Journal of Clinical Sport Psychology, (Ahead of Print)
https://doi.org/10.1123/jcsp.2022-0016

Human Kinetics
ARTICLE FOR SPECIAL ISSUE

A Narrative Review of Heart Rate Variability as a Good Index of Psychophysical Health in Athletes and in Biofeedback Training

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Stress is a psychophysical condition that causes an impairment in athletes' performance by causing an increase in sympathetic activity and an autonomic imbalance. The current methods for the measurement of psychophysiological stress introduce the use of the heart rate variability as a useful index of the well-being of these people. The heart rate variability corresponds to the time intervals between consecutive heartbeats, such as an irregularity in the normal sinus heart rhythm whose variability is due to the control exercised by a complex system of mechanisms, including the respiratory control system, and provides information about the activity of the sympathetic and parasympathetic branches of the autonomic nervous system. This review aims at summarizing the promising results, despite small amount, of the recent literature on the efficacy of heart rate variability biofeedback on the autonomic imbalance and psychophysical well-being of athletes as well as cognitive and motor performance.

Keywords: sympathovagal balance, overtraining, psychophysiology, stress

The term "stress" was used for the first time by Selye (1998), which described an activation of the hypothalamic–pituitary–adrenocortical (HPA) axis as a general condition with nonspecific symptoms activated by the central nervous system (CNS) and the autonomic nervous system (ANS). This set of reactions was called general adaptation syndrome (GAS). The univocal response to any adverse stimulus occurs in three phases (Selye, 1956, 1998). The activation of the sympathetic nervous system (SANS) with consequent activation of the medullary portion of the adrenal glands and secretion of adrenaline and noradrenaline characterizes the first phase (alarm). Both catecholamines increase cardiac output and increase the blood supply of skeletal muscles. The body mobilizes and directs energy resources toward a fight or flight behavior. Additionally, the HPA axis is activated with secretion of glucocorticoids. Cortisol (known as the "stress hormone"), triggers the conversion of proteins into glucose, involves lipids in the production of immediately available energy, increases blood flow, and activates behavioral responses. During the second

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phase (adaptation), the body tries to adapt to the new situation with an overproduction of cortisol. Lastly, two possible outcomes characterizes the third phase (exhaustion): (1) the extinction of the stress response or (2) a condition of functional exhaustion that occurs when the organism does not have the resources to resist and/or adapt further because the stimulus continues for a long period (Frisone, et al., 2021; Kemeny, 2003; Rice, 1999) (Figure 1).

Stress-Related Disorders in Athletes

Keeping in mind that stress corresponds to a psychophysiological arousal that supports cognitive and behavioral functions, it is considered important to individuate a "normal" or a "dysfunctional" level as described by the Yerkes–Dodson law of 1908. According to this theory, the level of performance increases with the augmentation in physiological activity but up to an optimum point. In other words, if stress increases beyond this level, performance decreases and adaptation rapidly decays (Calabrese, 2008; Figure 2).

Looking at athletes, several research have examined nonfunctional overreaching (NFO) and/or overtraining syndrome (OTS), the two athletes' stress-related disorders (Djaoui et al., 2017; Düking et al., 2021). In particular, an initial stage of distress (it matches the acute phase of the GAS) corresponds to a subclinical condition that is characterized by an increase in cortisol and sympathetic tone activity. This situation can cause symptoms such as reduced sleep quality and duration, feelings of depression or anxiety, fatigue, and excessive sensibility to pain (Djaoui et al., 2017; Manresa-Rocamora et al., 2021).

The second stage of distress is called sympathetic overtraining (or NFO, it matches the adaptation phase of the GAS) and is associated with a further increase

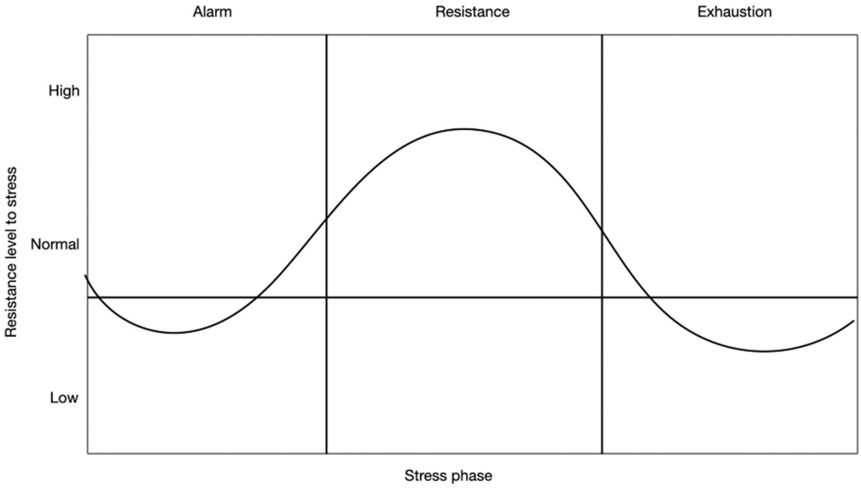

Figure 1 — Response pattern of the general adaptation syndrome described by Selye (1956).

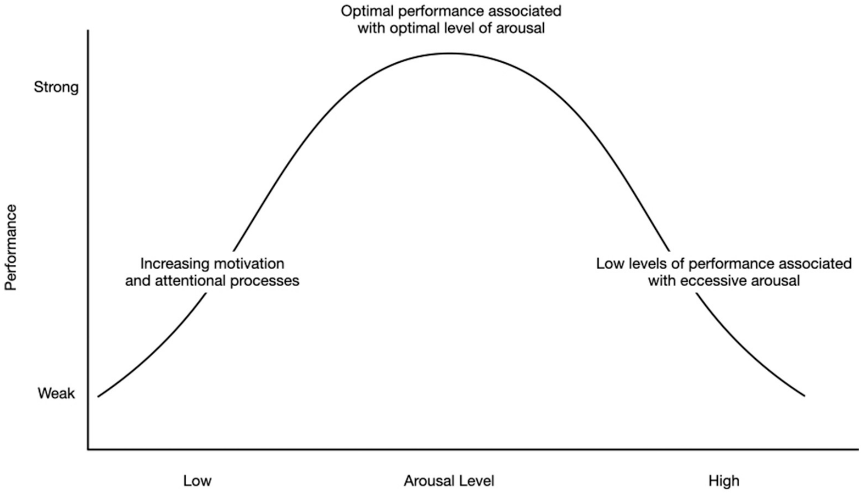

Figure 2 — Yerkes–Dodson's law: A correct individual activation leads to the optimal zone while a condition of low (underarousal) or high (overarousal) arousal both lead to poor performance.

in HPA axis activity, which, in turn, leads to a hyperproduction of cortisol and adrenaline. This increased stress is associated with sleep disturbances, daytime sleepiness, pain, and reduced desire to exercise. Immunity problems (increased colds, flu, upper respiratory tract infections, and asthma) and gastrointestinal dysfunctions (indigestion and excess gas) are also possible (Brooks & Carter, 2013; Senttä & Hassmén, 1998). The highest level of chronic stress is called chronic overtraining (or OTS, it matches the exhaustion phase of the GAS) and is characterized by autonomic dysfunctions. In fact, it is associated with decreases in the activity of the HPA axis, a reduction in growth hormone and low responses from adrenocorticotropic hormone. The lack of SANS activity causes an abnormal decrease in heart rate at rest and worsening of the athlete's performance.

Stress Measures

Heart Rate

A recent trend in clinical psychophysiology, and especially in clinical sport psychophysiology, is characterized by the attention given to the use of the electrocardiography (ECG) to derive heart rate (HR; and its inverse, and the interbeat interval [IBI]) and HR variability (HRV) of athletes (Porges, 2007, 2021, 2022).

Usually, to record the HR, the ECG is used, which analyzes the phases of heart contraction (Berntson et al., 1997; Bhoja et al., 2020; Ernst, 2017; Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). These stages are expressed in letters: P WAVE: atrial depolarization; QRS COMPLEX: ventricular depolarization; ST COMPLEX and T WAVE: ventricular repolarization; QT INTERVAL: depolarization and repolarization time; and PR TRACT: impulse propagation from the atria to the ventricles (Figure 3).

HR is linked to the activity of the SANS (activator) and parasympathetic branch of the ANS (PANS; inhibitor). The control of cardiac activity is mediated through the simultaneous intervention of the SANS and PANS (An et al., 2020). PANS innervates the sinoatrial node, the atrioventricular node, and the heart muscle of the atria. An increase in PANS activity reduces the frequency of generating action potentials in the sinoatrial and atrioventricular node, thus causing a decrease in HR. Conversely, a decrease in vagal activity causes an increase in HR. The SANS also innervates the sinoatrial node, the atrioventricular node, and the muscle fibers of the heart. Unlike PANS, an increase in sympathetic activity increases the frequency of generation of action potentials in the sinoatrial and atrioventricular node, thus increasing HR. During rest situations, both the sympathetic and parasympathetic nerves have a tonic activity, with a predominance of parasympathetic activity (Berntson et al., 1997; Bhoja et al., 2020; Ernst, 2017; Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996).

There are different types of reflexes that induce chronotropic effects (modification of the HR) through increases or decreases in sympathetic and parasympathetic activities. Some of them involve the baroreceptors (the receptors sensitive to arterial pressure, located in the aortic arch, in the carotid sinus, and in the heart chambers), while others involve chemoreceptors (receptors sensitive to changes in the chemical composition of the blood—oxygen and carbon dioxide—and other biological fluids, also present in the aortic arch and in the carotid sinus; Porges, 2007, 2021, 2022; Shaffer et al., 2014).

Another control mechanism linked to respiration is known as the respiratory sinus arrhythmia (RSA): It is due to the presence of lung stretch receptors. RSA is

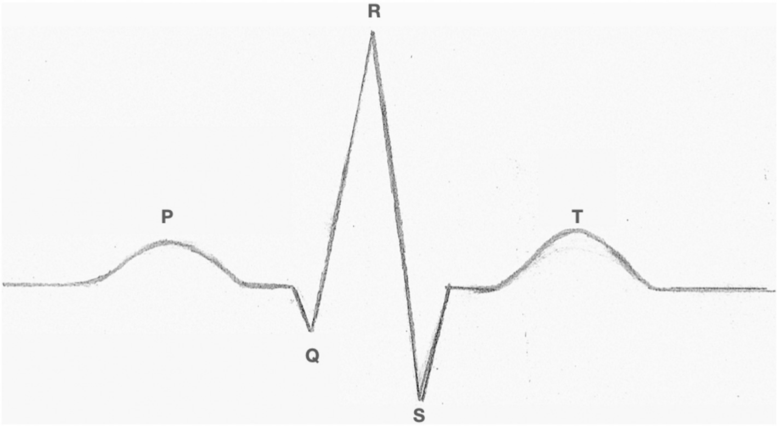

Figure 3 — ECG and PQRST complex.

a physiological arrhythmia associated with a synchrony between respiratory rate and HR, in which beat-to-beat intervals (RR) shorten during the inhalation phase (HR increase) and lengthen during the exhalation phase (decrease in HR) as a consequence of changes in vagal activity (Bhoja et al., 2020; Cosentino & Pruneti, 2015; Karemaker, 2009; Porges, 2007, 2021, 2022; Figure 4).

The cardiovascular system is crucial for survival, thus it is not surprising that this system is regulated by complex central mechanisms, including lower-level reflex systems as well as higher neurobehavioral mechanisms (Cacioppo et al., 2010; Figure 5).

For instance, the baroreceptor HR reflex circuit is comprised of stretch receptor afferents from the carotid and other great arteries to the nucleus tractus solitarius (NTS), the major visceral receiving station in the brainstem. In this sense, peripheral information conveyed by the baroreceptors to the NTS is transmitted directly and/or indirectly via noradrenergic projections to higher brain centers, including the amygdala, the cortex, and the hypothalamus, particularly its paraventricular nucleus (PVN; Michelini & Stern, 2009). NTS projections can excite

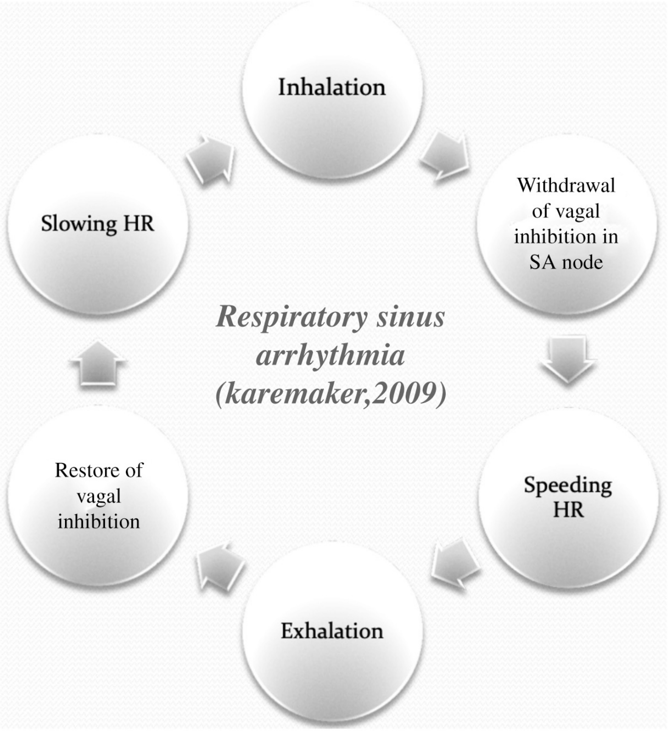

Figure 4 — Physiology of respiratory sinus arrhythmia. The rhythmic variations in the heart rate are associated with the frequency of breathing. During the inhalation phase, the beat-to-beat intervals (RR) get shorter, while during the exhalation phase get longer as a consequence of changes in vagal activity.

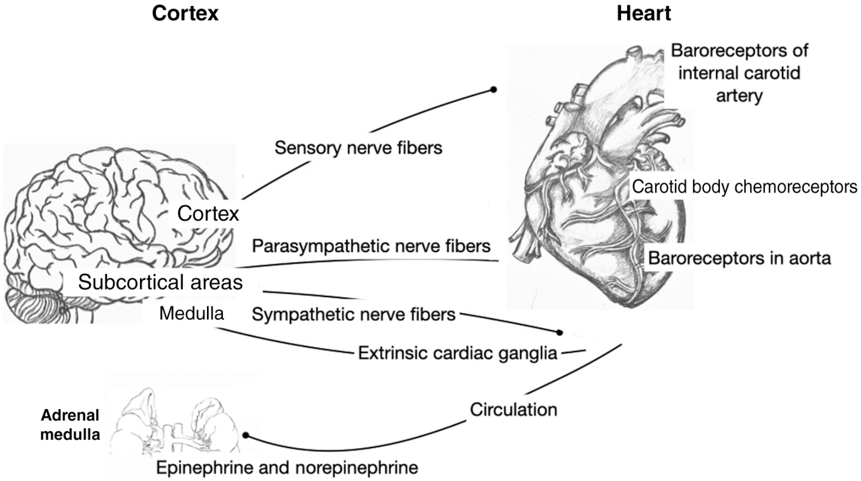

Figure 5 — The connection between brain and heart and the involvement of the medullary portion of adrenal glands.

activity in parasympathetic source nuclei and via an indirect pathway can inhibit the rostral ventrolateral medulla (VLM), which is a major descending source of tonic drive on the sympathetic output neurons of the intermediolateral cell column. More specifically, there is a mutually interconnected network between the NTS and PVN, central component of the stress system as it releases the corticotropin-releasing hormone (CRH). A growing body of research indicates somatosensory afferents (carried by skeletal muscle receptors, baroreceptors, and/or cardiopulmonary receptors) as well as projections from central command neurons have an effect on the cardiovascular response (Ang et al., 2016; Cacioppo et al., 2010; Michelini & Stern, 2009). In addition, higher levels of neural substrates, including neurobehavioral areas of the limbic system and other forebrain areas, can influence (i.e., control, inhibit, or bypass) lower reflex mechanisms that regulate the autonomic balance. For instance, the stress-related suppression of the baroreflex is mediated by rostral neurobehavioral systems (Cacioppo et al., 2010). Growing evidence indicates that not only somatosensory afferents (carried by skeletal muscle receptors, baroreceptors, and/or cardiopulmonary receptors) but also projections from central command neurons have an effect on the cardiovascular response (Ang et al., 2016; Cacioppo et al., 2010; Michelini & Stern, 2009). Furthermore, higher levels of the neuraxis, including neurobehavioral substrates of the limbic system and other forebrain areas, can control, inhibit, or even bypass lower reflex mechanisms in the regulation of autonomic outflows. An example is the stress-related suppression of the baroreflex, which is mediated by rostral neurobehavioral systems (Cacioppo et al., 2010). Moreover, the higher neural autonomic controls are far more flexible and variable than brainstem reflex substrates. There are ample routes by which higher behavioral substrates can impact autonomic cardiovascular regulation. For instance, positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) studies have reported that a mental arithmetic, a Stroop-stress paradigm, or emotional contexts engage several forebrain areas that have been implicated in psychological processes and autonomic control, including the cingulate cortex, orbitofrontal cortex, insular cortex, and medial and dorsolateral prefrontal cortex, as well as related areas such as the hypothalamus, amygdala, and cerebellum (Gianaros et al., 2005; Matthews et al., 2004; van der Veen et al., 2014). In addition, these studies found that the magnitude of cardiovascular responses (blood pressure and HR) was significantly related to the magnitude of activation in specific brain regions (Cacioppo et al., 2010).

HR Variability

HRV analysis begins with construction of a series of successive electrocardiographic R-wave time intervals (RR intervals) yielding tachograms (ectopic beats, compensatory pauses, artifacts, and noise must be excluded). HRV can be evaluated with different methods. Among the most common, there are the analysis in the frequency domain, or analysis of the power spectral density, and the analysis in the time domain (Cacioppo et al., 2010; Moraes et al., 2018; Valderrama et al., 2010; Figure 6).

The high-frequency (HF) band is included within the frequency ranges of 0.15–0.4 Hz and reflects the activity of the PANS. It is also called the respiratory band as it reflects changes in HR related to RSA. A reduction in parasympathetic activity was found in patients suffering from heart disease, under stress, or suffering from panic attacks, anxiety, or worries (Berntson et al., 1993; Bhoja et al., 2020).

The low-frequency (LF) band corresponds to the range of 0.04–0.15 Hz. This region is called the "baroreceptor range." The latter are mechanoreceptors and are sensitive to pressure variations. They are located inside the atria and ventricles, carotid sinuses, and aortic arch. Normally, the baroreceptors are tonically active, but, in correspondence with an increase in pressure, they generate action potentials with greater frequency. The activation of the baroreceptors determines the inhibition of the SANS and the activation of the PANS. This leads to a decrease in blood pressure. In fact, the inhibition of SANS decreases peripheral vascular resistance, and, therefore, decreases the frequency and contractility as well. Instead, the opposite effect occurs when the pressure decreases (Berntson et al., 1993; Bhoja et al., 2020). In the LF band, there are both the activities of the SANS and of the PANS. In correspondence with physical activity or psychological stress, the oscillations fall back into the LF band and generally do not exceed 0.1 Hz. Hence, during meditation or the following of slow breathing, parasympathetic activity generates oscillations that fall back into the LF band (Berntson et al., 1993; Bhoja et al., 2020).

The ratio of LF to HF power is called the LF/HF ratio. The interpretation of the LF/HF ratio is controversial (Shaffer et al., 2014). However, once the mechanisms are understood as well as the importance of the recording context (i.e., ambulatory vs. resting conditions and normal vs. paced breathing), the controversy is resolved. The power in the LF band can be influenced by vagal, sympathetic, and baroreflex mechanisms depending on the context, whereas HF power is produced by the

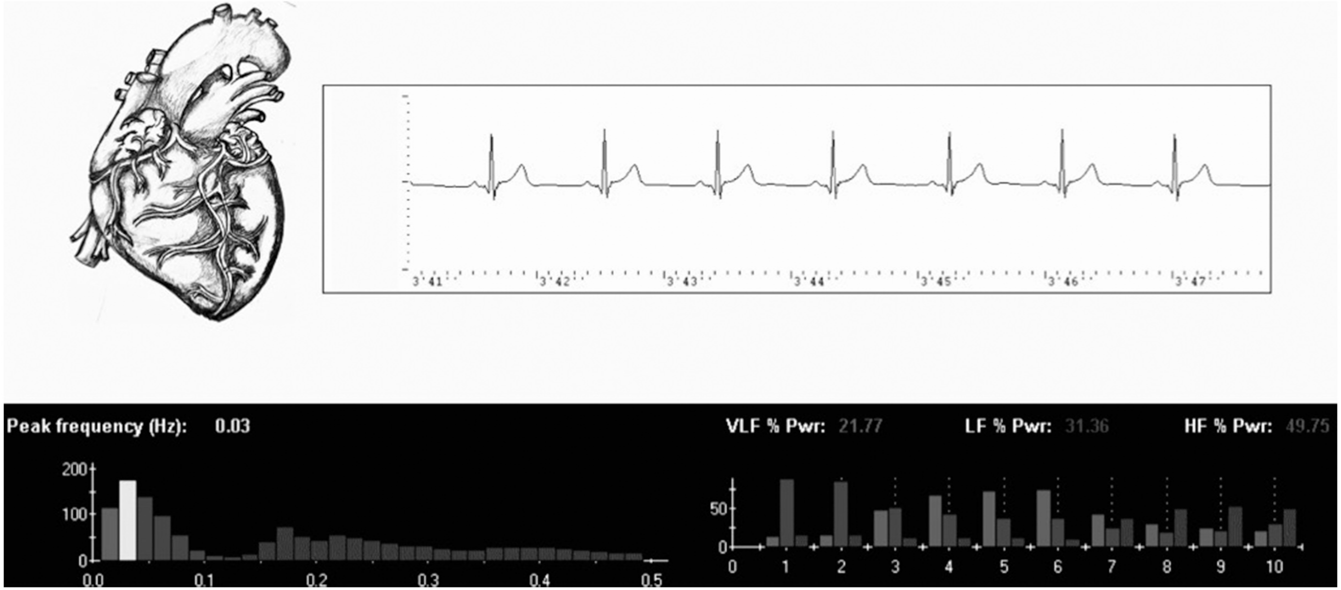

Figure 6 — HRV analysis. The figure shows an example of frequency domain analysis. Name of the Product: BioGraph Infiniti (SA7900); Thought Technology Ltd. VLF = very LF; LF=low frequency; HF=high frequency.

efferent vagal activity due to respiratory activity. In accordance with the recent psychophysiological literature, low LF/HF ratio reflects the parasympathetic activity due to energy conservation and engaging in "tend-and-befriend" behaviors. Therefore, the LF/HF ratio should be interpreted with caution because is often shifted due to reductions in LF power. In contrast, a high LF/HF ratio may indicate higher sympathetic activity and that the subject primarily presents "fight-or-flight-behaviors" (An et al., 2020; Bhoja et al., 2020; Berntson et al., 1997; Ernst, 2017; Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). Again, the same cautions must be taken into consideration, especially in short-term recordings (Shaffer et al., 2014).

The very LF (VLF) band is in the 0.0033–0.04 Hz frequency range. Long-term regulatory mechanisms such as thermoregulation, the renin–angiotensin system, and humoral factors (rumination and worry) can contribute to this band. An increase in the power of this band could reflect an augmentation in SANS activity. The oscillations present within the VLF band by the SANS can cause them to cross over within the LF band due to physical activity, stress, or other factors (Forte et al., 2019).

The ultra LF (ULF) band falls below the 0.0033 Hz frequency. The fluctuations in heart rhythms within this band are mainly due to circadian fluctuations. They can also be affected by very slow adjustments, such as body temperature regulation, metabolism, and the renin–angiotensin system (Forte et al., 2019).

The time-domain analysis provides indices that quantify the autonomic dynamics or determine the oscillatory activity generated by the various physiological control systems. The main indices that are calculated are standard deviation of NN (SDNN), SDNN index, root mean square of successive differences between normal heartbeats (RMSSD), proportion of NN50 divided by the total number of NN (R-R) intervals (pNN50), and average of the difference between the maximum heart rate and its minimum (HR_Max-HR_Min) (Buchheit, 2014; Cosentino et al., 2018; Penttila et al., 2001; Plews et al., 2013).

Defined as the clinical index of HRV, the SDNN parameter provides the *SD* of the normal IBIs (NN), measured in milliseconds, and reflects the influence of all the factors that contribute to HRV. Furthermore, it allows one to classify a "systemic" state of health. Considering the SDNN index, this parameter is obtained in the 24-hr acquisitions and is the average of the SDNN.

Another index is the RMSSD that is the root of the mean squared sum of the differences between successive NN beats. It is the most used metric to determine the basic recovery of HRV, and, therefore, PANS activity (HF band).

Moreover, pNN50 represents the percentage of adjacent normal beats that differ from each other by 50 ms and is correlated with the RMSSD and the power in the HF band.

Finally, HR_Max-HR_Min is calculated as the average of the difference between the maximum and minimum of HR in each respiratory cycle and is highly correlated with the SDNN and RMSSD measurements (Buchheit, 2014; Cosentino et al., 2018; Penttila et al., 2001; Plews et al., 2013).

Likely, the HR also for the various HRV indices interesting aspects related to cognitive domains emerges. For instance, low LF, which is influenced by both sympathetic and parasympathetic branches of ANS, is linked to worse cognitive performance, in particular, considering memory, language, and global cognitive scores (Frewen et al., 2013), while high HFs are associated with better verbal reasoning ability. On the other hand, lower HF, which reflects vagal modulation, appears to be associated with weaker performance in global cognitive functions, such as those measured by the Mini-Mental State Examination (Kim et al., 2006), verbal reasoning abilities (Solernó et al., 2012), inhibition of memory responses (Gillie et al., 2014), or executive functions (Colzato & Steenbergen, 2017; Mahinrad et al., 2016; Mann et al., 2015). These results can be due to the lateralization of autonomic functions (Melis & Van Boxtel, 2001): In particular, sympathetic activation is related to visual and motor cortices, while parasympathetic activation is linked to the activity of prefrontal areas (Forte et al., 2019).

Thus, in conclusion, the analysis in the frequency domain and the analysis in the time domain are the most common methods in the field of applied psychophysiology in clinical and sports fields, as indicated by Cacioppo et al. (2010), Valderrama et al. (2010), and Moraes et al. (2018). However, it is important to mention that a recent line of research is starting to apply nonlinear measures of HRV that provide new opportunities to monitor cardiac autonomic regulation (we refer directly to the systematic review of Gronwald and Hoos (2020) for an in-depth analysis).

Acquisition of HR/HRV at Rest

Since the activity of the ANS is highly sensitive to environmental conditions (e.g., noise, lights, and temperature), it is important to standardize the recording conditions to isolate various artifacts. Recording HR(V) during the night is one of the best conditions, but differences in sleep quality can create misinterpretations. To avoid this, recordings during deep sleep phases (slow-wave sleep [SWS]) are preferred. However, daily activities (e.g., very intense workouts) can affect HRV during the first hours of sleep, when SWSs are greater (Bellenger et al., 2016; Dellal et al., 2012).

At present, the best solution for detecting HRV in rest is a short-term recording (5 min), upon awakening in the morning. The main indices that are taken into consideration are those of the time domain. In particular, both RMSSD and SDNN reflect the modulation of the PANS and are considered reliable markers of the subject's health status (Bellenger et al., 2016; Dellal et al., 2012; Djaoui et al., 2017).

Acquisition of HR/HRV During Exercise

The measurements of cardiovascular changes during training allow one to collect information on training preparation, physical fitness, and fatigue (Buchheit, 2014; Djaoui et al., 2017).

Exercises for a duration of about 3–4 min allow an athlete to reach a stationary situation during an exercise below the maximum, while the following 30–60 s are generally used for HR analysis. Since HR is closely related to VO_2, HR during exercise provides a good marker of exercise intensity for the athlete, because the lower the relative HR (as a percentage) at a given intensity, the higher the fitness level of the athlete. Many teams monitor the cardiovascular fitness index using a protocol that involves a 4- to 5-min run at an intensity under a stationary ceiling (12–14 km/hr). To summarize, HR during exercise is an important tool for monitoring positive adaptations in response to aerobic training (Bellenger et al., 2016; Dellal et al., 2012; Djaoui et al., 2017).

Unlike HR measurement, the analysis of HRV during training is a lesser used parameter, as there is still no scientific evidence to support its usefulness. In fact, HRV measurements during exercise might present several limitations because they would be intensity dependent, environment dependent, and nonexclusively related to the ANS activity (Aubert et al., 2003; Buchheit, 2014; Djaoui et al., 2017). Furthermore, the recording of HRV during exercise presents some limitations with the technical problems related to the nonstationary signals and the "noise" in the recordings caused by the belt movement (Aubert et al., 2003; Buchheit, 2014; Djaoui et al., 2017). Therefore, during exercise, HRV monitoring presents too many limitations to be a relevant tool for practitioners on the field.

Acquisition of HR/HRV Postexercise

Postexercise HR and postexercise HRV are the measures that can be recorded and analyzed after training and help to describe the levels of fitness or cardiovascular fatigue.

Postexercise HR or HR recovery (HRR) reflects various hemodynamic adjustments in relation to body position, pressure adjustments, and metaboreflex activity. It causes a decrease in the activity of the SANS and a reactivation of the PANS (Djaoui et al., 2017; Shetler et al., 2001).

HRR is a parameter that indicates, in percentages, how much HR decreases after exercise, so it reflects the interaction between the activation of the PANS and the decrease of the SANS (Bellenger et al., 2016). This condition also depends on the degree of training of the subject: The more a subject is trained, the shorter the time with which the HR decreases.

It is important to be aware that HRR is influenced by several factors, such as the intensity of exercise, type and duration of exercise, rules or instructions of exercise, and environmental factors. Indeed, high intensity will induce a high HR that is achieved by the end of exercising and, therefore, will most likely create a larger decrease in HR (Djaoui et al., 2017; Seiler et al., 2007). Training involving intermittent exercise leads to a faster HRR compared with continuous exercise training via long term-induced adaptation (Djaoui et al., 2017; Seiler et al., 2007). Finally, it was observed that practicing in the heat increases vasodilatation and consequently causes an increase in HR. Therefore, HRR was found to be slower in high ambient temperature than in moderate conditions (Djaoui et al., 2017; Kilgour et al., 1993).

The factors that determine HRV postexercise are different depending on the regulation of blood pressure, activity of baroreceptors, and metaboreflex activity following exercise. Different factors cause a decrease in sympathetic activity and a reactivation/increase of the parasympathetic activity (Djaoui et al., 2017). Furthermore, cardiac parasympathetic activity is known to be influenced by the duration and intensity of exercise, age, gender, baseline physical fitness, training status, psychological status, central fatigue, and fluid intake (Djaoui et al., 2017; Stanley et al., 2013).

Very high-intensity exercises (above VT2: anaerobic threshold >4 mmol of lactate) cause a minor decrease in HRR and vagal activity related to HRV. In fact, to verify the true influence of postexercise HRV, low/moderate-intensity activity (below ventilatory (VT1): aerobic threshold <4 mmol of lactate) is to be preferred

(Bellenger et al., 2016). For these reasons, HRR and HRV are typically both measured and used to rate postexercise cardiodeceleration. Precisely in this regard, Javorka et al. (2002) found that cardiodeceleration rate (HRR) is independent of HRV measures during the rest period but is related to early postexercise recovery HRV. The authors concluded assuming that these data confirm the parasympathetic contribution of HRR during the specific phase of recovery.

Acquisition of HR/HRV During a Psychophysiological Stress Profile

The severity/intensity of stress can be defined through a psychophysiological assessment (Cacioppo et al., 2010). One of the most used procedures is the psychophysiological stress profile (PSP; De Vincenzo et al., 2022; Fuller, 1979; Pruneti & Guidotti, 2022; Pruneti et al., 2010, 2011, 2021, 2022) that allows the detection of the physiological indices linked to the activation of the ANS and to the complex system involved with the stress response, as defined by Selye's GAS. Several psychophysiological parameters are usually registered during a PSP, and the most frequently used are as follows: surface electromyography of the frontal muscle (sEMG); HR, IBI, and HRV; peripheral temperature (PT); and skin conductance level and response (SCL/SCR; Kim et al., 2019; Pruneti et al., 2014, 2016; Schiweck et al., 2019). PSP is generally divided in three continuative phases: registration at rest; stress presentation; and recovery. While in the first (rest) and last (recovery) phases, the basal autonomic activity is detected and recorded, and in the halfway phase (stress), the physiological response is elicited through asking the individual to perform a mental task. The principal aim of the PSP is to verify how far the psychophysiological balance seems to be maladaptive, utilizing the observations from one or more parameters: level of autonomic nervous activation in the rest phase; stress-induced arousal in one or more parameters during the stress phase; and restoration of the values of one or more parameters in the recovery phase. In general, it provides information to highlight conditions of neurovegetative hyperactivation (typical of the alarm and resistance phases of the GAS, as in anxiety disorders; Clemente-Suárez et al., 2022; Hoehn et al., 1997; Kim et al., 2019; Lin et al., 2022; Pruneti et al., 2014, 2016; Schiweck et al., 2019) or, on the contrary, psychophysiological hypoactivation with signs of autonomic unbalance (typical of a prolonged exhaustion phase of the GAS, as in depressive, obsessive, and eating disorders; Kim et al., 2019; Pruneti et al., 2014, 2016, 2022; Schiweck et al., 2019). For instance, values are considered normal at rest if they fall between 1.7 and 2.5 μV for sEMG, 2.2 and 6 μS for SCL, 31 and 32 °C for PT, 60 and 90 bpm for HR, and 1.2 and 2 value for HF/LF ratio of HRV (Cacioppo et al., 2010). Fuller's protocol (Fuller, 1979) allows to describe the stress response by simulating the presence of stress capable of altering the psychophysical balance of the individual. This tool is useful for the assessment of all the stress-related disorders of mind–body integration (psychosomatic and somatopsychic) both in the context of clinical, hospital, and sport psychology because it provides useful information in the diagnostic evaluation phase, and it can be used as an outcome measure of the efficacy of any treatment implemented. More specifically, the common procedures for acquiring physiological measures, including HR and HRV, in the clinical setting (to delineate the PSP and/or record these parameters before and/or after exercise) require the recording to take place in a dedicated room, silent, and with a temperature between 18 and 22 °C. The chair must be comfortable because subjects are invited to sit and keep their knees at an angle of 90°, hands on thighs with palms facing upward, and eyes closed. The three ECG electrodes (two on the left forearm and one on the right forearm) are applied after cleaning the skin with an alcohol-soaked cloth. In case HR and HRV need to be recorded during physical activity, the physiological recording device must be wearable ECG devices. For instance, Kubios HRV Premium (version 3.2.0; Kubios Oy Limited) and BioGraph Infiniti (T7900, Thought Technology Ltd.) are suitable for this purpose.

However, some aspects related to the practical implementation must be considered. More specifically, it should be noted that HRV analysis (both for the evaluation phase and for the biofeedback training) can be influenced by different factors (such as age, gender, ethnicity, physical fitness, health status, body composition, use of alcohol, tobacco, illicit drugs, and medicine in regular use) as well as physiological conditions (i.e., circadian rhythms, sleep cycle, core body temperature, and metabolism), environment (noise, temperature, humidity, and the time of the day), contextual factors (recording method, sampling frequency, recording period length, and removal of artifacts), influences of body position, breathing mechanics and movement, recent physical activity, and so forth. To summarize, the HRV recording needs to be conducted by specialized personnel that can accurately describe the individual's medical history, focusing on (1) general clinical data; (2) previous medical tests (i.e., laboratory tests, electrocardiogram, etc.), comorbidities, and medications (dosage and duration); (3) any clinical complaints and the symptoms' history; (4) any recent illnesses, hospitalization, or surgeries; and (5) aerobic functional capacity, habit lifestyle, and stress levels (regarding the different areas of life); and (6) family history (cardiovascular, pulmonary, metabolic diseases, etc.) (Catai et al., 2020).

All methods and conditions have advantages and disadvantages, with different determinants and adaptation times. The appropriate combination and data collection can be decisive for improving the training process. It is possible to collect HRV measures in various locations (i.e., research laboratories, hospital environments, and external and occupational work environments, offices and residences, etc.). Various aspects should be considered in order to accurately collect the data, such as the environment and the volunteer's familiarization with the site, procedures, equipment, and previous preparation of the patient/client (Catai et al., 2020). Just to give an idea regarding the interpretation of the data collected, research and clinicians usually refer to the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (1996) guidelines, updated by Nunan et al. (2010). For instance, HR and HRV values provided by BioGraph Infiniti (Thought Technology Ltd) of a trained subject's psychophysiological assessment (at rest, under induced stress, and during the following recovery phase) are shown in Table 1.

Clinical Psychophysiology of Stress in Athletes

Acute Stress

The activity of the ANS varies throughout the day in response to different stimuli (e.g., training). In general, high-intensity physical exercise (VO_2max) causes a

Table 1 **HR and HRV Values of a Trained Subject at Rest and Under Induced Stress (Report of a Personal Event)**

Frequency domain	Baseline	Under stress	Recovery
HR mean (beats/min)	51.59	73.54	68.15
HR standard deviation	2.91	28.92	27.76
HR peak frequency mean (Hz)	0.18	0.17	0.08
VLF% power mean	13.18	8.88	24.41
LF% power mean	11.97	23.67	26.9
HF% power mean	57.01	53.17	40.68
VLF total power mean	107.84	1531.78	2313
LF total power mean	77.33	4171.48	2668.38
HF total power mean	350.50	9887.92	4520.26
LF/HF ratio	0.22	0.42	0.59

Note. HR = heart rate; HRV = heart rate variability; VLF = very low frequency; LF = low frequency; HF = high frequency.

decrease in the vagal activity of the HRV indices for a period ranging from 24 to 48 hr. This phenomenon is due to the signal of restoration of homeostasis (Djaoui et al., 2017; Stanley et al., 2013). Therefore, HRV can be used as a guiding parameter for training plans despite the affects of the environmental conditions and state of hydration. For example, an intense training in a warm environment increases the vagal HRV indices in the 24 hr after, although there is a decrease in the well-being of the athletes. Furthermore, in the 2005 “Marathon Des Sables” (Sahara Marathon), an intense run in extreme conditions (even temperatures of 50 °C), there was an initial decrease in vagal indices for the first 3 days and an increase in parasympathetic activity even though there was a presence of increased fatigue. This is due to the fact that the plasma volume increases as a response to training (mainly aerobic) but also from acclimatization, which tends to increase the RR (HRV beat–beat) (Buchheit & Laursen, 2013). HRV and HRR undergo variations in response to training loads. Generally, moderate-intensity exercise is associated with increases in vagal response, while intense exercise is associated with a decrease in vagal responses. Moreover, in professional athletes, interesting aspects associated with the period in which the detection is carried out have been described: increase and improvement in the vagal response during the first phase of training while, as the date of the race approaches, the opposite effect observed (Buchheit & Laursen, 2013).

Chronic Stress

There is evidence to support the usefulness of the HRV during rest days, that is, days without any training or competition (Djaoui et al., 2017). In fact, even if the players are not training, the cardiac ANS and neuromuscular complexes are still stimulated during the recovery process. In particular, after exercise, in the short-term perspective (0–90 min), metaboreflex stimulation predominates, while in the long-term perspective (1–48 hr), baroreflex stimulation influences parasympathetic reactivation (Djaoui et al., 2017; Porges, 2007, 2021, 2022; Stanley et al., 2013). Furthermore, it has been observed that the HR marker increases during sleep when individuals are overtrained (Achten & Jeukendrup, 2003; Djaoui et al., 2017).

Overtraining is considered to be a training imbalance that occurs when the physical activity practiced is too intense in terms of volumes and intensity to the point that the body is unable to eliminate the accumulated fatigue during the recovery time period. This adaptive imbalance causes a continuous state of psychophysical stress, which culminates in staleness syndrome (refusal to train), damaging athletic performance and making the body more vulnerable to possible infections (Brooks & Carter, 2013; Kajaia et al., 2017).

Mourot et al. (2004) conducted a study with the intention of investigating the use of this parameter by involving control subjects (sedentary), trained subjects (regular physical activity for at least 3 years), and subjects with OTS. Subjects with OTS suffered from chronic fatigue, muscle pain, sleep disturbances, depression, irritability, loss of memory and concentration, loss of coordination, and increased susceptibility to the infections. In this study, it emerged that the subjects with OTS, compared with the group of trained subjects, showed significantly different values, both in the time domain and frequency domain. The overtrained athletes had a marked predominance of sympathetic activity when compared with trained athletes and sedentary persons, with less marked changes in HRV with respect to healthy athletes.

Similar results had already been described in 2000 by Hedelin et al. involving nine elite canoeists. The athletes were investigated concerning changes in performance, HRV, and blood chemical parameters over a 6-day training camp (Hedelin et al., 2000). The training regimen consisted of cross-country skiing and strength training with a 50% increase in training load. The authors found that the reduced maximal performance indicates a state of fatigue/overreaching. Furthermore, reduced submaximal HRs are probably a result of increased plasma volume. Finally, HRV did not seem to be affected by short-term overtraining.

More recently, Kajaia et al. (2017) compared the functioning of ANS, measured with HRV at rest, in athletes with NFO and OTS and without NFO/OTS. The results showed that NFO athletes had lower HRV and lower vagal influence, along with greater sympathetic cardiovascular control. This aspect emerged even more pronounced in athletes with OTS when compared to highly trained athletes without NFO/OTS. Sympathetic dominance in NFO athletes, as well as in those with OTS, is considered a sign of physical or mental fatigue and chronic stress due to low parasympathetic activity, which is not conducive or favorable. Furthermore, the total autonomic dystonia has been described in 67% of athletes with OTS: This reflects a more advanced stage of maladjustment associated with a depressed regulatory function of the ANS. It is, therefore, considered useful to use HRV in order to detect NFO and OTS situations for psychophysical balance and, therefore, optimize the athlete's training program.

Optimizing training implicates that one must manipulate the level of stress together with recovery skills, favoring an increase in the athlete's performance. When the balance between stress and recovery is not adequate, symptoms attributable to overtraining may occur (Djaoui et al., 2017; Manresa-Rocamora et al., 2021). Establishing markers that allow one to monitor the athlete's physiological situation has become increasingly important. Repeated exposure to stress induced by training requires continuous responses from the body to maintain homeostasis (Djaoui et al., 2017; Düking et al., 2021).

Several methods are used to evaluate changes in the ANS, such as examining the response of the ANS because it indicates the body's ability to tolerate or adapt adequately to a stimulus. HRV could be a good indicator for the various phases of training: HRV at rest, HRV during and after exercise, HR at rest, HR during exercise, and HR postworkout recovery (HRR; Djaoui et al., 2017; Figure 7).

HRV-Biofeedback Training

Biofeedback training (BFB) is a form of operant conditioning that aims to train individuals to be able to recognize their physiological activity in real time (Fuller, 1979).

First, a clinical–psychophysiological evaluation is carried out. Specifically, a PSP is useful to detect any physiological parameter that might require further investigation (i.e., the sEMG in the case of tension-type headache [TTH]). Subsequently, auditory and/or visual feedback methods can be implemented, which provide the subject with information on physiological functions that are not subject to conscious control, including HRV. Therefore, following the training,

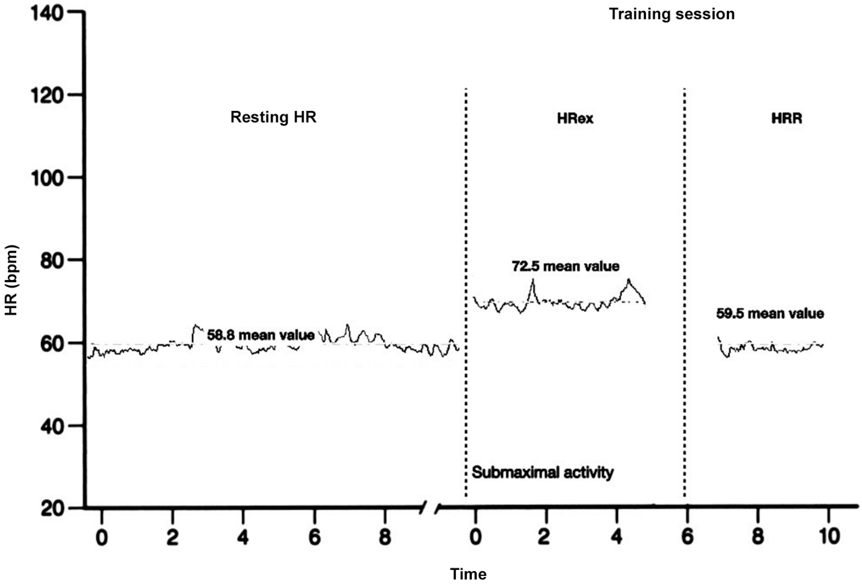

Figure 7 — Trend of HR(V) during the day of an athlete: Just awake, during a submaximal race (VT1), post training. HR = heart rate; HRR = heart rate recovery over 60 s; HRV = heart rate variability; HRex = heart rate during exercise; VT = ventilatory threshold.

the person acquires greater awareness about the different activation states of the ANS (Jiménez Morgan et al., 2017). The HRV-BFB provides easy-to-interpret information about ANS modulation. It produces synchronization between the SANS and PANS and moderates the heightened sympathetic activity to achieve a relaxed state of mind. For instance, in an HRV-BFB training session, the HRV is recorded and analyzed in real time. Similar to the procedures for acquiring HR and HRV in the evaluation phase, also for the BFB it is necessary that the training takes place in a dedicated and silent room with a temperature of between 18 and 22°C. The chair must be comfortable so that the ECG electrodes or a finger sensor that uses photoplethysmography can be connected and the person can comfortably see the BFB monitor. For instance, emWave2 (HeartMath), BioGraph Infiniti (Thought Technology Ltd.), and HRV4Biofeedback (HRV4Training) are few examples of software that can be useful to capture, process, and interpret HRV, which, moreover, autonomously eliminate the artifacts. Kubios HRV 2.0 is one of the most common software used to collected and analyze data (Tarvainen et al., 2014). These kinds of software enable computation of single segment power spectra via Fast Fourier Transform (FFT) and then calculate the averages to yield the mean Total HRV, LF, and HF. Additionally, the index of coherence (IC = [LF/HF − 1.75]/[LF/HF + 1.75]) is usually calculated and considered an immediate index of the state of sympathovagal balance. One of the software that provides the representation of IC to customers is the Inner Balance application (HeartMath, LLC; McCraty, 2016). This program shows the IC as a percentage of time in either high, medium, or low coherence. A green box indicates the percent of time during which subjects are in a high coherence state, a blue box indicates the percent of time that patients are in a medium coherence state, and a red box indicates percent of time of incoherency, meaning increased stress. In summary, these boxes represent 100% of the time (Dziembowska et al., 2016; Paul et al., 2012).

In other cases, such as the programs provided by BioGraph Infiniti (Thought Technology Ltd.), subjects can receive a feedback in real time regarding HF, LF, and VLF values in the form of a visual and/or auditory signal such as images that progressively color as the client reaches lower and lower states of physiological activation (Figure 8).

HRV-BFB interventions are typically delivered following Lehrer et al. (2000) resonance frequency model and methods of deep, rhythmic, and abdominal breathing to achieve one's resonant frequency, or breathing pace cycle that most amplifies the response in vagal tone (Lehrer et al., 2020; Pagaduan et al., 2020). Six breaths per minute (4 s of inspiration, 6 s of expiration) concentrate the frequency at approximately 0.1 Hz. High-amplitude oscillations in the heart rate are elicited when individuals breathe at their resonant frequency, thus, respiratory effects on the heart rate are modulated by the baroreflex closed-loop system (Lehrer et al., 2003). An HRV-BFB breathing intervention shows significant effectiveness and increases in resting baroreflex gain across 10 sessions (Lehrer et al., 2003). A minimum of 4 hr has been established to effectively learn the HRV-BFB techniques (Karavidas et al., 2007), while more recent studies show a minimum of five sessions to improve emotional regulation in elite support staff (Gross et al., 2018).

With this in mind, it is possible to consider the stress as a multifaceted construct and composed of different aspects such as emotional–psychophysiological, cognitive, and behavioral. In this review, we have analyzed studies with different

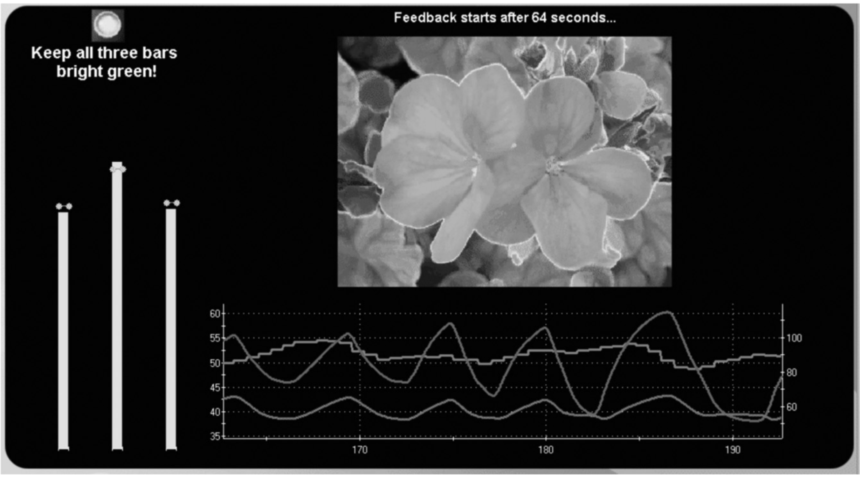

Figure 8 — HRV-biofeedback training (power and animation). Screens are scheduled for raise the LF band of the HRV spectrum while decreasing the VLF and HF bands. The three bar charts on the left are configured to automatically follow these values. At the bottom right, it can be seen the variations over time for each frequency band. Name of the Product: BioGraph Infiniti (SA7900); Thought Technology Ltd. LF = low frequency; HF = high frequency; VLF = very LF; HRV = heart rate variability.

types of outcomes. Considering that OTS causes a worsening on a cognitive, emotional, and motor level, it was considered important to summarize the emotional–psychophysiological symptoms of athletes as well as their motor and cognitive performance. In particular, research that investigated a decrease in HRV and/or in other measures of subjective distress, such as anxiety or depression (with tests such as State and Trait Anxiety Inventory [STAI] and Beck Depression Inventory [BDI]), has been assessed. Moreover, in order to include an indirect measure of cognitive and behavioral efficiency studies that measured the athlete's performance have been included.

Several studies have seen how HRV-BFB can have positive effects in reducing symptoms such as depression and anxiety (Lehrer & Gevirtz, 2014; Saito et al., 2021; Schäfer et al., 2018), and many other studies have highlighted its clinical efficacy. Especially in the rehabilitation field, the HRV-BFB techniques have been applied with poststroke patients (Spencer et al., 2021), patients with traumatic brain injury (Wearne et al., 2021), and when treating patients with organic diseases, such as asthma (Taghizadeh et al., 2019) and dysmenorrhea (Vagedes et al., 2019).

However, within the past two decades, very few studies in the literature have applied HRV-BFB to a sample of athletes or on the effects on sports performance (Gross et al., 2018; Karavidas et al., 2007; Laborde et al., 2022; Lehrer & Gevirtz, 2014; Lehrer et al., 2003; Saito et al., 2021).

One of the few studies that took into consideration the emotional–psychophysiological structure of the athletes and investigated the presence of anxious symptoms is by Paul and Garg (2012). The authors divided basketball players who scored a minimum of 20 in STAI in three groups: control, placebo (with visualization of motivational video clips), and experimental. In the latter group, athletes were subjected to sessions of HRV-BFB (for 10 consecutive days for 20 min). This included breathing at individual's resonant frequency (respecting the protocol of Lehrer et al., 2000) and visualizing a pacing stimulus, which is a light display that moved up and down on the computer screen at the target respiratory rate. The results of this study showed that the experimental group reported a significant reduction in anxiety in both the state and trait scales when compared with the placebo and control group, maintaining this benefit even at a distance of 1 month to follow-up. Psychophysiological benefits have also been described as follows: a greater activity of the parasympathetic branch emerged during the registration at rest. Another interesting aspect concerns the improvement in self-efficacy scores (measured by Coping Self-Efficacy Scale [CSES]). This aspect is particularly useful in an athlete as it favors the learning process linked to the ability to relax. The fact that a decrease in anxiety, both at the cognitive–behavioral and at the psychophysiological level, is associated with an increase in self-efficacy that underlines how the promotion of self-confidence is indirectly, but significantly, promoted by a BFB intervention. Furthermore, the improvement in sports performance (measured by dribbling, passing, and shooting tests) confirmed other studies already present in the literature involving wrestlers, dancers, baseball players, and golfers (Lagos et al., 2008; Raymond et al., 2005; Strack, 2003). This aspect could be attributed to the HRV-BFB procedure that causes resonance in the cardiovascular system and provides an athlete with a better ability to manage anxiety, which can be used during times of stress such as training and matches. In particular, the trend of scores on basketball performance tests, including dribbling and passing, is interesting. Although significant pre- and posttraining improvements were observed on all three groups, only the experimental group maintained and further increased their performance 1 month after the end of the intervention. This aspect underlines how the self-regulation processes can nourish themselves and favor the achievement of the "state of flow" of the mind, which is essential for maximum performance (Jordanova & Demerdzieva, 2010).

Paul et al. (2012) replicated this last study with the same research protocol also involving basketball players. They confirmed a significant improvement at the psychophysiological (HRV increases and respiratory rate decreases) level as well as motor performance (shooting test). At a cognitive level, significant ameliorations were observed in the response time (both for reaction time and for movement time) and concentration tasks (assessed by a concentration grid). These results confirm the strong interconnection between cognitive functions and autonomic arousal (Forte et al., 2019; Pruneti et al., 2021) and provide promising results on the interventional level, highlighting that it is possible to intervene on a better management of stress and arousal also to improve efficiency of attentional functionality. Finally, a better efficiency of the attentional functions, such as the frontal–executive one focusing on concentration, and improving the speed of information processing and decision making, is particularly useful for athletes.

Dziembowska et al. (2016) obtained parallel results. These authors involved 41 basketball and soccer players, aged between 16 and 22 years old, and subjected them to 10 HRV-BFB sessions lasting 20 min. An improvement was described both on a cognitive–behavioral and emotional–psychophysiological levels. In particular, significant pre- and posttraining differences emerged both in the value of HRV and in STAI.

Another interesting study was conducted by Rijken et al. (2016), who tested the effectiveness of an HRV-BFB training (3-min sessions three times a day and 6 days/week), supported by a mental coaching program (four meetings of 2.5 hr) involving soccer players. In this pilot study, an improvement in the HF/LF ratio was also matched by a significant increase in the perceived level of emotional stability and attentional efficiency, investigated with the Sports Improvement Measurement-60 test. An increase, albeit not significant, was detected in the performance level, indicating that a better management of the arousal level can, in some way, affect the athlete's performance abilities.

Although HRV-BFB is often associated with breathing exercises (Lehrer et al. 2020), in a very recent study by Laborde et al. (2022), the aim of the study was to distinguish the effects of slow-paced breathing (SPB) with HRV-BFB in order to identify the factor to attribute greater efficacy.

In line with the only previous study (Wells et al., 2012), the author found that the physiological effects of SPB, linked to the activation of the vagus nerve (Gerritsen & Band, 2018; Zaccaro et al., 2018), potentially via the stimulation of the baroreflex (Lehrer & Gevirtz, 2014; Shaffer & Meehan, 2020), the action on pulmonary afferents (Noble & Hochman, 2019), and the creation of brain oscillations (Mather & Thayer, 2018), are not influenced by the presentation of the HR signal as BFB. Nevertheless, another interesting aspect was included. Regarding the self-report variables, a significant difference emerged between the two groups regarding the positive valence (investigated with the self-assessment manikin of Bradley & Lang, 1994): Athletes subjected to SPB, together with HRV-BFB, scored higher on this scale. This could be attributed to the positive reinforcement (Frank et al., 2010) and the increase in self-efficacy BFB (Fox et al., 2021; Nestoriuc & Martin, 2007).

In order to provide further validation of the effectiveness of HRV-BFB, the need to conduct other studies and enrich the scientific literature emerges. At the time, the need for a multidimensional assessment emerges strongly as it is necessary to describe the motor and cognitive impact on performance, but, also, the psychophysiological and emotional well-being of a single athlete. With respect to this, the most recent study (Laborde et al., 2022) has underlined the significance of the athlete's experience and of important constructs such as coping and self-efficacy, beyond physical performance.

Conclusions

In this review, we focused on HRV as a useful parameter to measure the level of psychophysical health of athletes. We aimed to analyze the literature, highlighting studies and reviews that made it possible to identify the utility of this parameter when defining the level of mind–body integration and psychophysiological activation. In the literature of the past two decades, there are only few studies aimed at evaluating its effectiveness for rehabilitation purposes. The literature focused more on the possible application within the sports field by examining studies that involved athletes and subjected to HRV-BFB.

The research analyzed has evaluated the effectiveness of this training in both primary and secondary prevention interventions. The need to educate sportsmen to better emotional management is emerging and has a double objective: to favor an optimal psychophysical activation, which corresponds to a better cognitive and motor efficiency, and to promote recovery through parasympathetic restoration. The attention is, therefore, aimed precisely at a correct balance of the two branches that can activate and deactivate properly.

Particular attention should be paid to prevent and avoid stress-related disorders in athletes. For this purpose, there are specific psychophysiological indices that allow for clinical detection of NFO and OTS. The HRV recording during a PSP and/or before/during/after exercise can be useful in this case and offer a starting point for BFB training. In the past years, there are few studies that have evaluated its effectiveness in improving athletes' well-being but the results stand in a prospect of promising advantage.

Thus, the need to support the athlete from every point of view emerges and HRV-BFB seems to be a useful method that directly involves emotional, psychophysiological aspects, and, indirectly, cognitive- and motor-behavioral functions.

Acknowledgment

The authors thank Claudia Grimaldi for the hand-drawn images.

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