Heart Beat Based Recovery Analysis for Athletic Training

White paper by Firstbeat Technologies Ltd.

This white paper has been produced to describe a heart beat based 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

RECOVERY ANALYSIS METHOD AT A GLANCE 1
Introduction 1
Athletic training and recovery 1
Methods to analyze recovery 1
HEART RATE VARIABILITY BASED RECOVERY ANALYSIS METHOD 1
Definitions for stress and recovery 2
Recovery analysis during sleep 2
Individual interpretation 2
Validation 2
HOW TO APPLY RECOVERY ANALYSIS IN TRAINING 2
Verify sufficiency of training load 3
Prevent overtraining 3
More individual training in team sports 3
High altitude training 4
Other factors to be considered in recovery analysis 4
REFERENCES AND FURTHER READING 4

RECOVERY ANALYSIS METHOD AT A GLANCE

- The method is based on both traditional and newly developed heart rate variability (HRV) analysis.
- The method has been shown to be more sensitive than traditional HRV analysis and heart rate (HR) level measurement.
- Quick and easy-to-perform recovery analysis which requires only beat-by-beat heart rate recording.
- Allows daily recovery monitoring.
- Has been used in different sports, especially by international level endurance athletes.

Introduction

In precise and effective training management, an athlete and/or a coach should assess the load and effectiveness of different training sessions and also recovery from these sessions. Methods to measure training load and training effect have been recently introduced in separate white papers (see EPOC and training effect white papers). This paper introduces a new easy-to-use method to assess the recovery of an athlete or a team and represents the benefits of this recovery assessment.

Athletic training and recovery

In addition to high training load, also recovery plays an important role in athletic training. There has to be a balance between hard and easy training and rest both within a single training week and within longer training periods. When a hard training session or training period that causes a significant disturbance in body's homeostasis is followed by sufficient recovery, performance improvements are likely to occur. The importance of sufficient recovery is due to the fact that performance improvements actually occur during recovery from training, not during workouts. Finding a balance between training load and recovery is a key factor in improving athletic performance.

Periodization is important in training. Usually athletes have several very hard training periods each year, during which both the intensity and volume of training are very high. These kind of overreaching periods are very exhaustive but necessary for elite athletes to further improve their performance. However, performance can improve only if hard training is followed by adequate recovery.

Too hard training without sufficient rest may lead to overtraining, which is characterized by decreased performance and in the worst case also other harmful effects on health. Recovery from overtraining may take from several weeks to months, but it is also possible that an athlete never reaches the same level of performance as before overtraining. Prevention of overtraining is therefore crucial, and is possible by systematic assessment of the athlete's recovery.

Methods to analyze recovery

Different methods available for assessing recovery from training are presented in Table 1. Basic problems related to most of the methods include insensitivity or invalidity for this purpose, high cost or time consuming measurement and/or analysis. For these reasons, these methods cannot be used frequently enough to support training and coaching optimally.

Firstbeat's heartbeat based recovery analysis is easy to perform and gives valuable information on the function of the autonomic nervous system (ANS), which has been shown to reflect the recovery state. The role of ANS is to control the function of visceral organs without voluntary control. ANS has two branches, sympathetic and parasympathetic nervous systems. From an anatomical point of view, sympathetic and parasympathetic nervous systems involve both central and peripheral nervous systems. The sympathetic nervous system prepares the body systems for challenging situations and is activated during e.g. physical activity and mental / cognitive tasks which we all encounter daily. For example, increased sympathetic activity elevates the heart rate and heart's stroke volume. The parasympathetic nervous system has the opposite role: increased parasympathetic activity enables recovery. Activity of the parasympathetic nervous system restores a resting state in body systems by for example allowing faster digestion of food and decreasing the heart rate.

If the body is exposed to mental stress, high training load or other sources of stress (high altitude, jetlag, illness), or their combination for prolonged periods without adequate rest, it is possible that a state of overtraining or exhaustion develops. Before the actual overtraining syndrome develops, it is possible to detect signs of inadequate recovery. This is shown by increased sympathetic nervous system activity and decreased parasympathetic activity even when the athlete should be recovered and free from all stress factors. Firstbeat's recovery analysis reveals signs of accumulated stress and lack of recovery. Since only heartbeat data collection is needed, development of more harmful disorders can be prevented.

HEART RATE VARIABILITY BASED RECOVERY ANALYSIS METHOD

The described recovery analysis method has been designed to sensitively measure athletes' stress and recovery. The method is based on measurement of heart rate variability, which has been proven to be a valid measure for this purpose (See Figure 1) (e.g. Uusitalo 2000). The method can be used to assess athletes' recovery and daily stress round the clock, but this white paper focuses on the assessment and follow-up of night time recovery.

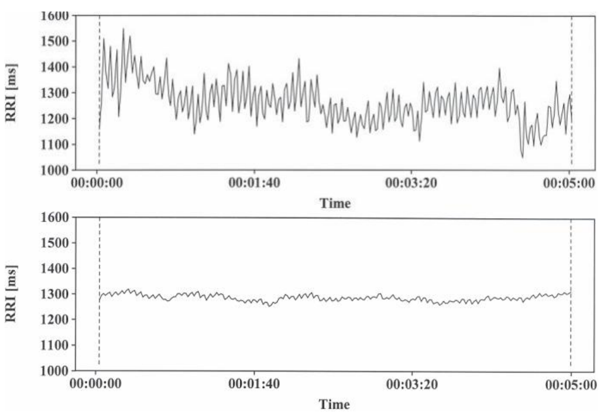

Figure 1. Two different heartbeat data collections (in supine position with controlled breathing) from a female long distance runner: Well trained and well recovered (upper chart) and overtrained (lower chart). There is a lot of variation in RR-intervals (RRI) when the athlete is well recovered. On the contrary, there is hardly any variation in RR-intervals when the athlete is in an overtrained state, despite the same heart rate level (48 bpm in well recovered and 47 in overtrained condition). Heart rate variability indices are very efficient in overtraining detection, whereas heart rate is not (modified from Uusitalo 2000).

Table. 1. Comparison of different methods evaluating athletic recovery.

Method	Physiological and scientific basis	Advantages	Limitations
Lactate measurements	Lactate is formed in anaerobic metabolism. Observations have been made about reduced lactate levels in fatigued state, usually when the muscles are emptying of glycogen.	Relatively easy to measure. Inexpensive.	Cannot distinguish between overreaching and overtraining. Requires control exercise. Usually needs to be combined with information on subjective feelings. Mainly measures short term recovery after a single training session or a few sessions and is related to muscle glycogen level.
Hormonal, immunological and biochemical measurements	Poor recovery, overreaching and overtraining may be detected by observing hormonal, immunological and/or biochemical markers (e.g. cortisol)	Specificity: Possible to locate the "problem area" precisely if changes in these markers are detected.	Not sensitive enough for the measurement of daily training status. Expensive. Instant feedback is not possible.
Orthostatic test	Cardiac reactivity to postural changes has been found to be associated with recovery state.	Inexpensive. Relatively easy and quick to perform.	Other factors, such as mental arousal or anxiety may confound results. Heart rate level may either increase or decrease due to high training load.
Subjective feelings (e.g. Profile of Mood States, other questionnaires or personal feeling of recovery or fatigue)	Training induced fatigue is linked to psychological factors. Experienced athletes can feel when they are recovered.	Inexpensive and easy to assess.	Not objective.
Traditional HRV-analysis	Single HRV indices (e.g. HF power, RMSSD) have been found to detect excessive training load either alone or combined with orthostatic test.	Inexpensive. Relatively easy and quick to perform.	Necessary artefact correction requires signal analysis skills. If done awake, other factors such as mental arousal or anxiety may confound results. Traditional HRV indices are hard to interpret.
Firstbeat Recovery Test	Based on advanced HRV analysis and physiological modeling of body functions.	Very fast measurement, automated analysis and interpretation. Has been found to be more sensitive than traditional HRV indices.	Beat-by-beat HR recording is required.

In the method, stress and recovery are assessed based on heart rate level, heart rate variability and heart beat derived respiration rate. The used heart rate variability measures, low frequency power and high frequency power, are calculated second-by-second using the short-time Fourier Transform method (Saalasti 2003). In the reports generated by Firstbeat software, recovery can be assessed by observing the "Stress and recovery chart", see Figure 3 and by using the "Recovery index" (Figure 4). Beat-by-beat heart rate recording is the only requirement for performing the analysis.

Definitions for stress and recovery

The analysis of stress and recovery is based on the detection of sympathovagal reactivity of the heart that exceeds momentary metabolic requirements of the autonomic nervous system.

Stress state is defined as increased activation in the body, induced by external and/or internal stress factors (stressors), during which sympathetic nervous system activity is increased and parasympathetic (vagal) activity is decreased (= sympathetic tone). In the described recovery analysis, stress is detected when heart rate is elevated and HRV is reduced and there are inconsistencies in the frequency distribution of HRV due to changes in respiratory period.

Recovery is defined as decreased activation in the body during relaxation, rest and/or peaceful working, related to lack of external and internal stress factors when parasympathetic (vagal) activity is great and sympathetic activity is low. Recovery is detected when HR is close to the resting level and HRV is great and regular according to the breathing rhythm. Figure 3 presents an example of the detection of stress and recovery during sleep.

Recovery analysis during sleep

Recovery analysis is performed with data collected during night sleep to get the most accurate results. During sleep, all confounding factors are minimized, and the level of ANS activity is most reliably recognized. The recommended 4-hour window for determining the recovery index is set to start 30 minutes after going to bed. When used during the first four sleeping hours, Firstbeat's recovery analysis was found to be the most sensitive recovery analysis method (Hynynen et al. 2006). Night time measurement is recommended if one wants to have the most accurate and reliable follow-up method to monitor athletes' recovery.

Individual interpretation

Level of HRV is individual. This must be taken into account when interpreting the measured data since analysis is based on HRV. It is recommended that reference values are measured for both high training load / poor recovery and for low training load / well recovered conditions. These reference values should be updated whenever needed, for example between different training periods if changes appear in ANS function. Analysis in Firstbeat SPORTS automatically scales the recovery index according to the measured and analyzed data.

Comparison between different individuals is not usually reasonable or even required. The method will reveal whether the individual athlete is recovered or not. In general, the stress and recovery chart can be used as a quick glance to see when recovery starts to occur. The recovery index provides more accurate information on current recovery status because of the comparison to individual baseline values.

Validation

The described method has been validated in a study including hospital employees (Rusko et al. 2006) as subjects. This study aimed to investigate whether stress and recovery states can be determined from HR and HRV. It was found that temporal percentages of stress and recovery were valid measures for employees' physiological resources (see Figure 2). In another study including professional athletes (Hynynen et al. 2006) the aim was to investigate the effects of training on nocturnal cardiac autonomic modulation using new methods of heart rate variability analysis. The measures used were derivative from the present athlete recovery analysis method. It was concluded that the intensity of stress and recovery were the most valid measures to describe athletes' recovery status in all conditions when compared to the use of heart rate or HF or LF powers of heart rate variability. Furthermore, researchers found that the Firstbeat method measured recovery state accurately both after a single hard training day and after an overreaching period.

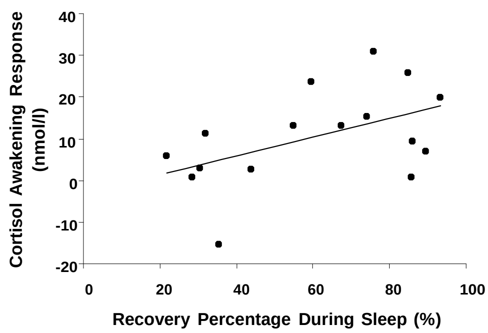

Figure 2. The higher the temporal percentage of recovery during sleep, the higher the cortisol awakening response (r=0.50) in the morning, representing that better recovery during nighttime is associated with higher resources the next day. Cortisol awakening response = [Salivary cortisol level 30 min after awakening] - [Salivary cortisol level immediately after awakening] (Rusko et al 2006).

HOW TO APPLY RECOVERY ANALYSIS IN TRAINING

Night time recovery measurements have been widely applied among international level endurance athletes (e.g. in kayaking, swimming, cross-country skiing). Night time heartbeat recording does not disturb sleep significantly or at all and enables decision making immediately after awakening, allowing changes in training program if needed.

Regular recovery assessment is a key factor in successful training programming. More frequent recovery index follow-up is recommended during harder training periods and especially to ensure recovery when it is supposed to occur. For effective time management, recovery index follow-up can be done less frequently during periods of less demanding training when the risk of overtraining is small. Verification should be made both to assure the sufficiency of training load during hard training periods and to assure that the athlete really recovers during easy periods. Changes in recovery state are needed for training to be effective (see Table 3 and Figure 4).

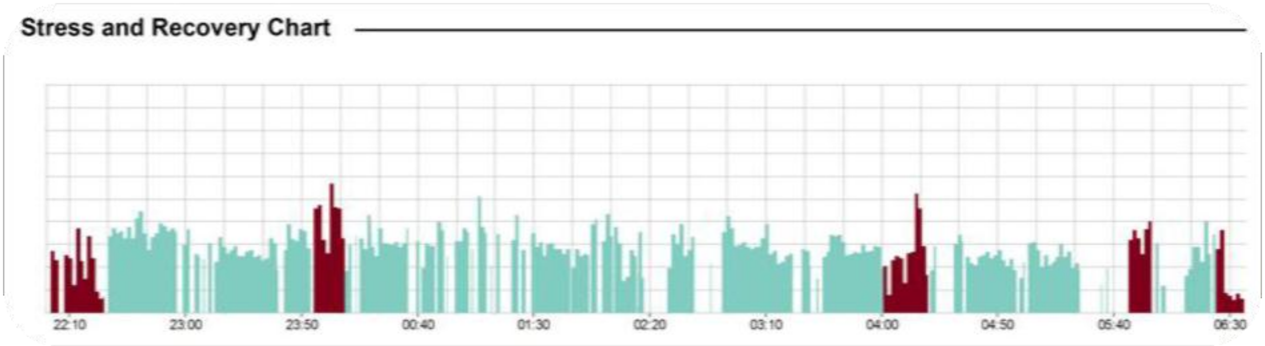

Figure 3. Example of stress (red) and recovery (green) detection during sleep (included in Firstbeat SPORTS and HEALTH softwares).

Verify sufficiency of training load

Recovery assessment is recommended even after a single hard training day. Recovery status should be lower than normal during the first night after a hard training day. Recovery intensity should move closer to the baseline during the following nights if the athlete performs easier training or has a rest day.

Overreaching periods are needed for a high level athlete to achieve performance increments. This means that training-related fatigue accumulates from one training session to another in such a manner that the athlete is actually exhausted at the end of the training period.

During an overreaching period, the recovery index should decrease towards the end of the period. When the recovery index decreases as expected, continue training as planned. Adjust training plan if the recovery index does not decrease at all or decreases only slightly. In this case, it is likely that the training load has been too easy and could be a bit harder than the initial plan. If the recovery index drops unexpectedly to a low or poor recovery level, determine if the training has been too hard and control or remove other stressors (e.g. travel, other life stress, illness), if possible. Table 2 shows a few examples of endurance athletes whose recovery has been assessed both after easy and hard training periods.

Prevent overtraining

If training load is high for prolonged periods and proper recovery is neglected, overtraining may occur. Thus, easy training should be applied for a short period after harder training periods to assure recovery and performance increments.

When training load is high, recovery index follow-up is the best way to notice whether the athlete has a risk of overtraining. Table 3 represents changes that occur in the body in different training states and that can be utilized in recognizing signs of excessive or unexpected fatigue. With follow-up, one can track whether it is safe to continue the overreaching period or if it is time to start the recovery period.

When easier training is carried out after harder training, you should verify whether the recovery index increases as expected. The recovery index should start to increase and come closer to the reference values of a well-recovered state. Also the temporal proportion and intensity of stress and recovery in the stress and recovery chart should return to the normal level (if they were disturbed during the training period). Intensive training should not be restarted before these values come close to or reach the reference values of a well recovered state

More individual training in team sports

A major challenge in team sports is how to optimize training and recovery for all team players because of different training load during training sessions and games, as well as individual differences in the ability to recover from training . Some individuals must put in a higher effort during team training sessions and games and some others may have a reduced capacity to recover due to e.g. previous injuries. If an individual's recovery is incomplete, it may lead to decreased personal performance or even exhaustion or injury, which of course affects the whole team.

In addition to attempting to provide an equal or appropriate training load for all team members, also individual recovery status should be controlled. The coach can either assess a few players who are suspected of having difficulties with recovery or track the whole team. A recovery test for the whole team can be managed by collecting overnight heartbeat data from all players. Analysis is highly automated and quick to perform and can be performed first thing in the morning, before the team training session. If necessary, training of the exhausted players can then be adjusted. Of course, some players may not be exhausted at all, and their training load can even be increased.

Table 2. Examples of recovery index values in endurance athletes (cross-country skiers) in a well recovered and poorly recovered state (unpublished data from Hynynen et al. 2006)

Subject	Well recovered	Poorly recovered
1	283	225
2	141	78
3	139	96
4	177	129
5	159	104
6	128	109
7	198	144
Average	175	144

Table 3. Effects of different training states on recovery measures. Letters A-C refer to Figure 4, which presents these different states in a practical example.

Training state	Physiological findings	Appearance in recovery analysis	Appropriate reaction
A. Well recovered. No training related fatigue.	Low training related stress and high resources. Low level of sympathetic activity and high level of parasympathetic activity.	HR is low and HRV is great. High recovery index.	Harder training can be programmed or hard training can be restarted after a recovery training period.
B. Not fully recovered from a single hard training session.	Increased training-related stress and slightly reduced resources. Slightly increased sympathetic activity level and slightly decreased parasympathetic activity.	HR is higher and HRV lower than in a well recovered state. Recovery index is slightly decreased.	Train more easily until recovery index returns to a normal level unless you have an ongoing overreaching period.
C. High training-related fatigue after an overreaching period.	High training-related stress and low resources. Symptoms of e.g. tiredness and cardiac tachycardia. Significantly increased sympathetic and significantly reduced parasympathetic activity.	HR is significantly higher and HRV significantly lower than in a well recovered state. Recovery index is low.	Good recovery should be allowed immediately after the overreaching period. Before restarting harder training, check that recovery index has returned to a normal level.
D. Overtraining caused by a long period of hard training with inadequate recovery.	Depleted body resources due to excessive long-term training stress. Near normal level of sympathetic activity and very low parasympathetic activity.	HR may be at normal level but HRV is diminished. Recovery index is very low.	Rest or very light training until the recovery index returns to a normal level, which may take from weeks to several months.

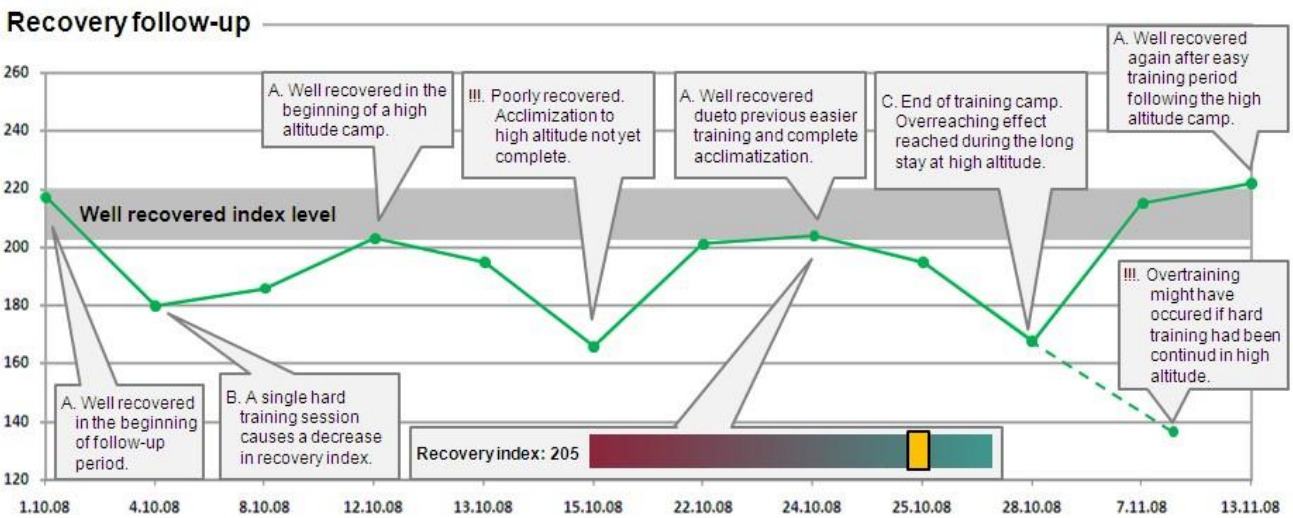

Figure 4. Example of a cross-country skier's recovery index follow-up. Successful training requires both hard training and proper recovery. (The recovery index is included only in Firstbeat SPORTS software.)

High altitude training

High altitude training is an important consideration in all types of sports where endurance and VO_{2max} play a role. High altitude training provides a significant benefit whenever a game or race is held in high altitude, but the benefit is more controversial when the competition is held at or near sea level.

Acclimatization to high altitude is always a stressor to the human body. When the acclimatization is complete, athlete's recovery and stress measures should reach values that are near to the values measured at sea level. Too hard training during the acclimatization period, interacting with high altitude stress may delay or inhibit reaching a normal recovery state, and thus, valuable days available for training are lost.

Since high altitude causes additional stress to the body, intensified recovery monitoring is recommended during the entire high altitude period. During a high altitude training period, the same rules of overtraining prevention can be applied as during any intensive training period (see Table 2), i.e. a very hard training load (in interaction with high altitude stress) cannot be continued for too long.

Other factors to be considered in recovery analysis

The described recovery analysis method reflects ANS stress from different sources. These sources of stress are listed below and should be taken into account in interpretation:

- High Altitude
- Illness
- Medication
- Jetlag
- Lack of sleep
- Adaptation to hot climate
- Hard training session or race performed late in the evening
- "Hangover"
- Work-related stress factors
- Social stress factors
- Emotional stress factors

It is also possible that an athlete's performance is decreased due to training-induced tension or soreness in musculature. This is not necessarily revealed by the recovery analysis method because some new (unfamiliar to the athlete) types of exercises or monotonous training may lead to decreased neuromuscular performance that doesn't have a significant effect on ANS function.

Recovery assessments should always be started before hard training periods. It is difficult to detect inadequate recovery if there is no reference level. It is even possible that inadequate recovery is not detected at all if recovery assessments are started only when the athlete is already overreached or overtrained.

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