# Stress and Recovery Analysis Method
# Based on 24-hour Heart Rate Variability

Firstbeat Technologies Ltd.

This white paper has been produced to review the method and empirical results related to the heart rate variability based stress and recovery analysis method developed by Firstbeat Technologies Ltd. Parts of this paper may have been published elsewhere and are referred to in this document.

## TABLE OF CONTENTS



## SUMMARY


- Autonomic nervous system (ANS) plays a key role in maintaining physiological functions of the body, including flexible and appropriate regulation of the cardiovascular system according to the task or behavior.
- Stress is a part of normal daily life, and physiologically manifested by increased sympathetic and/or diminished parasympathetic activity of the ANS.
- Recovery periods such as sleep are regularly needed to replenish the body physiologically and psychologically. Recovery occurs when physiological arousal is diminished, and parasympathetic activity dominates the ANS state.
- Heart rate variability (HRV) is associated with ANS activity and it can be used for modeling physiological stress and recovery reactions.
- The analysis method presented in this paper utilizes HRV from long-term (24-hour), real-life measurements to analyze stress, recovery, and physical activity.
- The method can be utilized widely to explore and improve well-being, health, and performance.


## KEY TERMS

- **Stress =** Increased activation level of the body when sympathetic activity dominates the ANS and parasympathetic (vagal) activation is low
- **Recovery =** Reduced activation level of the body when parasympathetic (vagal) activation dominates the ANS over sympathetic activity
- **Physical activity =** Increased activation level of the body due to metabolic demands of the task causing significantly increased oxygen and energy consumption
- **Body resources =** Ability to cope with demands put upon individual. The balance between stress and recovery reactions is used for estimating whether the body resources have been accumulated or consumed during the measured period. Stress reactions can therefore be compensated with good recovery.
  (See Figure 1 for how key aspects can be illustrated)

## AUTONOMIC NERVOUS SYSTEM AND HEART RATE VARIABILITY

### Introduction

Cornerstones of healthy life and well-being are lifestyle-related choices and behaviors. Extensive scientific literature shows that appropriate physical activity [1], and restful sleep support recovery from day-to-day and long-term stress [2], and both contribute positively to well-being along with a healthy diet and moderate use of alcohol [3].

Although the key aspects of health and well-being are well known, challenges in those aspects remain. Stress, poor sleep, physical inactivity, overweight and obesity may all cause adverse health outcomes, increase the risk of severe chronic diseases, and reduce the quality of life. The overall burden of unhealthy lifestyles is heavy both at individual and the societal level [4].

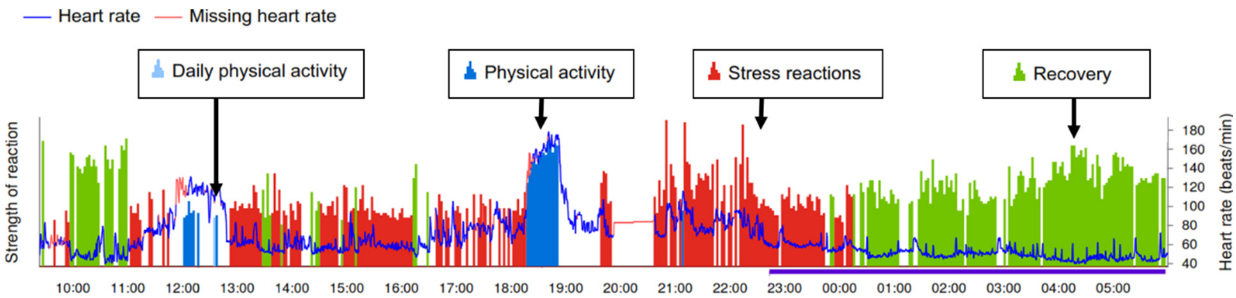


**Figure 1.** The Firstbeat method recognizes stress (red), recovery (green) and physical activity (blue) periods from 24-hour real life HRV measurements, helping to link these physiological reactions to individual's daily events and activities. Stress reflects sympathetic reactions, recovery parasympathetic state and physical activity increased oxygen consumption.

The social, economic, and physical environment form the framework for lifestyle-related behaviors of an individual [4]. The combination of environmental factors (such as work demands, family obligations, personal finances or major life events) and lifestyle-related factors (such as nutritional and physical activity habits) form the aggregate of stress factors that may challenge the individual's ability for coping. Stress reaction is a normal and helpful physiological response to factors perceived as challenging, demanding or threatening. However, prolonged distress has been associated with an increased risk for illnesses such as cardiovascular and immunological diseases and ill health [5-7].

In order to assess the effects of demands put upon the individual through daily behaviors and the environment, easily performed measurements would be of great value. The produced information could be used to support lifestyle changes when needed, check the current status of an individual, and prevent more severe long-term well-being threatening consequences. Therefore, objective methods for assessing stress, recovery, and physical activity are needed to obtain reliable information about the effects of individual lifestyles on bodily reactions.

This paper describes a method for analyzing stress and recovery from long-term, real-life beat-by-beat heart rate measurements developed by Firstbeat Technologies Ltd, Finland. The developmental work is based on an advanced combination of mathematical modeling and algorithm development with extensive empirical physiological and behavioral research conducted by Firstbeat Technologies Ltd and many research institutes. The datasets for developing the method include thousands of laboratory assessments and more than 100,000 field assessments.

The method is being applied in the areas of corporate wellness, work ergonomics, preventive occupational healthcare and lifestyle coaching, as well as sports settings. The principle of the method is to utilize heart rate variability (HRV) and heart rate (HR) reactions as a tool for analyzing autonomic nervous system activity in order to build a digital model of human physiology for recognizing different bodily states.

## Autonomic nervous system and regulation of bodily functions

The human nervous system consists of central nervous system and peripheral nervous system. The latter has two major divisions, the voluntary and the autonomic systems. The voluntary nervous system is concerned mainly with movement and sensation. The autonomic nervous system (ANS) mainly controls functions over which we have less conscious control. These include for example the cardiovascular system, whose regulation is fast and involuntary.

The ANS is divided into sympathetic and parasympathetic nervous systems (Figure 2). Sympathetic and parasympathetic nerve cords start from the central nervous system and lead to different target organs all around the human body. Sympathetic and parasympathetic divisions typically function simultaneously in opposition to each other. The parasympathetic division is primarily involved in relaxation, helping the body to rest and recover. The sympathetic division prepares the body to fight by accelerating bodily functions, and is also associated with stress.

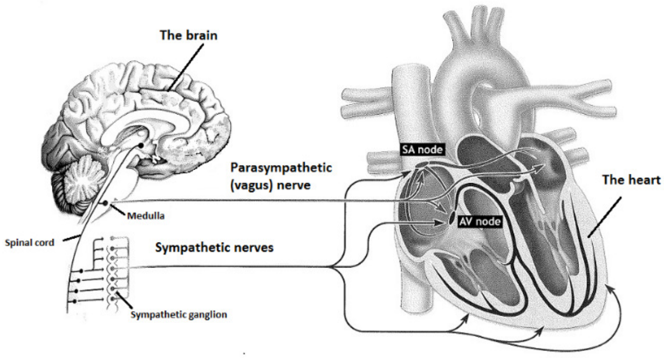


**Figure 2.** Autonomic nervous system controls different target organs via parasympathetic and sympathetic nerve cords. The parasympathetic nerve controlling the heart is called vagus nerve. [modified from 8].

With stress reactions, the human body tries to cope with the demands of the surrounding environment. Positive stress gives energy "to get the job done". Negative stress causes negative emotions and reactions. Physiologically the response to positive and negative stress is similar. As a result of the stress reaction, the ANS is activated and stress hormone production starts along with an increased rate and force of contraction of the heart [9]. The magnitude of the neuro-endocrine response reflects the metabolic and physiological demands required for the behavioral activity [10].

This means that the body should adapt to the demands put upon it in different situations (e.g. during a stressful task, physical activity, or rest/sleeping). Problems arise when the body is not able to adapt to the changing demands. Thus, during stressful periods, active working, or physical activity, the body needs to utilize more sympathetic activity to be able to perform according to the needs of the task. Likewise, parasympathetic activity – and not sympathetic activity - should be dominating the ANS activity during for example the sleep period.

Therefore, although there is an ongoing debate of the exact definition of stress in the scientific literature, stress can be physiologically characterized by reduced recovery of the neuroendocrine reaction [10] and sympathetic dominance of the ANS function, whereas recovery is characterized as parasympathetic dominance.

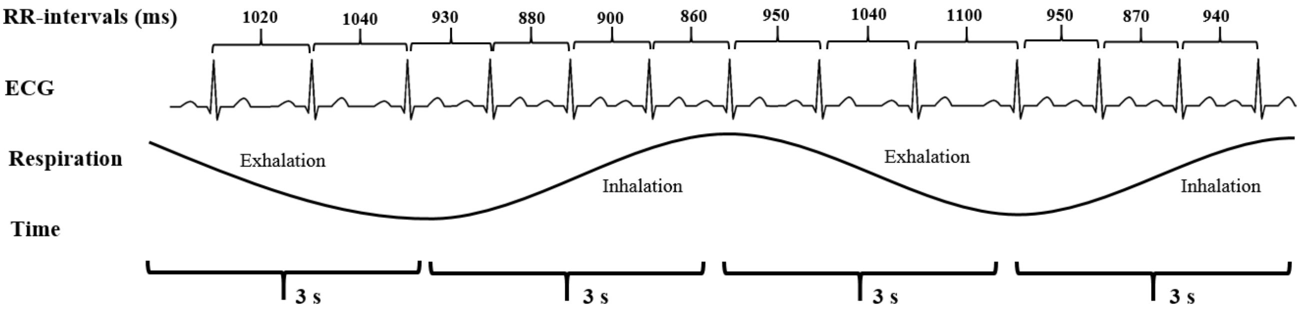


**Figure 3.** Electrocardiogram (ECG) exhibiting respiratory sinus arrhythmia. Heart rate increases and thus the time between successive RR-intervals gets shorter during inhalation (inspiration) and longer during exhalation (expiration). This fluctuation in the time between the successive RR-intervals is called heart rate variability (HRV).

One of the key elements of the health-enhancing effects of physical activity is that when the cardiovascular and hormonal system is strongly activated and loaded, and then recovers during rest, the body's adaptive abilities improve, supporting flexible adjustment of physiological homeostasis in everyday life [11]. In other words, physical activity gives the individual more resources for flexible adaptation of the neuroendocrine and cardiovascular systems.

## HRV as an indicator of autonomic nervous system activity

The ANS plays a major role in modifying the heart rate according to need. Without nervous regulation, the heart contracts according to an automatic, or intrinsic, rhythm regulated by the sinus node. The intrinsic heart rate in a healthy adult in a sitting position is about 105 beats/min [12]. However, the normal resting heart rate in a sitting position is around 60-80 beats/min due to the effects of the sympathetic and parasympathetic nervous systems, hormonal factors, and reflexive factors [13]. There are fluctuations in heart rate caused by respiration and known as respiratory sinus arrhythmia (RSA): heart rate increases during inspiration and decreases during expiration (Figure 3). This fluctuation in the time between successive heartbeats is called heart rate variability (HRV) [14].

The sympathetic and parasympathetic nervous systems maintain cardiovascular homeostasis by responding to beat-to-beat perturbations that are sensed by baroreceptors and chemoreceptors. Sympathetic fibers increase the contraction rate of the heart and decrease HRV by stimulating the SA and AV nodes (see Figure 2). They also increase the contraction force by acting directly on the fibers of the myocardium. These actions translate into increased cardiac output [13]. During a stress response, the sympathetic nerves can boost the cardiac output to two to three times the resting value.

The parasympathetic nerve that supplies the heart is the vagus nerve. It slows the heart rate and increases HRV by acting on the SA and AV nodes [13]. These ANS influences allow the heart to meet changing needs rapidly. Parasympathetic stimulation decreases the heart rate to restore homeostasis e.g. after stress or physical activity. During physical activity, the parasympathetic activity is first withdrawn and then sympathetic nerve activity is augmented to meet the metabolic demands of the behavior [15]. At the same time, heart rate increases and HRV decreases with increasing exercise intensity.

The association between the ANS and HRV has been confirmed by studies of invasive autonomic blockade in laboratory settings, where blocking of parasympathetic and sympathetic activity with medication (atropine, metoprolol) decreased and reverted HRV, respectively (see Figure 4) [16].

Therefore, HRV provides a powerful tool for observing the interplay between the sympathetic and parasympathetic nervous systems, and it is broadly accepted to reflect autonomic nervous system activity [14, 17].

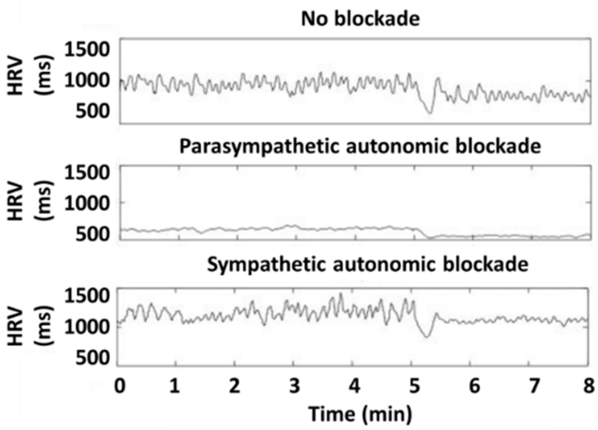


**Figure 4**. Heart rate variability (HRV) as a function of time during active orthostatic task before blockage (no drug) and after parasympathetic (atropine) and sympathetic (metoprolol) autonomic blockage [16]. The example is from one subject who sat for 5 min, stood up, and remained standing for 3 min.

**Different factors affecting HRV**

The number of studies concerning HRV has been rising steeply during the recent years. The studies have reported e.g. that higher HRV is associated with reduced morbidity and mortality [18-19], psychological well-being and quality of life [20], as well as better physical fitness and lower age of the individual [21]. Moreover, acute stress has been associated with decreased HRV during sleep [22] and during daytime [23]. In addition, decreased HRV has been associated with work stress in many [24-27] but not all studies [28]. In a recent review, it was concluded that in the majority of studies that examined the association of HRV and work stress, higher reported work stress was associated with lower HRV [29].

Furthermore, also the training status of athletes may affect HRV [30-32]. Figure 5 shows an example of HRV in normal and overtrained situation in the same athlete [32]. Overtraining is caused by long-term stress or exhaustion due to prolonged imbalance between training, other external/internal stressors, and recovery. The results indicate increased activation of the cardiorespiratory and sympathetic nervous systems in the overtraining state.

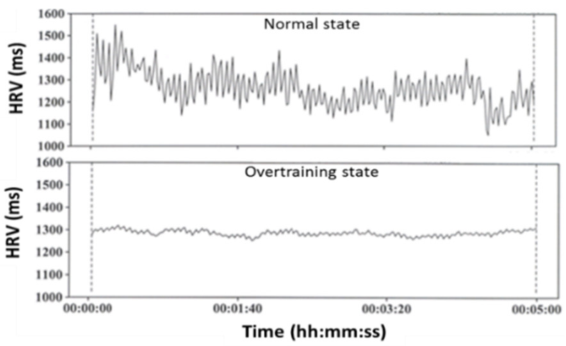


**Figure 5.** Overtraining causes changes in HRV. Overtrained situation increases the heart rate level and reduces HRV [32].

HRV is also affected by the training load of individual exercise sessions, i.e. the higher the training load, the lower the HRV after exercise [33]. Therefore, HRV is highly context dependent, and reacts to acute stressors such as physical exercise.

It has been found that HRV is highly affected by the individual's genetic background [34]. In one study, common genes contributed strongly to the occurrence of depressive symptoms and associated decreased HRV in twins [35]. There are also very high inter-individual differences in HRV, which makes it difficult to interpret absolute HRV values in a straightforward way. Still, increased parasympathetic modulation seems to increase HRV linearly, showing intra-individual validation of HRV to represent parasympathetic effects on the heart [36].

When summarizing all the information related to HRV, it can be concluded that HRV is the most promising non-invasive method to evaluate autonomic nervous system condition in real-life and includes a vast amount of information on physiological processes to be utilized. Due to very high inter- and intra-individual differences in HRV, new approaches for HRV analysis are needed in order to utilize HRV efficiently. The method described in this paper is based on forming an individual physiological model of the person, thus taking into account the individuality concerning HR and HRV values.

## METHOD OVERVIEW

Since HRV gives accurate information on ANS activity, which controls our physiological reactions, it can be used for modelling human physiology. Special laboratory equipment and controlled conditions are typically needed for measuring and analyzing HRV, but the method described in this paper applies HRV information from 24-hour ambulatory, real-life measurements.

The approach of the method is the following: HRV information is used as such and also further utilized to calculate physiological variables (e.g. oxygen consumption, respiration rate, excess post-exercise oxygen consumption) to model individual's physiological reactions. Thus, the method generates new measures for physiological phenomena that are impossible to obtain only from basic HRV measures. Feedback about different physiological states, such as stress, recovery or physical activity is given based on the created physiological model.

The method detects stress when sympathetic activity of the autonomic nervous system dominates over parasympathetic activity. Recovery is detected when parasympathetic activity predominates the autonomic nervous system. Physical activity is detected when the individual's metabolism, measured by oxygen consumption, is elevated indicating presence of physical activity.

## ANALYSIS PROCEDURE

Next, the procedure for analyzing different physiological states is described in greater detail. Figure 6 clarifies the analysis procedure for detecting stress, recovery and physical activity. First, the beat-to-beat heart rate data is collected and prepared. Then, required physiological information for state detection is calculated, including HRV variables, respiration rate, oxygen consumption ($VO_2$), and excess post-exercise oxygen consumption (EPOC). Thereafter, physiologically stationary segments are identified, and different states recognized. The following paragraphs describe each of these steps.

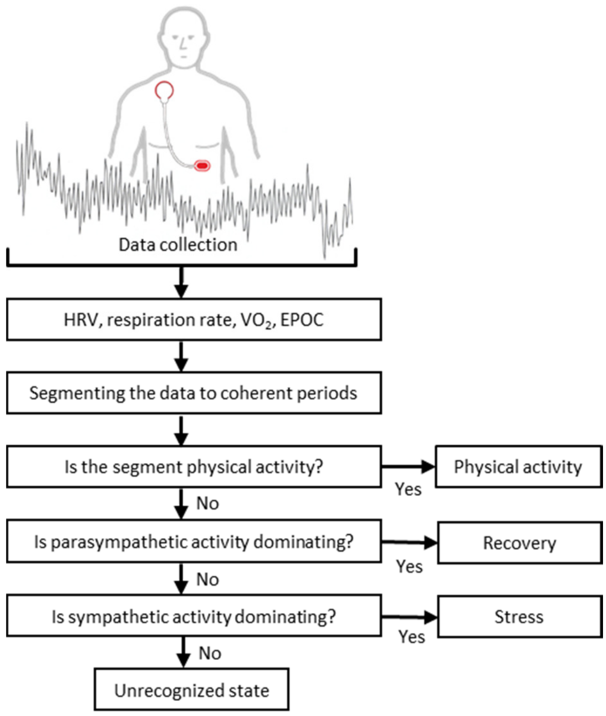


**Figure 6.** Simplified illustration of the analysis procedure.

## Data collection and preparation

First, beat-to-beat heart rate data (RR-interval data) is collected in real-life settings over a desired period, e.g. 24–72 hours, with a HR monitor capable of recording individual heartbeats. After the data is collected, the analysis process can begin.

The background information (age, gender, height, weight and physical activity class) has to be set first. Based on this information, the method estimates the person's maximal HR ($HR_{max}$), maximal respiration rate, and maximal oxygen consumption ($VO_{2max}$). The individual range of physiological variables is obtained from RR-interval data. This means that e.g. resting HR and $HR_{max}$ are automatically updated from the recorded data if lower or higher values, respectively, are observed.

The recorded ambulatory RR-interval data is scanned through an artifact detection filter to perform an initial correction of falsely detected, missed, and premature heartbeats [for more information, see 37-38]. The consecutive artifact-corrected RR-intervals are then re-sampled at a rate of 5 Hz by using linear interpolation to obtain equidistantly sampled time series [for more detailed information, see 39]. From the re-sampled data, the software removes low frequency trends and variances below and above the frequency band of interest using a polynomial filter and a digital FIR band-pass (0.03–1.2 Hz) filter.

## Calculation of required variables

Thereafter, the software calculates values for different variables that are used for detecting physiological states. The HRV variables needed for state detection are time domain and frequency domain HRV variables, such as root mean square of successive R-R intervals (RMSSD), high frequency power (HFP, 0.15–0.40 Hz), low frequency power (LFP 0.04–0.15 Hz), and amplitude of the respiratory sinus arrhythmia. Flexible methods that are able to process non-stationary physiological signals are required [39-41].

Next, using HRV variables and neural network modeling of data, the software calculates values that represent different physiological phenomena and that are required for detection of different bodily states. These phenomena are respiration rate, oxygen consumption ($VO_2$) and excess post-exercise oxygen consumption (EPOC).

The validity and accuracy of these aforementioned physiological parameters, calculated solely based on RR-interval information have been reported in several studies [42-48]. For detailed descriptions of the calculation of respiration rate, see the document "Procedure for deriving reliable information on respiratory activity from heart period measurement [49]. For descriptions of $VO_2$ and $VO_2$-derived energy expenditure calculations, see the related Firstbeat white papers [50-51]. For further information on calculation of EPOC and its utilization in athletic training, see the other two white papers [52-53].

Before the detection of different states, also movement, start-up of physical activity and postural changes have to be differentiated from other, non-metabolic factors that influence cardiac activity. Changes in HRV that are known to occur when standing up are utilized in these calculations.

## Detection of physical activity, recovery, and stress

Further analysis is based on segmenting the second-by-second data into various stationary segments, i.e. segments that include physiologically coherent data, by using neural network modeling and other mathematical techniques. The segments are then categorized using a stepwise decision tree, as illustrated in Figure 6. In each of these phases, reliability of the RR-interval derived data is evaluated to make sure that different physiological states are detected correctly.

### *Physical activity detection*

First, the data segments related to physical activity at different intensities, and those related to recovery from physical activity are detected. Detection of physical activity is based on both oxygen consumption and accelerometer data. Oxygen consumption is a fundamental measure of metabolism and the golden standard for measuring exercise intensity [54-55]. If the calculated $VO_2$ is more than 30% of the individual's $VO_{2max}$ the segment is determined to be physical activity and if $VO_2$ is 20-30% of $VO_{2max}$ the state is determined to be daily physical activity. Accelerometer data further improves the ability of the method to recognize movements that are related to increased activation level in the body. Recovery from physical activity is detected if EPOC has reached a value higher than a certain threshold, indicating physical activity, and if EPOC is thereafter decreasing.

### *Recovery detection*

For non-exercise related data segments, the segments when the body is in a recovery state, stress state or unrecognized state are determined. Recovery state is defined as a state of parasympathetic (vagal) predominance of the ANS. Therefore, variables related to parasympathetic domination of the ANS are utilized for detecting recovery. These include for example HFP and HR. During recovery state, HR is individually low, and HRV is great and uniform. Recovery typically occurs during sleep, relaxation, rest and/or peaceful working, and means low overall activation of the body.

### *Stress detection*

Finally, if the segment does not correspond to physical activity, recovery from physical activity or recovery (relaxation), the segment is determined to be either stress or unrecognized state. Stress state is defined as an increased activation in the body when sympathetic nervous system activity is dominating and parasympathetic (vagal) activation is low. Variables related to sympathetic dominance of the ANS are utilized in stress detection. These include for example HFP, LFP, respiration rate, and HR. During the stress state, individual HR is elevated, HRV is decreased from the individual's basic resting level, and respiration rate is low, relative to HR. Lastly, the data segments that are not recognized as any of the abovementioned states or have more than 75% artifacts are determined as unrecognized (other) state.

For stress and recovery, the method provides absolute indices to express the strength of the reaction, based on the variables described above. In addition, the method can assess the balance between stress and recovery by taking into account the strength of the reactions and duration of the states when producing an estimate of whether the body's resources have accumulated or been consumed during the measured period (see Figure 7).

More information regarding the method presented in this paper can be found in the patent application (granted) "Procedure for detection of stress by segmentation and analyzing a heartbeat signal." [56].

## PRACTICAL USE OF THE METHOD

The principles described in this paper can been utilized widely in different types of wellbeing and health promotion services, consumer products such as smart watches, as well as sports coaching and athletic training.

In corporate wellness, so-called Lifestyle Assessments have been conducted. The Lifestyle Assessment aims to increase the individual's understanding of the factors that cause stress or enhance recovery and relaxation, and gives feedback on performed physical activity in terms of intensity, duration, and training effect. The goal of the assessment is to help the person to find a balance between work and leisure time, as well as between stress and recovery. The essential focus is not a total absence of stress, but rather sufficient rest and recovery, and finding an individually suitable rhythm of life. Specific attention is given to sleep and work periods.

In sports settings, the method has been applied to assess training or competition induced stress, monitor training load and follow-up recovery in order to optimize training and performance and avoid overtraining. For more details about the analysis method used for supporting training and coaching, see Firstbeat white paper "Heart Beat Based Recovery Analysis for Athletic Training" [57].

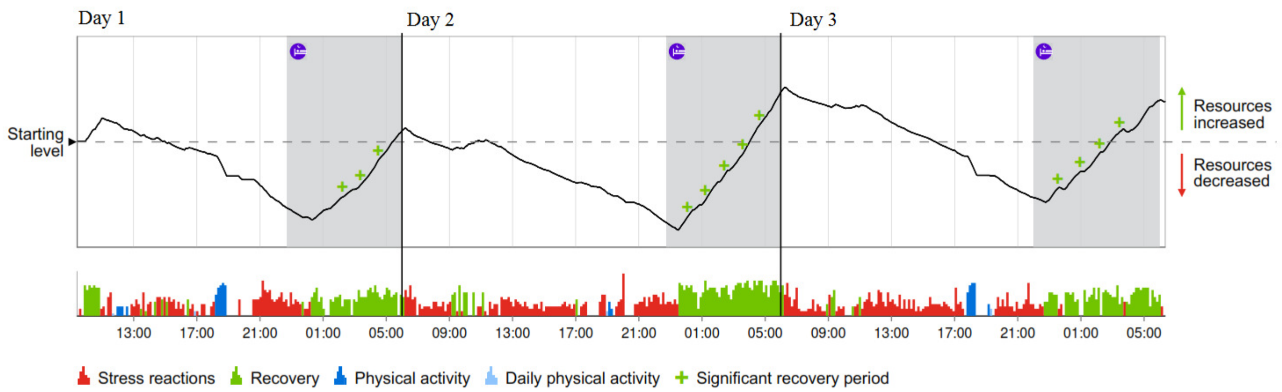


**Figure 7.** Body resources accumulate during recovery periods and decrease during stress reactions. Grey areas in the chart indicate sleeping periods.

In Table 1 different kinds of stress factors are presented. These stress factors may affect the results of this HRV-based method, and should therefore be taken into account when interpreting the results. It also needs to be pointed out here that the usefulness and validity of HRV-based methods can be limited in certain chronic conditions or illnesses that affect ANS functioning or when applied to persons using medications that affect the heart significantly.

**Table 1.** Different stress factors.

| Physical factors (external) | Physical factors (internal) | Psychological factors | Social factors |
|---|---|---|---|
| Alcohol and other drugs | Acute infections | Work stress | Presentation |
| Medications | Chronic diseases | State anxiety | Giving speech |
| Stimulants e.g. coffee | Pain | Strain | Fear of social situations |
| Hangover | Burnout | Negative feelings | Pressure |
| Extensive training | Overtraining | Fear | Lack of social support |
| Physical workload | Tiredness | Excitement | |
| Sauna | Pregnancy | Depression | |
| Sleep deficit or jetlag | Digestion | Psychological disorders | |
| Temperature, humidity | Dehydration | Relationship problems | |
| Noise, illuminance | | Traumatic events | |
| Altitude | | Sorrow | |

## COMPARISON OF DIFFERENT STRESS ASSESSMENT METHODS

Stress is a concept that has several different types of interpretations and definitions, both scientifically and in popular everyday speech. Typically stress can be viewed as a physiological stress response to the demands put upon the body, but it can also mean the physical, societal or environmental stress factors impacting the individual. To make it more complex, stress can also be viewed as the individual's own psychological perception of short- or long-term stress factors that challenge the individual's ability to cope with them.

Consequently, an extensive number of different measures and tests have been developed and used for assessing stress. Different stress measures have their strengths and weaknesses. Table 2 describes several different objective and subjective stress measures and shows their advantages and limitations.

The advantages of HRV for assessing stress, based on autonomic nervous system state is that it is objective and non-invasive. It allows direct measurement of the physiological stress response that can fluctuate on moment-to-moment and day-to-day basis. HRV also combines information of all the stress factors that affect the individual's

**Table 2.** Comparison of different stress measures.

| Measure | Advantages | Limitations |
|---|---|---|
| **Firstbeat method for 24h stress and recovery (HRV)** | • Objective and non-invasive method to assess ANS<br>• Allows individual analysis of both stress and recovery<br>• Physical activity can be separated from other stress factors | • Requires computational software<br>• Psychological stress does not always cause physiological arousal |
| **Basic HRV (e.g. RMSSD)** | • Objective and non-invasive method to assess ANS | • Requires computational software<br>• Psychological stress does not always cause physiological arousal<br>• High inter-individual differences in basic HRV values are not easily taken into account<br>• Does not differentiate different sources of stress reactions (e.g. exercise)<br>• Best fit for short time periods |
| **Quick HRV tests** | • Non-invasive and objective<br>• Quick to perform | • Not easily interpreted as stress varies from moment-to-moment<br>• Lacks the direct link to stress factors if measured occasionally |
| **Hormonal measurements – (cortisol or plasma catecholamines)** | • Objective method<br>• Combines different sources of stress | • Seems to be difficult to interpret and scientific results are mixed<br>• Diurnal variation causes reliance on timing of sampling<br>• Requires laboratory analysis and qualified personnel |
| **Blood pressure** | • Non-invasive and objective<br>• Provides important information for long-term health | • Challenging to measure continuously<br>• Lacks the direct link to stress factors if measured occasionally |
| **Skin conductance (GSR)** | • Non-invasive | • External variables such as temperature and humidity can affect results as is based on measuring sweat or moisture on the skin<br>• Cannot be used during physical activity |
| **Brain activity (EEG)** | • Non-invasive and objective measure<br>• Shown to be associated with chronic stress | • Not much utilized yet<br>• Requires laboratory testing and qualified personnel<br>• Difficult to measure long-term |
| **Psychological questionnaires (stress events, chronic stress, perceived stress, burnout)** | • Easy to perform<br>• Allows screening of large populations<br>• Many questionnaires include diagnostic reference values from large datasets<br>• Provides valuable subjective experience of stress | • Subjective measures<br>• Personality may affect the results significantly<br>• Different populations may need different types of questionnaires<br>• May lack direct link to individual stress responses |
| **Psychological interviews** | • Can be more personal than general questionnaires allowing more detailed analysis | • Time consuming<br>• Require trained interviewers |

**Table 3.** Comparison of the Firstbeat method and the traditional HRV measures.

| | Firstbeat method | Traditional HRV |
|---|---|---|
| **Aim of the method** | • To analyze different physiological states based on applied use of HRV information | • To analyze HRV parameter values as related to ANS function |
| **Principle and approach** | • Build a digital model of human physiology for recognizing different states and their intensity | • Analyze raw HRV from R-R intervals by using for example time-domain, geometrical, frequency-domain or non-linear analysis methods |
| **Preferred context and duration** | • Interprets reactions from real-life measurements for applied use<br>• Can assess different states also during long-term measurements, e.g. 24-hour | • Preferably used in controlled laboratory settings with stable physiological condition<br>• Mostly used in short-term measurements |
| **Ability to differentiate physiological states from each other** | • Differentiates individually reactions originating from stress, recovery, and physical activity<br>• Provides absolute and relative intensity of these reactions | • Does not differentiate physiological states, provides average HRV (e.g. RMSSD, HFP, LFP) that are composite of different factors |
| **Individuality** | • Takes into account individual scale of physiological features within the person | • High inter-individual differences in HRV are not easily taken into account |
| **Ease of interpretation** | • Provides individualized feedback from real-life activities | • Complex to interpret from long-term measurements as average HRV lacks meaningfulness when measurement contains e.g. stressful events, physical activity, and sleep etc. |

physiology. The Firstbeat method also allows us to link physiological reactions to daily life events and activities. It is also possible to differentiate physiological responses caused by physical activity from other stress factors by using the Firstbeat method. General long-term HRV and the Firstbeat method is compared with more details in the Table 3.

Hormonal measurements require laboratory analysis either from saliva, urine or blood samples. The challenge with hormonal measurements is that the timing of distinct samples may affect the interpretation of the results significantly as there are strong diurnal rhythms in hormonal secretion. In addition, it may also be difficult to interpret the effects of circulating hormones consistently. Indeed, a recent review concerning objective physiological biomarkers for work stress concluded that the findings for associations between plasma catecholamines or cortisol secretion and work stress are less clear than for HRV and work stress [29].

## EMPIRICAL RESEARCH RESULTS OF THE FIRSTBEAT METHOD

The empirical studies conducted with the Firstbeat method for analyzing stress and recovery have mostly focused on sleep, physical activity, neuroendocrine responses, and work stress [58–66]. In addition, the method has been utilized in forming novel service concepts for enhancing the psycho-physiological well-being of an individual [67-69]. Moreover, the principles described in this paper have been utilized in measuring stress and recovery in sports settings [70-74].

It has been shown that stress dominates the daytime and relaxation dominates the sleep time ($p<0.001$), confirming that the method differentiates the physiological states during awake and sleep correctly [58]. Further, an experimental sleep laboratory study found that recovery measured with the method was diminished during sleep after intensive late-evening exercise, although no changes were observed in EEG-based polysomnographic or movement-based sleep quality [59].

Complementally, another study considering recovery during sleep found that recovery was decreased and HR increased during sleep after days that included intensive or long-duration exercise compared to sleep after a day with easy or short exercise [60]. Both of the studies indicated delayed ANS recovery after more demanding exercise, which was reflected in the relaxation measured with the Firstbeat method. Still, long exercise duration was needed to induce changes in nocturnal traditional HRV during sleep.

The method has also been shown to correlate with other physiological methods: significant correlations have been reported (r between 0.40 and 0.50) between cortisol after awakening and indicators of stress and relaxation during sleep in hospital workers [61].

The results with the Firstbeat method have also been associated with psychological work stress related variables. A study reported that the higher the work effort, the lower the daytime HRV and relaxation time ($r=-0.66$ and $-0.54$ on two workdays). Feelings of stress and satisfaction at work were correlated with work time HRV, and feelings of irritation at work correlated with night time HRV. The results indicated that daily emotions at work and chronic work stress are associated with cardiac autonomic function [62].

In another study, significant correlations between stress and relaxation variables with the Firstbeat method and psychological self-assessment of contentment at work were found [63]. Contentment indicates subjective experiences of relaxation, and that correlated to low stress (r=-0.40 and -0.51 on two workdays) and high relaxation (r=0.37 and 0.38) by the Firstbeat method. In one study, sleep duration was negatively related to work stressors, and the longer the relaxation time during sleep, the less work stressors were perceived (r=-0.48) the next day [64]. In addition, one study revealed significant associations between stress measured with the Firstbeat method and self-assessments of stress [65].

Further, a very recent study reported that physical activity and fitness level, as well as body composition were associated with indicators of stress and recovery measured with the Firstbeat method. The study also found that objective stress measured with the method was associated with self-reported occupational burnout symptoms. The authors concluded that the results support the usability of the Firstbeat method in the evaluation of stress and recovery [66].

The results from studies that have developed new service concepts incorporating new technologies, including Firstbeat Lifestyle Assessment, have confirmed the feasibility of the interventions [67-69]. The studies have found positive effects on psychological symptoms, self-rated health, and self-rated working ability. Importantly, Firstbeat Lifestyle Assessment was rated as the most useful intervention component by the participants in a study utilizing several technology tools for enhancing well-being [67].

The studies related to sports coaching have highlighted that the Firstbeat method is a practical tool for monitoring stress caused by training, environmental (e.g. high altitude) or other factors in individual or team sports, for assessing training/match load, or for evaluating recovery [70-73]. Further, an interesting 3-year follow-up case study with an international level race-walker reported a simultaneous increase in HR and decrease in HRV during sleep after a hard training session or a race, which resulted in decreased recovery values provided by the method [74]. The researchers found that the method was able to detect decreased recovery after a hard training session, but the trends over a longer period also seemed to follow the stress of training and the subsequent recovery periods.

In addition to aforementioned studies, large real-life collected Firstbeat database has been analyzed to map different physiological patterns in daily life [75]. The database included approximately 51,000 measurement days containing about 1,200,000 hours of RR-interval data from 20,000 subjects (Figure 8). The reference values from the database allow comparison of the Lifestyle Assessment analysis results to values from scientific literature that are known to affect long-term well-being and health, such as sleep duration and physical activity habits.

A typical 24-hour measurement day included 51% of stress (=12h14min) and 26% of recovery (=6h14min). An average of 60% from the sleep time was detected as recovery. Moreover, a typical day included 2% of physical activity (=32min), 2% of light physical activity, 5% of recovery from physical activity, and 11% of unrecognized (other) state. Based on the database, workdays include more stress (52% vs. 49%) and less recovery (25% vs. 27%) than days off. A typical daily profile of different states in a workday is represented in Figure 9. The daily profile was similar during a work day and a day off.

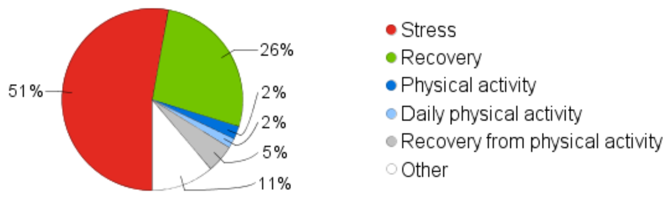


**Figure 8.** Proportion of different physiological states during a typical 24-hour measurement (mean values) in the Firstbeat database.

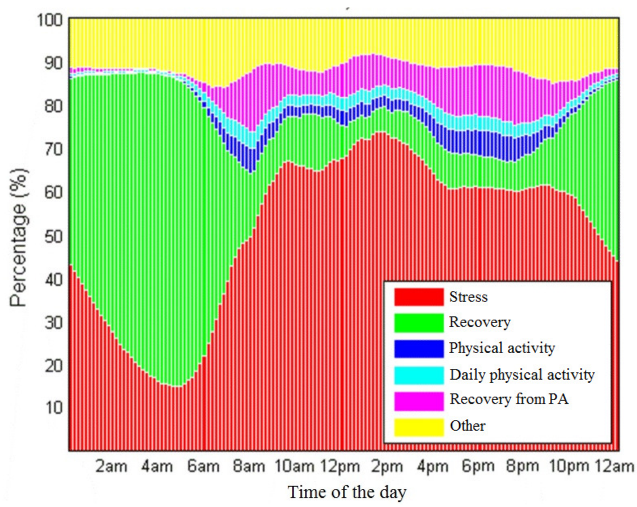


**Figure 9.** The average daily profile of different physiological states during a working day based on the Firstbeat database [modified from 75].

To sum up, the results showed that HRV, recovery during sleep as measured with stress balance, the proportion of stress, and energy expenditure decrease with increasing age. In both genders, high physical activity level and low BMI were related to good recovery during sleep, a low amount of stress, and high energy expenditure, and to higher HRV among men. Men had more stress, but also more health-promoting physical activity and better recovery during sleep than women [75].

## CONCLUSIONS

Heart rate variability provides a non-invasive window to autonomic nervous system activity, and can be used for detecting physiologically different states. The method described in this paper utilizes HRV information from long-term real-life measurements, expressing sympathetic and parasympathetic nervous system activity to recognize individually stressful and relaxing periods originating from lifestyle-related behaviors and environmental effects.

The method is based on forming a digital, physiological model of the individual by utilizing information provided by beat-to-beat heart rate data. The HRV data is used for calculating autonomic nervous system activity, oxygen consumption, respiration rate, and exercise related variables, such as excess post-exercise oxygen consumption, and then used to form the individual model. To make the model holistic and complete, also accelerometer data caused by body movement is utilized in the method.

The knowledge about stress, recovery, and physical activity during daily tasks and activities provided by the method can be utilized widely to explore health and well-being, and to support possible lifestyle changes.

## REFERENCES

**[1] Haskell WL, Blair SN & Hill JO (2009).** Physical activity: Health outcomes and importance for public health policy. Preventive Medicine 49 (4): 280–282.

**[2] Porkka-Heiskanen T, Zitting KM & Wigren HK (2013).** Sleep, its regulation and possible mechanisms of sleep disturbances. Acta Physiologica (Oxf), 208 (4): 311–328.

**[3] Poli A et al. [2013]** Moderate alcohol use and health: a consensus document. Nutrition, Metabolism & Cardiovascular Diseases, 23 (6): 487–504.

**[4] World Health Organization (2012).** The European Health Report 2012 – Charting the way to well-being.

**[5] Backe E-M, Seidler A, Latza U, Rossnagel K & Schumann B (2012).** The role of psychosocial stress at work for the development of cardiovascular diseases: a systematic review. International Archieves of Occupational and Environtal Health, 85: 67–79.

**[6] Segerström SC & Miller GE (2004).** Psychological Stress and the Human Immune System: A Meta-Analytic Study of 30 Years of Inquiry. Psychological Bulletin, Vol. 130, No. 4.

**[7] Schneiderman N, Ironson G & Siegel SD (2005).** Stress and Health: Psychological, Behavioral, and Biological Determinants. Annual Review of Clinical Psychology, Vol. 1: 607-628.

**[8] McArdle WD, Katch FI & Katch VL (2001)**. Exercise physiology: energy, nutrition and human performance. 5th edition. Williams & Williams, Baltimore.

**[9] Chrousos GP & Gold PW (1992).** The Concepts of Stress and Stress System Disorders - Overview of Physical and Behavioral Homeostasis. The Journal of American Medical Association, 267 (9): 1244–1252.

**[10] Koolhaas JM et al. (2011).** Stress revisited: a critical evaluation of the stress concept. Neuroscience & Biobehavioral Reviews, 35 (5): 1291–1301.

**[11] Radak Z, Chung HY, Koltai E, Taylor AW & Goto S (2008).** Exercise, oxidative stress and hormesis. Ageing Research Reviews, 7 (1): 34–42.

**[12] Jose AD & Collison D (1970).** The normal range and determinants of the intrinsic heart rate in man. Cardiovascular Research, 4 (2): 160–167.

**[13] Brownley KA, Hurwitz BE & Schneiderman N (2000).** Cardiovascular psychophysiology. In: Cacioppo JT, Tassinary LG, Berntson GG (Eds.). Handbook of Psychophysiology (2nd edition), Cambridge University Press, ISBN 62634X.

**[14] Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. (1996).** Heart rate variability: standards of measurement, physiological interpretation and clinical use. Circulation 93: 1043–1065.

**[15] Mitchell JH (2013).** Neural circulatory control during exercise: early insights. Experimental Physiology, 98 (4): 867–878.

**[16] Martinmäki K, Rusko H, Saalasti S & Kettunen J (2006).** Ability of short-time Fourier transform method to detect transient changes in vagal effects on hearts: a pharmacological blocking study. American Journal of Physiology – Heart and Circulatory Physiology 290, 2582–2589.

**[17] Acharya UR, Joseph KP, Kannathal N, Lim CM & Suri JS (2006).** Heart rate variability: a review. Medical & Biological Engineering & Computing 44: 1031–1051.

**[18] Sajadieh A, Wendelboe Nielsen O, Rasmussen V, Hein HO, Abedini S & Fischer Hansen J (2004).** Increased heart rate and reduced heart-rate variability are associated with subclinical inflammation in middle-aged and elderly subjects with no apparent heart disease. European Heart Journal, 25 (5): 363–370.

**[19] Stein PK, Domitrovich PP, Huikuri HV & Kleiger RE (2005).** Traditional and Nonlinear Heart Rate Variability Are Each Independently Associated with Mortality after Myocardial Infarction. Journal of Cardiovascular Electrophysiology, 16 (1): 13–20.

**[20] Geisler FCM, Vennewald N, Kubiak T & Weber H (2010).** The impact of heart rate variability on subjective well-being is mediated by emotion regulation. Personality and Individual Differences, 49, 7: 723–728.

**[21] De Meersman RE (1993).** Heart rate variability and aerobic fitness. American Heart Journal, 125 (3): 726–731.

**[22] Hall M, Vasko R, Buysse D, Ombao H, Chen Q, Cashmere JD, Kupfer D & Thayer JF (2004).** Acute stress affects heart rate variability during sleep. Psychosomatic Medicine, 66 (1): 56–62.

**[23] Dishman RK, Nakamura Y, Garcia ME, Thompson RW, Dunn AL & Blair SN (2000).** Heart rate variability, trait anxiety, and perceived stress among physically fit men and women. International Journal of Psychophysiology, 37: 121–133.

**[24] Clays E, De Bacquer D, Crasset V, Kittel F, de Smet P, Kornitzer M, Karasek R & De Backe G (2011).** The perception of work stressors is related to reduced parasympathetic activity. International Archives of Occupational and Environtal Health 84: 185–191.

**[25] Vrijkotte TG, van Doornen LJ & de Geus EJ (2000).** Effects of work stress on ambulatory blood pressure, heart rate, and heart rate variability. Hypertension 35, 880–886.

**[26] van Amelsvoort LG, Schouten EG, Maan AC, Swenne CA & Kok F. (2000).** Occupational determinants of heart rate variability. International Archives of Occupational and Environmental Health 73, 255–262.

**[27] Collins SM, Karasek RA & Costas K (2005).** Job strain and autonomic indices of cardiovascular disease risk. American Journal of Industrial Medicine 48, 182–193.

**[28] Riese H, Van Doornen LJ, Houtman IL & De Geus EJ (2004).** Job strain in relation to ambulatory blood pressure, heart rate, and heart rate variability among female nurses. Scandinavian Journal of Work, Environment & Health 30, 477–485.

**[29] Chandola T, Heraclides A & Kumari M (2010)**. Psychophysiological biomarkers of workplace stressors. Neuroscience & Biobehavioral Reviews, 35 (Suppl 1): 51–57.

**[30] Pichot V, Roche F, Gaspoz JM, Enjolras F, Antoniadis A, Minini P, Costes F, Busso T, Lacour JR & Barthélémy JC. (2000).** Relation between heart rate variability and training load in middle-distance runners. Medicine & Science in Sports & Exercise, 32 (10): 1729–1736.

**[31] Buchheit M, Chivot A, Parouty J, Mercier D, Al Haddad H, Laursen PB & Ahmaidi S (2010).** Monitoring endurance running performance using cardiac parasympathetic function. European Journal of Applied Physiology, 108 (6): 1153–1167.

**[32] Uusitalo ALT, Uusitalo AJ & Rusko HK (2001).** Heart Rate and Blood Pressure Variability During Heavy Training and Overtraining in the Female Athlete. International Journal of Sports Medicine, 21 (1): 45–53.

**[33] Kaikkonen P, Hynynen E, Mann T, Rusko H & Nummela A (2012).** Heart rate variability is related to training load variables in interval running exercises. European Journal of Applied Physiology, 112 (3): 829–838.

**[34] Uusitalo AL, Vanninen E, Levälahti E, Battié MC, Videman T & Kaprio J (2007).** Role of genetic and environmental influences on heart rate variability in middle-aged men. American Journal of Physiology, Heart and Circulatory Physiology, 293 (2): H1013–1022.

**[35] Su S, Lampert R, Lee F, Bremner D, Snieder H, Jones L, Murrah NV, Goldberg J & Vaccarino V (2010).** Common Genes Contribute to Depressive Symptoms and Heart Rate Variability: The Twins Heart Study. Twin Research and Human Genetics, 13 (1): 1–9.

**[36] Martinmäki K, Rusko H, Kooistra L, Kettunen J & Saalasti S (2006).** Intraindividual validation of heart rate variability indexes to measure vagal effects on hearts. American Journal of Physiology - Heart and Circulatory Physiology, 290, H640-H647.

**[37] Parak J & Korhonen I (2013).** Accuracy of Firstbeat Bodyguard2 beat-to-beat heart rate monitor. White paper by Firstbeat Technologies Ltd.

**[38] Saalasti S, Seppänen M & Kuusela A (2004).** Artefact correction for heart beat interval data. Advanced methods for processing bioelectrical signals. In: Proceedings of the ProBisi Meeting. Jyväskylä, Finland, 1–10.

**[39] Saalasti S (2003).** Neural networks for heart rate time series analysis. Academic dissertation. Department of Mathematical Information Technology, University of Jyväskylä, Finland.

**[40] Kettunen J (1999).** Methodological and empirical advances in the quantitative analysis of spontaneous responses in psychophysiological time series. Academic dissertation, University of Helsinki.

**[41] Kettunen J & Keltikangas-Järvinen L (2001).** Intraindividual analysis of instantaneous heart rate variability. Psychophysiology, 38: 659–668.

**[42] Smolander J, Ajoviita M, Juuti T, Nummela A & Rusko H (2011).** Estimating oxygen consumption from heart rate and heart rate variability without individual calibration. Clinical Physiology and Functional Imaging 31 (4), 266–271.

**[43] Smolander J, Juuti T, Kinnunen M-L, Laine K, Louhevaara V, Männikkö K & Rusko H (2008).** A new heart rate variability-based method for the estimation of oxygen consumption without individual laboratory calibration: Application example on postal workers. Applied Ergonomics 39(3), 325–331.

**[44] Montgomery PG, Green DJ, Extebarria N, Pyne DB, Saunders PU & Minahan CL (2009).** Validation of Heart Rate Monitor-Based Predictions of Oxygen Uptake and Energy Expenditure. Journal of Strength and Conditioning Research, 23 (5): 1489-1495.

**[45] Pulkkinen A, Kettunen J, Martinmäki K, Saalasti S & Rusko H (2004).** On- and Off Dynamics and Respiration Rate Enhance the Accuracy of Heart Rate Based VO2 Estimation. ACSM Congress.

**[46] Pulkkinen A, Kettunen J, Saalasti S & Rusko HK (2003).** Accuracy of VO2 estimation increases with heart period derived measure of respiration. ACSM Congress, San Francisco. Abstract: Medicine & Science in Sports & Exercise 35 (5): Suppl: 192.

**[47] Rusko HK, Pulkkinen A, Saalasti S, Hynynen E & Kettunen J (2003).** Pre-Prediction of EPOC: A Tool for Monitoring Fatigue Accumulation during Exercise? ACSM congress poster. 50th Annual Meeting of the American College of Sports Medicine, San Francisco, California, USA.

**[48] Saalasti S, Kettunen J, Pulkkinen A & Rusko H (2002).** Monitoring respiratory activity in field: applications for exercise training. Science for Success congress, Jyväskylä, Finland.

**[49] Kettunen J & Saalasti S (2005).** Procedure for deriving reliable information on respiratory activity from heart period measurement. United States Patent Application 7,460,901 B2.

**[50] Firstbeat Technologies (2012).** VO2 Estimation Method Based on Heart Rate Measurement. White paper by Firstbeat Technologies Ltd.

**[51] Firstbeat Technologies (2012).** An Energy Expenditure Estimation Method Based on Heart Rate Measurement. White paper by Firstbeat Technologies Ltd.

**[52] Firstbeat Technologies (2012).** Indirect EPOC Prediction Method Based on Heart Rate Measurement. White paper by Firstbeat Technologies Ltd.

**[53] Firstbeat Technologies (2012).** EPOC Based Training Effect Assessment. White paper by Firstbeat Technologies Ltd.

**[54] American College of Sports Medicine (2013).** ACSM's Guidelines for Exercise Testing and Prescription. 9th edition. Pescatello LS, Arena R, Riebe D, Thompson PD (eds.). Lippincot, Williams & Wilkins.

**[55] Franklin BA & Gordon NF (2005).** Contemporary Diagnosis and Management in Cardiovascular Disease. Premiere edition.

**[56] Kettunen J & Saalasti S (2008).** Procedure for detection of stress by segmentation and analyzing a heartbeat signal. United States Patent Application 7,330,752 B2.

**[57] Firstbeat Technologies (2012).** Heart Beat Based Recovery Analysis for Athletic Training. White paper by Firstbeat Technologies Ltd.

**[58] Kinnunen M-L, Rusko H, Feldt T, Kinnunen U, Juuti T, Myllymäki T, Laine K, Hakkarainen P & Louhevaara V (2006).** Stress and relaxation based on heart rate variability: Associations with self-reported mental strain and differences between waking hours and sleep. Nordic Ergonomics Society congress.

**[59] Myllymäki T, Kyröläinen H, Savolainen K, Hokka L, Jakonen R, Juuti T, Martinmäki K, Kaartinen J, Kinnunen M-L & Rusko H (2011).** Effects of vigorous late-night exercise on sleep quality and cardiac autonomic activity. Journal of Sleep Research 20 (1 Pt 2): 146–153.

**[60] Myllymäki T, Rusko H, Syväoja H, Juuti T, Kinnunen M-L & Kyröläinen H (2012).** Effects of exercise intensity and duration on nocturnal heart rate variability and sleep quality. European Journal of Applied Physiology 112 (3), 801–809.

**[61] Rusko H, Rönkä T, Uusitalo A, Kinnunen U, Mauno S, Feldt T, Kinnunen M-L, Martinmäki K, Hirvonen A, Hyttinen S & Lindholm H (2006).** Stress and relaxation during sleep and awake time, and their associations with free salivary cortisol after awakening. Nordic Ergonomics Society congress.

**[62] Uusitalo A, Mets T, Martinmäki K, Mauno S, Kinnunen U & Rusko H (2011).** Heart rate variability related to effort at work. Applied Ergonomics 42 (6): 830–838.

**[63] Feldt T, Rönkä T, Rusko H, Kinnunen M-L, Kinnunen U (2007).** The Associations between Self-Rated Affective Well-Being and Physiological Indicators of Stress and Relaxation among Cleaning Staff. European Congress of Work and Organizational Psychology.

**[64] Rönkä T, Rusko H, Feldt T, Kinnunen U, Mauno S, Uusitalo A & Martinmäki K (2006).** The Associations between Physiological Recovery Indicators during Sleep and Self-Reported Work Stressors. Nordic Ergonomics Society congress.

**[65] Antila K, van Gils M, Merilahti J & Korhonen I (2005).** Associations of Psychological Self-Assessments and Heart Rate Variability in Long Term Measurements at Home. European Medical & Biological Engineering Conference.

**[66] Teisala T, Mutikainen S, Tolvanen A, Rottensteiner M, Leskinen T, Kolehmainen M, Rusko H & Kujala UM (2014).** Associations of physical activity, fitness, and body composition with heart rate variability–based indicators of stress and recovery on workdays: a cross-sectional study. Journal of Occupational Medicine and Toxicology, 9:16.

**[67] Lappalainen P, Kaipainen K, Lappalainen R, Hoffrén H, Myllymäki T, Kinnunen M-L, Mattila E, Happonen AP, Rusko H & Korhonen I (2013).** Feasibility of a Personal Health Technology-Based Psychological Intervention for Men with Stress and Mood Problems: Randomized Controlled Pilot Trial. JMIR Res Protoc. 2 (1): e1.

**[68] Kaipainen K, Mattila E, Väätänen A, Happonen AP, Korhonen I, Kinnunen M-L, Myllymäki T, Lappalainen P, Hoffren H, Rusko H & Lappalainen R (2010).** Web, mobile and monitoring technologies in self-management of psychophysiological well-being: usage and user experiences. Proceedings of the IADIS International Conference e-Health, Freiburg, Germany.

**[69] Happonen AP, Mattila E, Kinnunen ML, Ikonen V, Myllymäki T, Kaipainen K, Rusko H, Lappalainen R & Korhonen I (2009).** P4Well concept to empower self-management of psychophysiological well-being and load recovery. Proceedings of the 3rd International Conference on Pervasive Computing Technologies for Healthcare, London, UK.

**[70] Mikkola J, Hynynen E & Nummela A (2012).** Nocturnal Heart Rate and Heart Rate Variability Based Training Load Monitoring, a Case Study of an Elite Junior XC Skier During a Glacier Training Camp. 2nd International Congress on Science and Nordic Skiing, Vuokatti, Finland.

**[71] Vänttinen T, Blomqvist M, Lehto H & Häkkinen K (2007).** Heart Rate and Match Analysis of Finnish Junior Football Players. Proceedings of the 6th congress on science in football, Antalya, Turkey.

**[72] Häyrinen M, Luhtanen P, Juntunen J & Hynynen E (2007).** An Evaluation of Physical Loading, Recovery and Stress in Youth Soccer. Science for Success II congress, Jyväskylä, Finland.

**[73] Luhtanen P, Nummela A & Lipponen K (2007).** Physical loading, stress and recovery in a youth soccer tournament. Proceedings of the 6th congress on science in football, Antalya, Turkey.

**[74] Hynynen E & Nummela A (2010).** A three year follow-up study of endurance performance and nocturnal HRV of an international level race-walker. EA innovation awards.

**[75] Pietilä J (2014).** Preparation and processing of a large-scale heart rate variability and Lifestyle Assessment results data. Master Thesis in Electrical Engineering, Tampere University of Technology.

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