Review   ⦿ Thieme

Practices and Applications of Heart Rate Variability Monitoring in Endurance Athletes

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ABSTRACT

Heart rate variability reflects fluctuations in the changes in consecutive heartbeats, providing insight into cardiac autonomic function and overall physiological state. Endurance athletes typically demonstrate better cardiac autonomic function than non-athletes, with lower resting heart rates and greater variability. The availability and use of heart rate variability metrics has increased in the broader population and may be particularly useful to endurance athletes. The purpose of this review is to characterize current practices and applications of heart rate variability analysis in endurance athletes. Important considerations for heart rate variability analysis will be discussed, including analysis techniques, monitoring tools, the importance of stationarity of data, body position, timing and duration of the recording window, average heart rate, and sex and age differences. Key factors affecting resting heart rate variability will be discussed, including exercise intensity, duration, modality, overall training load, and lifestyle factors. Training applications will be explored, including heart rate variability-guided training and the identification and monitoring of maladaptive states such as overtraining. Lastly, we will examine some alternative uses of heart rate variability, including during exercise, post-exercise, and for physiological forecasting and predicting performance.

Introduction

Athletes today have access to previously unimaginable amounts and types of data and metrics to inform their training, competition, and recovery practices. In this rapidly evolving landscape of athlete analytics, heart rate variability (HRV) remains one of the most broadly utilized tools, particularly for endurance athletes. Further, the applications and the nuanced interpretation of HRV data continue to evolve and inform athlete practices. While the opportunities for enhancing athletic practices are abundant, so are the potential pitfalls. This review provides a brief overview of HRV in the context of endurance athletes, addresses technical considerations, factors affecting daily HRV, the implementation of HRV-guided training, and alternative and future uses of HRV for athletes.

Definition and physiological basis of HRV

By definition, HRV analysis is done by measuring the beat-by-beat fluctuations of the cardiac rhythm, and assessing the patterns of observed variability over a given time period. This is done through measurement of either R-R intervals (as seen on ECG) or interbeat-intervals of pulse rate. Rather than smoothing the data to obtain the average heart rate (HR), HRV analysis assesses the variability within the sequence of heartbeats. Beat-to-beat variability is a physiological phenomenon that humans have been aware of for hundreds of years, which has been described and explored widely since the early 1970s [1]. The physiological basis of HRV was initially understood as a reflection of an individual's autonomic nervous system (ANS), specifically the sympathetic nervous system (SNS) versus parasympathetic nervous system (PNS), with greater HRV being attributed to increased PNS activity [2]. Crudely stated,

SNS and PNS activity embody, respectively, the "flight or fight" and "rest and digest" responses.

A more nuanced understanding of HRV has emerged, as a phenomenon reflective of complex, non-linear integration of multiple physiological processes including both the intrinsic cardiac nervous system and external regulators such as respiration and blood pressure [3, 4]. Modulation of HR is known to be affected in a non-linear manner by the baroreceptor reflex, which responds to pressure modulations with changes in neural output, classically described as a negative feedback loop, with increased blood pressure leading to rapidly decreasing HR [5, 6].

Respiratory sinus arrhythmia (RSA) is a well-characterized physiological phenomenon, wherein the phases of ventilation and HR interact, with HR slowing during expiration and accelerating with inspiration [7]. Slower respiration with larger tidal volumes increases RSA, and the use of prescribed or "paced" breathing yields different values than measurements taken without paced breathing [8] and is considered a common source of discrepant values in the assessment of HRV [9]. During exercise, coupling (or entrainment) of repetitive movement patterns, such as step rate or cycling cadence, with respiratory rate may occur, complicating the interpretation of HRV due to the effect of respiratory modulating effects [10].

While HRV was previously used extensively in a clinical setting to predict morbidity and mortality [11], a 2003 review paper noted the inconsistent findings and relative dearth of what is known about HRV in athletes [12]. Since that time, HRV has been explored in depth as a means of monitoring training stress and adaptation [13, 14], detecting overtraining [15, 16], as a biofeedback tool [17], and to assess recovery from concussion [18], among other applications. Overall, HRV has been established as a reliable tool that can be useful in monitoring athletes and informing their training practices.

HRV response to exercise

During exercise, cardiac PNS activity decreases (reaching a nadir at 50–60% of VO_2max) and SNS activity increases, driving further increases in HR [19]. In contrast with the original model proposing that complete PNS withdrawal occurs during exercise, a more nuanced understanding suggests a process of reciprocal antagonism between branches, with diminished PNS influences retained [20, 21]. While SNS activity predominates at higher intensities, there is evidence to support the measurable effects of PNS activity even at high intensities of exercise [22].

HRV monitoring for athletes

The use of HRV monitoring for endurance athletes has been studied as far back as the 1990s [23]. Endurance athletes generally exhibit greater resting HRV than healthy controls [24, 25]. This has been observed across a wide range of endurance sports, including rowers, cyclists, Nordic skiers, distance runners [12, 24]. Gradual increases in average HRV appear to correspond with improved aerobic fitness. In a study of distance runners, changes in HRV were correlated with both changes in aerobic capacity and 10-km time [26]. A cross-sectional study of male masters runners also found significant correlations between resting HRV and 10-km race time [27]. In recent years, use of HRV has become more common and

widespread, driven by the ease, availability, and portability of monitoring tools. It is now commonplace for athletes, coaches, and sports medicine staff to collect HRV data, with short-term measurements taken first thing in the day frequently recommended [13]. Given the accessibility of tools and technologies, the use of HRV is likely to become more commonplace. Thus, an understanding of the different measures, techniques, applications, and the complex physiological interactions that produce differing patterns of HRV can help guide this practice and improve interpretation of the data.

Technical considerations

Analysis techniques

The explosion of HRV research in 1980s and early 1990s led to the establishment of the "Task Force" guidelines for standardization of analysis procedures and considerations [2]. The numerous analysis methods have been broadly categorized into time, frequency, and nonlinear domains [28]. While the Task Force Standards focused on the more traditional time and frequency domain measures, a variety of nonlinear methods of HRV analysis have been developed and widely utilized in more recent years [29, 30].

The most commonly utilized time domain measures are the standard deviation of the normal-normal intervals (SDNN) and the root mean square of the successive differences (RMSSD) [28]. In brief, SDNN characterizes the average difference from the mean, whereas RMSSD captures the average difference from the previous interval. Thus, SDNN is a measure of the overall variability of the time series, whereas RMSSD captures short-term variability. Given the more rapid effect of the PNS than the SNS on HR, RMSSD is considered a reflection of PNS activity [9]. Of all the measures of HRV, RMSSD (or the natural log of RMSSD – lnRMSSD) is perhaps the most broadly utilized owing to the its low typical error, ease of calculation, and robustness to differences in respiratory patterns [13].

Frequency domain (or spectral analysis) measures are calculated by transforming the time domain data, most typically through the fast Fourier method, to a frequency spectrum of cycles per second (Hz), reflecting the contribution of various frequencies to the overall variability of the signal [2]. There are typically three peaks observed: Very low frequency (VLF, ≤0.04 Hz), low frequency (LF, 0.04–0.15 Hz), and high frequency HF, 0.15–0.4 Hz). Traditional theory proposed HF power as reflective of PNS activity and LF power as capturing a combination of SNS and PNS activity. This theory has been challenged and the notion of LF/HF as a reflection of sympathovagal balance is likely an oversimplification at best [19, 31]. Spectral analysis may be particularly sensitive to the effects of respiration and ectopic beats, leading some to advocate for the use of ECG and requiring a respiratory rate greater than 10 breaths per minute in order to reliably use these measures in athletes [32].

Nonlinear methods of analysis, including detrended fluctuation analysis (DFA) move beyond traditional means of quantifying variability, attempting to capture the complexity of the time series [29]. Complexity, in brief, refers to the amount of information, across multiple time scales, contained within a system or set of information [29]. Complex systems contain multiple interconnected feedback loops, such that the integrated whole contains proper-

ties that cannot be understood simply through examination of the component parts [28].

Sample entropy (SampEn) measures the relative regularity of the data sequence by quantifying template matches across a data sequence [33]. More frequent matches indicates more regularity, and therefore a lower entropy score, whereas a higher entropy score indicates more irregularity and less predictability in the data sequence [28, 33]. One benefit of SampEn is that it has been shown to be relatively reliable with short time series, though a minimum of 200 data points has been recommended [34].

Detrended fluctuation analysis is a nonlinear technique developed to distinguish between internal fluctuations and external perturbations to the system, making it a preferred method for non-static conditions such as exercise [35]. Patterns of variation across multiple measurement scales of differing window lengths are examined, with local trends subtracted. The scaling exponent α is related to the length of the time window, where α1 indicates short-range correlations and α2 specifies long-term correlations. An α value of 0.5 is indicative of no correlations (random data) and an alpha value of 1.5 is equivalent to highly correlated data. Values of α ~ 1.0 are consistent with complex systems data where self-similarity across time scales is observed. An optimal middle range can make traditional statistical analysis of group data challenging, as initially high and low values may both move toward the middle following training [36].

Monitoring tools

The gold standard of HRV monitoring is through the use of ECG, though chest strap heart rate monitors have been used extensively and have shown high reliability [37]. Pulse rate variability, as measured through photoplethysmography (PPG) has been used increasingly owing to the ease of use [38]. The accuracy of PPG may depend on the tool and condition in which it is used. Watches with embedded PPG have been shown to be relatively accurate at rest [39]. On the other hand, accuracy during exercise depends on the model of watch and type of exercise, with notable increases in error during exercise that is either vigorous or involves arm movement [40]. Similarly, PPG technology embedded in a finger clip pulse oximeter are reliable but prone to artifact when used during movement [41]. Resting measurement of HRV through a finger placed on the camera of a smartphone is another common use of PPG, with high accuracy reported when done according to suggested practices [38]. The ubiquity of smartphones and the ease of use of this technique makes it appealing to a broad population.

Stationarity and body position

Stationarity of data refers to the stability of the state of the individual, such that the mean and standard deviation of the data set remain consistent over the recording period [28]. Resting or steady state exercise data satisfy the definition of stationarity, but data collected in the transition from rest to exercise violates the requirement of stationarity [35]. Stationarity is an important consideration for most HRV measures [28]. A notable exception, DFA, corrects for non-stationarity [35], though the efficacy of this correction has been challenged [42].

Given the sensitivity of HRV measures to physiological state, the need for consistency of data collection procedures is clear. Research on body position during data collection illustrates this. Numerous studies have compared resting HRV in different body positions including supine, seated, and standing [15, 43, 44]. The highest HRV values are typically seen in the supine condition, with decreases in the seated condition and further diminishment in the standing condition. Seated measures have been suggested to be more strongly associated with changes in fitness level than supine measures [45]. Thus, when tracking HRV within an individual, or comparing with population norms, consistency of body position during measurement is a critical consideration.

Timing and duration of recording window

Measurements can be affected by such factors as time of day of the recording and duration of data collection. While 24-hour HRV monitoring has been utilized extensively in clinical and research settings [2], such long-term monitoring may be impractical for athletes. Further, it includes periods of varying activity, and therefore will fluctuate extensively over such an extended window of time [46]. Resting-only measurements of 30 minutes [47] or as short as 5 minutes have been recommended broadly [2] or for athletes in particular [13]. Ultra-short term measurements of one minute have been shown to have acceptable agreement with 5-minute recordings, while 30- and 10-second readings significantly decreased the level of agreement [48].

Time of day may affect HRV measurements. Long-term measurements show the highest levels of HRV during sleep [49]. The lowest levels of HRV are observed during the late morning and early afternoon hours [50]. Thus, use of either overnight readings [51] or at a standardized time of day such as first thing upon waking in the morning [13], are recommended to reduce the confounding effects associated with time of day. Strong correlations have been observed between morning and nocturnal HRV measures in young athletes [52].

Adjustment for average heart rate

Many measures of HRV are reported in time-specific units, often without adjusting for mean HR. In such cases, a mathematical association between HRV and HR exists, with a slower average HR associated with higher HRV values and vice versa [8, 53]. If no adjustment is made for mean HR, the same absolute fluctuation is indicative of a different magnitude of variability, relative to the mean. Unadjusted HRV, accordingly, includes information not only on the variability of the data but also on the mean. Both time and frequency domain – but not nonlinear measures – are affected by this collinearity [33, 35].

Sex and age differences

Population norms and applications in HRV have been described in pediatric and adolescent [54, 55], geriatric [56], and in various clinical populations [57, 58]. A large meta-analysis of healthy individuals including all ages showed higher HR and lower SDNN but greater HF power in women than men [59]. Females were shown to have 7 % higher HF power in the supine condition than males, but experienced a greater magnitude of reductions in HRV with standing [44]. Men peak in LF power in the morning hours, while women do

so in the afternoon [49]. An analysis of data collected through a commercial app found no sex differences on average, but among females HRV was 3.2 % higher during the luteal than follicular phase of the menstrual cycle [60]. The same study found a moderate negative correlation between age and RMSSD. Other studies have found that, with aging, adults decrease in both overall HRV and in magnitude of variation over the course of a 24-hour period [49, 61].

Factors affecting resting HRV

The most widely used application of HRV for athletes, and increasingly among other health-conscious individuals, is the daily HRV measurement. It is typically taken first thing in the morning in order to minimize confounding effects [13], yet some devices alternatively measure nocturnal HRV during sleep, which has the advantage of less potential for influence of extrinsic factors [51]. Previously available only to researchers and the technically savvy, daily HRV can now be monitored at home using a variety of devices, apps, or software. Some of these options provide raw data while others utilize HRV as part of black box algorithms to provide the user with a recovery score or strain score [62]. Popular brands that may be familiar to the general public include Whoop, Apple Watch, Fitbit, and Oura Ring. Many durations and types of measures are utilized by such devices, which can influence the outcome measurements. For the practical purposes of daily monitoring, consistency of measurement for the specific individual is the most important consideration.

Daily monitoring can provide insight into autonomic response to training. Undoubtedly, there are individual differences in HRV response to training, and longitudinal tracking of individual athletes allows greater insight into how these measures are best utilized for the individual [13, 47]. Population differences such as training status, cardiorespiratory fitness, age, sex, and other factors may all affect not only daily HRV readings but also how they respond to different training and lifestyle stimuli. However, some common observations of daily HRV responses can provide a framework for understanding that may help athletes interpret their responses.

Overall training load

Chronic training may lead to increased HRV in athletes, especially where training includes a strong aerobic component as is common practice among endurance athletes [12, 24]. However, acute reductions in daily HRV have been observed in response to heavy training [63–65], and days with decreased morning HRV may indicate a reduced performance ability [66]. Athletes with overtraining syndrome have been shown to exhibit reduced HRV compared to healthy, trained athletes [15]. Plotted against training load, a bell-shaped curve for HF power was observed in marathon runners, indicating high parasympathetic activity at moderate levels of training, and lower levels with both abnormally high and low training loads [67]. Similar suppression of HF power has been observed when tracking elite rowers over the course of a year of training and competition [68]. A study of elite-level French Nordic skiers over four years found suppression of HRV parameters in those tested in a fatigued state, as determined by a validated questionnaire [69]. Those in the fatigued state also exhibited greater intra-subject variance, indicating that HRV response may vary between individuals

in response to fatigue [69]. In a population of middle- and long-distance runners and triathletes, an intensive 2-week training camp induced significant reductions in HRV, which rebounded within 3–4 days of rest [47]. This is consistent with an "over-reached" state, in which a heavy training load temporarily alters autonomic function but is reversible within a few days of reduced training.

Exercise intensity

The intensity of an exercise session appears to have an influence on its impact on HRV measures, either immediately or in some cases the day after exercise. For example, HRV was suppressed in highly trained endurance athletes after exercise above but not below the first ventilatory threshold (VT1), regardless of duration [70]. In the same study, highly trained (national class) athletes returned to baseline more quickly that trained (non-elite) athletes. Similarly, comparing 3,500 m and 7,000 m runs at low (50 % of VO_2max), moderate (63 % of VO_2max), and vigorous (74 % of VO_2max; 3,500 m only) intensity, HRV was higher after the low intensity sessions, regardless of duration [71].

Comparing 30 minutes of exercise at 45 %, 60 %, and 75 % of VO_2max, nocturnal HR was elevated with the higher intensity exercise, but there was no effect on HRV [72]. In a study comparing interval training at 75 and 95 % of VO_2max, the higher intensity interval session led to a suppression of HRV at 1-hour post-exercise, but it returned to baseline within the first 24 hours [73]. A high-intensity interval training session (5-km run in 1-min increments at peak velocity attained during a VO_2max test, with 1-min passive recovery) produced a moderate to large effect-size suppression of HRV at 30 min and 1 hour after exercise but small effect size differences from baseline between 4 and 24 hours after exercise [74]. On the other hand, a similar study of ten intervals of 1-min duration at 85 % of HR reserve suppressed HRV only immediately after exercise, with a return to baseline by the 1-hour mark, continuing through 8 hours after exercise [75].

In a study comparing 30-minute supine cycling bouts at three intensities (2, 3, and 4 mmol of lactate), HRV suppression was present in all three conditions 5 minutes after exercise, in the 3- and 4-mmol conditions 15 minutes after exercise but had returned to baseline in all three conditions by 30 minutes after exercise [76]. Similarly, participants undergoing a 300-kcal exercise bout at either 50 % or 80 % of VO_2 reserve returned to baseline HRV levels within 30 minutes after exercise, though levels remained suppressed longer (up to 25 minutes) after the higher intensity condition [77].

Most studies of a single exercise bout have found minimal disturbance to HRV from the single session, though most of the sessions were not particularly challenging in intensity. In contrast, when comparing constant velocity exercise at VT1 with the same overall workload on a bike, but including 9 × 1 min of maximal intensity intervals, HRV was suppressed for both conditions in the hour immediately afterwards but with greater suppression in the high intensity group [78]. Further, there may be some effect of body position on the persistence of HRV suppression, as decreased HRV was observed in the standing but not supine conditions at 24 and 48 hours after exercise in both conditions [78].

The fitness level of the participant may impact the level of intensity that will lead to prolonged perturbation of HRV. After a

maximal intensity 75-km ski race, for example, HRV was suppressed one but not two days after the race, and the time to return to normal was inversely correlated with individual's VO$_2$max [79]. However, HRV measured after a marathon and an hour at 70 % HRmax in recreational runners found no relationship between VO$_2$max and nocturnal perturbation of HRV [80].

Exercise duration

Exercise duration is an important component of overall training load, and increases in overall exercise volume have been shown to decrease HRV [63–65]. However, the amount of training volume necessary to produce HRV suppression may be population-dependent and driven by relative difference rather than absolute volume. For example, in highly trained endurance athletes, HRV measures were unaffected by a 60- and 120-minute runs, provided they were performed below VT1 [70]. Even in the immediate post-exercise period, HRV returns to baseline levels fairly quickly after endurance exercise, provided it is of low to moderate intensity, such as 50 and 63 % of VO$_2$max [71] or below VT1 [70]. On the other hand, in a population of moderately active non-athletes, a 90-minute moderate (60 % of VO$_2$max) session reduced nocturnal HRV compared to control, whereas 30- and 60-minute sessions at the same intensity did not [72]. In ultra-endurance events, decreased HRV (measured as HF power) and decreased baroreceptor sensitivity have been observed in both elite and recreational athletes [81].

Exercise modality

Numerous studies have been done examining HRV in response to different types of training interventions, including continuous aerobic endurance, high-intensity interval, resistance, coordinative, and multimodal exercise [82]. However, few studies have compared the effects of different modalities of endurance exercise on athletes. A study of healthy young men performing three modalities of maximal exercise tests (cycling, walking, and running) found that HRV recovered more quickly after the cycling test, which also elicited a lower maximal HR [83]. A few studies have assessed differences in HRV during exercise in different modalities, though the challenges of matching intensity across different activities make it difficult to draw conclusions [19]. Research has focused primarily on land-based sports without restrictions on breathing, which may alter the interpretation of HRV data [84].

Lifestyle factors

The sensitivity of HRV to lifestyle factors such as life stress, diet, alcohol consumption, smoking, sleep, and body composition has been well-established in literature examining HRV as a means of assessing cardiometabolic risk [85, 86]. It is not unreasonable to expect that endurance athletes may also be subject to the influence of such factors on resting HRV.

Partial sleep deprivation in the form of a reduction of hours of sleep to 3 or 4.5 hours has been shown to decrease HRV [87, 88]. Alcohol use may also impact HRV, with a dose-response relationship. Only small effects were observed from a low dose (0.3 g/kg) [89], and significantly more suppression of HRV was seen with two drinks when compared with one [90]. In addition to the more obvious deleterious effects of smoking on endurance athletes, smoking has been shown to acutely reduce HRV and negatively impact leg cycling performance [91]. The use of other drugs and medications consumed either acutely or chronically, particularly those acting upon the autonomic nervous system, may also have a marked impact on HRV [92]. Given that the "stress response" is typically characterized by a reduction in parasympathetic activity, it is not surprising that some types of life stress have been shown to reduce HRV [93]. These may include perceived emotional stress [94], anxiety [95], depression [96], and transient stress before bed [97]. Self-perception may modify HRV, as the changes in HRV due to a mental stress task were smaller in students with higher self-esteem [98].

Training prescription based on daily HRV

HRV-guided training

The use of HRV-guided training prescription has been investigated in the literature and is being used in the real world to make training decisions [99–103]. Most studies of this approach have compared a training schedule with a set schedule of workouts with one that varies the inclusion of higher intensity work depending on the daily HRV score. Typically, an individual baseline resting HRV is established over a period ranging from 3 days to 4 weeks [99, 100]. Protocols of HRV-guided training vary, but typically moderate and higher intensity workouts are performed only when the HRV score falls within the normal range [99, 104]. Lower intensity workouts and/or rest days are prescribed until HRV returns to normal.

Defining the physiologically normal range is done on an individual basis, using the smallest worthwhile change [100, 105] established over a number of days. A number of applications, such as HRV4Training and EliteHRV [106], ithlete[107], and Welltory [108] have been validated for measurement of daily HRV and can be used by athletes to establish baseline levels and assess daily recovery status. Alternative approaches to the smallest worthwhile change have been studied. For example, vigorous training was prescribed if HRV either increased or stayed the same, while a decreased training load was prescribed when the HRV decreased [101, 103]. The interpretation of increases in HRV above the normal range remains a subject of debate, and one where individual variability of response may come into play [13].

A systematic review on HRV-guided training for runners found greater improvements in performance in the HRV-based groups than in those who followed a predetermined training plan [99]. In most cases, the HRV-guided training led to reduced volume of moderate and high intensity training. Another review including healthy cyclists, runners, and skiers, ranging from untrained to elite, found HRV-guided training to be as effective as but not superior to pre-determined training [104]. A meta-analysis of studies on HRV-guided training for endurance athletes found significantly greater improvements in submaximal exercise measures, whereas performance and maximal exercise measures did not significantly differ between groups [109]. However, there were proportionally more positive responders and fewer negative responders to HRV-guided training groups.

An 8-week intervention in distance runners found greater improvements in 3-km time trial in the HRV-guided training group compared to the traditional training group [100]. In a recreationally active population, the use of two different HRV-guided training

approaches compared to a pre-planned program resulted in similar gains in VO$_2$peak, though women in the study gained the same benefits with fewer vigorous intensity sessions [101]. Another study from the same group also favored the HRV-guided training group in maximal running velocity and VO$_2$peak [103].

In endurance trained males, there were greater improvements in peak treadmill velocity, countermovement jump, and resting HRV in the time and frequency domains when compared to a pre-determined block training paradigm, with no difference in 3-km running performance [110]. In a study of professional runners, HRV-guided training improved peak treadmill velocity and peak respiratory exchange ratio [111]. Unlike previous studies, where HRV-guided groups achieve comparable performance through fewer sessions above VT1, the HRV-guided group in this study spent more time between VT1 and VT2, raising the possibility that HRV-guided training may be beneficial for some runners who are able to handle more high-intensity sessions.

When implementing HRV-guided training, practitioners should be aware of the divergent changes in HRV seen with modifications in training volume or intensity [112]. Further, it is worth noting that all of these studies compared a pre-determined training plan with HRV-guided training, whereas athletes often work with an exercise professional such as a coach who may adapt training according to athlete response.

HRV and maladaptive states

In addition to its use in guiding training, HRV has been suggested as a means of detecting and assessing severity of maladaptive states, including illness [113, 114], overtraining [15, 115], and concussion [18]. Concussion is an area of great interest in sport science research in recent years, but is much more prevalent among team sport athletes. Illness and overtraining, on the other hand, are common among endurance athletes.

Overtraining is thought to be a result of an imbalance between training and other stresses and recovery, leading to symptoms such as disturbed sleep, fatigue, mood disturbances, altered hormone levels, prolonged muscle soreness, and a reduction in exercise capacity [116]. Detection of overtraining syndrome is challenging, and with no clear diagnostic criteria, it often becomes a diagnosis of exclusion [117]. Overtrained athletes have been observed to have reduced HRV in both supine and upright positions [15]. On the other hand, a case study of a junior cross-country skiers experiencing overtraining symptoms showed an increase in HF and total power in the supine position [118]. One study showed an increased strength of relationship between RR interval length and HF power in overtrained endurance athletes [115]. In a group of elite canoeists engaged in a 6-day intensive training camp, VO$_2$max and maximal lactate decreased, but HRV measures did not change [119]. This suggests the possible use of HRV to distinguish between overtraining and short-term training fatigue.

A recent meta-analysis found a negative correlation between HRV and inflammatory processes, such as illness [113]. In a critical care setting, HRV suppression has been used to predict severity of illness and mortality risk [120, 121]. Less severe illness may also impact HRV. In elite-level swimmers, HRV was suppressed during weeks characterized by upper respiratory or pulmonary infections [114]. However, the predictive ability of HRV in this study was unclear; during the week prior to infection, HRV was higher in the supine position but lower in the upright position.

The potential for HRV monitoring to successfully identify early-stage illness and/or overtraining remains to be determined. In the face of such health issues, it is unclear whether HRV could be utilized to successfully adapt and adjust in order to reduce severity or duration of illness and other medical issues. However, HRV-guided training and monitoring of health status using HRV and other biometric markers represent potentially useful tools to assist athletes and coaches in navigating such challenges.

Alternative HRV monitoring options

Exercise HRV

Exercise leads to an increase in heart rate to meet increased metabolic demands, while time and frequency HRV measures decrease dramatically [19, 122–125]. Although there are differences between the methods as well as possibly between modes of exercise, the general pattern is that HRV decreases in a dose-response relationship with exercise intensity. At moderate intensities, HRV reaches a relatively stable, low level, and there are minimal changes with further increases in exercise intensity [19]. As a result, these measures are difficult to interpret in the context of exercise at the levels of intensity at which athletes often train. Evaluation of HRV during exercise is not as common as resting HRV at rest. It is, however, fairly reliable and reproducible, though reliability may be compromised at very high intensities [126].

Nonlinear measures of exercise HRV have been used to monitor and adjust exercise intensity during a discrete workout session. Specifically, a DFAα1 value of 0.75 has been suggested to be equivalent to the aerobic threshold as measured using ventilatory data [127]. Monitoring applications such as Heart Rate Variability Logger and FatMaxxer use DFAα1 calculated in real time to adjust exercise intensity [127, 128]. Though it can "detrend" and adjust for changes in exercise intensity, staying at the same exercise intensity for a minimum of two minutes is recommended for these applications.

Post-exercise HRV

As noted in the section above on factors affecting daily HRV, recovery of HRV upon cessation of exercise may differ between exercise sessions. The monitoring of HR and HRV recovery after exercise may provide valuable insight into the stress of the session. Recovery back to baseline HRV levels commonly occurs within the hour after exercise [19, 70, 71, 75, 77, 78, 129–133]. Low-intensity exercise may even increase HRV immediately after exercise if the intensity is appreciably low [71, 134]. However, exercise at intensities above VT1 appears to contribute to greater or longer periods of HRV suppression [70, 78, 133, 135]. Nighttime monitoring may also be of value, as Hynynen et al. [80] showed moderate to strong correlations between nocturnal HRV and post-exercise suppression of HRV. Post-exercise HRV may also be correlated with improvements in anaerobic fitness, as post-exercise RMSSD was correlated with improvements in repeated sprint ability after a nine-week training program [136]. The monitoring of post-exercise HRV as a tool for HRV-guided training has not been explored to our

knowledge, but could serve as a useful tool for endurance athletes, particularly those engaged in high training volumes and/or multiple training sessions per day.

Future directions

Given the abundance of data and metrics available to coaches and athletes, there is increased interest in physiological forecasting, or predicting outcomes or performances based on an array of variables that may be collected using wearable technology and other means. These technologies may be able to quantify stress and recovery outside of the training period to improve quantification of training load [137]. It seems clear that HRV alone is not linearly predictive of performance, as it has been observed that HRV may diminish slightly during the peaking phase [13]. Additionally, changes in endurance performance are not always coupled with changes in HRV or other metrics used to monitor training such as the countermovement jump [138]. However, observation of individual patterns and responses to training, carried out longitudinally, allow for an understanding of individual physiological response to training and other stimuli. In one study, correlations between HRV and measures of training load were not significant between individuals, but were significant within individuals when using repeated-measures correlations [139]. This and other studies support the notion that exercise prescription may be improved with longitudinal HRV monitoring. Some recreational runners may improve more with high volumes of endurance exercise instead of greater intensity, and these differences are correlated with changes in nocturnal HRV [140]. Baseline HRV at the start of a training period may also be related to improvements in training in a recreational population [141]. These factors should be considered when attempting to guide training using HRV in combination with physiological and psychological variables. Exploration of practices such as HRV-biofeedback training, which have been used successfully used to increase HRV [8], could also be assessed as a training tool.

Previous research applying HRV to sport has focused largely on endurance sport. While that population is the focus of this review, it is worth noting that endurance athletes often also engage in resistance exercise and anaerobic activities. Little is currently known regarding the use of HRV for guiding resistance training or exercise prescription in team sport environments. A study of recreationally active adults engaged in high-intensity functional training found similar improvements in body composition, strength, and VO_2peak when training was guided by HRV, despite a 20% reduction in high-intensity sessions over a 9-week period [142]. Resistance exercise suppresses HRV but may [143] or may not [144] effectively differentiate differences in fatigue from varying exercise bouts. The timeline of HRV recovery may differ from other variables, including countermovement jump and psychological variables. Nuuttila et al. [135] observed different fatigue recovery patterns for countermovement jump and post-exercise HRV depending on exercise intensity. Similarly, Vacher et al. [145] noted linear changes in HRV despite nonlinear changes in perceived stress and recovery. Thus, HRV data can be viewed as one piece of a puzzle, contributing to improvements in predicting performance, enhancing training and competition strategies, and refining the science of endurance sport.

Conclusion

Many endurance athletes at all levels are using HRV in a variety of applications. Increased availability and ease of access to tools for measuring and processing HRV data carry the promise and possibility for further enhancement of training and competition practices. However, athletes and coaches are cautioned to use a rigorous approach to controlling for the quality of data being collected and to be aware of key variables that can affect HRV measurements. Practices such as daily HRV monitoring and HRV-guided training are well-established, promising applications that should be considered by endurance athletes. Finally, the use of HRV should be understood as one piece in the complex network of physiological regulation and adaptation. Future research integrating a variety of metrics – including HRV – promise to further our understanding of endurance performance and training, and to aid individual endurance athletes in developing a nuanced understanding of their own physiology.

Conflict of Interest

The authors declare that they have no conflict of interest.

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