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A Systematic Review on Heart-Rate Recovery to Monitor Changes in Training Status in Athletes

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Heart-rate recovery (HRR) has been proposed as a marker of autonomic function and training status in athletes. The authors performed a systematic review of studies that examined HRR after training. Five cross-sectional studies and 8 studies investigating changes over time (longitudinal) met our criteria. Three out of 5 cross-sectional studies observed a faster HRR in trained compared with untrained subjects, while 2 articles showed no change as a result of training. Most longitudinal studies observed a corresponding increase in HRR and power output (training status). Although confounding factors such as age, ambient temperature, and the intensity and duration of the exercise period preceding HRR make it difficult to compare these studies, the available studies indicated that HRR was related to training status. Therefore, the authors conclude that HRR has the potential to become a valuable tool to monitor changes in training status in athletes and less well-trained subjects, but more studies and better standardization are required to match this potential.

Keywords: heart-rate variability, oxygen uptake

Heart-rate recovery (HRR) can be defined as the rate at which heart rate declines, usually within minutes after the cessation of physical exercise.¹⁻³ The autonomic nervous system (ANS) regulates both the initial increase in heart rate after the start of physical activity and the decrease in heart rate immediately after physical activity ends. The ANS is composed of a parasympathetic and a sympathetic branch that operate in a reciprocal and inverse manner: An increase in heart rate is caused by an increase in sympathetic activity combined with decreased parasympathetic drive, whereas HRR is characterized by parasympathetic reactivation and sympathetic withdrawal.³⁻⁷ Cardiac output is adjusted during exercise based on the metabolic demand. The regulation occurs by intrinsic autoregulation of cardiac pumping (the so-called Frank-Starling law of the heart) and by sympathetic activation and parasympathetic deactivation, which increases heart rate and the contraction force of mainly the left ventricle.⁸ Increased sympathetic activity combined with parasympathetic withdrawal (eg, during exercise) leads to reduced skin blood flow and increased blood flow to the muscles.⁹ When the exercise stops, cardiac output is reduced by intrinsic autoregulation (by the ANS), more

specifically by parasympathetic nervous system reactivation and inhibition of sympathetic impulses.

Although it is well documented that changes in HRR coincide well with changes in training status in patient populations,¹⁰ to our knowledge a systematic review on the use of HRR in athletes is missing. HRR may be an indicator of fitness, which is currently generally expressed in terms of VO_{2max} or VO_{2peak} , the maximum oxygen uptake during exhaustive exercise. Although VO_{2max} has a strong relationship with training status in a general population, it loses its predictive value for aerobic performance in already well-trained and elite athletes.² In addition, the typical error of measurement of VO_{2max} is relatively high, which makes VO_{2max} unreliable to monitor training changes over time.² In contrast, parameters such as HRR, peak power output, and/or peak treadmill running speed have lower typical errors of measurements, which makes them more sensitive to detect changes in training status.

Therefore, the aim of this study was to conduct a systematic review on the use of HRR in athletes to track long-term changes in training status.

Methods

Data Sources

An electronic literature search was performed in the digital databases of Scopus, EMBASE, and PubMed. The search terms used were a combination of *heart/pulse rate(s)*, *recovery/deceleration*, *(physical) exercise*, and *health(y) subjects/population*. This search yielded 90 scientific articles (see Figure 1).

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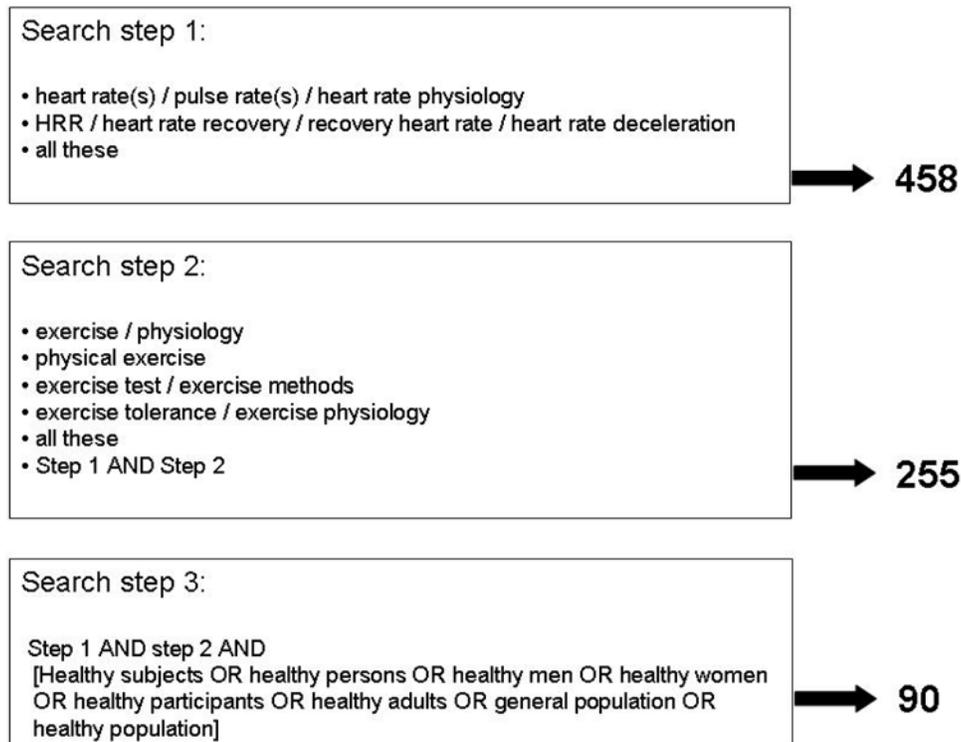


Figure 1 — Schematic overview of the literature search process.

Study Selection: Inclusion and Exclusion Criteria

All considered articles were published before 2011 in generally accessible, English-language, peer-reviewed scientific journals. The abstracts of the 90 articles were read independently by the 4 reviewers to decide whether inclusion criteria were met.

Inclusion was based on

- HRR being the dependent variable: The method to determine HRR was not considered as an inclusion or exclusion criterion.
- Applying a period of physical training of at least 5 days. The type of training was limited to endurance training or interval training aimed at increasing endurance. As a result, 2 articles using strength training were excluded.
- The selected sample being specifically recruited from healthy athletes.

Using these inclusion criteria, 5 of the original 90 articles remained, mainly in the area of sports research.^{1,2,11–13} These articles were read and the reference lists were checked. Based on this analysis, 7 other articles were found that met the inclusion criteria^{14–20} but had been missed using the original databases and search terms.

Therefore, 12 articles were included as part of the current systematic review. After reading the articles and comparing the references, we have the impression that the selected articles cover the area of the review topic. We evaluated the included articles independently using the COSMIN (COnsensus-based Standards for the selection of health Measurement INstruments) method as a guideline.²¹ Using the COSMIN guidelines, we conducted a structured qualitative analysis of the available studies. The results of this analysis are presented, together with our common observations and overall conclusions.

Results

The results are presented as cross-sectional and longitudinal studies. Table 1 summarizes the essential parameters of the selected studies.

Cross-Sectional Studies

In the 5 cross-sectional studies, trained and untrained subjects participated in a maximal or submaximal test after which HRR was measured. Four studies^{14–16,22} reported the HRR measurements after a single test, while 1 study¹² measured HRR after several tests. An overview of the 5 cross-sectional studies is given in Table 2A.

Darr et al¹⁴ found that HRR was about 6 beats/min faster in trained subjects (average VO_{2peak} 60 mL · kg⁻¹ ·

Table 1 Overview of Studies Included in the Review

	N (gender)	Groups	No. of participants per group	Selection criterion groups	Measurement	Training or observation period
Cross-sectional studies						
Bosquet et al ²²	26 (M, F)	2	13,13	% VO _{2max}	HRR (60 s)	
Buchheit et al ¹²	33 (M)	4	8, 10 (<15 y); 5, 10 (<17 y)	fitness, age	HRR (60 s)	
Darr et al ¹⁴	20 (M)	4	5, 5, 5, 5	training status, age	HRR (60 s) and others	
Dixon et al ¹⁵	24 (M)	2	10, 14	training status	HRR (300 s)	
Du et al ¹⁶	14 (F)	2	6, 8	training status	HRR (60 s) and others	
Longitudinal studies						
Borresen and Lambert ¹	28 (M, F)	3	9, 8, 11	performance increase, decrease, or same	HRR (60 s)	2 wk
Buchheit et al ¹²	33 (M) (teen-agers)	1	33	n/a	HRR (60 s)	3 wk
Giallauria et al ¹³	49 (M, F)	2	24, 25	over 70 or under 60	HRR (60 s)	8 wk
Hautala et al ¹⁷	95 (M, F)	2	80, 15	trained and control	HRR (60 s)	2 wk
Lamberts et al ¹⁸	14 (M)	1	14	n/a	HRR (60 s)	4 wk
Lamberts et al ¹⁸	14 (M)	2	8, 6	HRR increase or decrease	40-km TT time and HRR (60 s)	4 wk
Lamberts et al ¹⁹	15 (M)	1	15	n/a	HRR (60 s)	5 wk
Sugawara et al ²⁰	10 (M)	1	10	n/a	HRR (30 s)	8 wk

Abbreviations: M, male; F, female; VO_{2max}, maximal oxygen uptake; HRR, heart-rate recovery; TT, time trial. HRR (60 s) means that the difference in heart rate is calculated between the last value at the end of exercise and the value 60 min after the end of exercise.

min⁻¹) than in untrained subjects (average VO_{2peak} 40 mL · kg⁻¹ · min⁻¹), while no age effect of HRR was observed. Dixon et al¹⁵ showed that HRR recovered faster in 10 highly trained male long-distance runners (average 58 beats in 5 min) than in 14 sedentary male control subjects (average 35 beats in 5 min). Du et al¹⁶ showed that HRR was faster in 6 well-trained female marathon runners (about 62 beats in 1 min) than in 8 female subjects who were not physically active (about 55 beats in 1 min). Bosquet et al²² showed no differences in HRR between a group who reached their ventilatory threshold at a relatively low or at a relatively high percentage of maximal running speed. Buchheit et al¹² observed that HRR was faster in under-15 than the under-17 soccer players after a submaximal running test (5'-5' test).

In summary, 3 of the cross-sectional articles reported a faster HRR in trained subjects than in untrained subjects.¹⁴⁻¹⁶ The article by Bosquet et al¹¹ showed no difference in HRR as both groups possibly had a similar training status and as VO_{2max} has a limited power to detect change in training status.^{23,24} The article by Buchheit et al¹² showed no difference in HRR between subjects who had a fast and slow maximal aerobic speed. However, as

none of the training-status parameters differed between the groups, no conclusion can be drawn.

Longitudinal Studies

The longitudinal studies investigated changes in HRR over longer periods of time and were frequently interspaced by programs that aimed to either improve or maintain performance. A comprehensive overview of the 8 included longitudinal studies is presented in Table 2B.

Buchheit et al¹² showed no changes in HRR during a 3-week soccer competition camp. Borresen and Lambert¹ showed that HRR remained unchanged in the group that kept their training load constant, decreased (ie, slower HRR) in the increased-training-load group, and showed a tendency to increase (faster HRR) in the decreased-training-load group for 2 weeks. However, these outcomes need to be interpreted with care because changes in training status were not measured using maximal-performance tests in this study.

Lamberts et al² showed an increase in HRR after 4 weeks of high-intensity training (measured after a 40-km time trial). A strong relationship was found

Table 2A COSMIN Evaluation of the Evaluated and Described Cross-Sectional Studies

Study	Strengths	Remarks	COSMIN evaluation
Darr et al ¹⁴	Representative sample(s): 4 groups. High sampling frequency HRR (every 30 s).	Although VO _{2max} is included, it is not used to validate HRR. (Very) small size. No comparison of different cardiovascular variables.	Mediocre to reasonable: Although representative sample, subsamples are too small; no cross-validation using the other cardiovascular variables.
Dixon et al ¹⁵	Small, though representative, sample. Comparison of HRR and HRV (validation). Assessment or measurement design. Matching for relevant covariates.	Small sample size, only men. Due to design, no specific effects of physiological challenges over time in the control subjects can be evaluated.	Reasonable: only men, though nice comparison between groups. Comparison HRR with HRV outcomes.
Du et al ¹⁶	Athletes vs controls. HRR and HRV included.	Small sample. Only females. No cross-validation of HRR using HRV.	Reasonable: small sample size, only females. Comparison HRR with HRV outcomes.
Bosquet et al ²²	Homogeneous sample. VO _{2max} , HRR, and HRV included. VO _{2max} used as selection criterion for 2 subsamples (high and low). Comparison HRR and HRV.	Athletes, consequently not a representative sample for general population. Groups different on relevant covariate.	Mediocre to weak: homogeneous, nonrepresentative sample. Although sample is divided on relevant selection criterion, both subsamples appeared to differ significantly on relevant covariate (weight).
Buchheit et al ¹²	Apart from longitudinal design, relevant comparison subsamples are being selected (transversal). HRV (lnRMSSD) and HRR included. Naturalistic setting. Multiple measurements over time.	Division in 4 subsamples (young vs old, fit vs less fit) may be too much for sample size. Not aimed at HRR: no conclusion can be drawn regarding how changes in training status are mirrored in changes in HRR.	Reasonable: from a transversal-perspective, repeated-measures design. Though nonstandardized training load, what makes it hard to interpret: only little information on HRR, only indirect validation.

Abbreviations: COSMIN, COnsensus-based Standards for the selection of health Measurement INstruments; HRR, heart-rate recovery; VO_{2max}, maximal oxygen uptake; HRV, heart-rate variability.

between the change in HRR and the change in 40-km time-trial time. When the subjects were allocated to a group that showed a continuous increase in HRR throughout the entire training period (I) and to a group that showed a decrease in HRR (D), group I improved their mean and absolute relative power more than group D.¹⁸ However, as these groups were not fully matched, these outcomes must be interpreted with care. Another study by Lamberts et al¹⁹ looked at the reliability and predictive capacity of a novel submaximal cycle test including HRR. Training status and HRR did not change, while the typical error of measurement for HRR measurement was 2 beats.

Sugawara et al²⁰ showed an improvement in HRR in 10 healthy untrained men during an 8-week training

program, which returned to baseline during the following 4 weeks of detraining. No objective performance parameters were measured after 8 and 12 weeks.

Hautala¹⁷ showed an improvement in VO_{2max} in 80 sedentary men and women after a 2-week endurance program, while HRR did not change. However, as no changes in peak power output were reported, confirming no change in training status, these outcomes need to be interpreted with care.

Since participation of the elderly in athletic events has become more common, it is interesting to include the study of Giallauria et al¹³ in this review. This study shows significant improvements in VO_{2max} and HRR after 8 weeks of training in elderly subjects. However, again, no peak power output values were reported.

Table 2B COSMIN Evaluation of the Evaluated and Described Longitudinal Studies

Study	Strengths	Remarks	COSMIN evaluation
Sugawara et al ²⁰	Elaborative protocol. Naturalistic setting, normal adults. Actual validation of HRR. Alternative algorithm for HRR.	Small sample size. Only (young) men. Comparison t30 with classical methods would have strengthened the article.	Mediocre: small sample size and lack of external validation of t30.
Giallauria et al ¹³	Naturalistic setting. Elderly: representative sample. Standardized, longitudinal physical training program. Change in HRR in response to exercise program (8 wk).	Letter to the editor/abstract. Young sample showed no changes in HRR, though did not follow training program either: 2 × 2 design might have been more appropriate.	Reasonable: Sample size is considerable; comparison of (changes in) HRR with other cardiovascular outcomes; describes changes in HRR over time as a result of regular physical exercise.
Hautala et al ¹⁷	Representative sample. Used cardiovascular variables. Used parameters of HRV.	Information control group is lacking. Opportunity to investigate relation between different HRV components and HRR (external validity) missed.	Reasonable to good: nice design with clear-cut hypotheses and although not specifically used for that aim strong external comparison of HRR.
Borresen and Lambert ¹	Standardized protocol. Naturalistic setting. Covariates included.	Sample size may be (too) small to justify subsamples. No changes in performance parameters measured.	Reasonable: no real measurements available that can show a change in training status before and after the observation period.
Lamberts et al ²	Longitudinal (standardized) design. Participants intensively monitored. Standardized outcome measure. Comparison with peak power output and 40-km time-trial performance.	Specific population (well-trained athletes). Monitored during period of high-intensity training.	Reasonable to good: comparison with peak power output and 40-km time-trial performance outcomes contributes to external validation.
Lamberts et al ¹⁸	Allocation to group based on HRR. Longitudinal (standardized) protocol.	Groups were not fully matched.	Reasonable: As groups were not fully matched, relative changes in performance parameter were also compared between the 2 groups. Although sufficient, a relatively small sample size.
Lamberts et al ¹⁹	Longitudinal (standardized) design. Naturalistic sample. Standardized assessment battery.	Repeatability design. Athletic sample. No change in training status.	Reasonable to good: from a statistical perspective (measurement error, intraclass correlation) a well-designed and -described study.
Buchheit et al ¹²	Developmental factor included (age). HRV (lnRMSSD) and HRR. Naturalistic setting.	Specific outcomes (above-average physically active adolescents). Not particularly aimed at HRR. Sample size may be (too) small to justify subsamples. No change in training status. Significant changes in subjective feelings of fitness/fatigue and total activity time.	Reasonable: the inclusion of both HRV and HRR is a major advantage of this study as it provides the opportunity to check for external validity. Relatively large variations in HRR and significant changes over time in subjective feelings of fatigue.

Abbreviations: COSMIN, COnsensus-based Standards for the selection of health Measurement INstruments; HRR, heart-rate recovery; HRV, heart-rate variability.

In summary, the longitudinal studies can be subdivided into 3 categories: category 1, studies reporting a change in HRR with a concomitant change in training status^{18,20,25}; category 2, studies that report no change in HRR with no change in training status^{12,19}; and category 3, studies that show a change in HRR but do not report adequately how training status changed in their subjects.^{1,13,17} Based on these findings there appears to be empirical evidence that an increase in HRR occurs when the training status or (physiological) fitness improves in healthy individuals.

Discussion

Although an extensive literature search yielded 90 scientific articles, only 12 articles matched the criteria and described HRR and training status in healthy subjects. Seven of these studies were not found by standard search terms but were indirectly derived from the 5 articles that remained after the search protocol. In some cases the keywords attached to an article were not optimal to cover its content. The available studies substantially differed in methodology (both in design and ways to calculate HRR), research population, and type of physical challenges used to induce a cardiovascular effect. The available studies could be divided into cross-sectional studies (comparing HRR between groups) and longitudinal studies (studying changes in HRR over time). In general, the results of longitudinal studies are more reliable than those of cross-sectional studies since they exclude the possibility of selection bias. In addition, this research design provides the opportunity to determine the association between the change in HRR and the change in training status. These associations have a practical application for the ongoing monitoring of athletes. In 1 study¹² both designs were combined.

The focus in this review is on HRR. However, both HRR and heart-rate variability have been identified as powerful indicators of an individual's well-being and physiological training status due to their close link with the autonomic nervous system.²⁶ Although some authors suggest that HRR seems to be more responsive to recently applied training loads,^{26,27} more recent work^{28,29} shows that heart-rate variability can also track fast changes in training status.

When reviewing the articles it became evident that changes in HRR could only be well interpreted if changes in training status were also well documented. As several studies^{1,12,17} did not accurately report training status and changes, these studies were hard to objectively interpret.

Overall, 3 cross-sectional studies^{14–16} showed a faster HRR in well-trained than untrained healthy individuals. In addition, 3 longitudinal studies reported a faster HRR with an improvement in training status after a training intervention.^{2,18,20} Two longitudinal studies^{12,19} showed that HRR did not change when training status did not change. The groups were not well matched for body composition (eg, body-mass index, sum of skinfolds) or training status (eg, maximal running speed and competi-

tive playing time) in the study of Buchheit et al,¹² and their results should be interpreted with caution.

These results support the notion that HRR has sufficient sensitivity to also be used as an indicator for training status in healthy individuals. In support of this, the cross-sectional study by Bosquet et al²² showed similar HRR rates in subjects with same peak treadmill-running velocities (training status). We challenged their concept that ventilatory threshold should be seen as the only indicator of training status. We were unable to objectively interpret the findings of Hautala et al,¹⁷ as no real changes in training status were measured, and subjects took part in a relatively short training program (2 wk).

The findings by Borresen and Lambert¹ seem to contradict the findings in the other articles, as they show that HRR decreases with an increase in training load and there was a tendency for a faster HRR with a decrease in training load. The authors speculate, however, that the decrease HRR with an increase in training load can possibly be explained by a sharp increase in training load (training impulses increased by $55\% \pm 22\%$), which made the subjects show symptoms of overreaching. The findings by Lamberts et al¹⁸ support this hypothesis since subjects with a decrease in HRR improved their 40-km time-trial power output less than subjects who had a continuous increase in HRR. In contrast, in a case study in an elite cyclo-cross cyclist, HRR increased along with a large increase in training load.³⁰ The authors explain this observation as representing a decreased sensitivity to the sympathetic nervous system in line with earlier work of Lehmann et al³¹ and speculated that a faster HRR will be observed with acute fatigue while a slower HRR is found with a chronic fatigue state. These findings suggest that HRR can be used not only to predict changes in training status but also to monitor the accumulation of fatigue.

Confounders

Apart from training status and possibly the accumulation of fatigue, other factors can affect HRR. These factors are briefly discussed following and are based on the available literature, including articles not included in the systematic review.

Personal Factors

Age can affect HRR. The maximum heart rate varies considerably between subjects and decreases with increasing age³² but may also have a small dependency on training status.³³ As age increases, maximum heart rate decreases. If thresholds for HRR such as 12 beats/min³⁴ are used as risk indicator for cardiovascular diseases, elderly subjects will therefore easily be assessed to be at risk. In line with the decrease in maximal heart rate with age, Antelmi et al³⁵ observed a slower HRR in older subjects. Even independent of age, subjects with high peak heart rates have better HRR.³⁶ Age can therefore be a potential confounding factor when assessing change in HRR measurement over longer periods (>5 y).

Gender may be a factor of relevance, as well. Although Arena et al³⁷ observed faster recovery in males, Antelmi et al³⁵ found just the opposite, while Lamberts et al³⁸ did not report gender-based differences.

The article by Hautula et al¹⁷ showed that genetic polymorphism in acetylcholine receptor M2 (CHRM2) also partially explains HRR. This finding indicates that, especially within homogeneous groups, changes in HRR need to be used with care as an indicator of overall training status and, rather, changes in HRR should be used as an indicator of a change in training status.

Exercise Intensity, Type, and Duration

Exercise Intensity. In contrast to heart-rate variability-analysis, measurement of HRR has to be preceded by an exercise period. Obviously, high exercise intensities will result in high heart rates and therefore are likely to create a larger decrease in heart rate after the cessation of exercise.³⁹ HRR from maximal exercise seems to be slightly slower, mainly because sympathetic activation may carry on into the early stages of recovery.^{25,40}

Type and Duration of Exercise. The mode of exercise (intermittent vs continuous, endurance vs resistance⁴¹) and exercise duration³⁹ affect HRR. Since the human body adapts to exercise, differences are observed in HRR between different types of exercise: Athletes engaged in intermittent sports have faster HRR than endurance athletes.⁴² In addition, differences are observed in HRR for different types of endurance exercise. HRR yields higher values for running than for cycling, which is probably related to the higher aerobic demands in running.⁴³ Otsuki et al⁴⁴ observed that both strength- and endurance-trained subjects show improved HRR compared with controls.

Based on the mentioned confounders, the use of a standardized exercise protocol before HRR is measured is imperative to yield consistent results. Standardization has to address the exercise mode, intensity, duration, and frequency. Examples of standardized protocols are the HIMS,^{2,38} a submaximal running test consisting of 4 stages that aims to elicit a submaximal heart rate 90% to 95% of heart rate maximum, from which HRR is measured, and the 5'-5' test,⁴⁵ a submaximal running test in which subjects run for 5 minutes at speed of 9 km/h, which is followed by 5 minutes of seated rest during which HRR is measured. However, since these tests have a fixed exercise intensity, a change in training status might result in a different heart rate at the end test, and subsequently one would calculate HRR from a different heart rate. A recent study by Lamberts et al,⁴⁶ however, shows that this possible confounding effect can be minimized if the heart rate at the end of the test is 86% to 94% of the maximal heart rate. Minimization of the measurement error improves the ability to detect small changes between interventions.

Another way around this limitation is to fix the submaximal heart rate before the measurement of HRR. This approach has been adopted in the submaximal cycle

test when it is designed to finish at 90% of heart-rate maximum.¹⁹ This method ensures that HRR is always measured from the same submaximal heart rate and thus reduces variation in HRR.

Environmental Factors

It is increasingly difficult to release body heat to the environment when the ambient temperature and humidity are high, wind is absent, and the sun heats the body through radiation. In those cases of climatic strain, the blood vessels in the skin open up, resulting in reduced venous return, which is compensated by an increased heart rate.⁴⁷ In line with these observations, Kilgour et al⁴⁷ found a slower HRR after work in the heat than after work under thermal-neutral circumstances. The same mechanism also applies for rest in the heat.

Calculation Methods

HRR is calculated over different time frames, generally ranging between 30 seconds and 2 minutes. Most studies use the difference between the end value of exercise and heart rate after 60 seconds of recovery as the dependent variable. Lamberts averaged the heart rate at the end of exercise over the last 15 seconds and took the 1-minute value as the average over seconds 45 to 60.^{2,38} This method seems to be more objective and is less dependent on the exact actual moment of cessation of exercise.

If 2 minutes are used to calculate HRR instead of a single minute, the decrease in heart rate is obviously higher. After 2 minutes, the heart rate is closer to baseline values. It is well documented that the results differ between methods:^{37,48} HRR after 1 and 2 minutes should be considered different parameters. Some authors argue that using the values only after 1 or 2 minutes of exercise disregards the information between the time intervals and propose fitting an exponential function.⁴⁹ However, the simplicity of the 1-minute method should be appreciated. Although Bosquet et al¹¹ observed no differences in reliability between the HRR after 1 minute, 2 minutes, and the fitted function, Lamberts et al³⁸ clearly showed that the coefficient of variation of the HRR measurement was significantly higher after 2 minutes than after 1 minute. It is important that a consensus be reached on the time frame over which HRR should be calculated. The available data suggest that HRR after 1 minute has a better capacity to detect meaningful differences over time than HRR measured after 2 minutes. HRR is generally expressed in absolute terms (beats/min). It may be useful to express it relative to the heart-rate recovery (ie, the difference between resting and maximal heart rate) to minimize interpersonal differences.

Traditional Statistics and Magnitude-Based Inferences

In most studies, traditional statistics ($P < .05$) are used to test a hypothesis and determine if a parameter has

significantly changed over time. Although sometimes no significant differences can be shown (due to, for example, a small sample size), the change in parameters can still be clinically relevant. To objectively quantify this, Batterham and Hopkins⁵⁰ have proposed an additional statistical analysis known as magnitude-based inferences. This method quantifies the likelihood of a difference being clinically relevant. For this procedure, normal day-to-day variations of the parameter need to be known. Normal day-to-day variation in HRR have been studied by Lamberts et al^{25,38} and Buchheit et al.¹² HRR in a large group of individuals working at different exercise intensities varies by 8 ± 3 beats on a day-to-day basis³⁸; individuals who reach heart rates of 85% to 95% of heart-rate maximum vary by only 6 ± 2 beats.²⁵ In addition, Lamberts recently showed that adapting workload decreases the typical error of measurement of HRR, achieving the highest sensitivity to detect meaningful changes at 86% to 94% of heart-rate maximum.⁴⁶ The typical error of measurement of HRR in the submaximal cycle test was 2 beats.¹⁹ In addition to magnitude-based inferences, day-to-day variation in HRR can also be used for sample-size calculations for future studies.

Practical Applications

Cross-sectional studies show that HRR is faster in trained than in untrained healthy individuals. All longitudinal studies, except for that of Hautala et al,⁵¹ support the capacity of HRR to quantify differences in training status between trained and untrained healthy individuals. When fatigue or a state of overreaching are excluded, HRR improves with a better training status, remains unchanged with no change in training status, and decreases with a decrement in training status. Therefore, based on the limited and diverse literature available, we recommend HRR as a possible tool to monitor training status in athletes and less well-trained subjects, to optimize training programs and monitor the accumulation of fatigue. The use of HRR to indicate overreaching still has to be investigated.

Nonetheless, changes in HRR need to be interpreted with care. Confounding factors such as the testing protocol after which HRR is measured, environmental factors, genetic polymorphism, state of fatigue, and possibly age and gender need to be taken into account when interpreting changes in HRR. The effect of confounding factors such as climate on HRR needs to be further investigated and at least taken into consideration when interpreting HRR on both an individual and a group level.

While it is difficult to make a fair comparison between studies due to presence of several factors influencing HRR, each study itself can be seen as a valuable contribution to the knowledge pool. Most of the investigated studies observed improvement of HRR when training status improved, and we could identify methodological flaws in the studies that did not show consistent results.

In addition, it is important that HRR be measured after a standardized test, which elicits a similar heart rate relative to its maximum and is associated with the lowest possible typical error of measurement. The error can be brought down to about 2 beats/min, which guarantees the highest sensitivity to detect meaningful changes in HRR due to training or fatigue in athletes. Focus of future studies should be to confirm that fatigue can be monitored with HRR and to establish the difference between heart-rate variability and HRR.

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