states analysis of dynamic monitoring.

The current study aims to formalize the parameters of sensors, subjective questionnaires, and active tests to reflect the physiological, subjective and objective measures of mental fatigue. The listed parameters are significant to the selected method of evaluation of a fatigue component and are categorized by human physiological subsystems. The research analyses methods to gather measurement parameters from different domains of interest in fatigue evaluation. The mental fatigue as a base type for this research is chosen in context with its application in cognitive workability evaluation corresponding the project requirements.

II. Conceptual Method for Mental Fatigue

Task-related fatigue formally is classified as central or peripheral, that later is mental or physical. This paper mainly focuses on mental fatigue, however, some physical fatigue components (psychological, motor-sensory) also used to evaluate the affecting mental performance of cognitive abilities. Mental fatigue is an inability to maintain optimal cognitive performance. The onset of mental fatigue during any cognitive activity is gradual and depends upon an individual's cognitive ability, manifests as a diminished capacity for work and possibly decrements in attention, perception, decision making, and skill performance [3].

Mental fatigue is a transient decrease in maximal cognitive performance resulting from prolonged periods of cognitive activity. It can manifest as somnolence, lethargy, or directed attention fatigue [4]. Fatigue as a multidimensional concept (Fig. 1) implemented in the World Health Organization's Classification of Functioning, Disability, and Health. The multidimensional concept of fatigue is integrated into the World Health Organization's

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International Classification of Functioning, Disability, and Health (WHO-ICF), representing the effect of disease on body function and structure, activity and participation of the patient. Both subjective fatigue and physiological fatigue have an effect on activity and participation and are in most diseases related to health status and disease severity. Psychosocial factors have an influence on fatigue and on activity and participation [5].

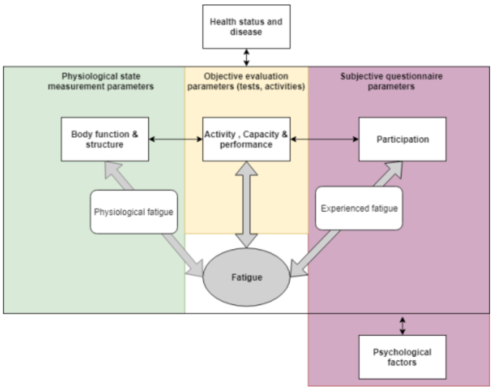


Fig. 1. Fatigue as a multidimensional concept. Parameters from three dimensions reflected in the conceptual model of functioning.

In addition to the model, the current paper focuses on three main workability evaluation perspectives reflecting the overall state of mental fatigue. The physiological states are manifestations known to the literature which serves as a measure for certain mental fatigue related physiological condition. Physiological measurements are grouped under physiological subsystems from which the biological feedback is received and relations to mental fatigue physiological states can be determined (Fig. 2). Further research will focus on the wearable and non-intrusive aspects of the sensor selection.

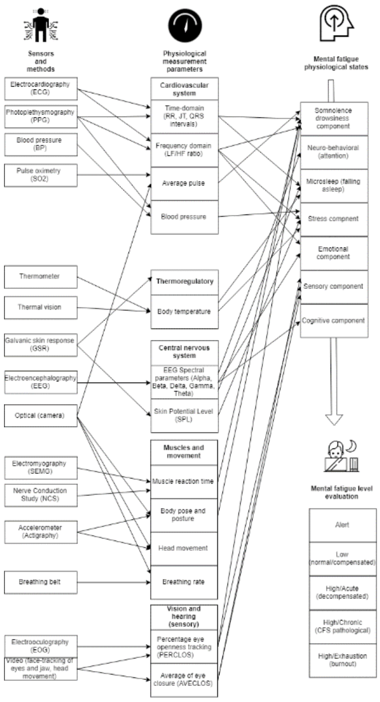
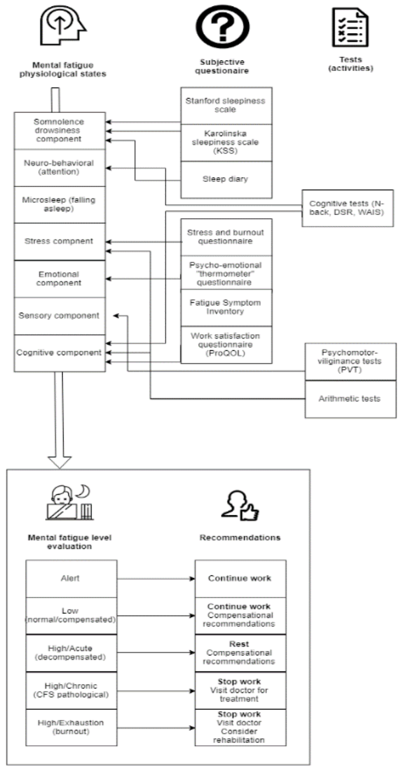


Fig. 1.Part I. Conceptual model of physiological parameters and relation to mental fatigue states.

Mental fatigue physiological states represent a set of indications which can be used in mental fatigue level evaluation. The later stages of the project will focus on the evaluation of fatigue level gradation [6] and possible recommendations (Fig. 3).



Part II. A conceptual model of subjective and test parameters and relation to mental fatigue states, recommendations.

III. Parameters

There are three aspects to fatigue: physiological, objective (work decrement), and subjective fatigue [7]. The process of parameter acquisition in the medical literature follows the steps of symptoms gathering in differential diagnostics [8] where fatigue is generalized as a symptom for at least 10 general diseases, including Chronic Fatigue Syndrome (CFS) [9]. The physiological measurements and tests in practice have dynamic properties, however, a subjective questionnaire can serve as a static measure obtained independently. The combinations of results obtained from three perspectives, which are further discussed in detail, introduce comprehensive human functional state evaluation.

A. Physiological parameters

Generally, human health state is defined by interdependent physiological parameters which respond to mental fatigue and are detectable by sensors. Selected parameters are grouped under corresponding measurable functional systems typically reflected in the literature and are mostly related to symptomatic of mental fatigue.

1) Cardiovascular system

As the heart rate variability (HRV) is coupled to autonomic nervous system activity, it provides a suitable proxy for examining how we feel. There are different methods of HRV analysis. One of the methods is time domain analysis. This method extracts a few special measures using only the temporal RR interval signals. Another method is spectral analysis. This method interpolates the RR interval at a certain rate and transforms this interval into the frequency domain. There are some standards for these two methods [10]. There are also other methods such as Time-Frequency Domain and Nonlinear method. Frequency domain (LF/HF ratio) method is used in the context of human fatigue monitoring to detect or monitor the level of drowsiness [11]. Across diverse tasks and populations, [12] have found evidence for an association between higher levels of resting HRV and superior performance on tasks that tap executive functions. Of the frequency-domain methods, data related to the amount of low frequency (LF) heartbeats is often used (0.04 to 0.15 Hz) as a measure of sympathetic nervous system activity. Measurements of high-frequency (HF; 0.15 Hz to 0.4 Hz) and very-low-frequency (VLF) are also used. ECG recordings are therefore a clear measure of autonomic nervous system activity [13]. The single most common way to analyse HRV is a time-domain method called RMSSD. This is the Root Mean Square of Successive Differences between each heartbeat. HRV analysis is performed through assessment of time-domain indices, the square root of the mean of the sum of the squares of differences between adjacent normal R-R intervals (RMSSD) measured during short (5 min) recordings and particularly the logarithm of RMSSD (LnRMSSD) has been proposed as the most useful resting HRV indicator [14]. These results suggest that the frequency domain is related to psychological symptoms of mental fatigue [15]. The ECG carries information about a person's vigilance state. Hence, HRV measures could potentially be used to predict when an individual is at increased risk of attentional failure [16]. Respiration rate and blood pressure have a significant difference before and after fatigue: respiration rate decreased after fatigue. Blood pressure showed a significant upward trend after fatigue. The respiratory rate and blood pressure can be used as a field fatigue sensitive indicator [17].

2) Central nervous system

The impact of physical and mental work on the processes of human's nervous system has great practical importance. The activity of the human brain can be determined by electroencephalography (EEG) in the form of electric activity curves of brain cortex cells (neurons). Because the brain is the leading element of the nervous system, it can point to different physiological states of the human being, i.e. sleepiness and fatigue. The EEG is widely considered as the physiological 'gold standard' for the assessment of mental fatigue. Delta rhythm (slow waves) is associated with recovering processes, especially during sleep. Theta waves are associated with changes in the state of human consciousness. Theta rhythm can increase by severe cognitive work and a load of a complex task. The high amplitude of this rhythm may indicate a state of drowsiness and fatigue, as well as chronic stress [18]. Sensory, motor and memory functions may be reflected in the alpha rhythm. The lack of these waves can appear when a person opens his eyes, thinks about a task. At increased brain functional activity, the alpha-rhythm amplitude decreases and may disappear completely. It may also indicate anxiety, fear and other physiological conditions associated with increased activation of the vegetative and central nervous system. The fastest are beta-waves. They are associated with higher cognitive processes and attention focus when human is engaged in mental work and is focused on solving a problem. Rhythm is rapidly increasing with increasing work intensity and cognitive load [19]. Many literature sources show a gamma wave link with increasing attention [20] and semantic operations, cognitive performance [21]. As soon as a person wakes up, the gamma rhythm appears again. In 1937 - 1938 English scientists Lumis, Horvey, Habart, Devis made the first attempts to systematize curves and have described 5 stages of electroencephalographic sleep [22]. A number of researchers later showed that mental fatigue mainly manifests itself in a noticeable increase in alpha and theta rhythms in different areas of the brain, depending on the specificity of the performed work [21], [23]. To simultaneously evaluate fatigue after all EEG curves, the term fatigue index was introduced and represents the relationships between different EEG rhythms. Authors [23] used 3 indexes: theta / alpha, beta / alpha, alpha + theta / beta. As a result, the fatigue condition is best determined by the alpha + theta/beta ratio. This value rises sharply after long mental stress and is most sensitive to changes in human functional condition.

Galvanic Skin Response (GSR) reflects the variation in the conductivity of the skin and is measured in micro-Siemens (μS). GSR originates from the autonomic activation of sweat glands in the skin and is typically recorded from feet, palm or fingers on hands. Skin is responsible for bodily processes such as the immune system, thermoregulation, and sensorimotor exploration together with other organs [24].

3) Muscles and movement

Surface ElectroMyoGraphy (SEMG) - is a non-invasive technique for measuring muscle electrical activity that occurs during muscle contraction and relaxation cycles. Surface electromyography is widely used in many applications, such as physical Rehabilitation, Urology (treatment of incontinence), biomechanics (sports training, motion analysis, research), ergonomics (studies in the workplace, job risk analysis, product design, and certification).SEMG is clinically indicated for biofeedback, relaxation, muscle re-education, treatment of incontinence. The SEMG signal generated by the muscle is captured by the electrodes, then amplified and collected by the sensor before being converted to a digital signal by the encoder. Note that fatigue is not always something that we want to prevent. For instance, in muscular training, short-term fatigue is a necessity for muscle growth and is actually looked for. In polysomnography, EMG is routinely measured from below the chin to detect the REM sleep phase (low tonic level) and sleep onset (continuous reduction of tonus). However, EMG can theoretically also be measured from other muscles, which is less intrusive for the subject and the changes in the signal pattern may be more pronounced at sleep onset at these locations. The problems of EMG are similar to those of EOG. Automatic analysis of EMG signals uses the frequency spectrum and the signal power features [25].

Respiration (Breathing rate) is the first step in the chain of events to transport oxygen to the cells of the body for metabolism to provide the body with energy. Respiration ventilates the lungs with air through inhalation and exhalation. The respiratory rate of a healthy adult at rest is usually between 12 and 20 breaths per minute [26].

Actigraphy is an objective measurement method that assesses limb movement activity and is a part of polysomnography. Recorded data are subjected to a proprietary algorithm that produces estimates of sleep-wake variables. Current standards of practice outline the primary roles of actigraphy in insomnia as the characterization of circadian or sleep patterns and the evaluation of treatment response [27]. Normally, accelerometer-based EE estimation is based on the magnitude of acceleration. It is based on a notion that the higher the resultant acceleration, the more intensive the physical activity. A comparative analysis of actigraphy devices capable of tracking temperature, sleep and activity rhythms with minor discrepancies [28]. Actigraphy is used in Fatigue Risk Management systems for Airline operations as part of the protocol, to gather data used in biomathematical models of fatigue.

4) Sensory(vision)

Use of non-invasive methods, such as making a video of the driver and alerting him/her on using cues that may help in anticipating the presence of a sleep pattern, can be a useful way to detect driver fatigue.

Percentage of Closure of eyes (PERCLOS) is a commonly used method for detection of driver fatigue. It determines the percentage of eye closure by taking the number of frames in which the driver's eyes are closed and dividing this by the total number of frames over a specified period of time.

Average closure of eyes (AVECLOS) is a simple binary measure indicating whether or not the driver's eyes are fully closed. This is a less complex measure of drowsiness than PERCLOS, and, as a result, it permits the use of an automotive-grade data processor as opposed to a high-grade PC processor required for PERCLOS. Validation testing at Delphi has shown a very close correlation between AVECLOS and PERCLOS (Pearson correlation coefficient = 0.95) [29].

5) Thermoregulatory

Thermoregulation is primarily achieved through physiological processes, as a function of the autonomic nervous system. The thermoregulatory function is characterized by body temperature (core, peripheral). Normal human core temperature varies between 36.5 ◦C and 37.5 ◦C. The temperature variation follows the circadian rhythm. The suprachiasmatic nucleus (SCN), which contains the central clock, controls the daily rhythms of sleep-wake behaviour and food intake via hypothalamic connections. The SCN controls the circadian rhythm in the secretion of hormones affecting glucose tolerance, including cortisol, melatonin and growth hormone. Body core temperature follows a sinusoidal circadian cycle and sleep onset is located where core temperature is decreasing and the wakeup is initiated when the core temperature is increasing [30]. Sleep is controlled by a thermo-regulatory process [31] showed that distal skin temperature increased at sleep onset and had a dramatic decrease at wake up (2° C).

B. Subjective parameters

Subjective perception of fatigue expressed as a self-rated effort with the help of questionnaires to evaluate somnolence, stress, cognitive and emotional components of fatigue physiological states.

Stanford sleepiness scale (SSS) - developed by Dement and colleagues in 1972, is a one-item self-report questionnaire measuring levels of sleepiness throughout the day. The scale, which can be administered in 1–2 minutes, is generally used to track overall alertness at each hour of the day. The scale has been validated for adult populations aged 18 and older. The SSS is used in both research and clinical settings to assess the level of intervention or effectiveness of a specific treatment in order to compare a client's progress [32].

Karolinska sleepiness scale (KSS) - has been widely used in studies of shift work, sleep deprivation, and driving. It has been found to correlate well with polysomnographic measurements (PSG), like alpha (8–12 Hz) and theta (4–8 Hz) activity in the EEG, as well as with performance-based measures, indicating that worsening of performance is associated with increased KSS values. A recent review summarizes a number of studies of KSS in different laboratory and field settings [33].

The Multidimensional Fatigue Symptom Inventory-Short Form (MFSI-SF) - a 30-item short form of the MFSI that yield scores only for the empirically derived subscales. Preliminary research suggests that it has acceptable psychometric properties and may be used as a substitute for the MFSI when time constraints and scale length are of concern [34].

Professional Quality of Life Scale (ProQOL) - a 30-question self-report test, that most commonly used to measure the negative and positive effects of helping others who experience suffering and trauma. The ProQOL has sub-scales for compassion satisfaction, burnout and compassion fatigue. This is similar to Burdon (post-traumatic) questionnaire and Stress-burnout adrenal fatigue questionnaire [35].

Sleep diary in aviation is usually concerned with the analysis of the work and rest patterns of aircrew, but they are also helpful in dealing with a suspected disorder of sleep - particularly with a disturbance of the circadian rhythm. Diaries should provide day-to-day details of duty, including time-zone changes, and daily estimates, through subjective, of the quality of sleep [36].

C. Objective parameters

Aspects which characterize workability are evaluated by using tests or activities which exercise physical, self-regulatory, cognitive or psychomotor capabilities. Test results serve as objectively measurable indices of human performance. The activities can be created as games, simulations or tests.

Cognitive tests are assessments of the cognitive capabilities of humans and other animals. Various cognitive capabilities, IQ, arithmetic, memory to measure human mental performance and also evaluate performance decrease caused by fatigue components. Long term mental arithmetic task has a significant effect on psychology, behaviour and physiology of subjects, which induces the changes of subjective sleepiness and mental fatigue, performance, autonomic nervous function and central nervous system [37].

The n-back task is a continuous performance task that is commonly used as an assessment in cognitive neuroscience to measure a part of working memory and working memory capacity also with an audio/visual (sensory) feedback [38].

Wechsler Adult Intelligence Scale (WAIS) is an IQ test designed to measure intelligence and cognitive ability in adults and older adolescents [39].

Psychomotor vigilance task (PVT) is a sustained-attention, the reaction-time task that measures the speed with which subjects respond to a visual stimulus. Research indicates increased sleep debt or sleeps deficit correlates with deteriorated alertness, slower problem-solving, declined psychomotor skills, and increased rate of false responding. The PVT lapse count was significantly associated with MFSI-sf physical fatigue ($r = 0.324$, $p = 0.025$). In hierarchical regression (full model R2 = 0.256, $p = 0.048$), higher BMI ($p = 0.038$), and higher MFSI-sf physical fatigue ($p = 0.040$) were independent predictors of the PVT lapse count [40].

IV. Conclusions

A conceptual model for the assessment of human mental fatigue as a multidimensional concept is described in this article. The parameters listed in this paper are required for a comprehensive evaluation of the functional state which indices human performance and workability and can be applied in areas with elevated mental effort and risks associated with low performance or loss of attention or productivity, road safety or critical operations. The observed fatigue assessment problem evolves in a complex environment where the measured parameters have multiple reflections on fatigue thus can be used within a variation method for evaluation of physiological states. Machine-augmented decision making is required in this area of biofeedback, thus it can benefit from a better definition of the measurement parameter effects when the sensor constraints allow modelling of physiological states based on the correlation. The ambiguity of parameter usage in decision making per-subject base can be improved by statistical analysis of characteristics. The reflection of mental fatigue on human performance is guided by the domain of application, it is required to assess the dynamic change of parameters while subject experiences a task-related activity modelled to specific task.

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